CHAPTER II GEOLOGY

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SHORELINES AND COASTS OF THE GULF OF MEXICO [1]

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INTRODUCTION

The scientific study of shorelines is inextricably involved with that of the hinterland, the coastal zones, the adjacent inshore waters and the climate. This linkage brings together regional geology, geomorphology, sedimentation, oceanography of the inshore zone, meteorology, climatology, biology, chemistry, late geologic history and the ecology of some marine and coastal organisms. As the study of shorelines and their classification is in somewhat incomplete and controversial condition today, it is necessary to give a brief review of the subject before discussing the shoreline of a particular region, such as the Gulf of Mexico, where there are new types and where we have previously had few over-all geological oceanographic conceptions to guide us.

STATUS OF STUDIES OF COASTS AND SHORELINES

The geological study of shorelines and coasts has been intermittently developed by numerous geologists and geographers. The principal discussions of costal geomorphology that are readily available are Johnson's (1919) detailed treatise on shoreline development and his study of the New England-Acadian shoreline (1925), Shepard's (1937a, 1948) revision of Johnson's shoreline classification, Steers' (1946, 1952) analytical description and history of the shoreline of England, Wales, and Scotland, and Russell's (1940) study of the development of variations in deltaic shorelines in Louisiana. McCurdy's (1947) discussion of criteria for the delineation of shorelines from air photographs yields critical details of some types not found elsewhere. Fleming and Elliott (1950) have made a beginning of an over-all quantitative and qualitative oceanographic approach to the study of shorelines which is here revised, enlarged and treated in greater detail, in some of its aspects, for the Gulf of Mexico. Some of the oceanographic data treated by these workers have not been considered here.

Among the greatest present needs in geomorphic coastal studies are a critical analysis and description of the coastal plain shoreline and regional studies combining the geomorphic and oceanographic approaches. The research on which this paper is primarily based was a comprehensive survey of the shorelines of the Gulf from existing data, including results of the writer's 20-year study of the northwestern Gulf Coast. The survey was made by the writer in 1951–1953.[3] It has revealed a number of new types and relationships not yet critically discussed in publication. Because of this situation, the writer is handicapped in attempting a discussion of the coasts of the Gulf of Mexico within as condensed a scope as that of the present paper.

The application of quantitative oceanographic science to the analysis of the development of shorelines is being slowly accomplished through the work of numerous scientists and engineers by isolated studies of beaches, cliffs, deltas and estuaries, but has only lately been attempted for whole regions. In the writer's current research, an attempt is being made to apply a quantitative regional approach to the study of the influence of oceanographic processes on shorelines and the associated coastal and shallow-water bottom conditions. Some of the results of this work are reflected in this paper.

SHORELINE CLASSIFICATION

Eduard Suess (1888) showed that regional or continental shorelines might be classed as concordant or discordant with the grain (dominant trend) of the geologic structures of a coastal region, but King (1942, p. 99) cautioned that marine activities subsequent to the drowning of a coast or the formation of its folds and faults may have

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[3] Contains no references to the work of others after March 1, 1953.

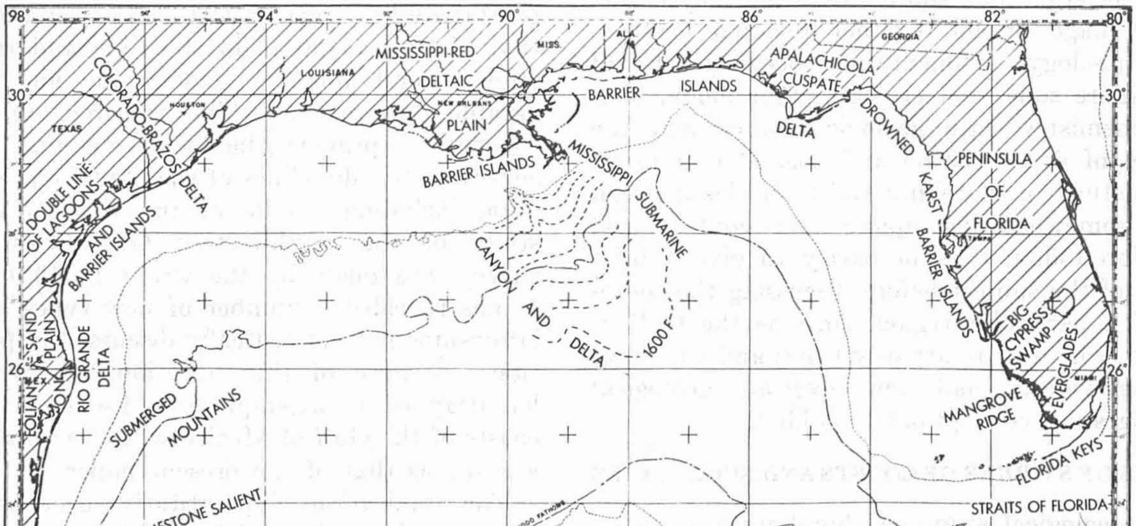

Figure 12.—Shorelines of Gulf of Mexico, showing locations of major geographic features. (Contour lines off the Mississippi delta are drawn at 200-fathom intervals.)

altered the shoreline so that it may no longer conform to a simple structural classification. Johnson (1919) assembled and extended previous ideas of coastal development and classification to produce a detailed genetic-geomorphic system that has since been followed by most writers. However, it seems not to have been applied by its users to the detailed mapping of the coasts of a large, diversified region such as the Gulf of Mexico, although Johnson (1925) applied it to the drowned and largely discordant shoreline of the New England-Acadian region of northeastern North America.

Shepard (1937a, 1948) modified and extended Johnson's system, giving a tabulation in which shoreline and coastal types then described were inserted. His major divisions differ from Johnson's and seem not to have been accepted by all of Johnson's followers, although the scarcity of papers on the classification of shorelines indicates that this may be due to inertia rather than to a working appraisal of the usefulness of Shepard's revised system. Johnson's text is out of print and has not been supplemented by a similarly detailed work.

Regional variations in the known physical oceanographic conditions in the "inshore" zone[4] of the coasts of the United States and Mexico were discussed by R. H. Fleming and F. E. Elliott (1950) in lectures. They regarded the scarcity of such information too great for elaboration of their method at that time. It, however, classifies coastal sectors into glacial, alluvial, young orogenic and biogenous types, with erosional and depositional sub-types for the first three. The continental coasts of the Gulf of Mexico were included in the maps and discussion. The Fleming-Elliott system has been modified and extended in some of its aspects for use in the present study as the geo-oceanographic classification system. Changes in their mapping of the Gulf coasts include the introduction here of young orogenic sectors and the relegation of biogenous coasts to a secondary condition imposed on a framework of regional geologic and geomorphic types. In the latter instance, the suggestion made by Shepard (1948, pp. 78–79) is followed that a regional classification could be made by using large subdivisions such as coasts with young mountains, old mountain ranges, broad coastal plains, glaciated coasts, and such specific but less common items as volcanic coasts and tableland coasts.

Space does not permit including here an elaboration of the detailed genetic-geomorphic classification systems. As detailed knowledge of many coasts accumulates, including coastal plains such as those of the Gulf, the list of the distinctive small-unit features becomes encylopedic and the classification headings numerous, beyond the simplicity desired (Lucke 1938) for text-book and lecture purposes.

Definitions.—The shoreline is the line where land and water meet. It moves back and forth over the shore or shore zone. The shore on a beach has been defined (Beach Erosion Board, Corps of Engineers, U. S. Army) as the zone between mean low tide (or lower low tide) and the inner edge of the wave-transported sand. The lagoonal shore is that of the tidal bays and lagoons. Estuaries are tidal stream courses. Their shores are not studied here except where they are embayed. On some coasts there are extensive, muddy shore-flats. Tidal flats are properly those within the range of normal gravitational tides. In some places winds blow the water across broad, gently sloping wind-tide flats[5] that extend inland from the true shore, hence, beyond the high tide limits for gravitational tides, and have been floored by deposits left by the water.

The coast is a zone of indefinite width back of the shoreline that is affected by or closely affects offshore or shoreline processes and forms. The waters lying near the coast where the effect of a shallow bottom is felt may be called coastal waters. The continental shelf (fig. 13) is a submerged, gently sloping plain that extends the continent oceanward to varying depths ranging, generally, between 40 and 100 fathoms. The shelf is terminated seaward by the steeper shelf slope that descends, in places precipitously, to the depths. Additional definitions will be given in later paragraphs when the barrier island, the shelf and its equilibrium profile, and the mangrove coastal ridge are discussed.

New and undescribed types.—New types recognized on the shorelines of the Gulf of Mexico which will be readily understood from previous geomorphological knowledge are (1) the drowned karst (sub-aerial limestone solution topography) of parts

[4] Shallow water or nearshore zone. Some writers use "inshore" for lagoonal and estuarine environments.

[5] New term.

of Florida and the Yucatán Peninsula (fig. 12; fig. 14, sector 2.1); two minor forms: (2) sand dunes briefly drowned by exceptionally high tides; and (3) wind-tide flats, previously described. Other new types that form striking features on the coast of southern Florida and the Yucatán peninsula, are (1) the great mangrove barrier ridge (fig. 12; fig. 14, Sector 4.1); (2) the irregular mangrove coastal lagoon between the mainland and the ridge, (3) the drowned lacustrine plain of the Bay of Florida (fig. 14, Sector 4.1 north of Florida Keys and east of Cape Sable; fig. 15) as interpreted by the writer, with former lakes of marsh or swamp now invaded and enlarged by salt water, and (4) what the writer believes is the same type of coast slightly elevated (elevated lacustrine plain) to form the pocket harbors (Hayes, Vaughan, and Spencer, 1901) of northwestern Cuba (fig. 12; fig. 14, sector 3.1). The present paper does not offer an opportunity for full critical discussion of these new types.

Besides the distinctly new types of shoreline and coast, noted here, a number of fairly well known geomorphic forms were found which have not previously been included in shoreline classification lists. Prominent examples for the northwestern Gulf coast are the broadly to roundly embayed drowned-stream valley with shallow, pan-shaped depositional bottom previously described and investigated by the writer (Price 1947) and the drowned deltaic topography (fig. 12, between Birdfoot delta of Mississippi and Lake Pontchartrain) described by Russell (1936, figs. 6, 7; 1940).

SOURCES OF INFORMATION

Published articles include (1) the numerous detailed geological reports and maps on coastal land areas in the United States[6] with a few generalized and regional reports on those of Mexico and Cuba, (2) shoreline and coastal studies of the United States Army Engineers, (3) a few ecological studies of coastal areas chiefly in Florida and Louisiana, (4) progress reports of the oceanographic survey of the Gulf of Mexico being conducted by the Department of Oceanography of the Agricultural and Mechanical College of Texas (Leipper, p. 125) and progress reports on investigations of sedimentation and other shallow water conditions of the northwestern Gulf of Mexico by the American Petroleum Institute and similar commercial projects. Among scattered reports on previous oceanographic cruises yielding shoreline or shallow water data (5) is a study of foraminifera in bottom sediments by Phleger and Parker (1951). Much geographic and some geomorphic information is found in Tamayo's (1949) extensive text and atlas of the general geography of Mexico.

[6] Most complete for Florida and Louisiana.

Important raw data, some of which are listed in the following paragraph, include (7) topographic maps and air photographs of the land, (8) original Federal hydrographic surveys, including some old surveys of the British Admiralty, (9) navigation and (10) aeronautical charts made from these sources, with (11) the coast pilot and sailing directions handbooks of these organizations, and (12) bottom-sediment charts of the shelf of the northern Gulf. Topographic data are scarce outside the United States and of unequal detail and coverage for the different States. For Mexico, air photography made by the United States and Mexican governments is available under restrictions. The Cuban hydrographic organization has issued a coast pilot (Derrotero) containing new coast charts.

Charts and other aids in study of coasts.—For any detailed study of these shorelines it is necessary to have first, a set of nautical charts. Figure 12, a finding map for this study, is drawn on the base of the general chart for the Gulf. The less accurate and detailed these aids are for any coastal sector, the more they need to be supplemented by air photography, topographic maps and geologic reports. The following charts are recommended.

U. S. Coast and Geodetic Survey Nautical Charts (U. S. Shores).—General Charts, 1002, 1007, 1290: Sectional Charts 1113–1117; Coast Charts 1249–1280. For special details, some of the large-scale charts of islands, harbors and canals, and Chart A634. See catalog: Serial No. 665.

Hydrographic Office, U. S. Navy, Nautical Charts (Mexico and Cuba).—General (coastal) Charts 1125BS, 1126, 1126BS, 2145, 2056, 0966, 5487. See catalog: Pub. I–N.

Marina de Guerra, Departmento de Inspeccion, Officina Hidrografica, Republica de Cuba.—Derrotero de la Isla de Cuba (sailing directions). Parte Segunda, 1951, 173 pp. 21 figs. has coast charts from recent surveys done on thin paper, bound in the book. Soundings and underwater contours are given to depths of from 30 to 60 brazos de agua (Cuban fathoms).

World Aeronautical Charts, U. S. Air Force (Mexico and Cuba).—Charts 522, 586–589, and 643–645. See: Aeronautical Chart Catalog, Coast and Geodetic Survey.

Topographic Maps, Air Photographs and Geological Reports.—The U. S. Geological Survey publishes a series of key maps for the United States, Alaska, and Insular possessions showing the status of topographic mapping and air (aerial) photography, including mosaic sheets and with some geologic mapping. State maps showing the areas covered by all published geological reports and articles are available for some States from this agency. The State geological surveys and bureaus also furnish lists of their publications. The Geologic Map of North America, Geological Society of America, 1946, and the American Geographical Society's Map of North America are useful regional aids, besides State geologic and topographic maps.

Areal summaries of oceanographic data.—Since Vaughan's (1937) survey of information available in this field no general key maps have been published. Articles on geological oceanography of coastal areas are now listed in geological bibliographies.

ACKNOWLEDGMENTS

The writer is indebted to a large number of persons and organizations too numerous to list here. Valuable aid was received from the State geological surveys of Florida and Louisiana, and some former members of the latter; several members of the United States Geological Survey; officials of the Coast and Geodetic Survey, Hydrographic Office, photographic branches of the Army, Navy, and Department of Agriculture, and the corps of Engineers; geologists of the Mexican federal geological survey and petroleum development agency, as well as numerous individual geologists, biologists, ecologists, and other persons familiar with remote and little-known parts of the shorelines of Mexico, Florida, and Louisiana. To his colleagues in the Department of Oceanography of the Agricultural and Mechanical College of Texas, the writer is deeply indebted for orientation and guidance in oceanography during the years of 1950–53, as well as for specific information and aid. The development of the research on which this condensed paper is based was followed closely by Warren C. Thompson and Charles C. Bates, while doing research in the Department, with whom many helpful discussions have been held. The impetus in the development of the geo-oceanographic classification here used, as has been said, came from the manuscript by R. H. Fleming and F. E. Elliott.

STRUCTURAL AND REGIONAL GEO-OCEANOGRAPHIC APPROACH TO SHORELINE DESCRIPTION AND CLASSIFICATION FOR GULF OF MEXICO

COASTS AND HINTERLAND

The Gulf provides a good example of the well-recognized relation (Weaver 1950) of the topography of the hinterland to the width of coastal plains and continental shelves (fig. 13).[7] The geologic structure of any hinterland largely controls its topography and has a direct or indirect effect (Suess 1888) on the character and positions of shorelines. These factors are dominant in determining the drainage and hence, the transport of sediment from the land to coastal areas.

[7] Taken from Price (1951 b).

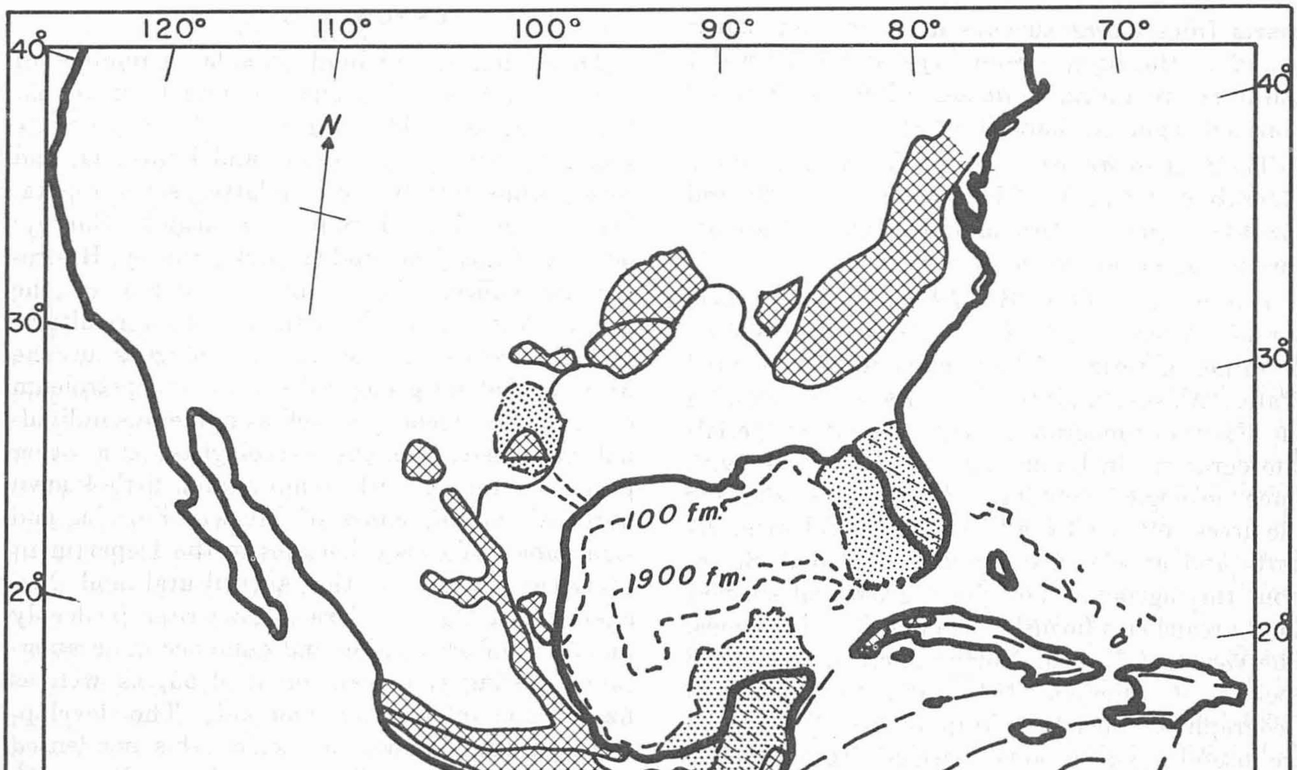

FIGURE 13.—Major geologic structures exposing uplifted rock masses surrounding Gulf of Mexico. Cross-hatched, folded sedimentaries, granitic areas, volcanic belts. Stippled, uplifted arches or horsts. Stipple and dash, emerged parts of arches form limestone plateaus at south and east. Under-water contours, 100 and 1,900 fathoms, the former out-lining the continental shelf, the latter, the Mexican Basin (Sigsbee Deep). Long broken lines, axes of arcuate Caribbean folding (axis of Gulf coast geosyncline, supposedly along northwest shore, not yet located. Scale: Hundreds of miles.

REGIONAL COASTAL TYPES

YOUNG OROGENIC COAST

Where geologically young mountains (Tertiary to Quarternary) closely border the coast (Umbgrove 1947, pl. 5), as in Cuba and the southwestern Gulf coast in Mexico (figs. 12, 13; fig. 14, Sector 3), coastal plains and the continental shelf are absent, narrow or of irregular width, and the shelf tends to be rocky with shoals and irregular elevations (Fleming and Elliott 1950) as well as somewhat steep (slope greater than about 5 feet per statute mile). Sand and mud[8] occur on the shelf and mud along the outer margin and in shelf deeps. The coast may have alternating narrower erosional and wider depositional sectors, the latter with smooth shorelines and bottoms, the former with uneven surfaces. These coasts and shelves are unstable and subject at any time to earthquakes, fracturing and warping of the crust.

[8] Sediment terminology used is that of the coast charts. "Mud" is a field term implying no accurate knowledge of the clay fraction.

Young orogenic coasts have their shorelines dominantly parallel (concordant, Suess 1888) with the structural trends (folds and faults) of the mountains. The Gulf provides no examples of coasts where the shoreline is more than very locally discordant with the structural trends on land.[9] This accounts to a large extent for the almost complete lack of islands in the Gulf other than sandy barriers close to shore, karst islets of Florida, some lava-rock islets in Sector 3 in Mexico, and coral and detrital reefs on shoals. From the meager data of the charts we conclude that, because the Mexican mountains are mostly not younger than Miocene, coastal sediments have built out around or otherwise protected most of their outpost hard rock folds from the Gulf. However, a large mountain range projects eastward under water some 50 miles off Tampico and two parallel mountain ridges trend northwestwardly from the edge of the continental shelf off the Rio Grande delta.

The Tertiary mountains of Cuba (Palmer 1945) rise from a short distance back of the coast. The folded rocks come down to the coast or are overlain there by a thin cover of younger deposits. The island may be divided into several areas of different tectonic structure, but overthrust folds rising up to the south dominate some sectors, as in the extreme west. The Gulf bottom off the north coast descends at angles of 4° to 6° or more, a slope which conforms fairly well to some of the folds. A narrow shelf occurs only where fringing reefs have grown up with a rising sea level to form barrier reefs, so that the lagoon has been filled to a shallow depth with sediment and organic growths (3.2 Sectors, fig. 14).

The drainage of northwestern Cuba is largely southward, so that only small streams enter the Gulf and the coralline lagoons. The sedimentation along the northwest shore has, therefore, been negligible except where coral reefs and mangrove growth have trapped marine and land-derived materials. An erosional sector occurs between the barrier reefs east and west of Havana.

The Sierra Madre Oriental, the eastern cordillera of Mexico, slants southeastward toward the coast, one of the outpost folds in limestone rock making a minor protuberance at Punta Jerez (fig 13).[10] The coastal plain becomes gradually narrower southward from the delta of Rio Grande. It is, however, as much as 60 or more miles wide in places.

The Southern Volcanic Range of Mexico (Sierra Neo-Volcanica, Tamayo 1949), a zone of Tertiary-to-Recent volcanic peaks, runs from the Pacific coast due east through Mexico City to form the broadly protuberant Jalapa Salient north of Veracruz at 20° N. Lat. A similar salient south of the city, that of San Martin Tuxtla, separated from the range, may be geologically associated with it. The range includes some of the greatest peaks of Mexico, including at the east, in sight of the Gulf, Orizaba and Cofre de Perote, reaching elevations of 18,696 and 14,048 feet, respectively, above sea. Between and on each side of these salients are sedimentary embayments (fig. 14, 3.2) with fairly broad coastal plains. Only a narrow belt of low shoreline deposits seems to be present along the fronts of the volcanic salients. These salients are composed of confluent and overlapping flows of volcanic rocks, some of which make small jutting points at the shoreline. Of these, Roca Partida and Punta Delgada have cliffed faces reported to be 1,000 feet high, with islets of lava rock.

There are several volcanic peaks in the San Martin salient, including San Martin Tuxtla, which has been active in historic time. On air photographs of this sector, the writer counted some 20 small cinder cones aligned in a zone about 10 miles wide and 40 miles long parallel with the coast. One of the cones stands in the intermountain Lake Catemaco with its crater invaded by the water.

The continental shelf off the orogenic coast of Mexico is poorly mapped. It is narrow and, where mapped, the gradient is convex, becoming steep, like that near the outer edge of the shelf of Texas and Louisiana. The grain sizes of the sediments, so far as is revealed by the data on the charts, decrease more regularly outward than on some better-known orogenic coasts, as that of California where there are separate offshore sedimentary basins both on and off the shelf, each with its own sedimentary distributional pattern. The small size of the sub-aerial drainage basins where mountains stand near the coast has

[9] Discordant coasts are found today chiefly where old mountain areas, as from New England to Newfoundland, have been drowned by sinking of coasts under load of Pleistocene ice sheets.

[10] The convexity here is exaggerated on H. O. Chart 2056 as compared with the later W. A. C. 589, made from a photographic base.

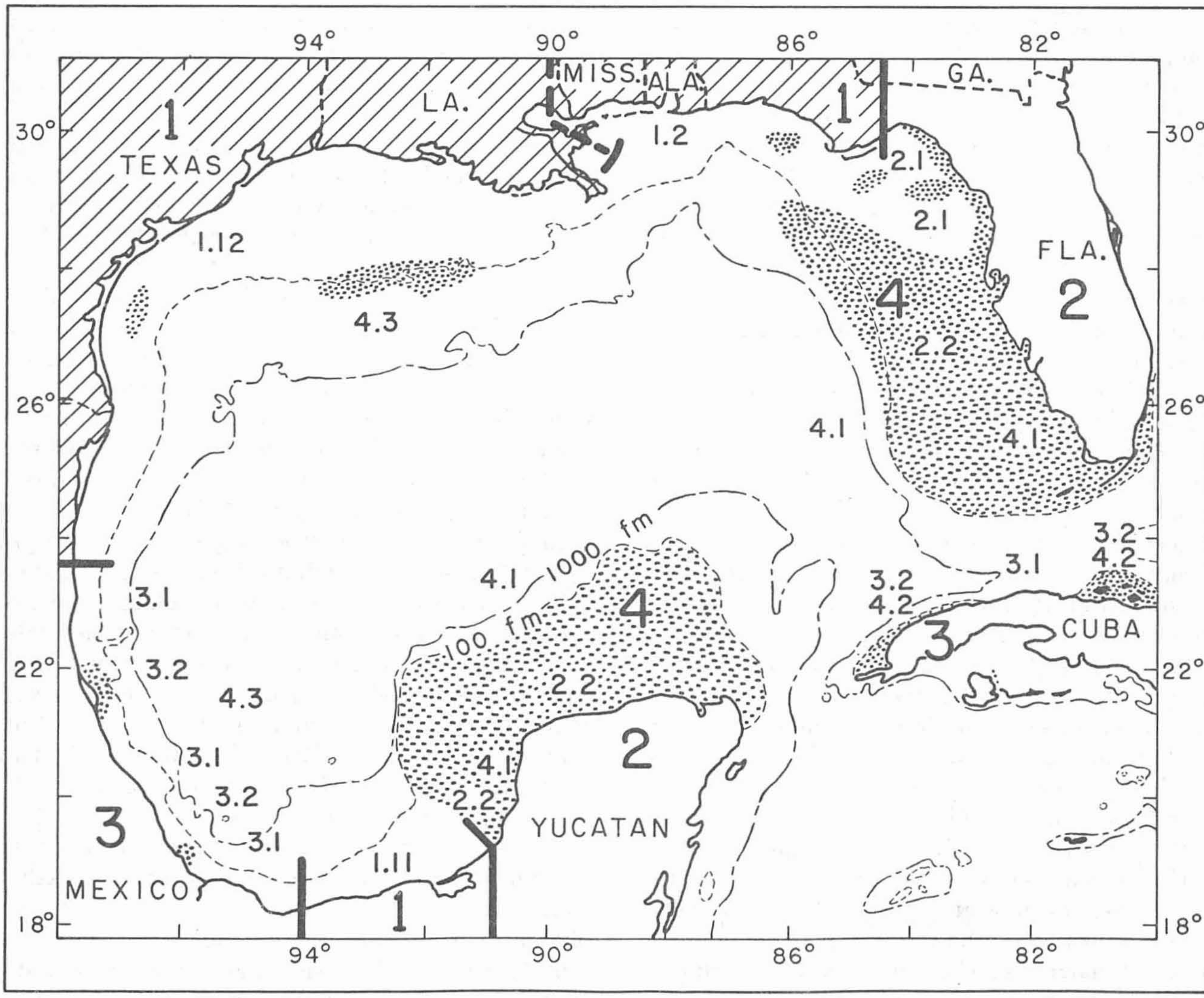

FIGURE 14.—Regional geo-oceanographic classification, shorelines and coasts, Gulf of Mexico: 1, alluvial coasts; 2, drowned limestone plateaus; 3, young orogenic coasts; 4, biogenous (organic) development on various coasts. Sub-sectors: 1.1, deltaic coasts, with 1.11, unentrenched simple deltaic plain, and 1.12, entrenched and embayed compound deltaic plain. 1.2, terraced deltaic coastal plain; 2.1, unsimplified to little simplified drowned karst; 2.2, limestone karst with beaches; 3.1, erosional, and 3.2, depositional, orogenic coasts; 4.1, broad shelf; 4.2 shelf absent to narrow; 4.3 lesser biogenous development (more extensive than shown). The two southerly Mexican 3.1 Sectors are volcanic salients.

been shown to restrict coastal sedimentation. This is true here, in that the shelf is wide off the several sedimentary salients, but narrow in front of the coastal mountain salients.

ALLUVIAL COASTS

Where the closest mountains, usually old mountains, are located far or moderately far inland (Umbgrove 1947, pl. 5), the runoff and sediment load from the lands has been large and long continued, interior plains are succeeded by broad coastal plains and continental shelves, and the coast is of the deltaic (Fleming and Elliott 1950) or alluvial coastal plain type. On such a coast, after sufficiently long stillstand, shelf bottoms are smooth except toward their outer margins, organic reefs are inconspicuous, few or absent, and shorelines are smooth or irregularly deltaic (fig. 13, and No. 1 Sectors, fig. 14). Sediments here are generally of even distribution to somewhat spotty (Lynch, fig. 16). Sands extend from shore out to about 5 or 10 fathoms, followed by silt or sand and mud (charts), with mud further out to the edge of the continental shelf. Mud or silt may come in very close to the mouth of a deltaic river that drains a large basin. The chief exceptions to the outward banding of sediments (Emery 1952) are any coarse sediments of local organic or chemical origin, or, along the northwestern shelf of the Gulf, sediments on mounds believed to lie above buried intrusive salt dunes (Shepard 1937 b).

The alluvial sectors of the Gulf of Mexico (Sectors Nos. 1.11, 1.12, and 1.2, fig. 14) have smooth shorelines with sandy beaches on the mainland, or on barrier islands (Price 1951 a). The beaches may be more or less interrupted by deltas of varying degrees of protuberance and shoreline irregularity (Russell 1940; Bates 1953). Offshore, the alluvial sectors have broad, smooth continental shelves, 130 miles wide at the maximum, with relatively steep inshore shelf-bottom profiles (fig. 15, Sector VII) and a rather uniform gradation of sediment from sand (generally inside the 5- or 10-fathom depth contour) to sand-and-mud, with mud at the outer margins. The elevated mounds on some outer parts of the northwestern shelf have nodular algal limestone on their tops and possibly some coral.

Subsectors, alluvial coast: terraced detaic plain.—Sector 1.2, Alabama, Mississippi, and western Florida (fig. 14), has a fairly steep coastal plain,[11] with two Pleistocene-and-Recent deltas (Apalachicola, Pascagoula, and Pearl), a minor amount of embayment of drowned stream valleys and a reported series of low, parallel elevated shoreline scarps (Carlston 1950). In places, the younger two of these have roughly parallel Pleistocene barrier islands and coastal lagoons (MacNeil 1950) in part entrenched by drainage and embayed. This coast is like that of the southern Atlantic coastal plain of the United States, with which it has a common geologic history. These similarities exist because of the position of the old (Paleozic), almost entirely quiescent Appalachian mountains fairly close (90 to 150 miles) to the coast but not in a bordering position. Drainage basins extending from the mountain front across the coastal plain are small in relation to those of the deltaic 1.12 alluvial coast. The large cuspate Pleistocene-Recent Apalachicola delta and the long, broad, and shallow Mobile Bay are striking features of this coast

[11] Eight feet per mile near the coast in some places.

Broadly embayed deltaic coastal plain.—Sector 1.12 (fig. 14), the coast of Louisiana, Texas, and part of Tamaulipas, receives the drainage of some ten major rivers. Three major Recent deltas now reach the Gulf; the Mississippi-Red, Brazos-Colorado, and Rio Grande deltas. A very broad, gently sloping deltaic coastal plain (Barton 1930) has been built, forming a fully concordant coast (Suess 1888). Coastal plain deposits form a new structural (monoclinal) trend in front of the abrupt southwestern ends of Appalachian folds once projected into the broad Mississippi embayment.

Sector 1.12 (fig. 14) is deltaic except between arcuate delta fronts where the active barrier and the Pleistocene Ingleside barrier island (Price 1933) with their parallel, active and entrenched coastal lagoons form a diversified inner coast transected by many broadly drowned and embayed stream valleys (Price 1947). There are, thus, intermittent terraced riverine plains between adjacent protuberant Recent deltas. Behind the terraced belt are continuously overlapping and coalescing Pleistocene deltas with their surfaces slightly up-warped inland. The great protuberant Mississippi-Red delta (Russell 1936; 1940; Bates 1953) dominates the eastern part of this sector both at the shoreline and on the shelf where large shoals seem to indicate submerged deltas. A minor feature of the deltaic coast is the saline marsh (paralic) environment described on a later page with the biogenous environments.

Saline plain of Rio Grande delta.—A broad, treeless, saline plain, the Jackass Prairie of Cameron County, dominated in the native state by coarse, bunchy *Spartina* salt grass (sacahuista), stretches inland across the Recent delta north of the natural levees of the present Rio Grande course for a maximum distance of 10 miles. The Gulfward edge of the plain is honeycombed by saline lagoons lined on their lee (N., NW., W., and SW.) sides by clay dunes (Coffey 1909, Price 1933, Huffman and Price 1949). The soil of the low deltaic plain is made heavily saline by windblown (cyclic) salt contained in clay pellets and dust blown from the saline tidal flats of the lagoons. These flats undergo strong deflation during the warm months. Sand-sized pellets of flocculated saline clay accumulate on lee shores to build the dunes, while saline dust passes over the 30-foot-high dunes under the strong steady hot winds of the warm months.

From detailed topographic data it is estimated that about one-fifth of the wind-blown clay excavated from playa lake basins is caught on the dunes as sand-sized pellets and the remainder passes inland as dust. The saline plain is narrower in Willacy County to the north where the Recent delta and the zone of playas and dunes is narrower than to the south near the Rio Grande.

Unentrenched deltaic sector.—Sector 1.11, the coast of Tabasco and parts of Veracruz and Campeche, Mexico (figs. 12, 14), is a simple deltaic coast with a tropical rain-forest and fairly wide tidal streams that are not embayed. The large Laguna de Terminos is a delta-margin depression, a feature which Bates (1953) thinks is normally a nondepositional basin. Sinking by compaction, former entrenchment and enlargement by wave and current scour are factors that aid in shaping some of the delta-margin basins. This sector has a broad, gentle deltaic plain, abundantly crossed by innumerable courses of the Tonala, Seco, Grijalva, Teapao, Usumacinta, San Pedro Y San Pablo, and Palizada Rivers. These courses are grouped into two main deltas; the Seco-Grijalva delta at the west, with a broadly and symmetrically bowed shoreline, and the asymmetrically bowed Grijalva-San Pedro Y San Pablo delta at the east. The latter has a small cuspate mouth.

DROWNED LIMESTONE-PLATEAU COASTAL PLAINS

Continental or insular shelves may exist off the above-water parts of oceanic shoals appearing as island groups or as peninsulas attached to continents. Very broad shelves, upwards of 100 miles wide, border the peninsulas of Florida and Yucatán in the Gulf (fig. 13 and No. 2 Sectors, fig. 14). These low peninsulas are great uplifted limestone shoals, now partly drowned limestone plateaus. Their origins have been discussed elsewhere (Price 1951b). The surfaces of these plateaus, both above and below water, show a young rolling karst topography of limestone solution with solution-basins and sinkholes. Surface drainage is locally absent and is supplemented by underground water circulation moving through solution channels. The Florida limestone is abundantly fissured, at least at the northwest (Vernon 1951).

The plateau peninsulas are terraced limestone coastal plains. They have delivered a minimum of land-derived detrital sediment to the shelves, so that, under tropical climates, these shelves in places abound and probably have long so abounded in great coral reefs (F. G. W. Smith, p. 291) and some reef-like bars and sand keys of shell detritus.

The sinkhole topography of the limestone plateaus is of subaerial origin, now modified in a broad belt near the shoreline, both above and below water, by coastal deposits (Vernon 1951)[12] and an undetermined amount of solutional activity (Fairbridge 1948). There are a few relatively narrow, submerged stream valleys. Submerged subaerial karst basins are, so far as known, only shallowly filled with a foot or two of sediment, yielding poor anchorage for ships. Offshore bottom slopes of the inner half or more of the continental shelf are very gentle (fig. 15, curve 6) to moderately gentle (fig. 15, curve 4), ranging from about 1.5 to 2.5 feet per statute mile. For a few miles offshore, there are many, irregular, shifting bars of shelly sand.

The limestone-plateau coasts have three types of subsectors: slightly elevated drowned karst salients of a low marshy coast (2.1), beach-bordered (2.2), and mangrove-ridge (4.1) shorelines. These show shoreline modification and smoothing ranging from a virtual zero modification through incipient planation to nearly completely smooth beach-bordered coasts. Coastal marsh and swamp of the limestone plateaus are abundantly channeled perpendicular to the shoreline by tidal scour. The tides are higher on the peninsula coast of Florida (range 2 to 4.5 feet) than on any other part of the Gulf shoreline. Inshore on the drowned karst coast, and offshore on it and on the other subsectors of the limestone plateaus, we have the so-called carbonate environment of the continental shelf (Trask 1937).

DROWNED KARST SHORELINE SUBSECTOR

Subsector 2.1 (fig. 14), along the northern coast of peninsular Florida north of Anclote Keys, near Tampa, has a new type, the drowned karst shoreline. Short convex areas have an intricate, crenulate shoreline with many small shoreline basins and archipelagoes of stony islets. Much of this karst shows, on the scale of the navigation charts, no modification by marine agencies. This entire subsector lacks embayed drowned stream valleys

[12] Zones of submerged bars and their uplifted counterparts on elevated terraces.

and sandy beaches (Martens 1931) except short, elevated stormbeach ridges and sandy beaches on some of the Cedar Keys archipelago at 29°10′ N. Lat. These latter beaches (Martens 1931) are somewhat muddy and unlike those of glaringly white sand on the front of the Apalachicola delta, Sector 1.2, and westward from it in Florida.

With this drowned karst coast of Sector 2.1, there are areas of transversely channeled marsh 2 to 3 miles wide occupied by grassy vegetation and forested swamp. This swamp is probably mostly saline. Patches of mangrove swamp occur in the southern part of this Sector.

The scattered mangrove swamps with offshore oyster reefs to be described mark a minor extension of the biogenous environment (Sector 4, fig. 14).

The drowned karst coast is conspicuous for its many and unique marine oyster reefs, located along a shallow-water zone extending outward to a distance of a mile or two from shore. *Crassostrea virginica*, the North American oyster of commerce, is notably lagoonal and estuarine, commonly being confined to brackish water environments by its marine-water foes. Only along parts of the Gulf coast are living reefs of this species known in oceanic waters in North America. On Sector 2.1, the highly fractured and channeled limestones of Florida are filled inland with fresh water to a considerable height above sea level. The slope of the groundwater surface (piezometric) toward the coast indicates a movement of underground water in that direction. Also, along much of the coast of Sector 2.1 there is an artesian groundwater head of about 10 feet near and at the shoreline (Cooper and Stringfield 1950, fig. 14). This pressure-head forms springs in the stream mouths and stream beds, as well as offshore.[13] The absence of land-derived sediment in these streams during most of the year and the protected nature of the shelf waters leave the water of the Gulf brackish here. Off the mouth of Atchafalaya Bay, Louisiana, oyster reefs also grow in the Gulf out to a distance of 3 to 5 miles, with the fresh water of the river mixing with Gulf water to produce a brackish environment.

Beach-bordered karst subsector.—Sector 2.2 (fig. 14) is represented both on the central coast of peninsular Florida and on the coast of the Yucatán Peninsula. On Florida, the sector has fairly continuous sandy barrier islands and barrier spits with some mainland beaches. This sector extends from Anclote Keys near Tampa at the north to Cape Romano at the south. The drowned karst lies behind the beaches and the coastal lagoons of the sandy barriers. The lagoons are bordered by mangrove swamp and with the karst depressions more or less filled with sediment and marshy growths.

The beaches of this sector (Martens 1931) have much shell material but also quartz sand. The quartz is derived from elevated sandy Pleistocene beach deposits of the elongated dome-shaped summit (300 feet or more) of the peninsula, which lies immediately inland, and from a sandy limestone formation that has been almost removed by embayment of several streams to form the broadly embayed harbors of Tampa Bay and Charlotte Harbor. These harbors are the only embayed, drowned, stream valleys of the Gulf coast of the peninsula, except the moderately widened tidal portion of Caloosahatchee River, nearby. The shelf-bottom slopes more steeply off this sector (2.2 feet per mile, fig. 15, curve 4) than it does farther north on Sector 2.1.

Cape Sable (fig. 12) protrudes into the Gulf where Florida Bay extends eastward at the end of the mainland of the peninsula. This major shoreline bend produces a convergence zone for waves, swell and currents with the local wave attack necessary to develop a beach, keeping the shore free of mangroves. The beach plain has cuspate points and encloses narrow lagoons behind it. The beach sand is presumably mainly shelly.

The oval area of plain behind the sandy beaches and the lagoons of the Cape is somewhat marshy. The origin of the broad, irregular lagoon known as Whitewater Bay, lying several miles inland from the beach is linked with the delivery of a concentration of drainage to a marsh. The bay is heavily fringed with mangrove swamp.

The beach-bordered subsectors (2.2) on the Yucatán Peninsula include the northern coast and the short Campeche–Champoton sector at the west. The northern coast has barrier islands and a number of slightly disconnected barrier spits which extend westward from moderate projections of the shoreline. Pinnacles of limestone

[13] Data on charts and reports of aviators via V. T. Stringfield, letter of 1952.

several feet high protrude through the beach in places (Sapper 1937). Marshy, swampy, and partly mud-filled coastal lagoons lie behind the barriers. They are extensively occupied by mangrove swamp forest. These lagoons are called "rivers" on some maps. They were formerly thought to form a continuous inner waterway across the north end of the Peninsula.

The short beach-bearing sector in the Campeche coast between the towns of Campeche and Champton (fig. 12), seems from air photographs and ground-elevation figures (20 feet to the north against 400 to 500 feet in the block) to be an uplifted fault block of limestone with entrenched stream valleys floored by narrow alluvial plains. The Gulf ends of these alluvial deposits have sandy-to-cobbly pocket beaches. Observers report seeing large blocks of limestone on some of them. One report, probably, erroneous, calls some of these blocks and a nearby outcrop "igneous" rock.

BIOGENOUS ENVIRONMENT

Where, on the coasts of the Gulf, land-derived sediments have been and are now scarce, sediments of organic origin with large marine organic structures become conspicuous. Such a biogenous environment (fig. 14, Sector 4) (Fleming and Elliott 1950) may vary, here and there, from a brackish lagoonal and inshore environment to a marine environment with waters of normal salinity or salinities somewhat above average (Trask 1937). Where the water is now, or has lately been, warm, tropical and of at least normal marine salinity, coral reefs thrive. The physical limitations of this environment have been long and widely discussed.

The biogenous environment is an oceanographic condition existing as an overlay on the basic geological coastal structures. It may occur on any type of shoreline where, and so long as, the requisite sedimentary and oceanographic conditions previously mentioned occur. The biogenous environment includes the carbonate environment, where Mollusca and corals are conspicuous among the sedentary organisms, and the paralic or marine swamp and marsh environments, such as those of the mangrove and salt-water grasses and reeds.

It may be that, with further analysis, a fundamental geological coastal type of biogenous nature may be recognized. Thus, the limestone peninsulas of Florida and Yucatán may, from the historical point of view, be considered geologically biogenous, since the limestones have been built up for millions of years under dominantly calcareous biogenous conditions. The Cuban coast, and the Gulf coast of Mexico west of the Yucatán Peninsula, are today only superficially biogenous, as the organic growths and sediments form a mere patchwork skin on the rock folds. Limestone series several thousands of feet thick among the folded and faulted rocks of Cuba, however, show that the site of the island was biogenous for millions of years. Deposits of argillaceous (clayey) shales and the great earth-deforming (tectonic) events, were major interruptions in the carbonate type of biogenous environment in Cuba. The structural conditions of Cuba today overshadow, for geologists, the biogenous history.

Carbonate subdivisional environment.—Subsectors of the biogenous coasts (Sectors 4) present a variety of structures and bottom types. Coral reefs and the carbonate environment in general occur on both broad (fig. 14, 4.1) and narrow (4.2) shelves. Large shelf areas have a conspicuous bottom-dwelling population. Among these, sponges are conspicuous. Actively growing coral reefs (Smith, p. 292) include fringing and barrier reefs on Cuba and a barrier reef along the outer side of the Florida Keys. This coral barrier runs along the edge of the shelf facing the Straits of Florida at the far southern end of the peninsula. Fringing reefs are also found here and there on other coastal sectors, as near the mouths of streams on the Mexican coast (Sectors 1.11, 3.1, 3.2) and on 4.1 on the Yucatán Peninsula. The great Colorados Barrier Reef of northwestern Cuba is fringing at its eastern end but encloses a 15-mile-wide lagoon to the west.

Atolls and atoll-like coral reefs of more or less tabular form occur west of the Florida Keys (Dry Tortugas atoll) and others form a great, discontinuous, barrier range along the northern and northwestern margins of the Yucatán shelf, called the Campeche Banks (Smith, fig. 62, p. 292). The best known of these is the large Alacran atoll. The Marquesas detrital atoll off Florida (Vaughan 1914; Cooke 1939, fig. 31) is not known to have coralline growth, the reef being a group of sand keys of shell detritus formed on the shelf by the strong westward currents and winds. The Marquesas is a great lunate key partly closed at the southwest by a series of smaller lunate keys curved oppositely to the major key and built by secondary currents from the west-southwest. The living barrier reef of southern Florida in front of the main Florida Keys stands in about 5 to 7 fathoms of water. The Colorados Barrier Reef of western Cuba stands in about 5 to 6 fathoms. The barrier range off northern Yucatán, however, stands in 20 to 30 fathoms, nearer to the edge of the shelf than to the mainland.

The Florida Keys are partly coralline, partly of other origin (Cooke 1945, pl. 1, and 1939, pp. 68-72). The main eastern Key range is considered to be a former barrier coral reef of the elevated Pleistocene Pamlico (25-foot) shoreline, now emerged and dead. Its highest present natural ground elevations are said to be about 18 feet above present mean sea level. This Key range ends to the southwest in the Boot, Marathon, and Vaca group of Keys. Westward along the line of the Keys, there is a large emergence of the Miami oolite limestone stratum to the present intertidal zone, somewhat built up, in places, by mangrove peat and marl. Marine carbonate and paralic deposits combine to form the Pine Island group of Keys. This low island mass has been broadly and abundantly channeled in a northwest-southeast direction by the strong tidal currents produced by the regularly recurring tidal difference of 2 to 3 feet between the Gulf and Florida Straits. Key West is the western terminus of this group of channeled-shoal Keys.

West of Key West and the Pine Islands lie the small Sand Keys (Davis 1942) where the main Miami oolite shoal lies below or mainly below low tide. These Sand Keys only sparingly fill the gap between the Pine Island Keys and the large Marquesas atoll.

Scattered coral patches.—The scattered patches of coral growth mapped by various agencies and persons along the northern coast of the Gulf (fig. 14, Sector 4.3), far out on the shelf are not well known. These notations may refer to growths on the tops of small salt-dome-like seamounts found along the edge of the shelf here. Studies by H. C. Stetson show that nodular algal limestone balls are common on the tops of some of these small seamounts. Specimens of solitary corals, possibly from the sea areas, are found sparingly upon the beaches. Coral patches occur widely as bottom growths off the central peninsula coast of Florida.

Paralic, or marine marsh and swamp subdivisional environment.—In the biogenous environment, as here defined, grassy to reedy marsh is dominant between the convex areas of drowned karst shoreline (fig. 14, Sector 2.1). It is also scattered among the mangrove swamps. The mangrove swamp forests (Davis 1940, 1942) form a conspicuous marginal coastal belt on the inshore sectors noted (4.1, fig. 14), and occur prominently in the lagoonal habitat on 4.1 and 4.2 Sectors.

Fresh-water marsh (paludal environment) has some of its most extensive known developments on the broad, very gently sloping coastal plain of southern Florida inland from the marine mangrove shoreline. The paludal areas include the famous Everglades and the almost as well known Big Cypress Swamp.

Marine marshes (paralic) are conspicuous in places in a relatively narrow zone along the coast of Louisiana in the deltaic alluvial environment. Here salt grasses (*Spartina*) and reeds have pioneered on deltaic and other shoals. Garden Island Bay, between two mouths of the Mississippi's active bird-foot delta, is reported (Russell 1936) to have extended its shoreline materially by the aid of paralic vegetation. Here, again, extensive fresh-water marshes lie inland in a very gently sloping coast from the more notable saline marshes. On the steeper deltaic coast of the western Gulf, shore and coastal marsh are narrow and relatively inconspicuous.

Mangrove swamp growth.—Charts of the near-tropical coast of Florida (4.1, fig. 14) south of Cape Romano (1113, 1253, 1254) and north of the Bay of Florida, and air photographs of a part of the west coast of the Yucatán Peninsula (4.1), show a broad, belted disposition of saline mangrove swamp forest with an irregular brackish lagoon or line of lagoons landward from it. This arrangement seems to be unique for North America and for those parts of the Antilles which have been studied by the writer. It depends upon the presence of a broad, shoal continental shelf in a tropical or near-tropical sea. Lesser mangrove growths on lagoonal shores seem to be incomplete approaches to this disposition of the swamp.

Mangrove swamp forests extend along the coasts of the biogenous sectors (4, fig. 14) with an extension on the drowned karst (2.1), and on the

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southwestern Gulf coast (1.11 and 3). The swamps occur either in lagoons or on outer coasts that lack beaches or cliffs. It is along the beachless and cliffless coasts, in quiet shallow waters, that the unique mangrove ridge and lagoon are found. Davis (1940) reports the growth on Florida as one of the greatest known. The tropical and near-tropical mangrove forests of the main biogenous environment are dominated by the red mangrove (*Rhizophora mangle*) and the white buttonwood or white mangrove (*Laguncularia racemosa*). Inland from the widely flooded zone, the black or honey mangrove (*Avicennia nitida*) grows. The latter outruns the other mangroves into the marginal tropical regions north of the main biogenous environment. The black mangrove grows as far northwest as the Chandeleur Islands of Louisiana off the eastern part of Mississippi delta and in spots in the Laguna Madre near the mouth of Rio Grande. In the mangrove forests of southern Florida numerous other trees and plants grow with the mangroves (Davis 1940).

The fact that red mangroves build out the shores on which they grow has long been known to geologists (Vaughan 1909). The abundant roots and the manner of seeding on shoals by the floating of well-sheathed seedlings aids these trees in occupying marginal marine and lagoonal areas in protected waters (Davis 1940). The black mangrove, however, seeds immediately under its branches, and tends to grow toward land from a shoreline fringe, rather than outward.

The mangrove barrier ridge and coastal lagoon.—Chart 1113 shows an extremely irregular outer shoreline beginning at the north with the Ten Thousand Islands archipelago. This belt of islands starts at the northwest in the coastal lagoon behind the Cape Romano barrier spit. It then curves to the southeast to end at Lopez River. From Lopez River southeastward to Cape Sable the mangrove swamp of the outer coast is mapped as being much more compact than in the Ten Thousand Islands, and is smoother, but far from regular. It is broken by transverse marshy channels and has, in the northwestern part, an outer line of islets and small peninsulas. From 3 to 8 miles inland, there is a zone of highly irregular, more or less intercommunicating swampy lagoons and channels running roughly parallel with the outer coast. Between the inner lagoons and the outer coast, there is a broad belt of mangrove swamp which is the ridge. Davis shows that the height of the ridge should be a function of both tidal range and the slope of the bottom and adjacent land surface across which the mangrove belt originally spread.

The entire coast southeast of Cape Romano (4.1) is composed of mangrove swamps and lagoons except for the sandy barrier islands, spits and beaches of the Cape Romano barrier at the northwest and of Cape Sable at the southeast. The delineation of shorelines for the mangrove forest is difficult (McCurdy 1947) because of the indefiniteness of shoreline position for a marine swamp, especially where the tidal range, as here, varies from about 2 to 4 feet. East of Cape Sable, there is a mangrove belt along the north side of Florida Bay.

The mangrove peat rests on limestone rock, marl, or shell beds (Davis 1940). The peat section varies from about 5 to 14 feet. Except where it descends into depressions in the karst, Davis thinks that the general average thickness is about 7.5 feet below mean low water. This would place the base of the peat at an average of 8 feet, or slightly more, below mean sea level. The red mangrove seats itself in as much as 2 feet of water, the roots spreading outward somewhat. The seedlings float and ground in a few inches of water. There was in many cores taken by Davis through the peat, an alternation of peat and marl, with an upper marl bed a foot or two thick present in most of the area. The roots of the present swamp trees penetrate this upper marl but without peaty development in it as yet. Alternations of marl and peat in a core may or may not indicate a vertical oscillation of sea level, as they, certainly in some cases, have been due to compaction or minor horizontal shoreline changes under essential stillstand of the sea.

The history of the formation of the mangrove barrier ridge and lagoon may be somewhat as follows: On a broad, well-protected tropical to subtropical shoal coast, especially, as in Florida, where the wind is dominantly offshore but swell and some on-shore wave movement is present, advance of the mangrove forest is assured. The elongated, winged, pod-shaped seedlings ground and take root at any depth down to 6 to 8 inches of water. Root growth may extend as far offshore as a 2-foot depth at low tide (Davis 1940). The dense growth of roots, trunks, and associated vegetation, slowly advances seaward by the consolidation of peaty growth and by trapping fine-grained inorganic sediment (Vaughan 1909). Shells are added by the accumulation of small species of Mollusca on the roots (Davis 1940). It may be assumed that the maximum of accumulation of marl, clay, and silt takes place always somewhat forward, that is, gulfward, in the slowly advancing swamp. Storm waters and tidal oscillations combine to permit the up-building of the accumulating swamp materials by these inorganic sediments which, in turn, may promote, at and above high tide levels, a denser undergrowth of the less aquatic plants.

As the zone of maximum arrest and accumulation of inorganic sediment advances Gulfward, lack of accretion or a decrease in rate of accretion in the zone nearer the original mainland permits normal compaction of peat and marl to show in an invasion of groundwater and brackish marine waters. The swamp is abundantly penetrated all along the western peninsula coast by transverse tidal scour channels, permitting Gulf waters to enter the rear zone.

If the foregoing processes and results depict the true history of the formation of the mangrove barrier ridge and lagoon on the western coast of peninsular Florida during the stillstand for the 3,000 to 5,000 years of Fisk's (1944) determinations, then the considerable width of 5 to 10 nautical miles of the mangrove belt is a product of the extended period of time during which approximate stillstand has persisted. If minor oscillations have occurred during this period, then some of the alternations of peat and of peat marl and in the types of peat reported by Davis may have been related to changes of sea level. An end condition of seaward advance may be found where the bottom slopes too steeply, or the growth has finally reached a zone where the processes outlined no longer produce bottom offshore that is sufficiently shoal to support mangroves. Under this hypothesis, we may understand why the mangrove growth on the southern part of the Gulf shore of Florida is exceptionally wide, as the combination of conditions required for the full formation of a mangrove ridge and lagoon are exceptional. Under this hypothesis the rate of Gulfward advance is the ratio between the width of the ridge, 30,000 to 50,000 feet, and the duration of stillstand, 3,000 to 5,000 years. Using the figure 5,000 from Fisk's estimate, we find that the net outward advance of the mangrove forest has been between 6 and 10 feet per year. This is a measurable quantity.

It has been said that Davis (1940) finds the present swamp forest to be resting on and rooted through a surficial zone of marl a few feet thick without appreciable peat deposition in it. Hence, his interpretation that the accumulation of the average of 7.5 feet of buried peat and marl took place mainly during a rise of sea level seems not to conflict with the present writer's hypothesis for forward growth during stillstand. Accumulating datings by the deterioration of radiocarbon may permit a rate of upward growth, less compaction, to be made, Davis having found no means of doing so.

The mangrove barrier ridge and coastal lagoon are similar, in accomplishing appreciable shoreline prograding, to the other barriers known, the barrier island of sand, the barrier coraline reef and the rare barrier oyster reef, noted in the Gulf of Mexico where a large reef of *Crassostrea virginica* forms a bay barrier 25 miles long across the mouth of Atchafalaya Bay.

EMERGENT AND SUBMERGENT SHORELINES OF THE GULF

USE OF TERMS

Johnson (1919) laid much stress, in his shoreline studies, on the determination of whether the features of a shoreline were dominantly those of the relative submergence of a land surface or the relative emergence of a sea bottom. His interest centered in the immediate history of sea level and its effect on shorelines. Others have found it impracticable to discriminate entirely on many coasts between the exact form of the present shoreline and the topography of the coastal zone which has determined major features of both coast and shoreline (Shepard 1937a, Price 1939). This distinction involves the difficulty in determining for each sector whether the several submergences or emergences of the coasts during the Pleistocene have produced its dominant features.

A major shortcoming of the Johnson classification or the way in which it came to be applied was its use of the common and widely developed barrier island as either a major criterion or a positive indicator (Price 1939, Johnson 1938) of emergence. Later work, here discussed, seems to invalidate this criterion entirely as an indicator of sea-level movement except where it may be found wholly emerged or submerged.

While not finding the concepts of submergence and emergence as valuable for shoreline classification as some others, we may well inquire what features plainly indicate such items of shoreline history.

SUBMERGENT SHORELINE FEATURES

Pleistocene entrenchment of stream valleys.—It is well established that the accumulation of large amounts of ice in the arctic and circumarctic regions several times during the Pleistocene, or Great Ice Age, caused strong lowerings of sea level. The latest well-established major lowering occurred in the late Wisconsin or Würm glaciation and amounted to about 450 feet in the Gulf of Mexico (Fisk 1944, 1952) and the Gulf of Paria, south of Trinidad, Venezuela.[14] In some regions the figure is set at between 240 and 350 feet (Flint 1947). Fisk (1944, 1948, 1952) has shown by borings cited in various reports of the Corps of Engineers that the northwestern Gulf coast had a large number of entrenched Pleistocene stream valleys that have now been filled with sediments. Configurations of branch estuaries show that entrenchment was general in the Gulf. Only on the hard shelf off peninsular Florida are such valleys found submerged and fairly well outlined by depressions. These valleys are marked by depths of as much as 10 to 15 feet on the coast charts off northern peninsular Florida.

Embayed drowned valleys.—Incompletely filled drowned valleys in the Gulf take at least two forms, those in which the branching, dendritic pattern of drowned tributaries is still prominent (Baffin Bay in Texas) and those in which waves and currents have broadened the valley at shallow depth, producing oval, rounded or other equidimensional shapes. The writer (Price 1947) has shown that on the northwestern Gulf coast elongated drowned valleys tend to become segmented by spits and other obstructions, separately embayed by segments and the bay bottoms made flat under a dynamic equilibrium between erosion and deposition. This equilibrium of basin shape is actually the result of the formation of equilibrium bottom-profiles along most bay radii.

Embayment of drowned streams is most prominent in the Gulf on the compound Pleistocene-to-Recent deltaic coast of Texas and southwestern Louisiana. There, the rivers are large and the gradient of the Beaumont is not steep (1 to 3 feet per mile). On the steeper plain of Sector 1.2 (fig. 14), only one large, transverse valley bay (Mobile Bay) occurs. Where the plain is composed dominantly of active deltas or hard rocks or has only relatively minor streams, Sectors 1.11, 2.0 and 3.0, long broadly embayed stream valleys are absent. The writer has further considered local meteorological influences in the shaping of the bays of the northwestern coast (Price 1952).

The harbor of Matanzas, Cuba, is thought to be a drowned valley cut in a structural depression or in a structurally weak zone.

Submerged base of mangrove peat.—Davis' (1940) conclusion that the mangrove swamps and peat of Florida formed during a gradual, more or less uninterrupted rise of sea level from about −8 feet relative to mean sea level has been mentioned.

Drowned lacustrine plain of Florida Bay.—Anaylsis of this unusual type of marine area needs somewhat extended exposition. The entire water area (Trask 1939, pp. 292, 293) is a honeycomb of shallow, rimmed basins individually upwards of 10 miles wide and 11 feet deep, the bottoms bare with a cover of soft marl or shell sand. The narrow rims are of marl and mangrove peat (Davis 1940). The writer's interpretation is that a rising sea moving up and across a very gently sloping shoal surface carried with it a transgressive shoreline zone of mangrove swamp. This coastal swamp belt, the mangrove ridge, moved slowly north and northeastward and is now present along the north shore. This ridge is of irregular shape and the marsh and swamp back of it to the north are now and were probably at all times honeycombed with lakes. Such lakes tend to become enlarged by wind scour if the banks are not encroached on too strongly by marsh and swamp growth. The result is that some large lakes occur among the innumerable small ones.

It is further postulated that, as the Gulf waters invaded the swamp, more and more deeply, vegetation was slowly killed, and the lakes gradually widened by drowning and wave erosion.

[14] Personal communication, T. H. Van Andel.

The outlines of the lakes and rimmed basins of Florida Bay today show the characteristic coalescing of small basins with each other and with large ones, the intervening rims being removed. The lacustrine plain, the so-called bay, with its network of marl ridges prevents the development of appreciable tidal flow and scour in and between basins except along the border of the bay at the south. Here tidal channels have been scoured through breaks in the line of the Florida Keys, locally deepening the rimmed basins.

Statistical study of the relation between width and depth in the rimmed basins shows a rough approximation to the progressive deepening with increasing size characteristic of the bays of the northwestern Gulf (Price 1947). In the Bay of Florida this relation is modified on the southeast by the limiting depth of the hard Miami oölite and at the extreme west by an excess of sandy or marly deposition in the relatively large basins that there border the Gulf. Some of the western basins are completely filled with sediment.

Partly submerged eolian sand plain of Rio Grande delta region.—Stretching inland across the Pleistocene plains of this delta in Tamaulipas and Texas to their inner erosional scarp is a plain of eolian sand, or erg, with scattered dune fields. All, except small blowout fans of bare sand (about 1 by 3 miles in size) and their fields of bare dunes, is stabilized by grassy vegetation, thorny brush and live oaks. The coastal lagoons now form traps for eolian sand blowing inland from the beaches of the barrier islands. Only in droughts is some of this sand able to cross to the mainland over narrow flats that locally close the coastal lagoon. This immense sand plain must have come on shore before the barrier island was formed. The simplest explanation follows that of Daly (1934, pp. 197–201) that large amounts of sand probably blew on some shores when the sea level was low during one or more of the glacial periods. Other possible explanations are that the sand has come from the reworking of successive barrier island sands and other beach deposits or from sandy sediments in the walls and on the floors of entrenched valleys.

EMERGENT SHORELINE FEATURES

Pocket harbors (emergent rimmed basins) of Northwestern Cuba.—Several writers on Cuba (as Hayes, Vaughan, and Spencer 1901) have referred to the purse-shaped or pocket harbors of Cuba. Those of the sector from Havana to Bahia Honda (fig. 12) on the northwest coast are of an unusual, petal-shaped type. They lie in a plain from 3 to 5 feet above sea being upwards of 6 miles long. A small stream usually enters one or more of the several marginal indentations of the small rounded-to-oval basin, not always in the axial position. Other similar marginal indentations have either no appreciable inflowing drainage or receive very slight drainage. Yet well-formed submerged channels converge from all these indentations toward a central channel of tidal type. This channel may be as deep as 8 fathoms. Such harbors do not seem to the writer to be explicable as normal embayments of drowned stream courses or of stream confluences, as some have suggested.

If the coast of Cuba west of Bahia Honda (3.1, fig. 14) is examined on the navigation charts, basins similar to the pocket harbors and the rimmed basins of the Bay of Florida, lying in swampy terrain, will be seen here and there behind the Colorados Barrier Reef, mostly clustering toward the mainland shore. These basins have axial or radial tidal channels draining to the Gulf below sea through passes or breaches in the reef. These small, rounded and rimmed basins of the Colorados lagoon seem to be features of a present mangrove-lined shoreline like those along the north shore of Florida Bay. The writer interprets the pocket harbors of the Havana type, surrounded by a slightly elevated plain (Palmer 1945), as similar mangrove lakes scoured out at sea level in the midst of a saline swamp and then slightly elevated on the unstable young orogenic coast (Sector 3) of Cuba.

Barrier Island not an indicator of long-period sea-level change.—Johnson (1919, 1925) thought that his offshore bar, called barrier island by the writer (Price 1951a, Shepard 1952), was a feature predominantly of an emergent shoreline. He believed that the structure was formed by a semipermanent sea level change, a slight worldwide lowering of sea level or an upwarping of the crust, along an offshore bar formed originally as a submarine feature. Fenneman (1938, p. 4), following some early writers, believed, however, that a barrier island was formed merely as an equilibrium structure produced on a shallow shelving coast by the balance between wave attack and bottom resistance regardless of any history of sea level change. The writer's study of bottom profiles in the Gulf (fig. 15) indicates that barrier islands are (1) associated with well-developed equilibrium profiles, (2) on a shallow coast where the bottom is now at least 15 to 45 feet deep within one to two miles of shore and (3) thereafter slopes outward between about 2.0 and 5.0 feet per mile, (4) where sand, gravel or cobble are abundant along shore, and (5) where onshore wave attack is strong. These observations tend to confirm Fenneman's interpretation. Other observations, briefly stated, indicate that the barrier island does not require a worldwide or other semipermanent fall of sea level to bring it above sea, but that the only change in level needed is a local, short-period change between storm levels and normal sea levels taking place during periods of a few hours or days.

A series of aerial photographs taken at intervals of several years over the period 1934 to 1949 (Bates 1953) shows that a bar formed just below the intertidal zone off a new mouth of Brazos River remained submerged until a hurricane had occurred, after which it became a typical emergent barrier island of cuspate outline. A second bar then formed off a breach in this barrier, after which other hurricanes occurred before the second bar was, in turn, raised above sea to form a second line of emergent barriers. The inference is strong that, in each case, a pre-existing submarine bar was built higher during a hurricane, so that during the storm it bore the same height relation to the elevated storm sea level as it had formerly borne to the normal level of the Gulf. The bars emerged as barrier islands after the subsidence of the temporarily high sea levels.

On October 3, 1948, a hurricane passed about 100 miles off the coast of southwestern Texas, causing a high sea level or storm tide of some 3 or 4 feet for two days or more along the barrier islands. A week later, the writer found that the summit of the beach, the beach ridge, in front of the shore dunes had been built up and remade by the storm and was slightly farther inland than its former alignment. The shift in position was evidenced by erosion of dune faces. The convexly rounded beach ridge then rested where the front part of the dunes had been.

The raising of the beach ridge, previously described, to an elevation above its position during normal times was shown by the rapid mass-wasting that had affected it in a single week. The beach ridge on this island formerly had, in places, a fairly well developed pavement of shell, but now the pavement had just begun to be formed on the newly made ridge. The pavement was formed from disseminated shell by the washing and blowing away of sand, according to a well-established process. It was evident that this ridge had lost some 6 inches of its height and would lose another foot or a foot-and-a-half before a pavement would be formed to protect it. The former paved beach ridges had evidently lost similar heights.

Reports and illustrations of hurricane damage to New England beaches (Brown 1939, Howard 1939) show that the beach ridges were remade at higher levels, moved inland from their former positions and their axes rotated slightly by the hurricane waters.

These observations indicate clearly that the summit ridge of a barrier island functions briefly during storm tides as an underwater offshore bar and thereafter emerges as a barrier island.

Evans (1942) found that waves operating at a steady sea level tend to modify the slopes and positions of underwater bars, but not to build them up above water.

The great development of active barrier islands on the Gulf coast, dominating the shorelines of the alluvial sectors (1, fig. 14), does not then, in the writer's opinion, tell a story of permanent or semipermanent sea level change, or mark either a submergent or an emergent shoreline condition.

The question of the source of the supply of material for the barrier, long thought to be a critical factor, is found to be secondary. Thus, barriers occur in the Gulf where longshore sediment drift is prominent (Sectors 1.12, 1.2, fig. 14) the sand derived largely from rivers (Bullard 1942), also where a longshore drift from a land connection (Chandeleur Islands, La.) is absent and where no land-derived sediment is present but onshore waves are strong and the barrier is built of broken shells from the adjacent bottoms, as on the north shore of Yucatán (2.2, fig. 14).

Emergent shoreline terraces and notches.—The lowest well-established elevated shoreline is that of the Pamlico of the Atlantic coast and Florida, standing at about 25 feet above mean sea level. This shoreline is marked in many regions by a well-cut and well-preserved terrace or by a broad elevated lagoon flat with a barrier island. Less well-developed and somewhat controversial shorelines are reported from many places in the interval from about +3 to +10 feet. However, carefully selected, stable, protected, inner shoreline sectors on North Pacific Islands (Stearns 1941, 1945) and in Australia (Fairbridge 1948) exhibit shoreline cliffs in even-grained limestones with solution notches at about +3, +5 and +8 feet. These seem to represent worldwide stillstands of the sea (eustatic shorelines). Shorelines reported at +16 and +20 feet (Daly 1934 and others), are not as yet substantiated by data of unquestioned accuracy.

In places around the shores of the Gulf, there are definite indications of shoreline terraces that seem to indicate stillstands at about +5 and +8 feet. An elevated barrier island and coastal lagoon caught by the 10-foot contour has been mapped in Florida by MacNeil (1950) as the "Silver Bluff shoreline" (Parker and Cooke, 1944, pl. 4, fig. B). He did not follow it across southern Florida or on the west side of the peninsula.

Low shoreline flats appear in many places around the Gulf, but have not been critically studied in the field. Such a low bench shows in air photographs along the base of the high bluffs of the Champoton-Campeche limestone fault-block salient (fig. 12; Sector 2.2, fig. 14). It seems to have a gray, sandy soil. A flat along the front of the elevated Ingleside shoreline between the Rio Grande and Brazos–Colorado deltas (fig. 12) lying at from about 1 to about 5 feet above mean sea level has low, subdued spits and bars on its surface [15] and seems to be an emergent marine plain. It is about 0.3 mile wide. This flat may be a nondeltaic part of the original Pleistocene surface in front of this barrier. Deltaic deposits appear along the Gulf side of this barrier east of Galveston Bay.

Marsh borders the Pleistocene delta of Brazos River in Texas to an elevation of 2 to 3 feet above mean sea level. Just behind the marsh is a bench 1.0 to 1.5 mile wide at 3.0 to 4.5 feet with a low nip or wall between 4.0 and 6.5 feet above sea. This bench may be a low Silver Bluff representative.

At Buhler, a few miles northwest of Lake Charles, Louisiana, the Ingleside barrier and lagoon clays are well preserved. The top-of-clays, representing the approximate shoreline position, lies between 22 and 25 feet above sea. This shoreline and the associated features are well defined running at the same elevation from near Lake Charles west to Beaumont and thence southwest through Fannette, Jefferson County, Texas. Where the shoreline comes within about 10 miles of Anahauc, Chambers County, it is sloping down to the southwest at about 1.5 feet per mile and reaches sea level at Smith Point on the shore of Galveston Bay. Before the formation of the bay, it was formerly tied there to the Brazos delta. The Ingleside shoreline seems to correlate with the Pamlico through the emergent barrier of Gulfport and Biloxi, Mississippi.

The deltaic plain lying south of the Ingleside in southwestern Louisiana and in Jefferson and Chambers counties, Texas, is of the same age as that immediately to the north of it, Prairie or Beaumont (Hayes and Kennedy 1903, pp. 27–38; Deussen 1924, p. 110). Along the shore of Jefferson and Chambers counties, it is a partly submerged deltaic plain.

The Ingleside appears again south of the Brazos-Colorado delta along the coastal lagoon that opens from Matagorda Bay at its southeast extremity and runs from there to the north flank of Rio Grande delta, the shoreline (top of clay) being at approximately 5 to 10 feet above sea.

The disagreements in the shoreline data for the northern Gulf coast would be removed if the coast from Florida to the Mississippi delta had been stable since Pamlico time, but a slight amount of gulfward downwarping had occurred between the vicinity of Galveston Bay and the coast of Mexico at some point north of Tampico.

The post-Pleistocene gulfward downwarp of the Beaumont Pleistocene plain (Doering 1935) increases in amount from about 1 foot per mile in southeastern Texas to 2 feet per mile southwest of Matagorda Bay. This downwarp seems to mark the influence of the young orogenic coast of Mexico, which it is approaching.[16] This interpretation suggests that the emergent shoreline flat on the Gulfward flank of the Ingleside barrier may be either of Ingleside age, downwarped some 15 feet, or a younger post-warping shoreline, possibly of Silver Bluff age. Against a Recent age for the low bench is the seeming absence of marine fossils

[15] Obscured by mima (pimple) mounds higher and wider than the spits (Price 1949).

[16] Corpus Christi lies 175 miles east of folded Cretaceous rocks at the surface in Mexico and 125 miles northwest of submerged mountains in the Gulf.

above present sea level in the much cored and studied post-Pleistocene alluvial fill of Mississippi River in the Atchafalaya river basin, Louisiana (Fisk 1952).

No unquestionable evidence seems yet to have been offered that elevated, unwarped (eustatic) shorelines below +25 feet are of Recent or post-Glacial age, despite continued statements by many geologists that they "seem to be Recent." R. W. Fairbridge and E. D. Gill of Australia [17] think that the materials of the shorelines of Australia below +10 feet are not sufficiently weathered and leached to have been formed before the last major sea level lowering. On Chesapeake Bay, G. F. Carter [18] finds no post-Pleistocene deposits above a maturely developed soil, supposedly of post-Pleistocene age, which dips beneath bay sediments and has been cored into off-shore. We do not know that the shores of the Chesapeake have been downwarped. The Pamlico terrace is reported as running level along this coast from Maryland to Florida.

The only dated shoreline deposits above sea level that are thought to be of historical or earlier Recent Age of which the writer has been able to learn, come from young orogenic coasts, as that of Tripoli [19] in Lebanon (Wetzel and Haller 1945) and on the Pacific coast of South America. These coasts must be suspected of having had crustal movements going on at any time, even in recent millenia. Thus, Jerico, 175 miles southwest of Tripoli, was once destroyed by an earthquake and 200 historical shocks are reported for the area of Israel (Ball and Ball, 1953).

SHORELINE CHANGES AND PROCESSES

SHORELINE SIMPLIFICATION

Terminology.—Shepard (1937a; 1948, pp. 70–73) says that "as numerous coasts and shorelines have undergone little modification since the sea level and the land came to rest, it seemed logical to refer to these as Primary . . . and to . . . those which have been considerably modified by the waves and currents as Secondary . . ." In his tables he calls "primary" shorelines youthful and "secondary" coasts mature. Following this concept, we find that mature marine coasts have in general become simplified in contour, with their irregularities reduced by erosion, solution or sedimentation, or a combination of processes. Hence, the end result of marine action on most types of coasts is smoothing, though not always straightening, as smooth coasts may be curved.

Processes.—Simplification of a coast may consist of the reduction of projections by erosion, and the deposition of beach and other deposits in reentrants. It may also be brought about by the formation offshore in shallow water of a barrier island or barrier spits (Price 1951a, Shepard 1952). Such inorganic barriers tend to follow along a bottom contour, crossing the sites of entrenched valleys on postentrenchment fill, while the mainland shoreline is deeply indented by the shallow embayments of the former valleys. Thus, the new marine shoreline is smooth and shorter than the mainland shoreline off which it is built.

Examples.—Simplification of Gulf shorelines is shown by (1) extensive development of sandy barriers where there are or were irregularities of the mainland shoreline, chiefly between the convexities of deltas (Sector 1), (2) the gradual filling of coastal lagoons (as east of Galveston Bay, sector 1.2), (3) the incipient smoothing of projections along some sectors of the drowned karst coast (2.1), (4) seemingly some smoothing of the front of parts of the mangrove ridge (Sector 4.1) facing the Gulf, in contrast with a possibly irregular original configuration such as that of the Ten Thousand Islands or the north shore of the Bay of Florida, (5) smoothing of the karst irregularities of the elevated Champoton-Campeche fault-block (Sector 2.2, Yucatán peninsula) so that only small cuspate points remain, (6) reduction by erosion of projecting folded limestone rock (northern Sector 3.1) and of the ends of narrow tongues of lava solidified to rock extending into the Gulf from the active volcanic salients of the young orogenic coast of Mexico (southern Sector 3.1).

Significance.—The several degrees of shoreline simplification evident in the preceding list, suggest a considerable quantitative range in the effective application of marine energy to shoreline modification during the 3,000 to 5,000 years of essential stillstand of the Gulf. Just as we find variation in simplification related to the hardness and resistance of the shoreline materials, rocks or soft sediments, so we may suspect that there have been differences in the amounts of energy available

[17] Letters of 1952.
[18] Letters of 1952.
[19] At 2 to 3 meters above sea 600 m. inland and possibly 3,000 to 4,000 years old.

for shoreline work. This supposition is justified by (1) the consideration that erosion at the shoreline has a vertical as well as a horizontal component, (2) comparison of variations in the form and offshore gradients of the bottom of the continental shelf on various sectors of the Gulf, and (3) inspection of the charts of resultant winds along the shorelines of the Gulf (U. S. Weather Bureau, 1938). These factors indicate that it may be feasible, from the partly quantitative, partly qualitative data presented or referred to here, to set up a preliminary energy classification of the coasts and shorelines of the Gulf of Mexico. This is attempted in the tabulation.

Extensive Marine Modification of Coasts of Gulf.—A summary of prominent shoreline conditions that indicate the degree of coastal modification is shown in tabular form below. The simplified coasts (the secondary or mature coasts of Shepard) greatly dominate in linear distribution, indicating that the sea has been at about the same level for a substantial period of time in relation to the resistance of most of the coastal materials to shoreline modification.

	Approximate length in statute miles	*Percentage of marine shoreline length*	
Gulf and major parts:			
Marine shoreline	3,000	100	
Coastal plains	2,500	83	100
Volcanic and other sectors	500	17	
Secondary shorelines:			
Simplified (smooth)	2,250	75	
Moderately smooth	250	8	100
Little modified	500	17	
Sandy beach	1,553	52	
Barrier islands and bay barriers	1,370	46	
Inactive and elevated beach plains	810+	27+	
Beach ridges, average of 10 (?) ridges per beach	20,000+	667+	

EQUILIBRIUM PROFILE OF CONTINENTAL SHELF BOTTOM

Definitions.—Figure 15 shows bottom profiles for sectors of the continental shelf having different steepness of curvature. Only for the broad shelves off the alluvial and limestone plateau coasts (fig. 14, Sectors 1 and 2) of the Gulf of Mexico are there enough data for analysis. On the shelf sectors studied, the profile of the bottom is concave in the first mile or two, this section being the shoreface, an extension of the beach or other shore. The shoreface grades into a nearly smooth plain, here called the ramp, the gradient of which flattens slowly in an offshore direction for varying distances, commonly to 30 fathoms or more. The profiles drawn on this section of the shelf are mathematically of the hyperbolic or asymptotic type, the so-called logarithmic or exponential curves.

The ramp grades, usually far offshore, into a usually smooth convex section, here called the "camber," the gradient of which usually increases rapidly to the top of the irregular, steep, continental shelf slope. The sparse soundings available for the shelf of the young orogenic coast of Mexico (3, fig. 14), suggest that, except where a beach or barrier is present, this coast may lack a ramp, the camber beginning at or near the base of whatever shore cliff or shoreface is present. The so-called shelf break (Dietz and Menard, 1951) should be the junction between ramp and camber.

Data showing the locations and ramp slopes of the profiles (curves) of figure 15 and the sectors on which the curves are located are given in a tabulation following the illustration.

Location of profiles in figure 15.—All profiles measured perpendicular to shoreline from navigation charts U. S. Coast and Geodetic Survey.

(1) Off old Corpus Christi Pass and Padre Island barrier island 27°35′ N. Lat., 97°13′ W. Long. Chart 1286, 1922 edition. A profile at same place from original survey sheet (1880) shows only minor irregularities and smoothly asymptotic curvature to 90-foot depth. Beach. Sand and clay bottom.

(2) Off Padre Island at Baffin Bay mouth, 27°18′ and 97°20′. Chart 1286, beach sector: "Little Shell." Beach. Sand and clay bottom.

(3) Off Matagorda Peninsula barrier island, off mouth Trespalacious Bay, 28°00′, 96°10′. Chart 1284, 1945 edition. Beach. Sand and clay bottom. Fathogram off Galveston shows ramp as smooth as curves 1–3.

(4) Off barrier island on Florida peninsula 10 miles north of Cape Rómano, 26°03′ and 81°48′. Chart 1254, 1931 edition. Beach. Sand inshore. Rock bottom (limestone) with some sand and shells.

(5) Off Pine Islands-Key West shoals (Miami oölite with mangrove swamp deposits above), Florida, at Johnson Keys, 24°42′, 81°36′. Chart 1251, 1940 edition. Profile begins at −8 feet. Add 8 to all depths for this curve in figure 15.

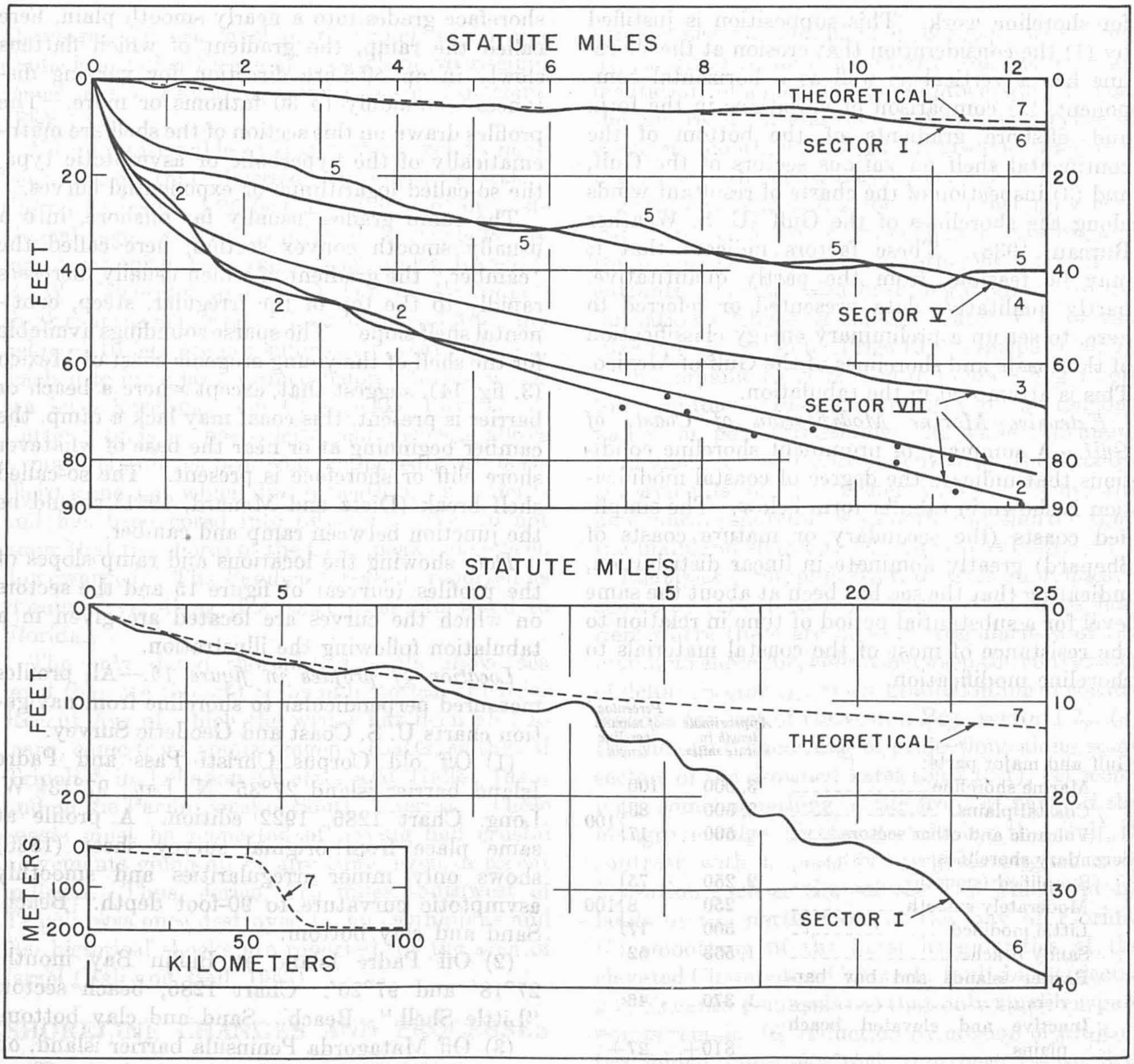

FIGURE 15.—Characteristic bottom profiles of inshore zone, continental shelf, north half, Gulf of Mexico. Steepening and progressive smoothing of bottom from profile to profile correlates with increasing energy of water, decreasing resistance of bottom, and increasing steepness of initial drowned surfaces. The theoretical low-energy, breakerless profile of Keulegan and Krumbein (curve 7) is compared with a beachless sector of drowned karst coast off Florida (curve 6). Profiles are listed on pages 59 and 60. Sectors are described in tabulation, pages 61 and 62. The shoreface extends 1 to 4 miles offshore. The ramp extends out from the shoreface as far as the profile continues to flatten. The outer parts of profiles 1 and 2 are averaged between the points shown.

Bottom "hard," mostly oölite limestone. Little sand reported in region. Beachless.

(6) Off rocky coast of Florida at Net Spread Key between Chassahowitzka and Weekiwachee Rivers, 28°38′, 82°40′. Chart 1258, 1944 edition. Beachless. Hard bottom (limestone). Very few notes of sand in region.

(7) Theoretical mathematical curve of Keulegan and Krumbein (1949) for the steepest bottom across which waves will move with the maximum height without breaking. A wave 3 m. high enters the shelf-sea on a bottom 4 m. deep 40 km. from shore. Depth equals the 4/7 power of the distance from shore. A hyperbolic curve.

TABLE 1.—*Gradients of ramp shown in figure 15*

Profile	Gradient	Statute miles from shore	Depth in feet	Sector of Gulf
7	2.0	0.1– 0.6	0.5– 1.6	Theoretical "breakerless" bottom profile, Keulegan and Krumbein.
	1.7	.6– 2.2	1.6– 3.3	
	0.6	2.2– 7.4	3.3– 6.6	
	0.4	7.4–15.0	6.6– 9.8	
	0.3	15.0–25.0	9.8–13.0	
6	1.5	0 – 4.0	1.0– 7.0	I.
	1.0	0 –13.0	1.0–10.0	
	2.0	13.0–27.0	10.0–40.0	
5	2.4	0.7–12.0	7.0–21.0	—
4	2.2	0.9–11.0	20.0–40.0	V.
3	6.0	1.0– 4.0	25.0–44.0	
	3.0	4.0– 8.5	44.0–57.0	VII.
	2.7	4.0–12.0	44.0–67.0	
2	5.0	1.8–12.2	41.0–87.0	VII.
	4.3	4.4–12.2	54.0–87.0	
1	3.5	1.8–12.2	45.0–83.0	VII.
	3.6	3.6–12.2	51.0–83.0	

Sedimentation and the profiles.—The shoreface, ramp and camber of the normal coastal plain shelf, as exhibited on the Gulf of Mexico, seem to have specific characteristics as to sedimentation (map, fig. 16, p. 79) and erosion. From meager data, it seems that sand and shifting bars characterize the shoreface. Contemporary sands, relict deltas and barriers of former sea levels, with some contemporary clay deposition, characterize the ramp. Except when the entire profile is migrating landward, transportation probably dominates the ramp after any relict elevations have been removed from the part under consideration. Fine-grained sediments, mostly land-derived clays, and presumably the process of deposition, characterize the camber. Off the mouths of large deltas, little or no coarse sand reaches the Gulf and the charts show "mud" beginning near shore. Where sand is present it usually extends to 5 to 10 fathoms (Bates 1953; Lohse 1952).

Dietz and Menard (1951) have lately advanced evidence and argument for the belief that, at the level of the passage of the shelf from the steep concavity into the gentler slope, in present terminology, where the shoreface joins the ramp, is found the depth of maximum wave action on the bottom. They term it the depth of maximum abrasion, replacing the older concept of "wave base."

If the Gulf has remained essentially at the same level for the past 3,000 to 5,000 years, as previously suggested, it is evident that, on bottoms closely approximating the hyperbolic curve the shelf bottom must be in equilibrium. This should be true especially in coastal materials of slight resistance and where large amounts of marine energy have been effectively applied. That the topography of the bottom is a simple mathematical surface with a hyperbolic bottom profile, is believed to indicate that the forces are in equilibrium. Where the bottoms are of hard rock and largely retain a subaerial topography, it may be concluded that the marine forces have inherited a surface produced under different conditions which they have been unable to destroy or to which they happen to be more or less adjusted.

The equilibrium profile of the coastal plain shelf is in a state of dynamic, not static, equilibrium. In dynamic equilibrium, variations of temporary, short-term value are to be expected. Thus, heavy storm waves are known to shift offshore bars [20] temporarily as much as a half-mile from their previous positions on the shoreface. Variation of the equilibrium will be about the mean. Marked departures from the mean are caused only by forces external to those in equilibrium. The shift of a river mouth, the coming of a lava flow, or the warping of the earth's crust, would be external forces or conditions which might upset a previously existing equilibrium on the shelf.

Usefulness of equilibrium profile.—Despite some pessimism (Kuenen 1950, p. 302) as to the value of the profile in geologic studies and much misconception on the part of writers as to the difference between static and dynamic equilibria in nature, the present writer finds that the profile of equilibrium is a suitable index of the response of a continental shelf bottom to the application of marine energy for a significant period of time. If, as some think, there have been several oscillations of sea level of as much as 10 to 20 feet during the past 4,000 years or so, a proposition that remains unproved, then the interpretation of the modification of the shorelines and shelf by marine energy is less clear than as here tentatively presented.

Theoretical breakerless curve fits Florida.—Keulegan and Krumbein (1949) made a theoretical study of the critical steepest bottom slope in shallow water on a shelf across which waves from deep oceanic waters may move but be constantly deformed and constantly lose energy so that they arrive at and near shore without enough height or energy to break or to develop shore structures, such as beaches or cliffs. The absence of such

[20] The true underwater feature, not the barrier island. This occured at Galveston, Texas.

shore structure along much of the western shores of the limestone peninsulas of Florida and Yucatán, and the low gradients prevailing there offshore, led the writer to investigate these regions for examples of the beachless and breakerless coasts. More information is available for Florida than for Yucatán.

It was found that the requisite combination of (1) unmodified or little-modified shorelines, (2) gentle offshore slope and (3) essential absence of breakers (Corps of Engineers, U. S. Army 1940) exists on long stretches (Sectors 2.1 and 4.1, fig. 14) of the Gulf shoreline of peninsular Florida.[21] By analogy, similar conditions are believed to exist on more than half the lengths of the western peninsular coasts of Florida and Yucatán, where the bottom gradient is low and the shoreline and bottom essentially unmodified by marine forces.

Comparison of the theoretical "breakerless bottom" curve of Keulegan and Krumbein (1949), described as profile 7 (p. 60 and fig. 15) with the actual rolling bottom profile of the drowned karst shelf of peninsular Florida (profile 6, fig. 15), shows that the two curves closely superimpose and are identical in over-all gradient. But the drowned karst profile has not been fully smoothed by erosion and deposition and is not yet a marine profile or equilibrium, although slight modifications of it indicate that such a development is going on.

DIRECTIONS OF LONGSHORE DRIFT

In the northwestern Gulf of Mexico, where a strong longshore sediment drift occurs, and wherever a barrier spit terminates, the dominant drift of the year is in the direction of the elongated, pointed barrier ends.[22] These criteria agree there with the known histories of inlet migration, although there is a weaker summer drift to the northeast. Using spit criteria, the dominant longshore drift is seen to be westward and southwestward, that is, counterclockwise,[23] from Apalachicola delta, Florida, to the poorly mapped volcanic sectors (Sector 3, fig. 14). Where sandy beaches and barriers occur on peninsular Florida, longshore drift occurs. A northward drift exists for 20 nautical miles from the headland at Indian Rocks (270°52′ N. Lat.) to Anclote Keys. A much stronger south-southeastward drift exists from Indian Rocks to Cape Romano and its large underwater bars, a distance of 75 nautical miles. Southeastward drift again appears south of Cape Sable, where fine-grained sediments have been carried into the northwestern part of Florida Bay. Colorados barrier reef at the western end of Cuba diverges from the shoreline to the west, suggesting a clockwise drift.[24] Split ends indicate a clockwise drift (to the west) on the north and northwest coasts of Yucatán to the Laguna de Terminos (Sector 1.11, fig. 14).

The unmodified and slightly modified drowned karst and mangrove ridge shorelines do not show appreciable longshore drift, judging by their irregular shorelines and dominantly transverse tidal channels. Convergence areas exist at the cuspate delta of the Apalachicola and the cuspate foreland of Cape Sable, Florida. The cuspate foreland of Cabo Rojo (fig. 12; Sector 3, fig. 14), is asymmetrical, showing that the counterclockwise drift persists across it despite convergence.

Bates (1953) shows from photographs and oceanographic data that there is a Coriolis effect[25] turning Mississippi River water westward along shore. This coincides in direction with a weak, westward-moving wind-powered drift. Together there is formed a dominant counterclockwise drift (to the right). Distribution of sediments along the delta front agrees well with this drift. Air photographs show that the Coriolis drift occurs also at the mouths of the other rivers of the northwestern Gulf coast. It is not operative, however, in equatorial and near-equatorial waters such as the southern Gulf of Mexico.

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[21] The data on waves and swell are being studied at the Agricultural and Mechanical College of Texas by Charles Bretschneider (Bretschneider and Reid 1953).

[22] The so-called Gulliver's rule (Johnson 1919, p. 376) cannot be applied here successfully in all cases from chart data and is of doubtful validity in any case. See Bullard (1942) and Price (1952).

[23] With reference to the center of the Gulf.

[24] Observations of drift in this direction have been recorded. The drift seems to be powered by a clockwise eddy developing off the right flank of the Yucatán current (N. to NNE. through Yucatán Channel; Leipper p. 121, fig. 34).

[25] Relative right hand turning of flows because of the rotating coordinates of the revolving earth. The turn is to the left in the southern hemisphere.

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GEOLOGY OF THE GULF OF MEXICO [1]

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The lower Gulf coast and the inner continental shelf of the Gulf of Mexico are the sites of oil fields in Veracruz, Tamaulipas, Texas, Louisiana, and Florida. Therefore, hundreds of geologists, geophysicists, and engineers are engaged in investigations of the structure, geologic history, and sedimentology of the fringe of the Gulf of Mexico. Due to the economic necessity for research to discover new trends and new provinces of petroleum accumulation and to the many data continuously being furnished by the drill and geophysics, great strides have been made in the knowledge of the continental shelf and the adjacent Coastal Plain of the United States. Even though these economic studies were of the coastal area and continental shelf, they have encouraged thought concerning the origin and geologic history of the Gulf of Mexico.

A modern study of the Gulf Stream was initiated by the United States Coast Survey in 1846, and some work in the Gulf of Mexico was started soon thereafter. During the last century, many capable students of geology have studied the geological history of the Gulf of Mexico, but there is still much diversity of opinion concerning its origin and manner of development.

EARLY CONCEPTS

Early European writers initiated the idea of North and South America being tied together by a continuous mountain system, and this century-old concept is still popular in Europe. Suess (1885, pp. 283–285) described the Gulf of Mexico bottom as an elevated "plate" and considered this plate the foreland of the Antillean chain. He believed the present deep Gulf did not exist in Paleozoic time, but an old metamorphosed and deformed basement formed a somewhat flat platform that continued southward the low-lying central area of the United States. The present Gulf of Mexico was formed by the collapse of the plate during Cretaceous and later time, and the general outline of the Gulf was "not influenced by the course of the mountainfolds unless perhaps in the west by the approach of the Mexican ranges to the coast of Vera Cruz" (1885, p. 551). The plate of Suess has influenced geologic thought concerning the origin of the Gulf for the past three-score years.

Spencer (1895, pp. 103–140) not only believed that the whole tract of the Caribbean Sea, the Antilles, and the Gulf of Mexico constituted an ancient continental region, but he attempted to restore the topography of the submerged continent. Using available soundings, Spencer found drowned valleys which he considered of prime importance in establishing the existence of a continental region which ever since the Miocene had executed vertical fluctuations of an amplitude of many thousands of meters. In discussing the area, he stated, "the Gulf of Mexico appears to have been a plain, with the fjords and embayments reaching nearly to its greatest depths" (1895, p. 119). Thus, Spencer agreed with Suess, at least in part, and postulated a Gulf floor more than 12,000 feet above its present deepest position.

Hill (1898, pp. 3–5) believed the Gulf of Mexico is more closely related to North America than to Central or South America. He declined to consider most of the Antilles as other than true oceanic formations and refused to believe that there is any connection between the northern Antilles and Barbados-Trinidad, the latter being by him assigned to the South American mainland. He saw that the Gulf is nearly surrounded by low plains composed of nearly horizontal, unconsolidated sediments deposited in an enlarged Gulf of Mexico. This border of plains is in direct contrast to the Caribbean and its mountainous periphery.

Willis (1929, p. 328) held that basins are permanent, and he did not believe the Gulf of Mexico

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was ever an area of shallow seas over a flat "plate." This is shown by his statement that

> The isostatic equilibrium of the Gulf is inconsistent with the conditions that should result if a continental mass had sunk . . . I, myself, regard the Gulf as representing a mass of basalt which was erupted in Pre-Cambrian time, either before or soon after the eruptions of the granitic nuclei of North America. If so, it has been a basin ever since . . . The Caribbean, Yucatan Deep, and the Gulf of Mexico are, from the point of view of actual isostatic equilibrium, all of the same nature. They are, I think, all of them basins of great antiquity.

Van der Gracht (1931, p. 121) discussed the origin of the Gulf of Mexico and the downbreaking of Llanoria. He believed the coastal plain "represents a sunken basin over old central chains" and that both the Caribbean Sea and the Gulf of Mexico were part of a great geosyncline and a "very complicated system of anticlinoria, ridges and chains . . . must now fill the original geosyncline, generated by its late-Paleozoic compression stage. Since then, complete abrasion and renewed sedimentation . . . have obscured the original structure."

Fifty years after Suess, Schuchert (1935, p. 340) confirmed the conclusion of Suess as to the Gulf of Mexico "plate" and described it as extending from Tabasco northward so as to include part of Texas, Arkansas, the southern tip of Illinois, Alabama, the peninsula of Florida, and the northern Bahama Banks, as well as other Mississippi embayment States.

The Gulf of Mexico and the Caribbean were separated, according to Schuchert, by a Central American-Antillean anticlinorium until Jurassic time. By mid-Cretaceous, the Gulf of Mexico area responded to crustal movements in Mexico and the Antillean geanticline and began to subside; this downward movement continued until great depths were reached. Thus, the Gulf of Mexico was a shallow sea probably from Proterozoic to mid-Mesozoic time, and by late Cenozoic time the depth had changed from possibly less than 1,000 to over 12,000 feet. Schuchert believed the cause of the inbreaking of the "plate" and the subsequent subsidence was related to "the geologic structures of the Central American-Antillean region, those of northern South America, and those of the present Caribbean sea bottom" and that all were "due to subcrustal flowage, to the rising of plutonic masses into the various arches, and to the subsequent cooling of these masses." He also believed that—

> The present depth of 12,000 feet was surely exceeded during Cenozoic time, since in the course of this era sediments thought to be many thousands of feet thick accumulated upon it . . . In the latitude of South Louisiana, the ancient Gulf bottom has subsided over 25,000 feet, about twice the depth of the present Mexican Basin (Sigsbee Deep). Therefore we may say that the greater part of the Gulf of Mexico has sunk since Middle Cretaceous time at least 20,000 feet. These are striking facts, indicating slow, but in the end enormous, loading and isostatic adjustment, accompanied by subcrustal movements and rock flowage toward the rising geanticlines of Mexico and the Central American-Antillean arch, a movement that is not yet completed.

GULF COAST GEOSYNCLINE

Barton, Ritz, and Hickey (1933, pp. 1446–1458) were among the first to publish concerning the Gulf coast geosyncline, and they presented both stratigraphic and geophysical evidence for the existence of a geosyncline in the Gulf coast of Texas and Louisiana. They showed geophysical calculations to indicate a horizontal increase in density of the basement rocks from the Sabine uplift to near the middle of the Gulf of Mexico, and they concluded that a geosyncline must occur in the basement surface with its trough axes slightly landward from the present coast line (op. cit., p. 1456). They also showed the great thickening of the Upper Cretaceous and Tertiary beds as they dip Gulfward, with the Tertiary beds reaching a stratigraphic thickness of more than 25,000 feet near the coast. Knowing that the deepest part of the Gulf of Mexico is 12,500 feet and assuming that the thickness of the Upper Cretaceous–Tertiary sedimentary deposits in the great depths of the Gulf are 10 percent or less of their thickness in the Gulf coast, it was concluded that "the basement of the Upper Cretaceous–Tertiary beds must be down-warped 6,000 to 16,000 feet in reference to the depth of that basement under the Sigsbee Deep."

The geosynclinal trough is a well-marked feature indicating considerable subsidence. Its westward limit is not definitely known, but some thinning of formations is noted in the longitude of Matagorda County, Texas. It is further complicated by transverse structures such as the Rio Grande syncline, the San Marcos arch, the Houston syncline, the Sabine uplift, and the Mississippi River syncline.

Howe (1936, p. 82) called attention to the great sinking in the region of the Mississippi Delta which he believed amounted to about 30,000 feet since the beginning of the Tertiary. He believed the Gulf coast is an active geosyncline resulting from the weight of the sediments brought down by the Mississippi River. Evidence of the sinking of the Mississippi Delta was also presented by Russell (1936, pp. 167–169) in his study of the physiography of the region. Russell and Fisk (1942, pp. 56–59) questioned the "strength" of the earth's crust and concluded that the crust appeared "weak" as it yielded and subsided "at essentially the same rate that the deposits thickened."

Meyer (1939, p. 206) did not subscribe to the sedimentary-load theory and among various objections stated that the "epochs of reversal of movement in the geosyncline, indicated by unconformities, shoreline migrations, entrenched streams, submarine canyons, and the elevated beach at Corpus Christi, are opposed to the basic tenets of the sedimentary-load theory."

Meyer also used the argument that the ocean deeps, which are structural troughs, could not have been caused by the weight of accumulating sediments. He suggested that the Mexican Basin and the Gulf coast geosyncline may be related structures and that the Gulf coast geosyncline was a "similar structural and topographic basin in early Tertiary time when the strand-line was far inland. After this basin had come into existence, it offered an opportunity for the accumulation of thousands of feet of sediments. The weight of the first several thousand feet of Tertiary deposits may have been sufficient to overcome the inherent strength of the crust and to cause further sinking" (op. cit., p. 206).

Storm (1945, p. 1330) considered the Gulf coast geosynclinal trough as a well-marked feature indicating considerable subsidence. He believed that, if subsidence continued at a fixed position and if sediment filled this trough and passed over it, there should be some sign of sinking inland and drainage should have caused deposition over the axis of the syncline. Such indications were lacking, and he therefore believed that the shape of the trough was a composite of past and present. He showed that sediments are accumulating principally on the seaward flank of the trough which pushes the bottom of the flank downward while the landward flank rises slightly. Thus, the trough tends to move seaward with continued sedimentation.

Glaessner and Teichert (1947, p. 586) thoroughly reviewed the subject of geosynclines and concluded that the origin of geosynclines is still unknown. Observed facts are too often overshadowed by an author's "attitude to one or the other of the current and mutually exclusive hypotheses of mountain building and of the origin of continents on which no finality has yet been reached. Concerning the actual mechanism of the formation of geosynclines it would seem that the school of Gulf coast geologists has produced such weighty arguments in favor of subsidence under load that the operation of the factor can no longer be doubted. On the other hand, there is evidence for 'autonomous' uplift and subsidence of parts of the crust which would make it possible for sedimentary accumulations to be formed as a result of active subsidence and uplift rather than of passive depression under the load of shifting products of erosion."

Bornhauser (1947, pp. 706–711) observed that, since the Tertiary transgressions affected the whole northern border of the Gulf of Mexico, diastrophic movements must have been the primary cause of the transgressions. He agreed that the subsidence of the Mississippi embayment and the Gulf coast geosyncline caused the Tertiary transgressions of those areas, and the subsidence was due to diastrophic movements. Bornhauser "has not found clear evidence to support the idea that the weight of the sedimentary column is the deciding factor for subsidence. On the contrary, all facts and evidences seem to point toward the conclusion that the formation of the Mississippi embayment is a tectonic incident closely related to the structural history of the Gulf of Mexico which underwent considerable epeirogenic movements during the Tertiary."

The idea of a Gulf of Mexico neutral plate was introduced by Suess and substantiated by Schuchert who considered it to be the foreland of the Antilles. Bornhauser accepted this neutral plate and suggested that the northern border of the plate may have formed the submarine plateau of southeast Mississippi, at least during earlier Tertiary. Deeper synclines separated this plateau from the land masses on the northwest and north, particularly during Midway-Wilcox time.

Bornhauser (op. cit., p. 709) stated:

In order to explain the progressive enlargement of the southeast Mississippi plateau and the corresponding shifting toward the north and northwest of its frontal synclinal zones during the Eocene, the theory is advanced that this plateau, together with the Gulf of Mexico "plate," drifted in successive stages to the north as a result of Tertiary orogenic movements in the Antilles. A maximum penetration of the plateau into the Mississippi embayment was reached at the close of the Eocene and early Oligocene periods, when it touched the northern land masses. A breakdown of the southern part of this plateau and a large part of the Gulf of Mexico followed during the Oligocene and Miocene, forming the present Gulf of Mexico. This downbreaking in connection with the emergence of the embayment probably caused a change in direction of the Gulf Coast geosyncline in south Louisiana. During the Eocene, the axis of this syncline followed a southwest-northeast trend, with the Mississippi embayment syncline forming its northeastern extension. With the formation of the present Gulf of Mexico during Oligocene and Miocene time, this axis was diverted to a west-east trend.

Trask, Phleger, and Stetson (1947, pp. 460–461) obtained sediments from the northwestern part of the Gulf of Mexico during the 1946 expedition of the *Atlantis*. In the central part of the Gulf, where the depth of water exceeds 11,000 feet, two distinctly different layers of sediment were found. A thin top zone of globigerina was underlain, in most cores, abruptly, by alternating clay and very fine, well-sorted silt containing a cold water fauna. In other cores, from the same depth, ripple marks and crossbedding were found. Such conditions suggest shallow-water deposition; and, to get such conditions, it is necessary to assume either a rather recent great depressing of the Gulf floor or an equally great lowering of sea level. The other alternate is to assume sufficient currents at depth to cause sorting, ripple marks, and crossbedding.

Lowman (1949, pp. 1986–1993) believed that the central part of the Gulf of Mexico might have been epicontinental in character during Eocene time. The evidence cited includes the wide extent of the Eocene into the transverse embayments, the gentle depositional slopes, the dominance of continental shelf faunas, and the character of the sediments of the southeast Mississippi platform. In contrast to the Eocene, the Upper Tertiary is absent from the transverse embayments and has continental-slope facies on relatively steep depositional slopes. Therefore, the Upper Tertiary supports a deep hole in the central part of the Gulf of Mexico, as it is today, though not necessarily in the same location.

Lowman did not believe the stratigraphic evidence was conclusive that the Mississippi River syncline subsided in response to load. He believed some workers have used facies criteria instead of planes of stratification in the isopach maps which find "maxima under the delta in the Quaternary and the Pliocene-Miocene" (op. cit., p. 1991).

Weaver (1950, p. 359) studied the continental shelves of the Gulf of Mexico and decided that a significant tectonic zone is at the outer edge of the continental shelf. He concluded that the topographic contours on the continental slope are really structural contours and that they exist in sufficient number to indicate active tectonic regional features. He proposed "the theory that the Gulf of Mexico as a deep sea is young, and that its present central great depth is due to downfaulting." The most intense faulting is indicated along the outer margin of the continental shelf west of Florida and near Yucatán, but even the more gentle continental slopes are considered fault zones. No definite time of faulting was given by Weaver.

Moody (1950) favored a single salt mass as the source of the Gulf coast and Mexican domes and suggested that it may extend across the Gulf of Mexico into the Isthmus of Tehuantepec. If this is true, the Gulf of Mexico was shallow enough to allow salt deposition beyond the present continent during the time of the deposition of the Eagle Mills salt, which is Jurassic in the opinion of Moody, although some writers place it in the Triassic or Permian. He believed the Gulf of Mexico had some downwarping during Upper Cretaceous; that it began to take shape at the end of the Laramide Revolution; and that it subsided, and maybe formed the Mexican Basin, in post-Reynosa (Pliocene) diastrophic movements. The finding of Reynosa gravels in Florida at an elevation of 360 feet suggests a great change in sea level to allow these gravels to be transported there. This means a great post-Reynosa diastrophic movement during which the west Florida shelf scarp and possibly the Mexican Basin came into existence.

Eardley (1951b, p. 2236) stated that "the Gulf of Mexico came into existence after the Appalachian orogeny by subsidence." Much of the Gulf is surrounded by the belt of late Paleozoic orogeny, and sediments dating back to at least the Permian are found in its marginal areas. Eardley believed that the margins of the Gulf have had a near balance between subsidence and deposition, while subsidence has exceeded deposition in the central Mexican Basin.

King (1951, p. 175) stated his belief that the origin of the Gulf coast geosyncline was uncertain, but he believed "that the geosyncline represents an independent tectonic feature and perhaps a new mobile belt in its early stage of development."

The theory of Weaver that fault scarps bound the present central great deep of the Gulf received additional support by Jordan (1951, p. 1991) who described the escarpment off the panhandle of Florida. This escarpment occurs in 700 to 900 fathoms of water, and the sea floor is offset 6,000 feet or more in some places. Comments on Jordan's paper by Stetson (1951, p. 1993) confirmed the findings of Jordan and noted that the escarpment maintains about the same height and slope southward along the west Florida shelf. Stetson further commented that "from the overall picture of the whole area, one gets the impression that the bottom of the Gulf has foundered and that at least this continental slope is due to a normal fault" (idem.).

To date little exploration in the Gulf of Mexico has had as its objective the determination of major tectonic features. The cost of marine geophysical surveying and the drilling of offshore wells are such that the tectonics of the Gulf must be approached indirectly by using soundings and bottom samples together with observations of the shore features.

GEOMORPHOLOGY OF GULF OF MEXICO

The topography of the Gulf of Mexico is too scantily mapped to show the degree of development of the different types of topography so far known there.

As early as 1878 Agassiz (1878–79, p. 1) noted two of the striking topographic features of the Gulf, the great limestone banks: one west of Florida and the other northward from the peninsula of Yucatán. In both cases the 100-fathom line is somewhat parallel to the shore and forms the inner edge of the steep slopes descending to the Mexican Basin, which is another major feature of the Gulf. The varying development of continental shelves and the irregular continental slope with its escarpments, basins, knobs, and troughs are also striking features of the Gulf of Mexico.

GENERAL CHARACTERISTICS

The continental shelf forms an almost continuous terrace around the margin of the Gulf of Mexico. The major breaks occur in the Straits of Florida and the Yucatán Channel which form outlets from the Gulf to the Atlantic Ocean and Caribbean Sea, respectively.

The shelf is not an expressionless plain lacking in interesting physiographic features as may be suggested by some maps with a contour interval too great to properly present the smaller features. This terrace or shelf has numerous depressions, troughs, ridges, minor knobs, coral heads, escarpments, and two known submarine canyons.

The widest parts of the continental shelf in the Gulf of Mexico lie off Texas and the peninsulas of Yucatán and Florida. The shelf width varies from 8 to 117 miles in the northern Gulf, the maximum width being off western Florida. Other shelf widths include: 40 miles off the southern tip of Florida, 52 miles off the Isles of Dernieres, Louisiana, 110 miles off the Sabine River mouth, 40 miles off the Rio Grande outlet, and 135 miles off western and northern Yucatán.

The continental slope differs from place to place not only in width and steepness but also in physiographic features associated with it. The continental slope, in general, constitutes one of the great relief features of the earth. The edge of the continental shelf is only very roughly parallel to the shore line as is shown by the varying width of the shelf. The continental slope varies greatly in width with a minimum width west of Florida and west and northwest of the Yucatán Peninsula.

ORIGIN OF MAJOR FEATURES

The continental shelves of the Gulf of Mexico seem to have a close geologic and physiographic relationship with the adjacent land. Broad shelves lie in front of broad coastal plains, and narrow shelves lie between steep continental slopes and rugged near-shore terrain.

There is no simple explanation of the origin of the shelves and slopes, or of some of the features of these provinces, that has gained wide acceptance.

In discussing continental shelves, Pratt (1947, p. 661) observed that "modern investigations have also confirmed Nansen's pioneer observation that the inland portion of the continental shelf is a surface of degradation." Umbgrove (1946, p. 249) stated, "it appears that the history of the shelf was rather complicated. Sedimentation, abrasion, and denudation played their role. The area was subjected to changes of sea-level and movements of the bottom. Wind-waves and tidal currents acted upon the sediments of the shelf. The influence of each of these and still more factors in the building of the submerged part of the continental margin is still an open question." He also believed that the landward part of the shelf may have resulted from planation when the sea was some 300 feet lower than at present.

Many workers believed that the topography of the shelves resulted from subaerial erosion. Dana (1863, p. 441) stated this was accomplished by the elevating of the land. Long coast lines would have to be uniformly elevated to such heights that most geologists agree the hypothesis has too many difficulties to be acceptable. The lowering of sea level could also produce conditions for subaerial erosion. Shepard and Emery (1941, p. 154) found that the formation of Pleistocene ice could account for lowering sea level 2,200 feet; Veatch and Smith (1939, p. 41) believed sea level was lowered 12,000 feet and restored in the last 25,000 years; Fisk (1944, p. 68) found evidence for a drop of sea level of 400 to 450 feet; and Carsey (1950, p. 375) suggested that if sea level was lowered 420 to 480 feet "the origin of the shelves could be attributed largely to wave planation."

The irregularities of the bottom of the shelves and the great valley-like notches along the outward slopes of the shelves are also unsolved problems. Umbgrove (1946, p. 249) believed "the phenomena of the continental margin are correlated with other periodic events occurring in the earth's crust and its substratum."

Daly (1936, p. 401) introduced the idea of density currents or "bottom streams of sea water containing mud in suspension and therefore temporarily endowed with density greater than that normal to the clean water overlying the respective continental terraces. It is further supposed that the conditions for the formation of such bottom currents were specially developed at certain stages of the Glacial Period . . ." This heavy mass of mud and water would naturally move into the depressions on the continental shelf, and in places it would flow over the margin of the shelf and down the continental slope with accelerated motion and force.

A new hypothesis for the origin of continental slopes and submarine canyons has been suggested by Emery (1950, pp. 102–104). He proposed that "thrusting along a shear plane at the continental margins may result in a temporary upbulging of the margins above sea level. During the time of exposure erosion by streams should have incised canyons which now, after isostatic readjustment of the margins, constitute the widely distributed submarine canyons. Known downwarped peneplains below the surface of continental shelves may have been developed on the bulged margins by long-continued erosion. The margins may, thus, have served as sources of some sediments now found on land and believed to have been derived from a seaward direction."

Kuenen (1950, p. 497) adhered to the belief that "the action of turbidity currents, especially during the ice ages" cut the submarine canyons along the edge of the shelf and slope of the continents.

An examination of the maps of the topography of the outer shelf and slope of the northern Gulf of Mexico shows many features which suggest an origin due to density currents and the deposition of the mass of mud. Also, continental shelf fauna dredged from the Mexican Basin may have been transported from the shelf by turbidity currents. Furthermore, these currents may have carried sediment to the central Gulf and, therefore, aided in developing the rather flat floor of the Mexican Basin.

GEOMORPHOLOGY BY AREAS

Soundings in only a few areas of the Gulf are adequate to permit the drawing of accurate maps of the surface of the continental slope. More information is available concerning the northern Gulf; therefore, this area is discussed in some detail starting with the Straits of Florida and progressing in a counterclockwise direction.

EASTERN GULF AREA

The Florida Plateau includes not only the State of Florida but an equally great or greater area that lies submerged beneath water less than 50 fathoms deep and forms the Florida shelf (H. Gunter, 1929, p. 41). This plateau has been in existence since ancient time and is a part of the Gulf of Mexico "plate" of Suess and Schuchert. Its history includes submergence during Upper Cretaceous, part of Oligocene, and Upper Miocene. Since Miocene time uplift has continued, and erosion has removed much of the once continuous cover of Miocene sandy limestone. The Florida Peninsula now has very little relief. It has a wide continental shelf off its west coast, thus demonstrating the physiographic similarity between the coastal plain and the adjacent continental shelf.

The 1947 expedition of the United States Coast and Geodetic Survey ship *Hydrographer* in the waters on the continental slope southwest of the Apalachicola River, Florida, has been reported, in part, by Jordan (1951, pp. 1978–1993). Many new and interesting data have been secured in the 25,000-square-mile area of this report.

The greater part of the continental shelf west of the peninsula of Florida is covered by about 40 fathoms of water, and the slope out to the 100-fathom contour is for the most part gradual. The westward slope varies from 1° at the north to 5° at the south end of the shelf.

In the 25- to 80-fathom depths, domes, ridges, and troughs were discovered; escarpments and knobs with a relief of more than 300 feet were found in the 70- to 90-fathom depths. Most of these features occur along the shelf margin.

Within the 400- to 1,760-fathom zone the continental slope contains a deep escarpment, faults, and the terminus of the De Soto Canyon, as well as domes and depressed areas.

The continental slope escarpment is of special interest since it may materially aid in the ultimate solution of the origin of the Gulf of Mexico. Jordan (op. cit., p. 1991) noted a 35° gradient on a 4,000-foot drop, contrasting with 1° gradients or less above and below the escarpment. A ridge 30 miles long parallels the escarpment at 700 to 800 fathoms, and ridges and troughs with relief up to 600 feet occur along the bottom of the escarpment. The main escarpment undoubtedly represents faulting, and some of the minor troughs and ridges may have a like origin.

There can be little doubt that the Florida Plateau has been faulted along its western edge, but the faulting is difficult to date. Schuchert believed this faulting was due to the inbreaking of the Gulf of Mexico "plate" and that it probably began in the Upper Cretaceous. However, Weaver (1950, p. 359) believed "that the Gulf of Mexico as a deep sea is young" and therefore the faulting must have occurred at a much more recent date.

MISSISSIPPI DELTA AREA

The Mississippi River brings to its mouth a daily load of sediment in the order of 2 million tons. This material has permitted the Mississippi to build its delta out on the continental shelf with the overlapping delta reaching within some 10 miles of the landward edge of the continental slope. It might be expected that a deep trough would exist in the outer edge of the continental shelf in front of the Mississippi River, but such is not the case.

An ancient, deeply buried channel is found about 30 miles southwest of the passes of the Mississippi River. Shepard (1948, p. 213) stated that this trough, which has a depth of 1,800 feet, is the only major indentation in the shelf margin in the Gulf of Mexico and that the trough-head penetrates the shelf for nearly 30 miles. The sides are steep, and the flat floor is filled with loosely consolidated sediments. The canyon has been traced out on the continental slope to a depth of 900 fathoms before it becomes merged in the irregularities of the slope.

A second trough, called De Soto Canyon, has been discovered off the Apalachicola River of southwestern Florida. Shepard (1948, p. 179, fig. 65) reproduced a map of this trough or canyon as contoured by H. W. Murray of the United States Coast and Geodetic Survey. This map shows a series of depressions, some with relief exceeding 20 fathoms, along the bottom of the trough and a few depressions along the sides of the trough. This canyon is shown in Jordan's map (1951, p. 1982, fig. 2) of the continental slope. The canyon has a relief of about 600 feet, heads near the 240-fathom contour, and terminates near the 500-fathom contour. Stetson (1951, p. 1993) stated that cores of the steepest walls of the canyon showed sediment and no bed rock.

Upwellings of clay, locally known as mudlumps, occur near the mouths of the Mississippi River passes and have never been reported from any other delta. These mudlumps have been the subject of written discussion for more than a century, but only a few writers have attempted a scientific explanation of them. The most recent study has been made by Morgan (1951) in conjunction with the Corps of Engineers at New Orleans.

Mudlumps and mudlump islands have attracted much attention since they may have mud cliffs with a relief of up to 10 feet in an area where the average relief is usually 2 feet or less.

Most mudlumps have central cores of fine-grained plastic clay surrounded and sometimes capped by irregularly stratified layers of clay and silt. The upwelling of the clay core usually produces fissures and faults with vertical displacements resulting in central grabens. The stratified layers dip away from the islands, often forming doubly plunging anticlinal structures. Local cones along the faults and fissures are formed by the discharge of mud, gas, and salt water.

Morgan (ibid.) believed that the "formation of new lumps and rejuvenation of old lumps occurs as a direct result of excessive sedimentation at the river mouths" and "the deforming force which caused mudlump uplift is the static pressure of the sedimentary mass continually being dumped beyond the mouths of the passes."

NORTHERN GULF OF MEXICO

The continental shelf off Louisiana and Texas is somewhat uniform and has a gentle slope to about the 50-fathom contour. From this point the slope increases to the 70-fathom line where it has an increase in gradient to the 100-fathom depth. Some increase in slope is noted beyond the 100-fathom line, but the bottom becomes so irregular that the true slope becomes obscure.

Probably the chief characteristic of the continental slope of the northern Gulf is the hummocky topography. Shepard (1937, p. 1350) found 26 topographic features off the coast of Louisiana some of which had a relief of several hundred feet. Charts revealed that the belt of domes can be traced definitely for 180 miles west and southwest of the Mississippi submarine trough. More recent data show that some of the depressions are 2,000 feet deep, and some of the hills have a relief of at least 2,500 feet.

Carsey (1950, p. 376) found 164 topographic features along the shelf off the coast of Louisiana and Texas. An area of apparent concentration of these features is shown in figure 16. However, it is probable that there are many somewhat similar features elsewhere on the continental shelf and slope. They seem to be most prevalent in the area between the 100- and 750-fathom contours.

It is particularly interesting to note that no stream patterns have been found other than the troughs on the margins of the slope off the Mississippi Delta and the Apalachicola River (Shepard 1948, p. 178).

Price (1951, p. 32) observed that the "rugged topography of the northwestern shelf-margin or slope seems to contain dislocated segments of submarine canyons" which differ in late history from the canyons along the less rugged slope to the east. This suggests that the front edge of the shelf was faulted down in slices as it was built out into the Gulf.

Available maps of the topography of the Gulf bottom vary widely in their representation of the physiographic features. The amount of time as well as the number of soundings available influence the choice of the contour interval. Thus, the Treadwell (1949) map of the continental slope of the northwestern Gulf of Mexico, contour interval of 50 fathoms, shows a great number of closed basins and knobs between 91° and 95° W. Long. and 27° to 28° N. Lat. Also, there are suggestions of drainage patterns that are not evident in the map by Shepard (1948, p. 178, fig. 64) with a contour interval of 100 fathoms. Some of these differences may be due to the contour interval, but some may also be the result of additional data and the choice of the cartographer when more than one interpretation of the data exists.

All available maps of the continental slope of this region show the same general characteristics of the Gulf bottom: a very irregular, hummocky, knob and basin topography.

Minor near-shore features of ridge and trough were noted by Kindle (1936, pp. 866–867) along the Louisiana coast. He waded across a 1,500-foot traverse and found ridges whose crests were 10 feet wide and separated by troughs from 60 to 90 feet wide. The same traverse was repeated

2 days later, and while the ridges were free of mud, the depressions were filled with several inches of mud. Therefore, the whole character of the local bottom was changed in 48 hours. This shows the futility of making sweeping conclusions from only a few data, especially in the shore zone.

MEXICO

Too few data are available on the topography adjacent to Mexico to make a detailed study of either the continental shelf or slope of this region. However, some generalizations may be made from the scanty sounding data and geological maps of the adjacent land.

Mountain ranges, trending northeast-southwest, have been mapped 90 and 110 miles east of the mouth of the Rio Grande. The range nearer the coast has a known relief of 2,750 feet with a summit reached at a depth of 540 fathoms and the other range has a known relief of 3,810 feet with a summit at a depth of 839 fathoms.

Due east of Tampico a mountain range, with a bearing of N. 65°–70° E., extends some 40 miles and has a relief of 5,800 feet with a summit rising to within 33 feet of the surface.

Along the extreme western edge of the Gulf of Mexico, south of Tampico, the continental shelf is narrow, and the adjacent coastal plain is also narrow, being locally practically absent. Tertiary and later igneous rocks occur in the Misantla-Japala area, northwest of Veracruz, and in the Alvarado-El Paso area, south of Veracruz. Some of the highest peaks of Mexico occur just northwest of Veracruz. Lava flows cover much of the near-shore land area and locally form 1,000-foot cliffs at or very near the shore. South of Veracruz other smaller cones are very near the coast. While local narrow beaches are formed and break the surface continuity of igneous rocks, undoubtedly the offshore irregular topography is due to underwater outcropping of these igneous rocks.

Practically all of the Yucatán Peninsula forms a broad coastal plain. This peninsula tilts northwestward and passes under the Gulf to form a continental shelf averaging over 125 miles in width. The shelf terminates abruptly to the west and north, and the topographic contours along its edge are undoubtedly also structural contours and represent faulting.

MEXICAN BASIN

There is within the Gulf of Mexico, but not centrally situated, a large triangular area with deeps exceeding 2,000 fathoms. It lies northwest of the Campeche Banks approximately between 22° and 25° N. Lat. and 89° and 95° W. Long. Regarding this area, Hilgard is quoted by Agassiz (1888, p. 101) as follows: "The large submarine plateau below the depth of 12,000 feet has received the name of the 'Sigsbee Deep', in honour of its discoverer." Since the "depth of the basin does not attain 3,000 fathoms, it is not a 'deep' in the Murray sense, but it is an enclosed, distinctive basin, for which Sigsbee's name may appropriately be retained" (Vaughan 1940, p. 66).

More recently, however, the name "Sigsbee Deep" has been restricted to the deepest measurement in the basin, and the name "Mexican Basin" is used here for the broad, enclosed basin.

The bottom of the Mexican Basin is very flat, especially when contrasted with the continental slope of the Gulf. The depths range from 2,000 to 2,070 fathoms over the deepest part of the basin. The bottom rises rather uniformly to the shore in the west in a distance of 180 miles, but the northern slope is more gentle and apparently more irregular in its distance of 300 miles. The slopes toward Florida and the Yucatán Peninsula are broken by abrupt changes which undoubtedly represent faults in the bottom.

One of the most prominent mounds in the Gulf is found in the northeast portion of the Mexican Basin. It has a relief exceeding 890 fathoms, a possible width of 60 miles, and its top is encountered at a depth of 916 fathoms.

SEDIMENTS OF GULF OF MEXICO

SOURCE OF SEDIMENTS

The near-shore sediments, at least, should be expected to be closely related to the sediments of the adjacent coastal plain except near the mouths of major rivers. Much study has been given samples obtained from wells and outcrops in the area surrounding the Gulf of Mexico. Such studies have shown that each formation varies widely in its composition as it curves around the Gulf from Florida to Mexico.

The Tertiary outcrops in the Gulf Coastal Plain include thick continental sandy and lignitic deposits and thinner marine sands and clays. Down-dip from the outcrops, drilling has shown that the Tertiary continental deposits pass into brackish water and near-shore marine deposits. According to Lowman (1949, p. 1941), rapid transgressions and slow regressions produced cyclical effects in the sediments with most of the sediments deposited during the regressive phases of the cycles. Farther down-dip or seaward the sediments change to a succession of offshore marine clays.

In general, the Gulf coastal area may be divided into intergrading depositional areas as follows: Rio Grande Embayment, East Texas Basin, Mississippi Embayment, the Gulf coastal region of Alabama, Georgia, and North Florida, and South Florida. The amount of rainfall on the land area surrounding the ancient Gulf may have been the chief factor in determining the contemporaneous deposition of many sedimentary deposits ranging from anhydrite and salt to shales and limestones. Rolshausen (1947, p. 5) suggested that during pre-Eagle Ford Cretaceous time, west of the Appalachian Mountains, rivers entering the Gulf from the north and northeast supplied the major load of sediments. East of the mountains the rivers entered the Gulf from the northwest and west. After Eagle Ford time, rivers entering the Gulf from the west, and probably draining the western part of the present Mississippi basin, were the chief source of sediments. The Rio Grande may have been the major source of sediments from the late Cretaceous through early Miocene time with the Mississippi River contributing little sediment during that time.

PLACE OF DEPOSITION

The sediments brought to the Gulf of Mexico are probably not carried far from shore. Parr (1935, p. 62) showed that at a point only 70 miles out in front of the mouth of the Mississippi River the water has "transparency practically equal to the clearest ocean water known." It is a generally accepted fact that water discharged from the Mississippi River is carried almost entirely to the west and that it stays relatively close to the shore. Clarke (1938, p. 91) found that measurements of transparency supported this conclusion. Geyer (1950b, p. 100) noted that the salinity of the offshore coastal waters of Louisiana west of the delta was largely controlled by the discharge of fresh water from the Mississippi River and the westward moving littoral current. The observations of the writer between 1948 and 1951 confirm the westward movement of the fresh water entering the Gulf from the Mississippi River.

Cogen (1940, p. 2101) examined samples of sediments taken from the bottom of the Gulf near the mouth of the Rio Grande and concluded that the present bottom sediments of this region were carried into the Gulf by the Rio Grande.

Bullard (1942, pp. 1021–1043) showed that each of the principal rivers carries a distinct suite of heavy minerals. The Rio Grande sand shows its primary source by the predominance of basaltic hornblende and pyroxene and only 30 percent of the stable minerals such as garnet, rutile, zircon, tourmaline, and staurolite in the heavy mineral residue. The Nueces, San Antonio, Brazos, Trinity, and Sabine Rivers, draining areas of sedimentary rocks, have little hornblende and pyroxene and a high content of stable minerals. Since the Colorado River derives its load from both primary and secondary rocks, its suite of heavy minerals is over half green hornblende. Northward from the Rio Grande the beach of Padre Island contains the Rio Grande suite of heavy minerals, but the influence of the other rivers is clearly shown by an increased ratio of more stable minerals in the samples farther north in Texas.

The sediments of the Coastal Plain do not end at the shore but extend out under the sea, and "if the basement surface on which they rest continues to slope uniformly, the mass of sediments must increase in thickness at least as far as the edge of the continental shelf, beyond which they should thin out rapidly as they merge into the oozes of the ocean depths" (Stephenson 1926, p. 463).

Land derived sediments are not being moved in a "continuous sheet of detritus all the way from the beach to the continental slope" (Daly 1942, p. 100). If this were true, much of the continental shelf would be some fathoms shallower than at present. With continuing deposition the sea would become more shallow, and wave and current action would push the sediments nearer the edge of the shelf. When the sediments reached the edge of the continental shelf and a profile of equilibrium was attained, the shelf surface would have been raised several fathoms. Therefore, it appears that a profile of equilibrium does not exist on the outer part of broad Gulf of Mexico continental shelves.

Sediments carried to the Gulf of Mexico largely remain in that body of water rather than being carried into the Atlantic. The Gulf of Mexico is of no importance to the deep-water circulation of the Atlantic Ocean (Kuenen 1950, p. 44). The unnamed current that becomes the Florida current is the major current of the Gulf, and "it is essentially a direct continuation of the current through the Yucatan Channel" (Sverdrup, Johnson, and Fleming, 1942, p. 642). The waters of the Gulf mainly form independent eddies and are only to a small extent drawn into the Straits of Florida. These eddies appear to be semipermanent features with their locations determined by the contours of the coast and the configuration of the bottom (idem., p. 641).[3]

EARLY STUDIES OF SUBMARINE DEPOSITS

The Coast Survey instituted a series of investigations on physical problems of the deep sea in 1846, with emphasis on the Gulf Stream. In 1850, L. Agassiz made an extended biological survey of the Florida reefs, and in 1867, Pourtalès and Mitchell began a more systematic deep-sea exploration. Dredging between Florida and Cuba in 1868 reached depths of 850 fathoms, and the bottom samples obtained showed a closer relationship to the cretaceous fauna rather than to organisms of the adjacent shores.

Commander Howell, U. S. N., began a systematic exploration of the Gulf of Mexico in 1872, starting in the shallow waters along the west coast of Florida, and the work was continued by Lieutenant Commander Sigsbee in 1875–78, using the United States Coast Survey steamer *Blake*. The specimens of bottom deposits were sent to John Murray of the *Challenger* for examination, and he published the results in 1885 (Murray, pp. 51–61). Excerpts from his original description are as follows:

> In all the deeper deposits in the Gulf of Mexico and Strait of Florida, the crystalline mineral particles are very small, rarely exceeding one-tenth of a millimeter in diameter. They consist principally of small rounded grains of quartz, with fragments of felspars, mica, hornblende, augite, magnetite, and rarely tourmaline. In a few places there were fragments of pumice, and glauconitic particles were occasionally noticed. The mineral particles and fine clayey matter appear to be almost wholly derived from North American rivers.
>
> The carbonate of lime in the deposits of these regions is mostly made up of the shells of pelagic Foraminifera and Mollusks. In depths greater than 2,000 fathoms the Pteropod and Heteropod shells appear to be nearly, if not quite, absent—the carbonate of lime then consisting of the shells of pelagic Foraminifera; in less depths the Pteropod and Heteropod shells are present, and in depths varying from 200 to 500 fathoms they make up the bulk of the deposits in many places. In several of the deposits, where the percentage of carbonate of lime is very high, the whole has a very chalk-like appearance; it appears, indeed, as if it were in the process of transformation to true chalk.
>
> The siliceous organisms consist of Radiolarians and Sponge spicules, with a few Diatoms, but these seldom make up more than three or four percent of the whole deposit.

A study of the United States Coast and Geodetic Survey maps of the continental shelf adjacent to Louisiana shows many different materials forming the Gulf bottom such as sands, muds, clays, shells, and local reefs. These represent the surface of the Gulf floor, and little is known about the material even immediately below the surface. Some borings have been made in the erection of the platforms required for petroleum exploration, but these platforms are all located approximately within the first 30 miles off shore. The wells drilled from these offshore structures have yielded no known information of the surface formations. Likewise, crews making geophysical surveys in the Gulf are not interested in the surface or near-surface formations (Willey 1948, p. 3).

Trowbridge (1927, p. 148) stated that the United States Coast and Geodetic Survey obtained 600 bottom samples in 1921 and that their map of 1926 included the results of this work.

RECENT STUDIES OF SUBMARINE DEPOSITS

According to Trask, Phleger, and Stetson (1947, p. 460) sediments in the Gulf of Mexico have changed in relatively recent time. During the 1947 expedition of the *Atlantis*, more than 600 cores were taken along 19 lines perpendicular to the Texas and Louisiana coast, crossing both the continental platform and the continental slope and continuing into the depths of the Gulf. The complete results of this expedition have not been published to date, but some data were discussed by Phleger (1950). It was found

[3] For a detailed discussion of circulation of water in the Gulf of Mexico see article by D. F. Leipper, Physical Oceanography of the Gulf of Mexico, in this book, pp. 119–137.

that sediments off shore were remarkably uniform. Out to a distance of some 40 miles from shore a combination of fine sand and coarse silt with an average diameter of 100 microns was found; this material was extremely well sorted. On the outer shelf the sediments were much finer, the average diameter being about 1 micron, and they were poorly sorted. In water over 11,000 feet deep in the central part of the Gulf foraminiferal ooze at the surface was underlain, beginning at 2 feet depth, by alternating clay, silt, and sand, the silt and sand being extremely well sorted.

A core taken in the Mexican Basin in 1947 is of unusual interest. Trask, Phleger, and Stetson (1947, p. 461) reported that:

> The upper foraminiferal zone, 50 cm. in thickness, is characterized by a subtropical planktonic fauna . . . Between depths of 50 and 68 cm. in a zone of red clay or red mud, the fauna is transitional between cold and warm water faunas. Between depths of 74 and 78.5 cm., at the top of the zone of banded clay and silt, the fauna is definitely sub-Arctic . . . Between 78.5 cm. and 125 cm., the fauna is cold-water in type but is warmer than that between 74 and 78.5 cm.; and from 125 to 128 cm., at the bottom of the core, the fauna is definitely sub-Arctic.

Trask (1948, p. 683) mentioned that ice-age deposits showing crossbedding or ripple marks were found in the coarse clastics of two cores taken in the central Gulf of Mexico. In other cores "well-sorted sand zones, one and three feet, respectively, were encountered at depths of more than three feet beneath the surface of the sediments. Such deposits, if hardened into rock and formed in a geosyncline, would be taken as compatible with the idea of shallow-water deposition. Yet they were encountered in 11,000 feet of water."

The Fish and Wildlife Service of the United States Department of the Interior, cooperating with the Agricultural and Mechanical College of Texas, is making a systematic survey of the Gulf of Mexico. Much of the physical oceanography is being done by the Texas A. and M. Department of Oceanography, and the Department of Geology is cooperating in the study of Gulf problems of marine geology. Samples of sediments obtained early in 1952 are now being studied.

SEDIMENTARY PROVINCES

The major sedimentary provinces of the Gulf are shown on the map in figure 16. The basic data for this map were collected from many sources, including the publications of Agassiz, Carsey, Gunter, Kindle, Lowman, Murray, Phleger, Price, Shepard, Stetson, Trask, and Weaver, and by personal communications from individuals principally W. A. Price, Department of Oceanography, Agricultural and Mechanical College of Texas. Unfortunately, the data resulting from some 600 cores taken from the *Atlantis* in 1946 are not yet available. Also, the systematic exploration of the Gulf now in progress will provide many bottom samples from the whole Gulf area, and these data will make possible more detailed sediment maps in the future.

The recent sediments are divided into lithological units which form somewhat indefinite zones parallel to the coast and extending outward on the continental shelf. In general, sands and shales predominate from Florida west and south to Cabo Rojo, Mexico, while limestone forms a wide platform west and north of the Yucatán Peninsula and west of Florida.

EASTERN GULF

Modern calcareous sediments were thought by Agassiz (1888, p. 286) to cover the continental shelf on the west side of Florida. The charts of this area show "sand and shells" and are therefore deceiving. Samples from this region that were examined by Shepard (1932, p. 1021) "were lacking in quartz-sand and the use of sand as a textural term seemed questionable." Little sediment goes to the Gulf in streams from the Florida Peninsula, and the shore deposits consist largely of calcium carbonate secreted by organisms. Even the Apalachicola River does not discharge an appreciable amount of clay and silt. However, some quartz sand is found relatively near shore from Mississippi eastward across Alabama and the panhandle and near shore along the northern part of the west coast of Florida. Also, recently, numerous sand bars have been found on the northern part of the continental shelf west of the Florida Peninsula.

The area off shore from Alabama and the panhandle of Florida has detrital sediments which show the influence of the southern Appalachians. These sediments contain an abundance of ilmenite, staurolite, kyanite, zircon, tourmaline, and sillimanite, and only minor amounts of magnetite,

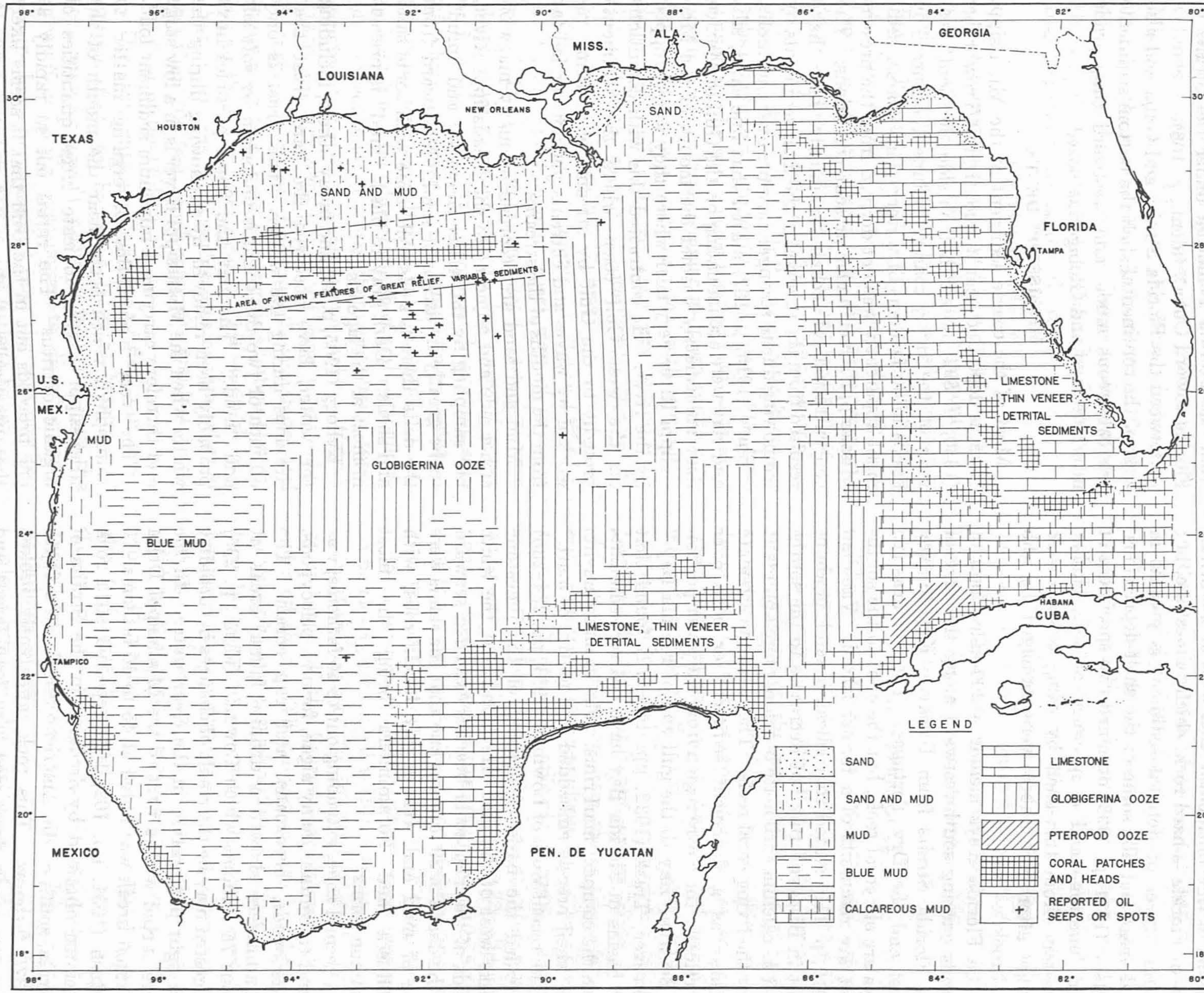

FIGURE 16.—Sedimentary provinces of the Gulf of Mexico. Data compiled from many sources.

amphiboles, pyroxenes, leucoxene, and hematite (Goldstein 1942, p. 81).

Most of the continental shelf west of the peninsula of Florida is hard rock, chiefly limestone, but a thin veneer of detrital sediment is present in local areas and fills some of the shelf depressions. Stetson (1951, p. 1993) obtained two specimens of hard limestone and a specimen of soft, chalky limestone from this shelf by using a steel rock dredge after core tubes were damaged by the hard rock.

The Florida Keys include a 200-mile chain of islands curving southwestward along the edge of the Florida Straits from Biscayne Key to Key West and the Dry Tortugas. The northeastern keys are old coral reefs, but the ones to the southwest are remnants of a former island. Vaughan (1910, p. 119) stated that silica, as sand, is abundant in Biscayne Bay but decreases to the southwest as calcium carbonate becomes more abundant near the living coral reefs. The calcium carbonate occurs "as a flocculent sediment or ooze over practically the entire region from the lower portion of Biscayne Bay to the gulf end of Florida Bay." However, Trask (1932, pp. 166–172) found that the basins in Florida Bay have coarser sediments than the compact marl rims. The basin sediments are "shell breccia embedded in a matrix of marl."

The recent work of Lowman (1951, pp. 234–235) provided the basis of division of the limestone banks west of Florida. He found that the white sands of the Pensacola beaches extended seaward to the depth of 20 fathoms and that the sands were free of mud and were highly fossiliferous, with Mollusca and Foraminifera being the most common forms.

A second zone, extending out to 40 fathoms, was found to contain many algae, forams, pelecypods, brachiopods, bryozoans, and cup corals. The Foraminifera showed a definite faunal break at about 75 fathoms which Lowman (idem., p. 235) suggested may be the result of changes in turbidity and light penetration in the clear water. In the more turbid waters west of the Mississippi Delta a faunal break was noted at 45 to 50 fathoms.

Bush (1951, pp. 102, 106) reported on a rock specimen obtained by dredging in the Straits of Florida, south of the American Shoals, at a depth of 375 fathoms. This rock, apparently broken from the ocean floor, was very fossiliferous and was correlated with the Chipola formation (lower Miocene) of northern Florida. This suggests "the dip and continuance of the lower Miocene strata from the Florida Peninsula under the Straits of Florida toward Cuba" (idem., p. 106).

Between the Florida Straits and Cuba and also west of the continental shelf the bottom sediments are calcareous muds, and westward they grade into blue mud and Globigerina ooze.

MISSISSIPPI DELTA

Most of the coarse sediment of the Mississippi River is deposited near its mouth, but Trowbridge (1930, p. 892) noted that outside the Southwest Pass of the river, coarser sediment occurred on knolls in 30 fathoms of water. This coarser sediment apparently was not derived from the present Mississippi River under present conditions. The concentration of coarse sediments may have resulted from the removal of the finer sediments by winnowing due to stronger currents over the knolls.

Shaw (1916, p. 107) stated that fine sand, silt, and clay were accumulating on the Gulf of Mexico floor immediately beyond the mouth of the Mississippi River very near where they were dropped by the river. He contrasted this with conditions on the west Gulf coast where the sediments brought to the Gulf by streams were being reworked by waves and currents yet not carried far from the mouths of the streams.

Mud and sand are recorded on many maps on either side and adjacent to the Mississippi River, but sampling by the writer shows silt and "mud" to be greatly in excess of sand. Westward from the delta there is a clay-silt zone with some sand and shells. Dark gray to black "mud" is present in most of the lagoons.

Kellogg (1905, p. 34) and many others, including the writer, have observed the hard crust that develops during the winter. This crust is only an inch or two thick and is underlain by soft silt and "mud." The clay and finest particles have probably been removed by winnowing during the winter when the Mississippi River is in a low stage and therefore carrying a minimum sediment load.

The very high ratios of organic matter to chlorophyll which occur near the mouth of the Mississippi River "indicate large quantities of organic detritus. The ratios fall so rapidly as one proceeds out in the Gulf that it seems likely that practically all the organic detritus of fresh water origin is removed from the surface water before it gets more than ten or fifteen miles from the mouth of the river" (Riley 1937, p. 91).

It is noted in figure 16 that the blue mud province extends northward to near the mouths of the Mississippi River. Since the front of the delta overlaps the continental shelf nearly to its outer edge, the sediments of the deeper Gulf approach the tip of the delta. Likewise, the Globigerina zone lies close to the land at the delta.

LOUISIANA SHELF

The numerous submerged hills rising above the sea floor near the outer edge of the continental shelf materially influence the local sediments. Trask, Phleger, and Stetson (1947, p. 461) noted that the slopes of these hills are covered with "silty, calcareous sand, and the tops by round *Lithothamnium* balls and little or no sandy material . . . while the adjacent flat continental shelf is underlain by sandy silt." The *Lithothamnium* balls, diameters up to 10 cm., must have been moved by the water since they seemed to be alive on all sides. Corals, similar to those common in the West Indies, were dredged with the *Lithothamnium* balls. These areas are included in figure 16 in the patches of coral lying along 28° N. lat. between 91° and 95° W. long.

The dominant sediment on the continental shelf along the Louisiana coast west of the Mississippi Delta is mud and sand. Locally, near shore, sand predominates to form a sand beach and shore zone. The common, heavy minerals of these sediments are amphiboles, epidote, dolomite, pyroxene, ilmenite, and biotite.

Near the outer edge of the shelf and particularly on the continental slope there are many topographic features of considerable relief. Carsey (1950, pp. 377–379) noted 164 such topographic features along the Louisiana-Texas slope and made a study of their density distribution according to their degree of relief. This study showed that two-thirds of these features have a relief of less than 300 feet, while some rise 600 feet above the floor of the Gulf.

The sediments on the tops and flanks of topographic features, having a relief in hundreds of feet, may be greatly different from those on the ocean floor only a short horizontal distance away. Corals have been dredged from the tops of a few of these knobs or domes, but little is known concerning the deposits on the flanks. The finer sediments may have been washed from the tops of these knobs to settle on the Gulf floor around the base. More detailed sounding and dredging in this area are needed to adequately study the sedimentology of the area.

Over a 50-year period numerous "oil spots" or "seeps" have been reported as having been observed in the northwest Gulf of Mexico. The locations of these seeps are noted on the map (fig. 16), and it is seen that they are concentrated between 91°–93° W. and 26°30′–27°30′ N. Since several of these "oil spots" were said to be several scores of miles long, their origin, although unknown, is of interest.

WESTERN GULF

The rivers of Texas are not heavily laden with sediment, except during flood stages, and for this reason it can be assumed that the Recent alluvial deposits found on the continental shelf will not be of great thickness. Also, these streams have little velocity as they cross the wide coastal plain, and only fine-grained mechanical sediments are carried to the Gulf. This has been shown by Storm (1945, p. 1313) in a series of samples collected in the Gulf out from Corpus Christi, Texas. Beyond the near-shore fine material sands with 0.21 millimeter average diameter occurred in a narrow belt about 12 miles from shore. Twenty miles from shore the grain size had decreased to an average of 0.03 millimeter, while 30 miles from shore it had increased to an average of 0.18 millimeter. From 30 to 40 miles off shore the grain size remained about the same, but beyond 40 miles it decreased again. These variations seem to be closely associated with the currents.

In 1948 Mattison (p. 77–78) found a string of coral heads off the Brazos River mouth about 8 miles off shore. They occur in 6 to 8 fathoms of water and have a relief of 2 to 3 fathoms. They have been seen by fishermen who describe them as having the appearance of sunken icebergs but having sea fans and other marine growth forming solid coral or white limestone in an area of black mud. Coral heads occur approximately along the 40-fathom line in front of Corpus Christi, Texas, and Smith (1948, p. 82) noted that six of these heads were reached within a foot or two of 31 fathoms of water.

Along most of the east coast of Mexico from Texas to the Gulf of Campeche the charts show "sand" near shore and "mud" off shore, showing an outward gradation of sediments.

Agassiz (1878, p. 1) found the fauna of the Yucatán Bank to be identical with that of the Florida Bank, being characterized by the same species of echinoderms, mollusks, crustaceans, corals, and fishes.

From Tampico southward beyond Veracruz volcanic rocks are found near shore, and possibly igneous rocks will be found in the adjacent Gulf waters. Therefore, the sediments in this area should be somewhat different from those off southern coastal Texas and from those associated with the limestone of the Campeche Banks to the east. The coastal plain is exceedingly narrow locally, and the beach sands give way to near-shore patches of coral. In many places mud extends out on the shelf beyond the coral.

YUCATÁN PENINSULA

The beach sands along the west and north shores of the Yucatán Peninsula do not spread far from shore except locally where sand and mud are found out to the edge of the shelf. To the southwest of the peninsula the sand becomes mixed with near-shore coral patches.

Numerous local patches of coral occur over the Campeche Banks, and in other places the bottom is very similar to the Florida Bank. The hard limestone is locally covered with a thin veneer of detrital sediments. The Globigerina ooze province joins the Campeche Banks apparently with the blue mud absent between these calcareous sediments.

CUBA

Corals are common at the outer edge of the narrow shelf off the northern coast of Cuba. Beyond these corals the Florida Straits contain calcareous mud with the exception of a local area to the northwest of Cuba where pteropod ooze has been found.

A bottom sample taken in 20 fathoms of water at 24°25′ N. lat. and 82°26′ W. long. was subjected to a chemical and spectrographic analysis. Also, use was made of electrolytic separation in a mercury cathode cell to concentrate the trace elements. No unusual trace elements were found, and the common elements were in approximately the same abundance as has been determined by others who analyzed the skeletal material of organisms which contribute to sediment formation.

MEXICAN BASIN

The upper surface of the floor in the deepest part of the Gulf consists of foraminiferal ooze. The few available cores show the underlying sediment to be clay, silt, and sand, which is cross-bedded and ripple-marked in some cores. The origin of this detrital material is unknown as is also the origin of the basin forming the Gulf. Turbidity currents may have brought much sediment to the central Gulf. Such an origin is further suggested by the presence of continental-shelf Foraminifera in the Mexican Basin sediments.

Agassiz (1888, pp. 280–282) quoted Murray who observed that the globigerine and pteropod ooze found in the central Gulf of Mexico differed materially from that found in the oceanic basins. Diatoms, radiolarians, and sponge spicules comprise the siliceous organisms but represent only a small percentage of the bottom deposits. Fish otoliths were found at depths from 392 to 1,568 fathoms. The globigerine ooze was found to extend northward to the Mississippi River slope where it was replaced by dark, rich muds containing "a number of interesting forms of annelids, mollusks, ophiurous and sea-urchins, characteristic of the continental Gulf slope, and typical of mud deposits" (idem., p. 282).

CONCLUSIONS

The Gulf of Mexico, with a surface area of 615,000 square miles, offers many rewards for research in geology, biology, and oceanography. Continued drilling at the extreme margins of the Gulf may produce new local data as greater depths are reached by the drill, but much of the search must be made far from shore. To date most of the geophysical prospecting has been in the very shoal areas where present methods of development may apply. The use of geophysics to study the tectonics of the Gulf largely lies in the future. Therefore, it seems that present aid in solving the many problems of the Gulf of Mexico must come from the oceanographer who can give other scientists new data from soundings, bottom samples, and the physical characteristics of the water.

While the time and manner of the origin of the Gulf basin are still undetermined, present evidence favors the existence of a shallow Gulf, the "plate" of Suess and Schuchert. Assuming that Llanoria extended into the Gulf, its submergence may have been completed by late Jurassic time, thus providing for the invasion by the Cretaceous seas. Post-Cretaceous downwarping tilted the Cretaceous deposits Gulfward, but, in general, the Gulf remained a shallow sea during most of the early Tertiary. During late Tertiary the basin of the Gulf further subsided, possibly both by downwarping and faulting along the basin margins. The escarpment along the west edge of the Florida shelf (Jordan 1951, pp. 1978–1993) undoubtedly has its origin in faulting, and similar conditions seem to exist at the outer edge of the Campeche Banks. Other areas along the continental slope suggest fault scarps. The basin of the Gulf may well have been deeper than the present 12,425 feet, with post-mid-Tertiary sediments filling the basin to its present depth.

There is no reason to believe that the irregularities of the continental slope are confined to the local areas which have had detailed study, and further hydrographic work should produce data of great scientific value.

Interest in the Gulf has been greatly accelerated in the past decade, and there is much evidence that this interest will continue, which should result in the eventual solution of many of the present riddles of the Gulf of Mexico.

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