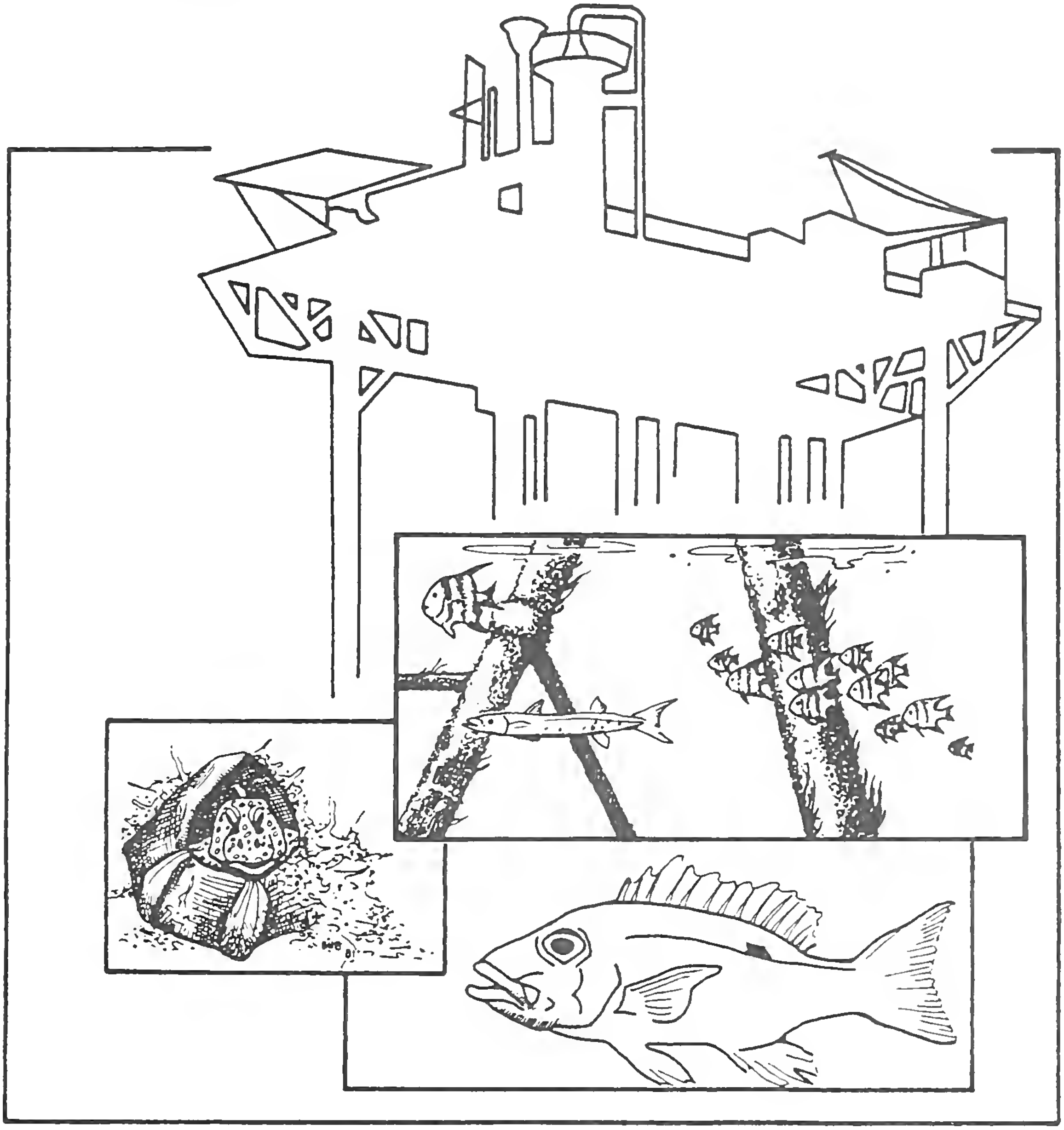
FWS/OBS - 81/27
Aug 1981

Biological Services Program

FWS/OBS-81/27
August 1981

AN ECOSYSTEM ANALYSIS OF OIL AND GAS DEVELOPMENT ON THE TEXAS-LOUISIANA CONTINENTAL SHELF



Bureau of Land Management
Fish and Wildlife Service

U.S. Department of the Interior

The Biological Services Program was established within the U.S. Fish and Wildlife Service to supply scientific information and methodologies on key environmental issues that impact fish and wildlife resources and their supporting ecosystems. The mission of the program is as follows:

- To strengthen the Fish and Wildlife Service in its role as a primary source of information on national fish and wildlife resources, particularly in respect to environmental impact assessment.
- To gather, analyze, and present information that will aid decisionmakers in the identification and resolution of problems associated with major changes in land and water use.
- To provide better ecological information and evaluation for Department of the Interior development programs, such as those relating to energy development.

Information developed by the Biological Services Program is intended for use in the planning and decisionmaking process to prevent or minimize the impact of development on fish and wildlife. Research activities and technical assistance services are based on an analysis of the issues, a determination of the decisionmakers involved and their information needs, and an evaluation of the state of the art to identify information gaps and to determine priorities. This is a strategy that will ensure that the products produced and disseminated are timely and useful.

Projects have been initiated in the following areas: coal extraction and conversion; power plants; geothermal, mineral and oil shale development; water resource analysis, including stream alterations and western water allocation; coastal ecosystems and Outer Continental Shelf development; and systems inventory, including National Wetland Inventory, habitat classification and analysis, and information transfer.

The Biological Services Program consists of the Office of Biological Services in Washington, D.C., which is responsible for overall planning and management; National Teams, which provide the Program's central scientific and technical expertise and arrange for contracting biological services studies with states, universities, consulting firms, and others; Regional Staffs, who provide a link to problems at the operating level; and staffs at certain Fish and Wildlife Service research facilities, who conduct in-house research studies.

FWS/OBS-81/27
August 1981

AN ECOSYSTEM ANALYSIS OF OIL AND GAS DEVELOPMENT ON THE TEXAS-LOUISIANA CONTINENTAL SHELF

by

Benny J. Gallaway
LGL Ecological Research Associates, Inc.
1410 Cavitt Street
Bryan, Texas 77801

Contract No. 14-16-0009-80-058

Project Officer

Ken Adams
National Coastal Ecosystems Team
U.S. Fish and Wildlife Service
1010 Gause Blvd.
Slidell, Louisiana 70458

Prepared for

National Coastal Ecosystems Team
Office of Biological Services
Fish and Wildlife Service
U.S. Department of the Interior
Washington, D.C. 20240

and

Branch of Offshore Studies
Bureau of Land Management
U.S. Department of the Interior
Washington, D.C. 20240

DISCLAIMER

This report should be cited as follows:

Gallaway, B.J. 1981. An ecosystem analysis of oil and gas development on the Texas-Louisiana continental shelf. U.S. Fish and Wildlife Service, Office of Biological Services, Washington, D.C. FWS/OBS-81/27. 89 pp.

PREFACE

The marine ecosystem overlying the Texas-Louisiana continental shelf area has been subjected to development of oil and gas resources since 1938, and is now one of the most intensively developed offshore areas in the world. Biological investigations of this area also have a long history, dating from the late 1800's. The purpose of this paper is to provide a first-order, holistic overview of the ecological systems of this area of the shelf and to describe the apparent effects of oil and gas development activities on the system.

The ecosystem is first characterized in terms of its major forcing functions, characteristic biological assemblages, and some of the known or suspected trophic processes considered to be of most importance. Following this section is a review of the impacts of oil and gas development on system components as they are known. The final section discusses the need for process-oriented studies as a basis for evaluating system-level impacts, (as opposed to conventional baseline studies of system components) and it is recommended that attempts be made to model the assimilative capacity of the ecosystem in question.

Comments or requests for this publication should be addressed to:
Information Transfer Specialist
National Coastal Ecosystems Team
U.S. Fish and Wildlife Service
NASA-Slidell Computer Complex
1010 Gause Blvd.
Slidell, LA 70458
(504) 255-6511, FTS 685-6511

SUMMARY

The Texas-Louisiana shelf ecosystem in the Gulf of Mexico is described (1) in terms of its physiographic, oceanographic, and biological characteristics and (2) as a recipient of oil and gas development activities and effluents. The northeast sector of the ecosystem is influenced by Mississippi River discharge, whereas high-salinity Caribbean water affects the southwest sector. Soft-bottom communities are prominent, characterized by economically valuable penaeid shrimps. The coral reef communities, because of their uniqueness and scarcity, are more important than would normally be assumed. Pelagic communities are little known and harbor only a few commercially valuable species. It is surmised that much of the primary productivity from the pelagic community is used by the bottom communities.

Observed effects of oil and gas development activities and effluents are described. Data from most field studies indicate that direct effects are limited in space, but the effects over time are unknown. One of the major problems has been separating effects of oil and gas development-related activities and other man-induced variations from natural changes. Particular concern is expressed relative to increased organic loading of the system and the apparently related low dissolved oxygen levels characteristic of some parts of the system during warm seasons. It is recommended that future research be directed towards defining key processes governing the ecosystem, with modeling workshops serving as the focus for these research and monitoring programs.

TABLE OF CONTENTS

FIGURES

FIGURES (cont'd)

ACKNOWLEDGMENTS

Liberal use was made of published and unpublished illustrative materials and in some instances, textual matter. It is hoped that full credits have been given in each of these instances and, if not, I apologize to the researchers who have described aspects of the Texas-Louisiana shelf ecosystem far better than I could have, and whose materials were used in the development of this report.

INTRODUCTION

Biological investigations in the Gulf of Mexico have a long history, beginning in earnest during the period 1877 to 1880 (Agassiz 1888) and continuing to the present. In contrast to other marine areas, offshore oil and gas exploration and production activities in the open gulf also have a long history, dating from March 1938 when a well was drilled 2.4 km from the coastline of Louisiana (Bedinger et al. 1980). Danenberger (1976) reported that during the period 1947-75, some 13,000 wells had been drilled in Federal waters of the Gulf of Mexico and, during 1971-75, production from the gulf accounted for more than 10 % of the Nation's domestic crude oil production, and approximately 15 % of the natural gas production. Danenberger (1976) further noted that at the end of 1975, there were approximately 65 mobile drilling units operating in the Gulf of Mexico in water depths as great as 541 m; that a total of 2,079 platforms were in operation in gulf waters up to 114 m deep; and that one platform was being constructed in the gulf in water deeper than 305 m.

More recently, Jackson (1979) reported that there were 3,342 petroleum platforms operating in the gulf, some as much as 220 km from shore and in waters up to 525 m deep. Based upon figures provided by the United States Geological Survey (USGS), some 2,437 of these platforms were in place in Federal waters as of March 1980, and that, within this area, 17,407 wells had been completed. By 1985, 14.5% of the domestic crude oil demand and 33.4% of the domestic gas demand will be supplied by Gulf of Mexico production (U.S. Army Corps of Engineers 1973).

If petroleum development activities constitute a real threat to marine ecosystems, the Gulf of Mexico could be among the first places in the Western Hemisphere to experience degradation of its biological resources (Sharp 1979). This should be especially true for the region of the Texas-Louisiana continental shelf lying between the Mississippi River Delta and Matagorda Bay, Texas, because (1) the area has been intensively developed (Figure 1), and (2) in a general sense, it is relatively isolated from eastern gulf water masses by the overall circulation patterns described in a later section.

Although ecological investigations generally intensified in the gulf from the early 1900's through the 1970's (see Pequegnat 1976 for a recent review), most studies were, by design, of a survey and descriptive nature. Although some early studies addressed the effects of oil and gas development on estuarine systems of the gulf (see Mackin

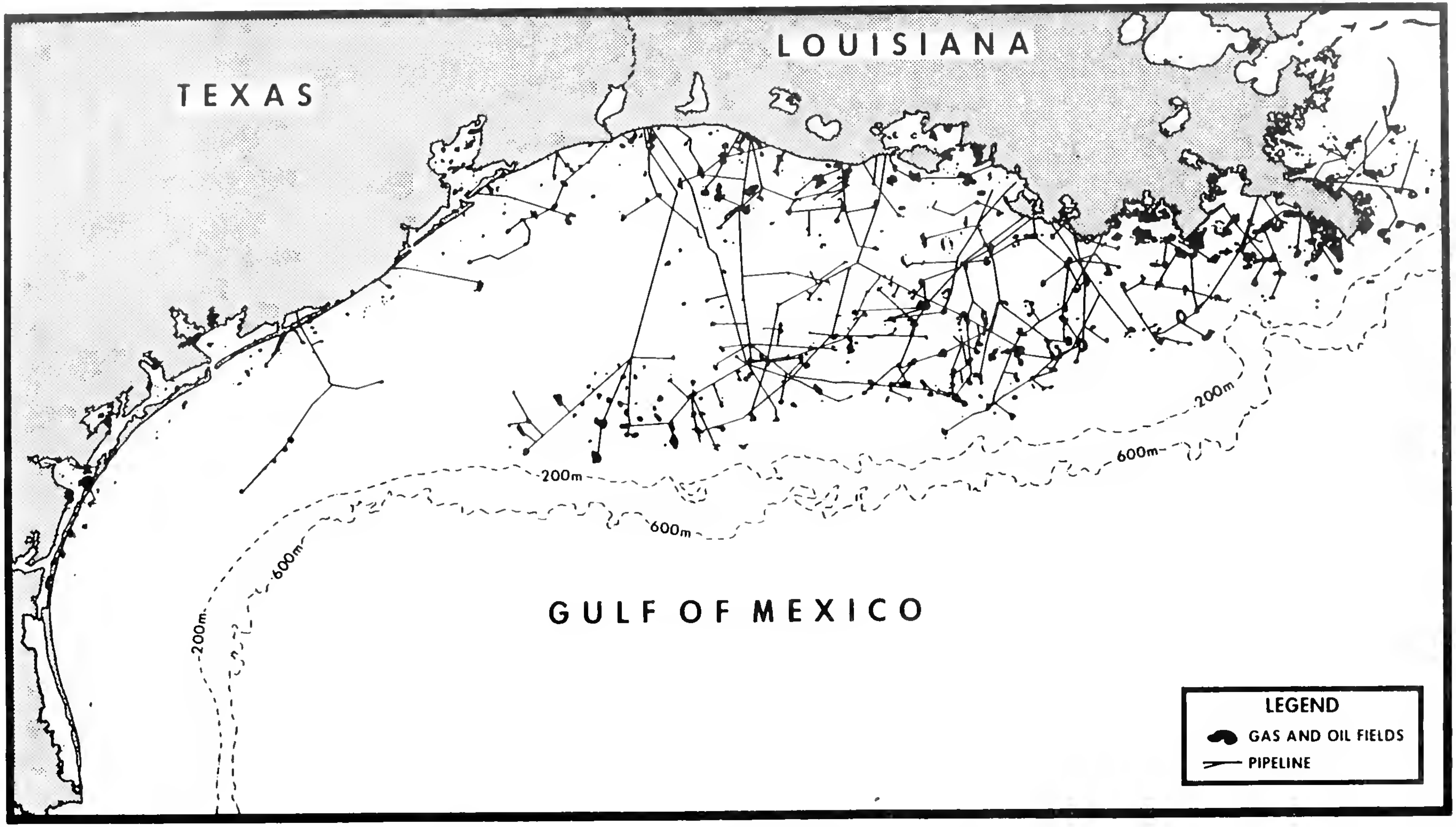


Figure 1. Distribution of gas and oil fields and pipelines on the Texas-Louisiana continental shelf. Map provided by TRANSCO Companies, Inc., 1979.

and Hopkins 1962 for a review), concern about the effects of petroleum activities *per se* on the open gulf environment and biological systems did not receive much attention until the late 1960's--a period of marked environmental awareness on a global scale. The initial major effort in response to the concern about the effects of petroleum activities in the open Gulf of Mexico was the *Offshore Ecology Investigation* (OEI). The OEI, a multidisciplinary field study conducted in waters offshore of Louisiana during 1972-74, was designed to assess the cumulative ecological effects of normal petroleum activities on estuarine and nearshore ecosystems. Analysis and evaluation of the voluminous data generated by this field effort extended this program to 1979 (Ward et al. 1979). Two other major field studies, initiated by the Federal Government in the northwestern gulf during the 1970's, were designed specifically to assess the effects of petroleum activities on the gulf ecosystem. The first project, conducted offshore of Galveston, Texas, was the *Environmental Assessment of Buccaneer Gas and Oil Field in the Northwestern Gulf of Mexico.* It was funded by the Environmental Protection Agency (EPA) through interagency agreement with the National Oceanic and Atmospheric Administration (NOAA) and managed by the National Marine Fisheries Service (NMFS), Southeast Fisheries Center (SEFC), Galveston Laboratory in Galveston, Texas. The major objectives of this program were to identify types and extent of environmental and ecological alterations associated with an active gas and oil field, to determine quantities and effects of specific contaminants, and to develop capabilities to describe and predict impacts from petroleum activities. An overview of the results of that program are provided by Caillouet et al. (in prep.). During 1978-79, the Bureau of Land Management (BLM) also conducted petroleum platform studies offshore of Louisiana (Bedinger et al. 1980). Each of the previously mentioned studies is completed (or nearly so). In addition to these, both the EPA and BLM have studies currently in progress in the northern gulf which are dealing directly with the effects of offshore drilling and/or production activities on reef fish communities.

One of the problems in evaluating the OEI data in terms of being able to recognize system changes was the lack of comprehensive pre-drilling ecological characterizations, a problem in many, if not most, areas of the gulf. The lack of such information is being augmented by several baseline ecological investigations, including in the northwestern gulf, the BLM's South Texas Outer Continental Shelf (STOCS) and topographic features studies, the Department of Energy's (DOE) investigations associated with offshore brine discharges from Strategic Petroleum Reserve (SPR) sites, and various other studies such as those associated with offshore supertanker ports (e.g. LOOP and SEADOCK).

Results of these studies and other programs underway in the northwestern gulf are only now beginning to surface in the published literature. Much of the recent unpublished information (including this author's research) will probably not appear for several additional years due to the involvement of investigators in ongoing programs. The primary purpose of this paper is to conceptualize the apparent structure and functional nature of the ecosystems of the northern Gulf of Mexico, and to describe some of the known or projected effects of petroleum development and other activities of man on these systems. The rationale for the ecosystem context of this paper is that systems ecology has matured in recent years and represents the most likely (if not only) approach which can produce an approximation of the assimilative capacity of the northwestern gulf to maintain its present equilibrium state before a new, unexpected and avoidable state is actually attained. Systems ecology has been developed to the point where succinct models of key elements of a problem can be produced and these models can cope with the non-linear relationships accounting for many multiple equilibrium situations. This paper is presented as a first-order, holistic overview, intended to identify some of the key system elements and processes which need to be approximated to determine the nature and direction of the present equilibrium state of the gulf, with emphasis placed on evaluating the effects of oil and gas development.

As a first-order overview, the approach in presenting the characterization is towards simplification--perhaps overly so. The volume of available descriptive information is very large and complex processes are indicated. A comprehensive, written review of all the data considering alternative scenarios would probably result in a report too cumbersome for assimilation and would likely be accompanied by a summary too shallow to allow an intelligent response. What I have attempted to present is a medium-level, comprehensible, logical characterization of the system which will increase insight into the system, making it easier to judge and determine the effects of either factors left out of the accounts or the errors in interpretation and gaps in the data.

THE TEXAS-LOUISIANA CONTINENTAL SHELF ECOSYSTEM

The Gulf of Mexico is an oval sea having an approximate surface area of over 1.6 million km^2 and a maximum depth of about 3,840 m (Figure 2). Oceanic water enters the gulf from the Caribbean Sea through the Yucatan Channel (<160 km wide and 1,650 to 1,900 m deep) and exits through the Florida Channel (<160 km wide and about 800 m deep); both openings are located in the southeastern sector of the gulf. This feature, combined with the fact that runoff from some two-thirds of the United States and more than half of Mexico empties in the northern and western part of the basin, serves to divide the gulf into two major provinces--a carbonate province to the east and a terrigenous one to the west (Uchupi 1967). Based upon topography, Uchupi (1967) further subdivided the gulf into additional major physiographic provinces--namely the continental shelf, the continental slope, the Mississippi Fan, the continental rise and the Sigsbee Abyssal Plain. The shelf province is subdivided as the West Florida Shelf, the Mississippi-Alabama Shelf, the Texas-Louisiana Shelf, the East Mexico Shelf, and the Campeche Shelf (Figure 2).

Antoine (1972) divided the Gulf of Mexico into seven distinct geological provinces. Of these, his Northern Gulf of Mexico Province corresponds with the Texas-Louisiana Shelf and the Slope Provinces presented by Uchupi (1967). Antoine (1972) described the Gulf of Mexico basin as geologically old and representing a subsided oceanic area that has been partially filled with sediments.

The Texas-Louisiana continental shelf ecosystem has reasonably distinct physical boundaries. It is bounded on the north and northwest by land, on the east primarily by the Mississippi River birdfoot delta which has bisected the shelf, and on the south and southwest by the rapid change in slope which marks the transition from the continental shelf to the continental slope (~118 m deep). The boundary to the extreme south and southwest is less distinct, but is roughly placed at the United States-Mexico border coinciding with the beginnings of the anticlinal folds that generally parallel the shoreline in this area. Some of the salient hydrographic processes and topographic features considered important for assessment purposes are characterized in the following section and are followed by descriptions of biological systems.

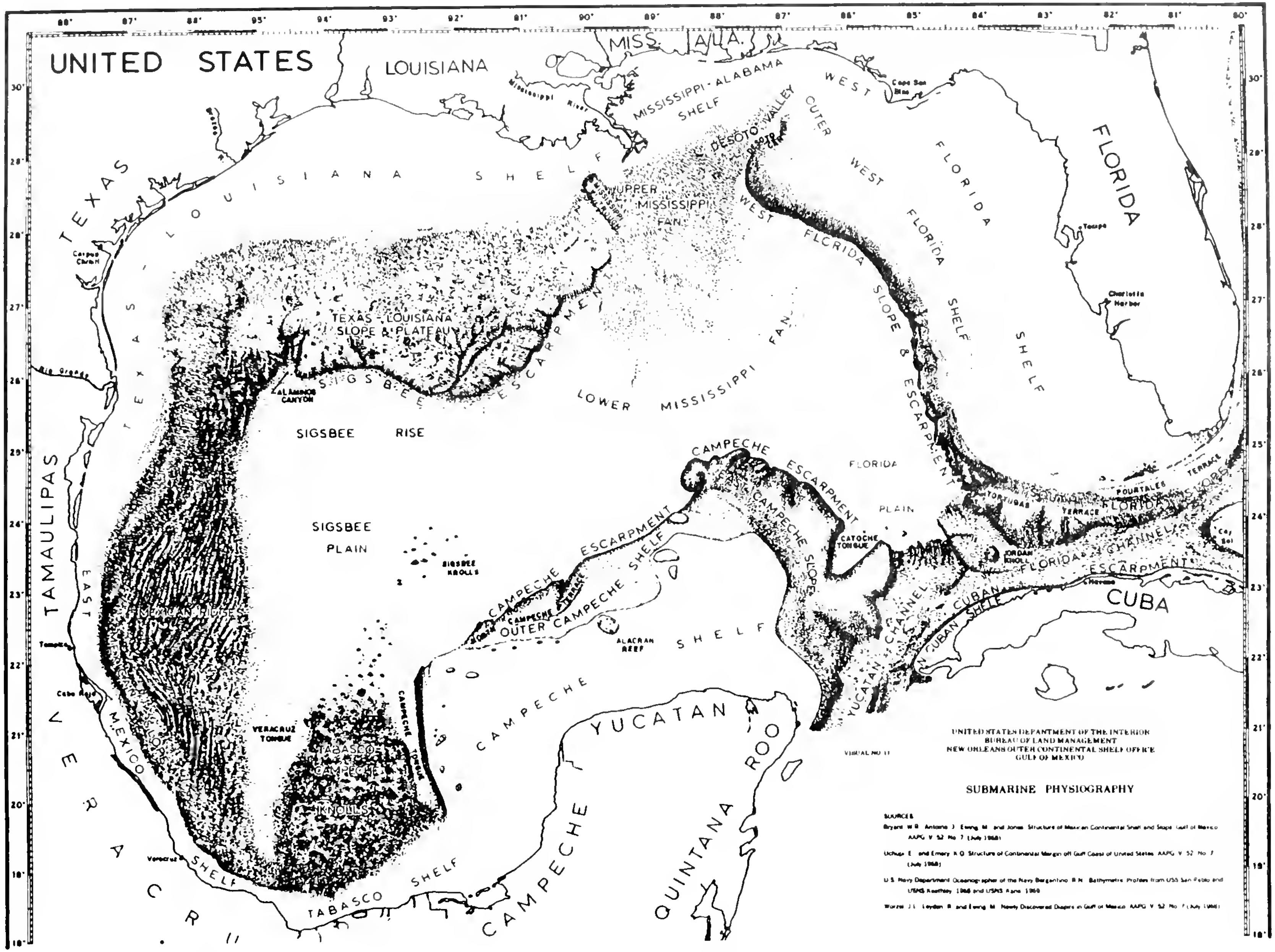


Figure 2. Bathymetric and physiographic province map of Gulf of Mexico. Visual provided by the Bureau of Land Management.

PHYSICAL-CHEMICAL FORCES

Marine biological systems are controlled, or regulated, by a number of physical and chemical variables including light, nutrients, temperature, salinity, and dissolved oxygen, as well as the physical nature of the habitat. Each of the above variables is, in turn, greatly influenced by riverine discharge and marine circulation patterns. Generalized surface current patterns, hydrography and prominent topographic features of the Texas-Louisiana shelf are described below.

Currents

The principal inflow of water into the gulf is from the Caribbean Sea through the Yucatan Channel. These waters are a mixture of South Atlantic water (transported northwestward by the Guiana and Equatorial current systems) with North Atlantic water (Pequegnat 1976). The ratio of South to North Atlantic water has been estimated to be between 1:4 and 1:2 (Harding and Nowlin 1966). The generalized current pattern for the gulf is shown by Figure 3. The Yucatan Current branches into three major flows (1) the Loop Current which dominates eastern gulf circulation and entrains some western gulf waters, (2) the Central Gulf Current (Moore 1973) which flows towards the Mississippi River Delta and to the west, and (3) the West Gulf Current which flows over and around the Yucatan Shelf to the west until it is forced to the north by the curvature of Mexico (Brucks 1971).

While the general flow of water along the Texas-Louisiana shelf is to the west, seasonal variation occurs and nearshore currents are greatly influenced by the shoreline and regional winds. Currents on the nearshore shelf are primarily driven by local and regional wind systems, passage by diurnal tide, and impingement of regional gulf currents onto the shelf. Results of drift bottle studies by Kimsey and Temple (1962) and Kimsey (1963) showed that, just west of the Mississippi River Delta, nearshore currents moved south, west, and east (Figure 4). Under conditions of an easterly flow, currents were deflected by the delta which resulted in a large-scale eddy development in the embayment west of the delta.

Additional detail describing the nearshore currents of the Louisiana shelf was provided by Oetking et al. (1979). These investigators summarized their findings as follows:

- The net movement of the water column, which was driven primarily by regional winds, was easterly in the summer and westerly from winter through early spring.

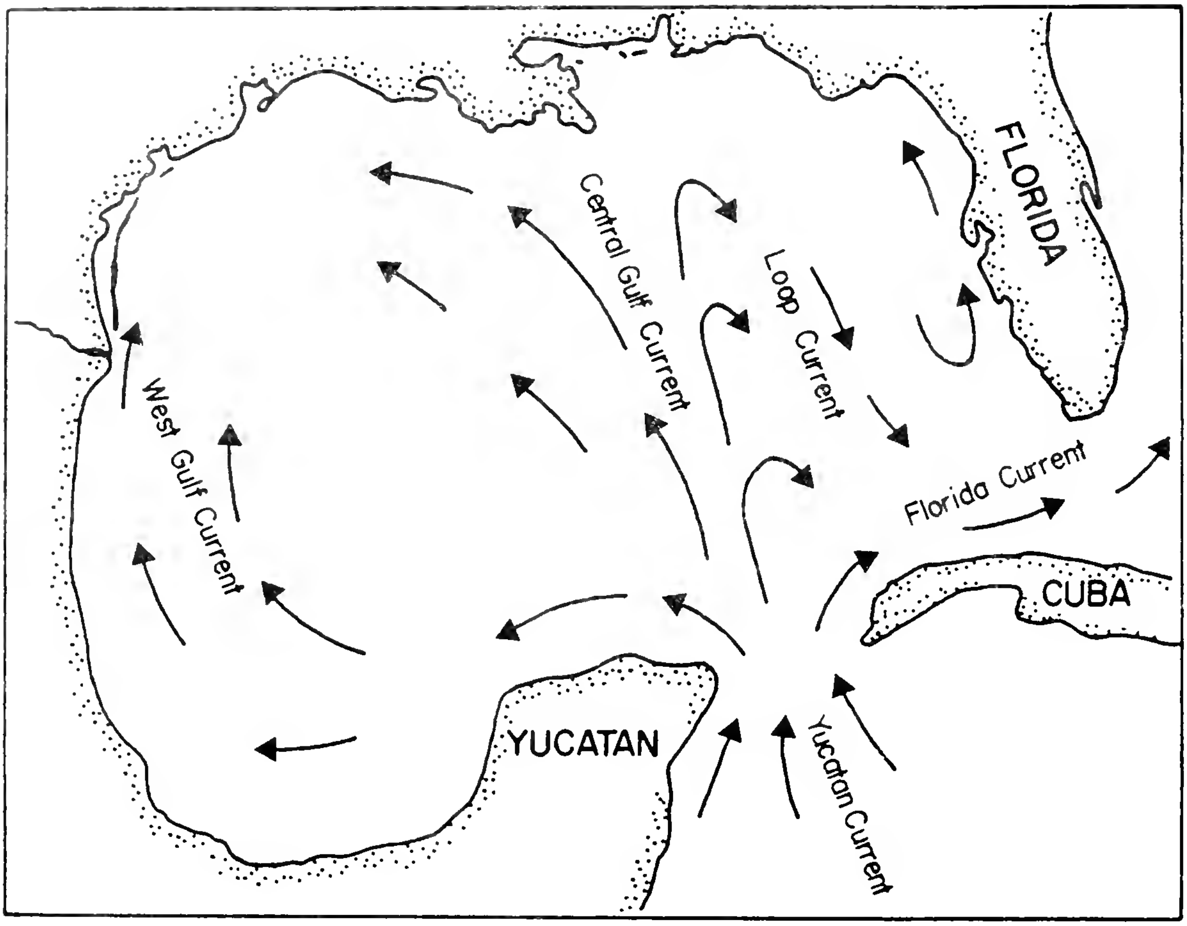


Figure 3. Generalized regional currents of the Gulf of Mexico.

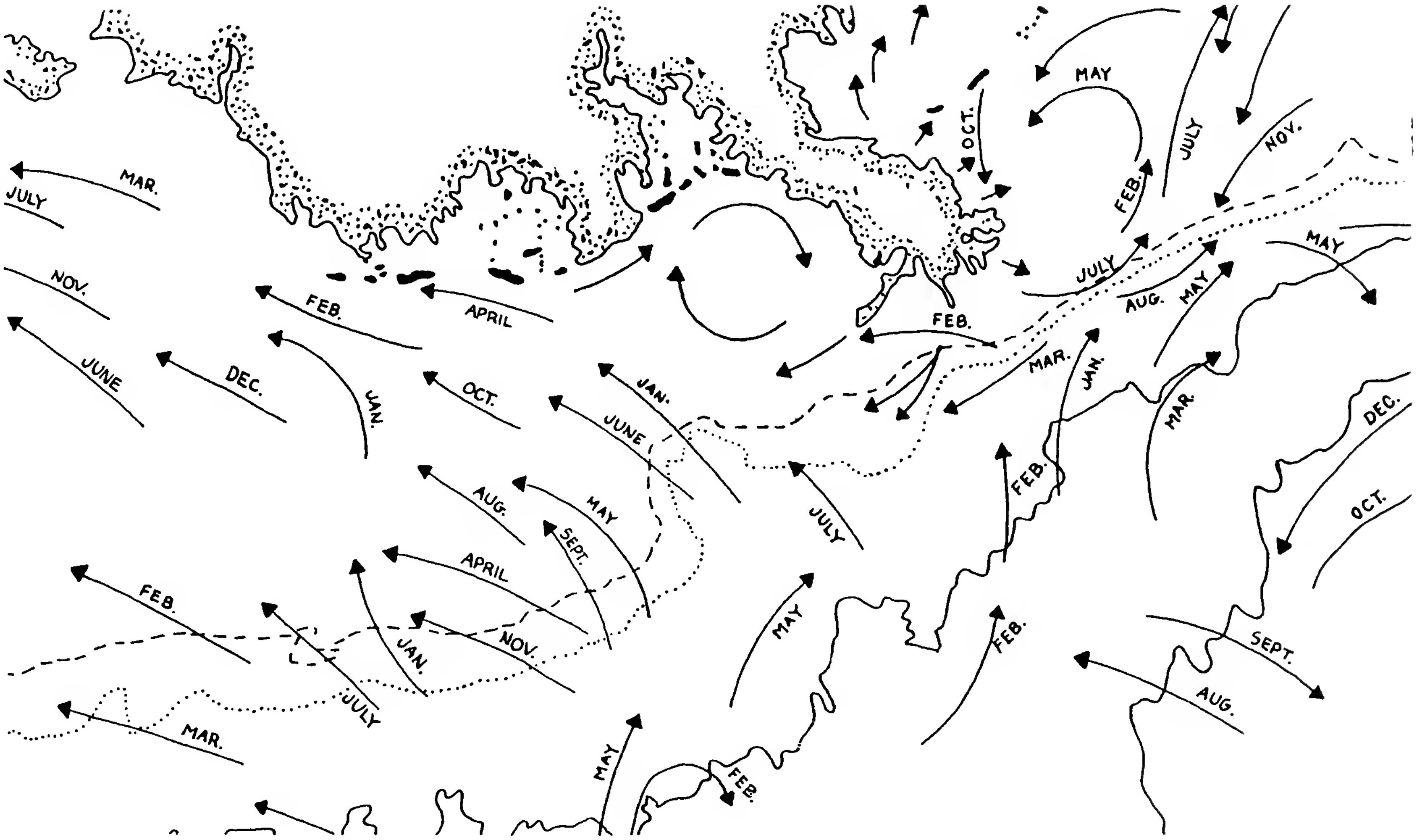


Figure 4. Generalized directions of flow of surface waters in the northern Gulf of Mexico by month (from Pequegnat 1976).

- Onshore and offshore currents prevailed in the fall and probably late spring.

- Surface currents were generally easterly in the summer (0.40 knots) and westerly from winter through early spring (0.82 knots).

- Mid-depth currents (0.26 knots) were easterly, onshore and offshore in the summer; westerly and offshore from winter through early spring.

- Bottom currents (0.22 knots) were mostly onshore and easterly in the summer; westerly, onshore and offshore from winter through early spring.

- Current speed decreased with depth.

- The net annual movement of water in the study area was westerly.

These determinations were consistent with the findings of current studies performed offshore Galveston in the Buccaneer Gas and Oil Field (BGOF) by Armstrong (1979). Currents in the BGOF were found to be aligned principally in long-shore directions, reversing seasonally from upcoast toward the northeast in summer (May-August) to downcoast toward southwest for October-April. Transitional conditions appeared to rule in September and April. Current meter records showed layering of contrasting flows during some seasons. Local winds were apparently the main driving force for the circulation. Flow was typically with the wind but was deflected by the coastline such that there was compensating offshore transport with onshore winds, or to the right of the winds due to Ekman transport. Distinct departures from local wind-driven circulation developed during spring, when it seems high river discharge established a downcoast, geostrophic current which, from current meter records, may have accounted for the layered currents of summer. Also, during early fall, currents of the area did not appear to relate to local winds, but may have been responding to larger-scale atmospheric alterations. Spectral analyses of current meter records indicated that tidal currents and wind shifts accounted for most of the variability in flow dynamics, with dominant periods perhaps associated with passage of continental air masses in winter and fall, and longer-period maritime air mass development during summer.

The Brownsville Gyre is a prominent and important feature of the circulation in the southwestern portion of the Texas-Louisiana shelf system. The seasonal movements of this gyre were described by Pequegnat (1976) and more recently by Smith (1980). During the winter, the counterclockwise gyre is typically located just northeast of Brownsville (Figure 5). It begins moving north during spring and often penetrates as far as Galveston by late summer-early fall. This phenomenon allows water from as far south as the Gulf of Campeche to move as far north as Galveston and perhaps beyond. The convergence of the Brownsville Gyre and coastal waters coming southwestward from Louisiana serve to transport nearshore water carrying living and non-living organic materials to the offshore and out of the shelf system. The Brownsville Gyre is also characterized by a transient summer upwelling phenomenon bringing cooler, saltier water onto the inner shelf (Smith 1980).

Salinity

Salinity of gulf waters over the Texas-Louisiana shelf is greatly influenced by the generalized current patterns and by river discharge--namely the Mississippi and the Atchafalaya Rivers. Although variable, highest discharge of freshwater runoff into the northwestern gulf occurs during March through May (peak in April) and is lowest in September (Figure 6). Although the annual runoff is only about 0.1% of the annual volume of the Florida Current (Figure 3) exiting the gulf, it represents 10% of the volume of the water on the continental shelf in the western gulf (El-Sayed et al. 1972). In general, surface water salinity increases on the shelf from the east to the west and southwest, as well as with distance offshore (Temple et al. 1977, Figure 7). During periods of peak river discharge in spring, the effects of runoff (low salinity) sometimes are evident over much of the shelf, extending to the south and west to beyond Galveston (Figure 8a). During periods of low flow (late summer-fall), the effects of river discharge on salinity are less pronounced. The most prominent salinity phenomenon during this period is the northward extension of high salinity water from the extreme southwestern gulf north to Galveston and beyond (Figure 8b, Temple et al. 1977).

The salinity regime of the water column over the shelf often shows marked stratification. In shallow, nearshore waters, the effect of lower salinity from freshwater discharge may reach throughout the water column, but farther offshore, the less saline water forms a band of shallow, surface water overlying higher salinity water below (e.g. Gallaway et al. 1980). In addition high-salinity, deep water from the open gulf is sometimes upwelled and advected inshore along the bottom of the shelf, also contributing to stratification by producing a bottom layer of high salinity water.

The pycnoclines or areas of interface between layers of water having different densities serve as accumulation points for suspended materials producing turbid layers in the water column (Figure 9). In the example shown by Figure 9, which depicts conditions offshore of Galveston during spring 1979, relatively low-salinity, turbid water

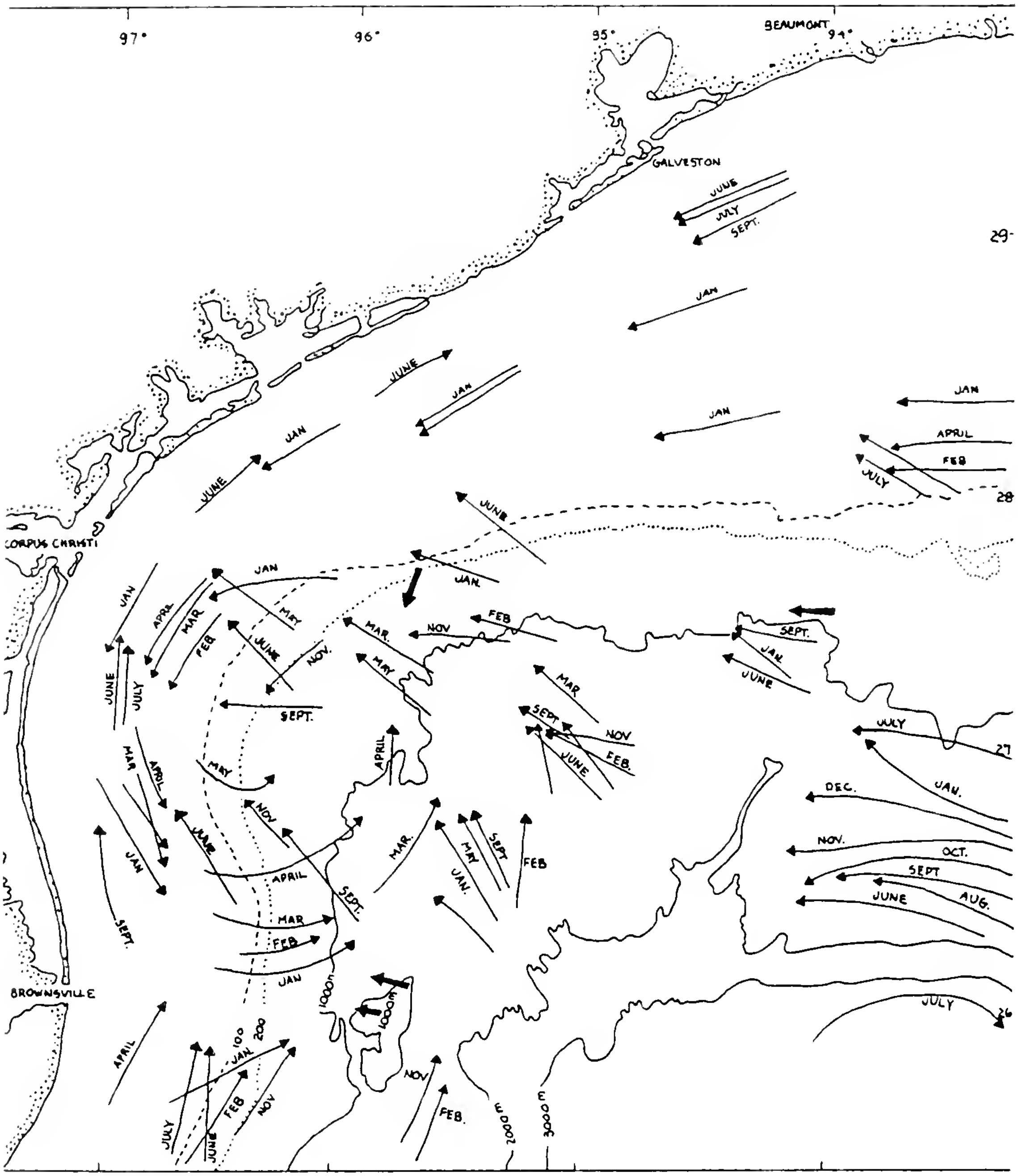


Figure 5. Generalized patterns of flow of surface waters in the western part of the northern gulf (shown by fine arrows) on a monthly basis. Note the counter-clockwise gyre northeast of Brownsville. Heavy arrows show submarine flow (after Pequegnat 1976).

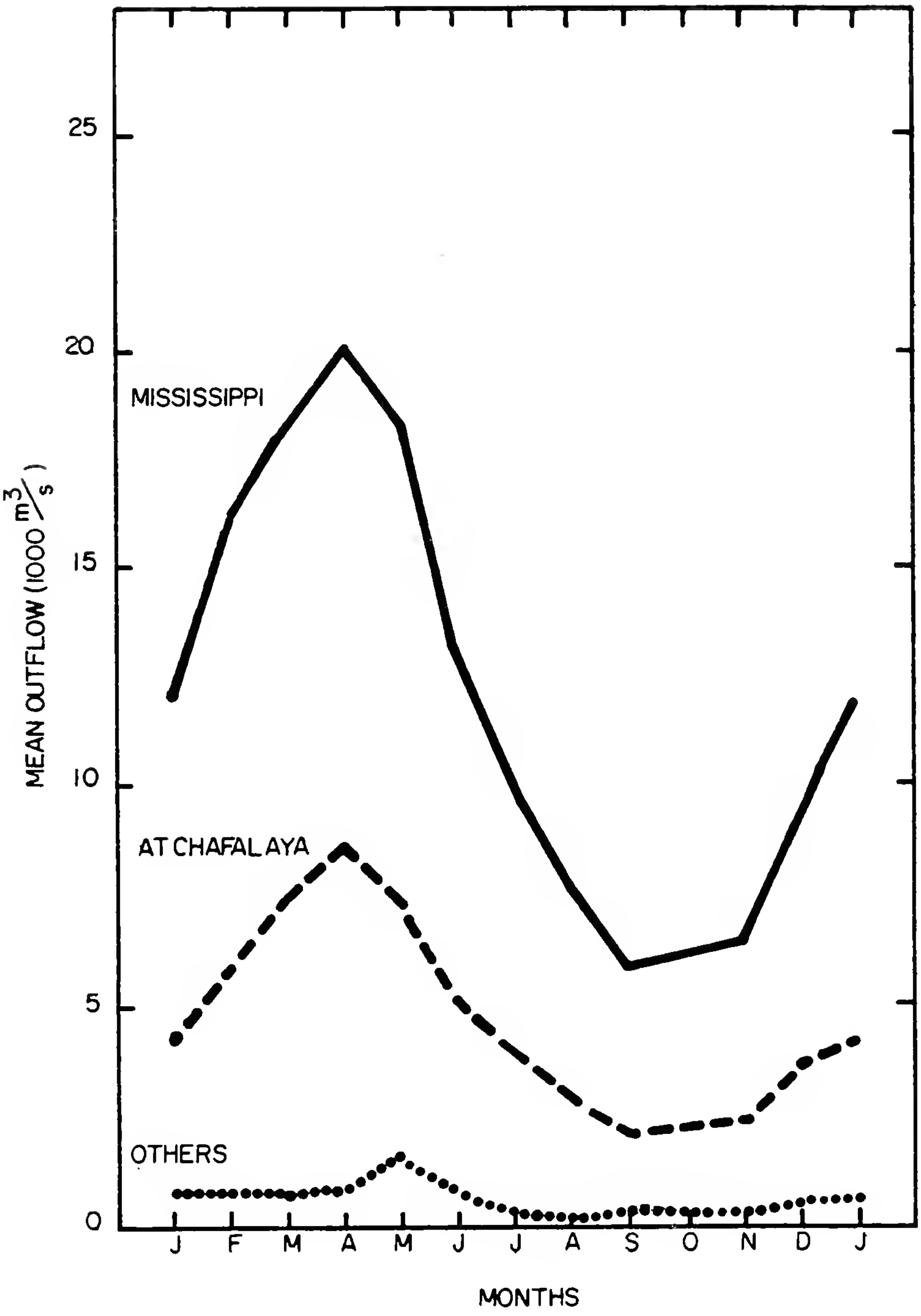


Figure 6. Monthly mean river discharge from the Atchafalaya and Mississippi Rivers and the sum of the mean outflows of the rivers west of the Atchafalaya to the Rio Grande (Source: U.S. Geological Survey Reports of surface water supplies of the United States 1950-1970).

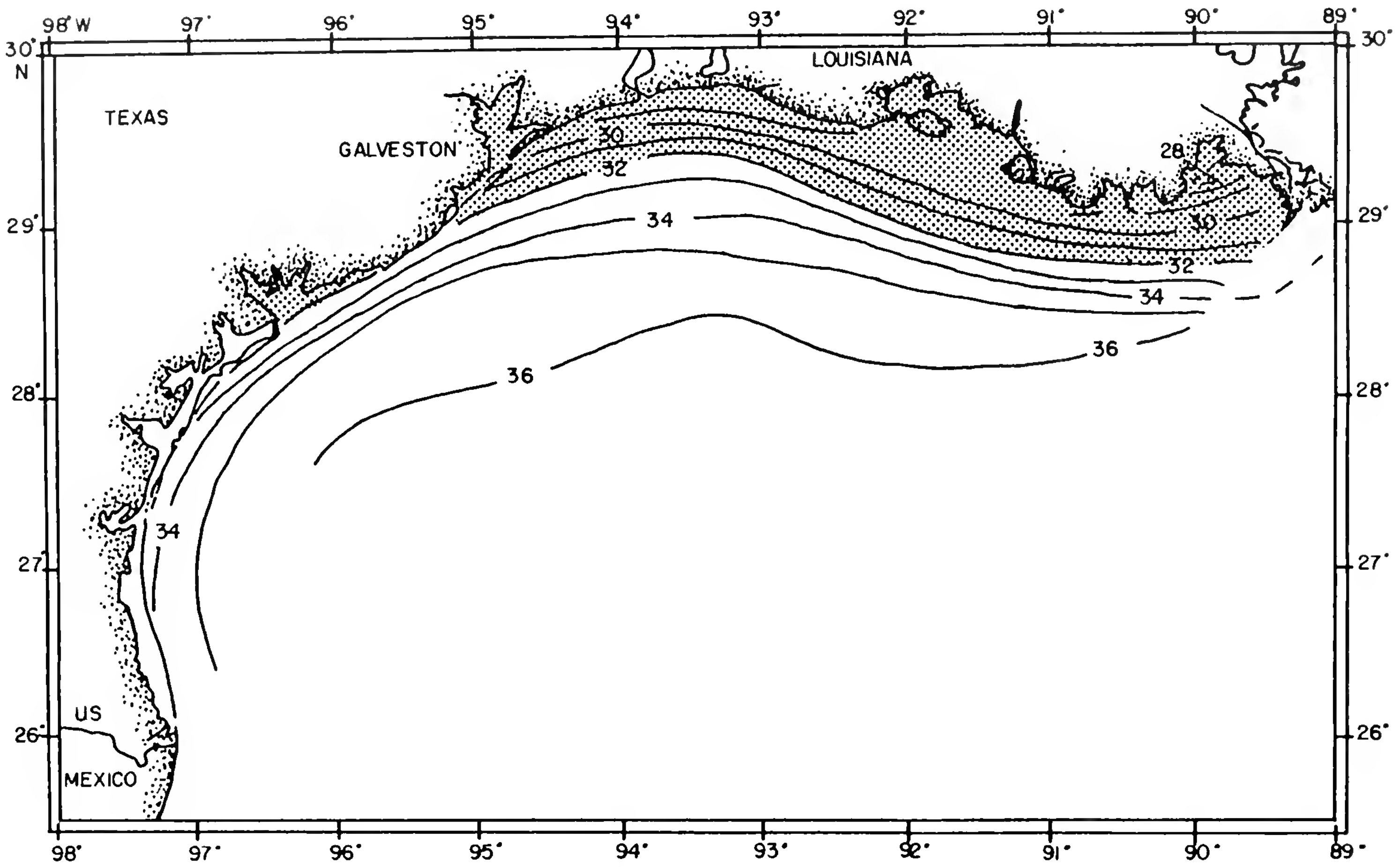


Figure 7. Surface isohalines (parts per thousand) for the northwestern gulf (from Temple et al. 1977). Shaded area represents zone where surface average is ≤ 32 ppt.

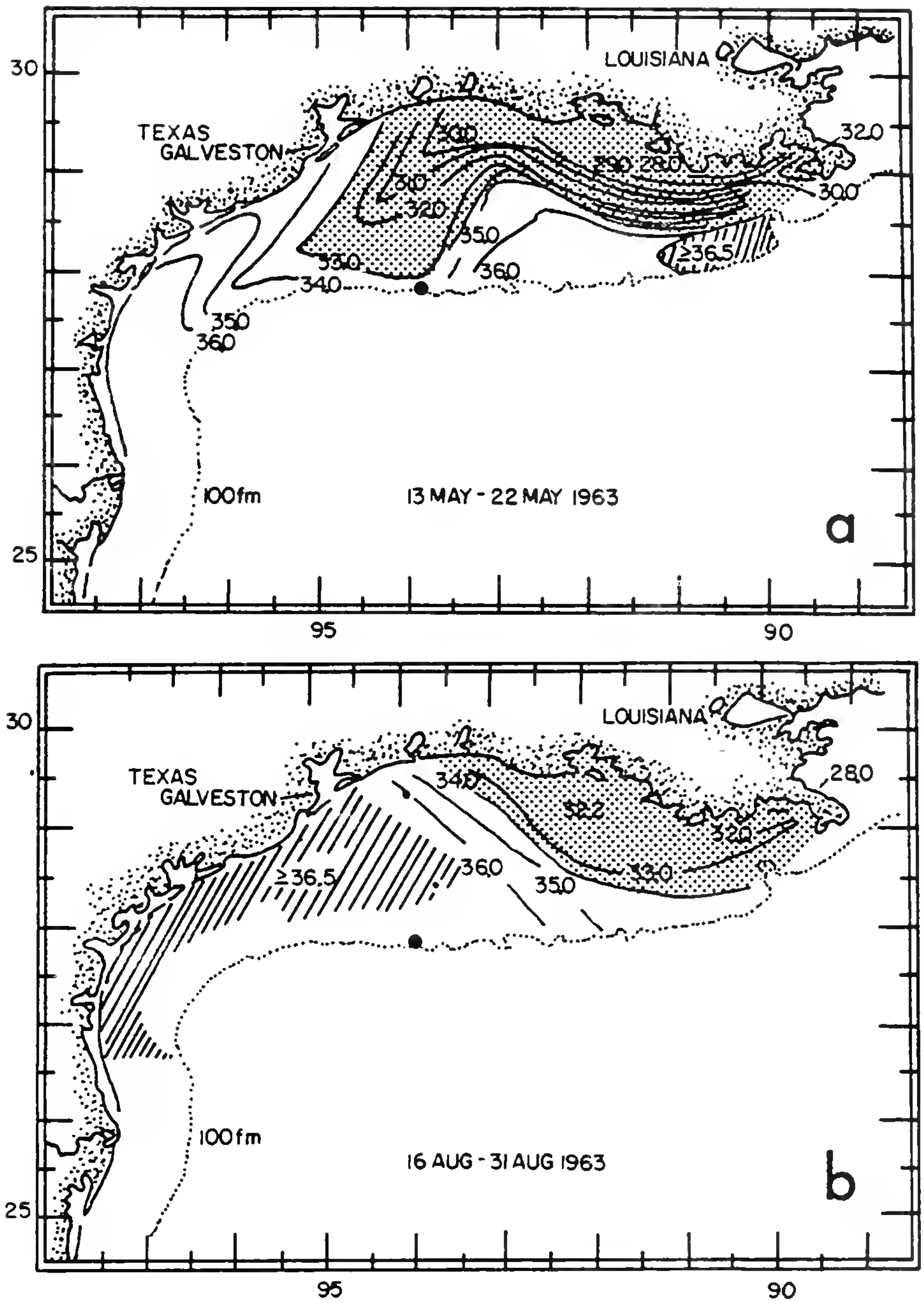


Figure 8. Surface isohalines (parts per thousand) showing extensions of low (stippled area) and high salinities (lined area) over the northwestern Gulf of Mexico shelf during spring (a) and summer (b) (from Temple et al. 1977).

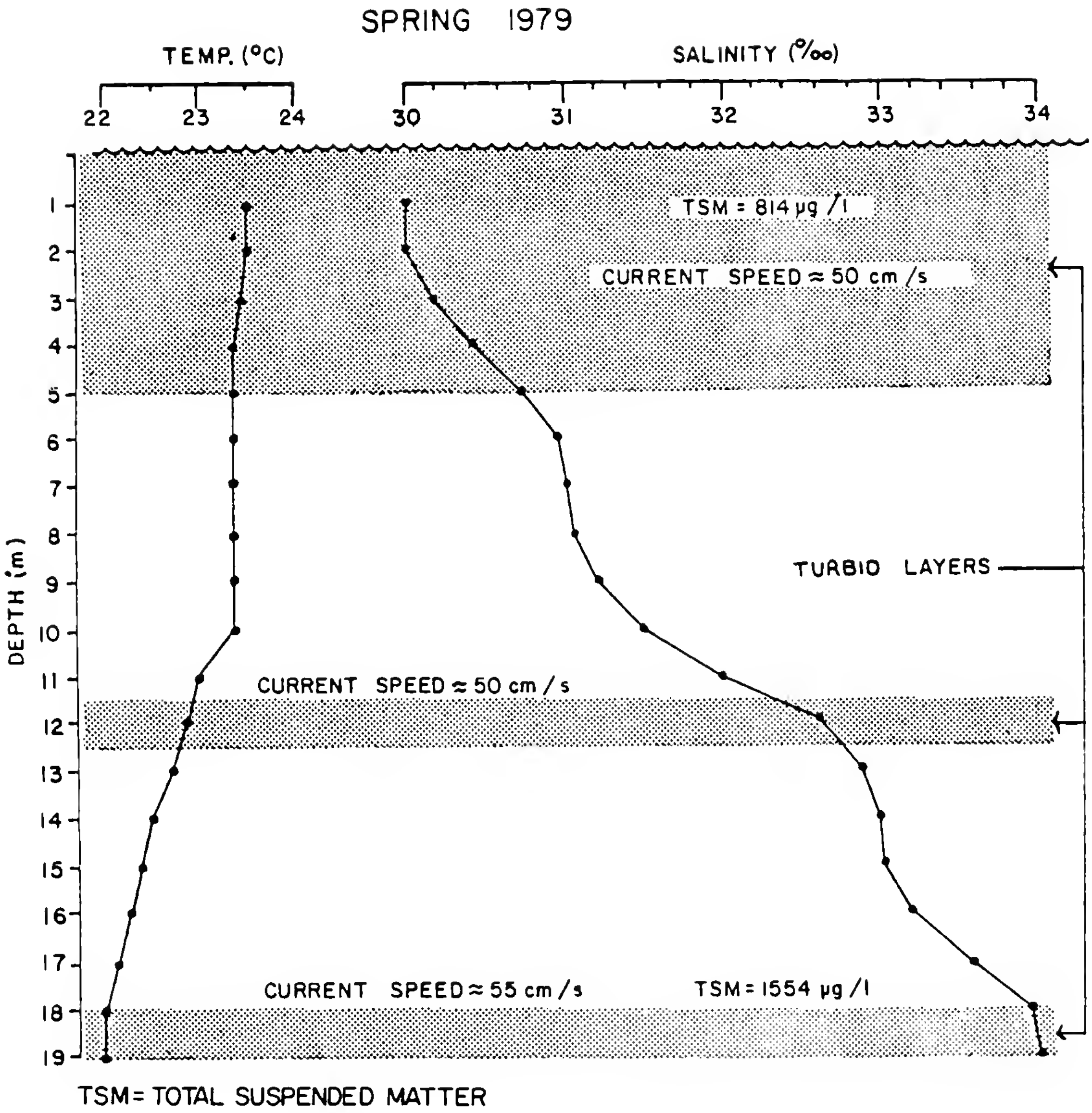


Figure 9. Characteristic environmental structure of the water column observed in the Buccaneer Gas and Oil Field during spring, 1979 (after Gallaway et al. 1980).

influenced by freshwater runoff comprised a 5-m deep surface layer overlying, clear, intermediate salinity water between 5- and 12-m depths. Waters below 13-m depth had relatively high salinities (≥ 33 ppt), and a 1-m deep turbid band was evident at the 12-m deep area of interface between these two water masses. This band was followed by a relatively clear layer of water extending down to the bottom meter, which was markedly turbid due to resuspension of sediment by bottom currents.

Turbid Water Layers

The shelf waters of the northwestern gulf are characterized, at least seasonally, by a two- or three-layered water column with bands of turbidity present at the interfaces. Of these, the bottom turbid layer is the most persistent, usually being detected during all seasons from Louisiana (Griffin 1979) to South Texas (Causey 1969). The source of much of the suspended material in the turbid layers is freshwater runoff from the land, primarily from the Mississippi Drainage Basin. A process model for turbid-layer transport of Mississippi River suspended sediment was presented by Griffin (1979) and is summarized below. Results of the EPA BGOF studies offshore of Galveston and the DOE baseline investigations for brine disposal offshore of Freeport, Texas, indicate that suspended sediments in those regions also appear to be mainly of Mississippi River origin--corresponding well with the previously mentioned effects of the river on surface salinity distribution (Figure 8a). Other rivers undoubtedly make proportional contributions, but their combined total discharge is relatively small as compared to that of the Mississippi (Figure 6).

Griffin (1979) noted that the river discharge emanates from the passes as a highly-turbid, distinct, surface plume carrying 40 to 500 g/ℓ suspended sediment alone. Because of the significant density differences between this plume and the clear mid-depth water in the open gulf, eddy diffusivity is limited and the plume may persist for miles away from the delta, perhaps even to South Texas. Slow erosion of the base of the turbid plume by internal waves at the density interface allows only small quantities of the suspended sediment to descend into the mid-depth layer at any point. Suspended material in the plume is therefore dissipated slowly into the mid-depth water and diluted as the surface plume drifts with the prevailing current (generally west except during summer periods when the general flow is often to the east). The net transport is to the west and the quantity of suspended material that settles through the mid-depth water at any one place is small, serving to maintain the relative clarity of this water mass (e.g. Figure 9).

The particles that pass downward continue to settle towards the bottom although sinking may be interrupted by pycnoclines. Eventually particles do reach the bottom where, through bottom currents, tidal action, waves, upwelling, and perhaps, biological phenomena, they accumulate as a nepheloid cloud of fine particles. The turbid bottom water moves not only towards the west but also towards the coast, and, due to multiple resuspension, the suspended materials remain in the water column as opposed to being deposited on the shelf. Nearshore (~8 km), the "shelf" turbid layer is joined by turbid water generated in the high-energy littoral zone, and the combined turbid water mass is transported westward. In the eastern part of the study area, much of this material is trapped in the coastal marshes and mudflats of the prograding Chenier Plain of southwestern Louisiana (Griffin 1979), but the remnants can be detected beyond Galveston.

The nature of the suspended material in seawater over the shelf is of major importance. The inorganic fraction is virtually identical to that of the Mississippi River (Griffin 1979). In addition to a high sediment load, the Mississippi River and waters being discharged from nearby estuaries in the eastern part of the study area were indicated by Brent et al. (1979) to have high organic carbon loads. Based upon Jacobs and Ewing (1969); Fredericks and Sackett (1970); and Harris and Sackett (1970) over 50% of the suspended material in shelf waters of the northwestern gulf may be organic. The levels of organic carbon (7.8 to 13.1 mg/ℓ) being discharged by the Mississippi River and estuaries in the eastern part of the study area were of the magnitude necessary to account for the observed carbon levels in gulf waters (Brent et al. 1979).

Particulate organic carbon is only recently in the process of being adequately characterized. Organic aggregates have historically been collected by traditional methods (nets, pumps, bottles) and have been characterized as small (25 to 100 μm). Results of in-situ observation and careful collection have shown that organic particles form aggregates ("marine snow") of much larger dimensions (millimeter to centimeter range) which are easily disrupted, and seldom taken by traditional methods (Campbell et al. 1980). These little-studied particles of marine snow are potentially very significant centers of nutrient regeneration and primary and secondary productivity. In addition, they provide a prepackaged food source for larger oceanic consumers such as herrings and spadefish.

Temperature

Water temperature over the Texas-Louisiana shelf fluctuates by season, distance offshore, and/or latitude and depth. In surface waters, particularly nearshore, seasonal variations in surface water temperatures correspond well with coastal air temperatures (Figure 10). Temple et al. (1977) showed that surface water temperatures over the shelf vary little in summer, ranging from ~29° to 31° C (Figure 11b). However, during winter, surface isotherms nearly parallel the coastline exhibiting a trend of increasing temperature with distance away from the coast (Figure 11a). Depending upon the presence of a surface freshwater layer, variation in temperature by depth is not markedly pronounced in shallow shelf waters (a few degrees). However, in deeper shelf waters,

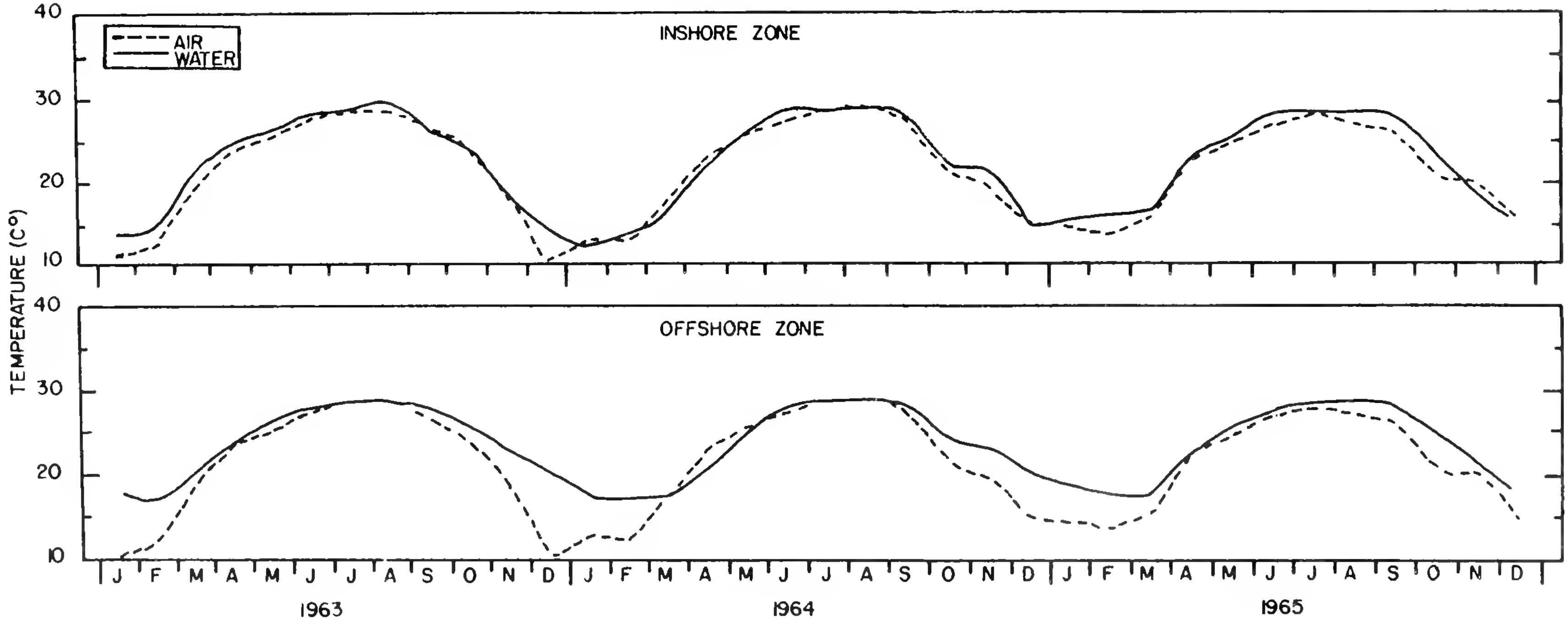


Figure 10. Seasonal trends in average temperatures of inshore and offshore surface waters with coastal air (from Temple et al. 1977).

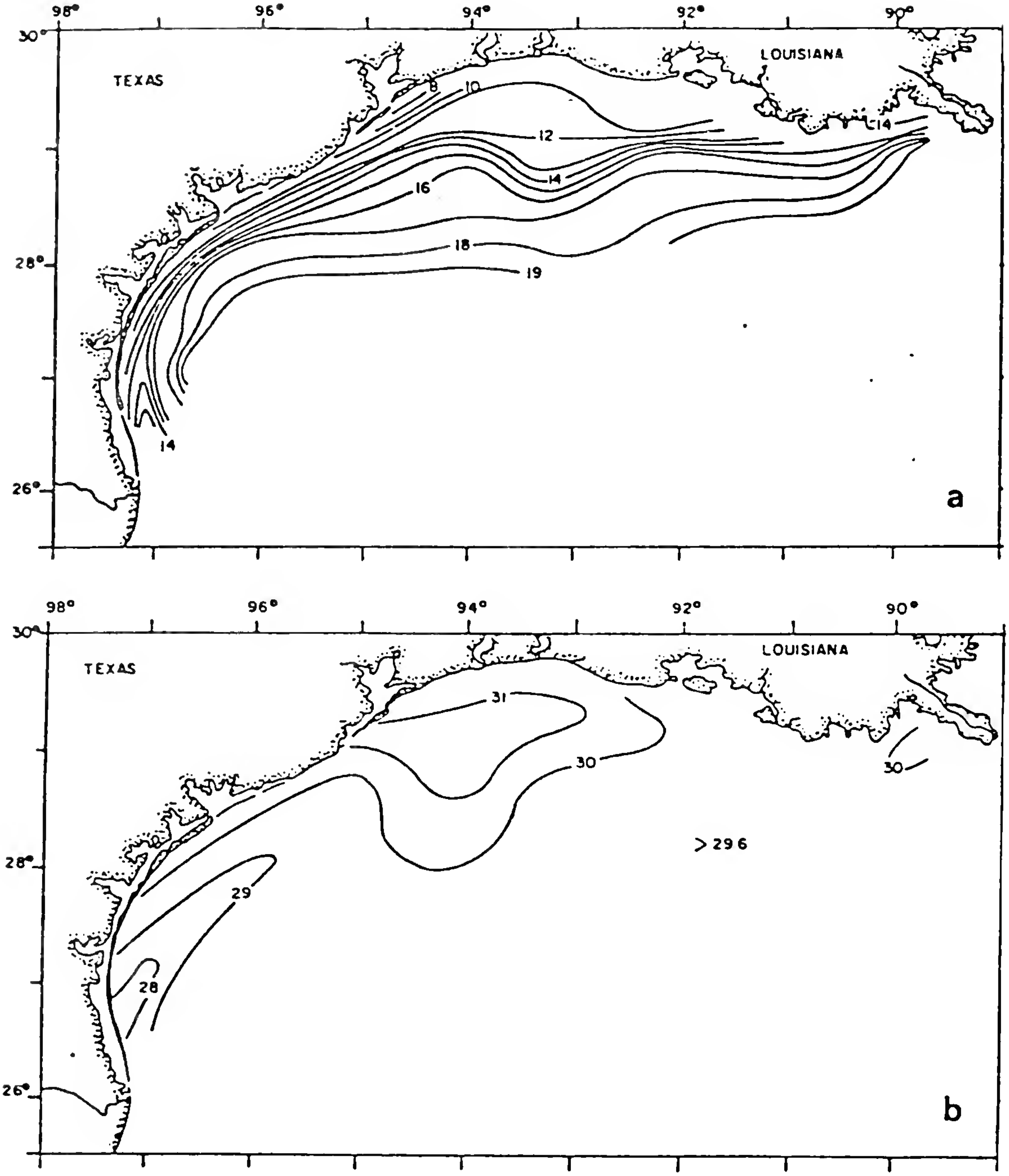


Figure 11. Surface isotherms (°C) for winter (a, January 1964) and summer (b, August 1963) (from Temple et al. 1977).

vertical temperature stratification may be pronounced in the upper 100 m, particularly during summer (Etter and Cochrane 1975, Figure 12).

Dissolved Oxygen

Dissolved oxygen levels in shelf waters vary with seasonal trends in temperature, mixing, salinity, organic carbon load, respiration, and photosynthesis. High dissolved oxygen concentrations are promoted by low temperature, high wave turbulence, high rate of photosynthesis and, in general, low salinity. Dissolved oxygen levels are generally higher in surface than in bottom waters due to atmospheric input, photosynthesis, and lower salinities of surface waters; and higher during winter than during summer periods, primarily as a function of temperature and mixing.

The occurrence of hypoxic ($\lesssim 2$ mg/ℓ) bottom waters has been noted for that area of the shelf lying between the Mississippi River Delta and about Grand Isle, Louisiana, since about the midthirties (Bedinger et al. 1980). Such conditions are pronounced during spring and summer months and have been associated with (1) high loadings of organic materials from the previous spring flooding of the Mississippi and Atchafalaya Rivers; (2) the resulting isolation of near-bottom water having a high oxygen demand from a surface layer of fresh water during periods when temperatures are high, and waves and other sources of energy are insufficient to mix the two water masses; and (3) the long residence time of water in the area due to the eddy current.

The extent of the area affected by hypoxia and the duration of the event appears related to flooding. Following the 100-yr maximum flood of the Mississippi River in 1973, Ragan et al. (1978) determined that between May 1973 and March 1974, an average of 52 % of bottom shelf waters fronting Grand Isle out to the 110-m depth contour were hypoxic (with over 50 % of the area being anoxic). The condition was pronounced between depth contours of 6 and 33 m. The size of the area affected within the sampling zone varied by month, ranging from 27 % in December to 93 % in July.

Ragan et al. (1978) continued their investigations from May 1974 through August 1976, a period accompanied by a decline in the volume of river discharges (outflows diminished from the record level in 1973 to a point well below the long-term mean in 1976). The hypoxic zone within the investigated area decreased to an average of 39 % in 1974-75, and 12 % in 1975-76. Based upon an expanded sampling regime in 1975-76, Ragan et al. (1978) reported that oxygen-deficient water covered about 7 % of the Louisiana shelf.

During the summer of 1978, Bedinger et al. (1980) reported an estimated 10- to 15-km wide band of hypoxic (or nearly so) bottom waters

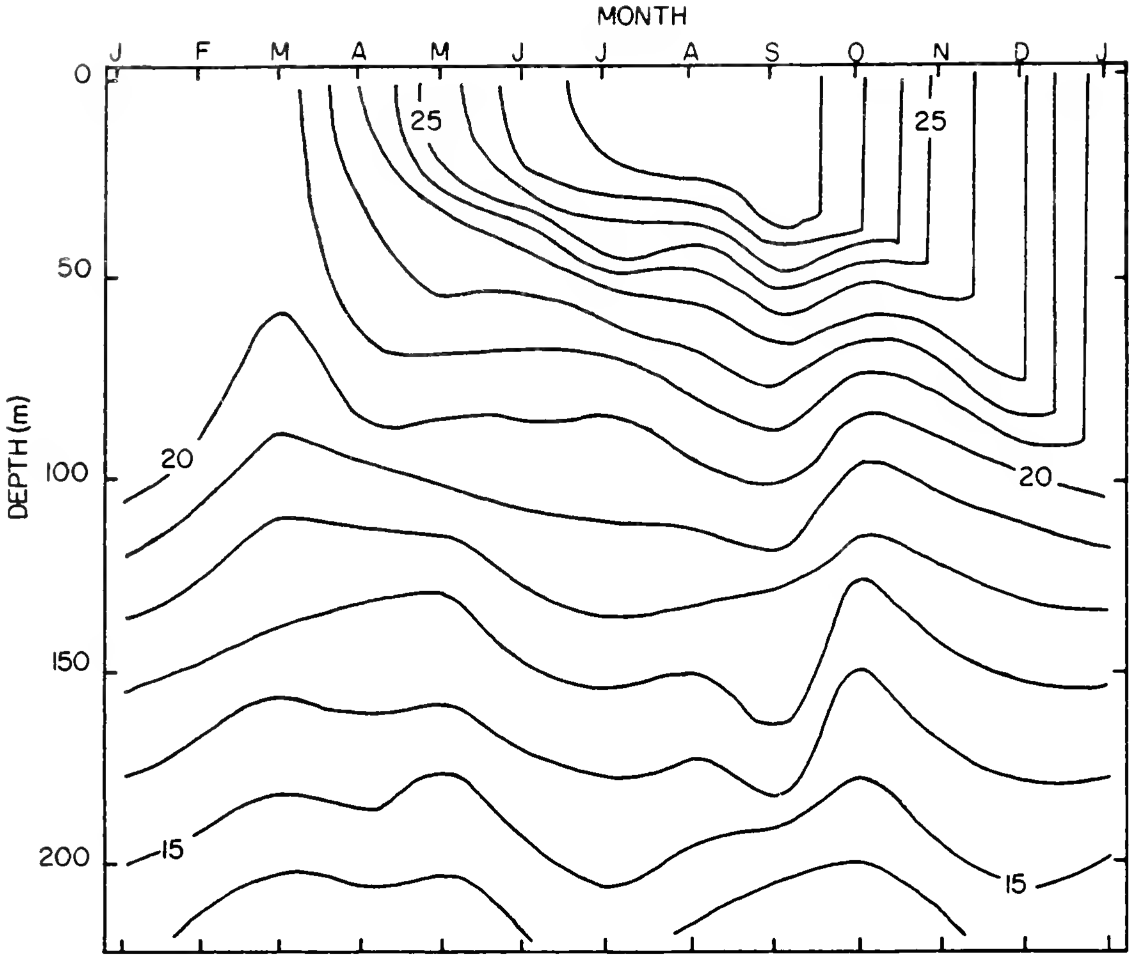


Figure 12. Annual variation of temperature (°C) with depth in the northwestern Gulf of Mexico (from Etter and Cochrane 1975).

offshore Louisiana extending along the 20-m depth contour from the delta westward to Atchafalaya Bay. During the same period, Reitsema (1980) observed hypoxic water as far west as offshore of West Hackberry, Louisiana (latitude 29°39'46", longitude 93°37'47") in waters in excess of about 6-m depths. Fotheringham and Weissberg (1979) had previously noted oxygen-deficient waters in this region during the same general time period.

Harper and McKinney (1980) were the first to document hypoxia in bottom waters offshore of the Texas coast. This event was observed during the spring and summer of 1979 for waters from about 10 m deep out to depths of 33 m and beyond. The area affected was estimated to extend north and eastward from Matagorda Bay to Sabine Pass and likely on into Louisiana. Harper and McKinney (1980) attributed the condition to large quantities of fresh water discharge resulting in water column stratification, which was then intensified by lack of mixing during calm, warm weather. The resulting oxygen depletion was believed to have been enhanced by the decomposition of river-borne organic material.

As in other parts of the United States and the world (Brongersma-Sanders 1957; Garlo et al. 1979), the occurrence of hypoxia results in mortalities of marine organisms. A fish kill was noted at the mouth of Timbalier Bay during 1973 (Brent et al. 1979), and Bedinger et al. (1980) reported extensive areas of dead bottoms (Figure 13) in hypoxic areas observed offshore of Louisiana during the summer of 1978. These areas were characterized by very poor trawl catches consisting largely of recently dead organisms. Harper and McKinney (1980) made in-situ observations during late June 1978 in the hypoxic waters offshore of Texas, and observed numerous dead benthic organisms including polychaete worms, brachyuran crabs, mantis shrimp, and hemichordates "strewn about the bottom in various states of decay." A rocky structure which had been previously observed to have had a healthy assemblage of sea whips, solitary corals, sea urchins, mollusks, crabs and reef fish was also observed. The reef fish component was absent; all sea urchins and corals were dead, as were many of the crabs. The mollusks observed were sluggish and many sea whips were missing sections of the colony and were characterized by exposed internal axial skeletons.

Processes controlling dissolved oxygen levels in shelf waters have not been quantitatively investigated. All reports of hypoxia for the northwestern gulf have noted stratification of the water column attributable to fresh water overflow, and have implicated degradation of river-borne organic materials as a major contributor to the phenomenon. The major source of oxygen-demanding materials is the Mississippi River which was estimated by Presley et al. (1980) to discharge some 280 Mtonne of sediment per year. Gunter (1952) showed that whereas, historically, sediment contained in Mississippi River runoff was deposited over the broad river plain, marshes, and shallow bays during floods, it is now funneled directly into the gulf in a rapid pulsed fashion attributable to the leveeing and channelization of the river

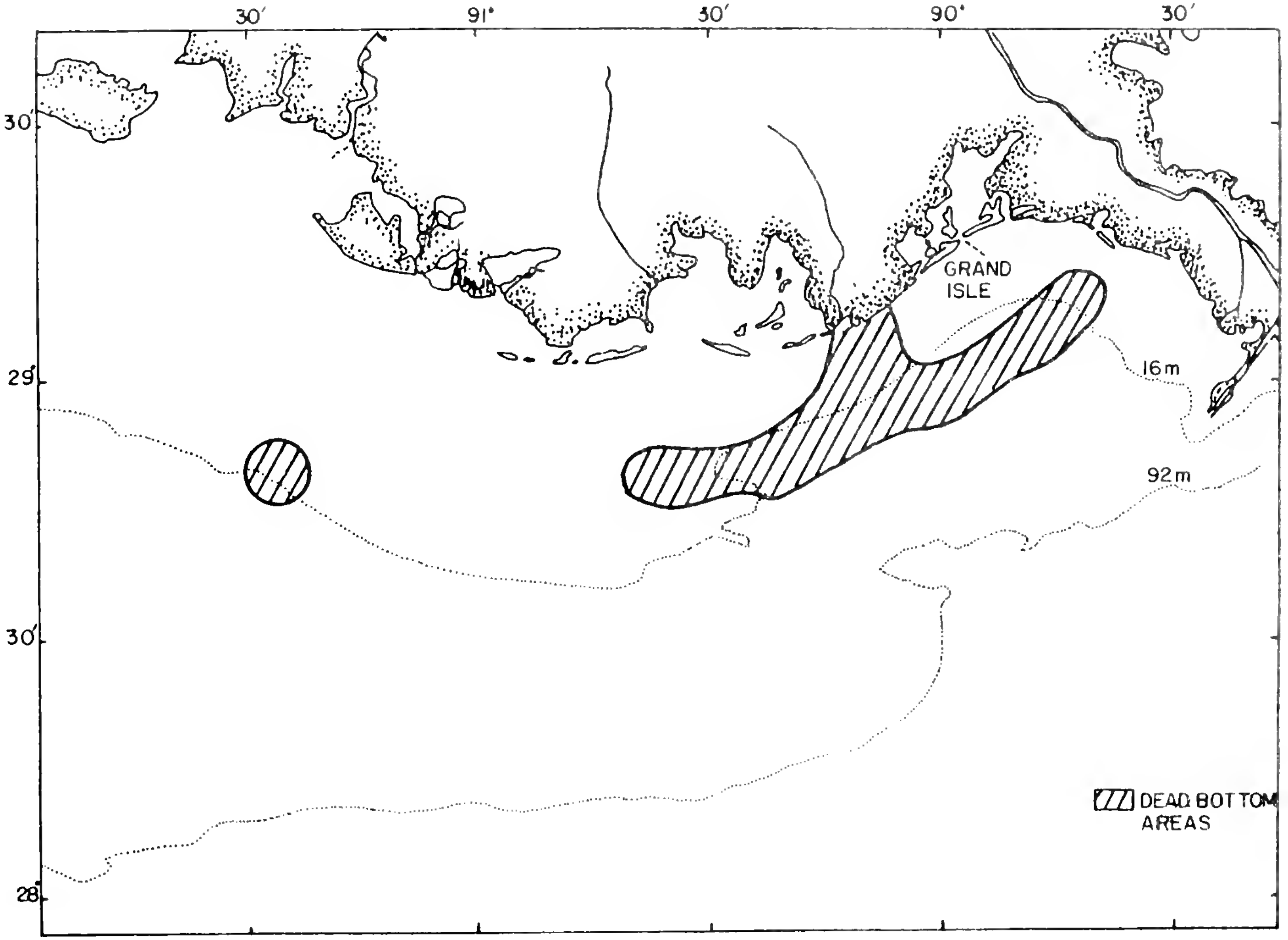


Figure 13. Areas with dead bottoms as evidenced by trawl catches and hydrographic data taken at platforms during Cruise II, August/September 1978 (from Bedinger et al. 1980).

over the past 100 yr. Also, Richards (1954) noted dissolved oxygen levels in the gulf were depressed in areas characterized by high organic sediment loading.

Sections of the eastern part of the Texas-Louisiana continental shelf ecosystem have long been known to have characteristics similar to a freshwater lake or closed marine system (e.g. Black Sea) in that stratification and isolation of bottom waters, particularly in conjunction with algal blooms, can result in anoxic conditions over the bottom due to degradation and respiration processes. Whether the frequency and extent of such areas have only recently increased and expanded from Louisiana southwestward to central Texas in response to increased pollution loads, or whether these areas have historically experienced hypoxia on a regular basis is not known. Given the implications of the former premise, research leading to an understanding of dissolved oxygen dynamics of the Texas-Louisiana continental shelf should be of high priority.

Topography and Sediments

The continental shelf of the Gulf of Mexico within the study area is primarily a generally smooth, gently sloping, sediment-covered plain extending from the shoreline out to the shelf break. Its typically flat relief is only occasionally broken by low-profile banks, or swells, usually representing the surface expression of salt domes or other relict features associated with ancient coastlines. Although low-relief shell and gravel ridges are exposed in some areas, most of these features are blanketed by sediment. The source of the sediment is freshwater runoff with recent sediments from the Mississippi Drainage Basin. During the mid-tertiary period, the rivers of Texas supplied much of the load and the large sedimentation of the Eocene was mainly from the Rio Grande. The small submarine canyon along the shelf south of Louisiana (Mississippi Trough, Figure 2), represents the Pleistocene outlet of the river. The shoreward portion of this canyon has been filled with sediment but it can be traced underground to the vicinity of Houma, Louisiana (Hedgpeth 1954).

A generalized sediment map of the gulf is shown by Figure 14 (after Grady 1970). In the eastern portion of the study area, sediments are predominantly clay and silt, whereas offshore eastern and central Texas, sandy sediments predominate. In south Texas, clays and sand-silt clays predominate.

The most conspicuous topographic feature associated with the shelf is the series of prominent submarine banks or highs which rise abruptly from the smooth bottoms along the shelf break (Figure 15). The best known of these are the East and West Flower Garden Banks, which are considered to be the northernmost, thriving shallow-water, hermatypic coral reefs on the eastern coast of North America. Sedimentary rock

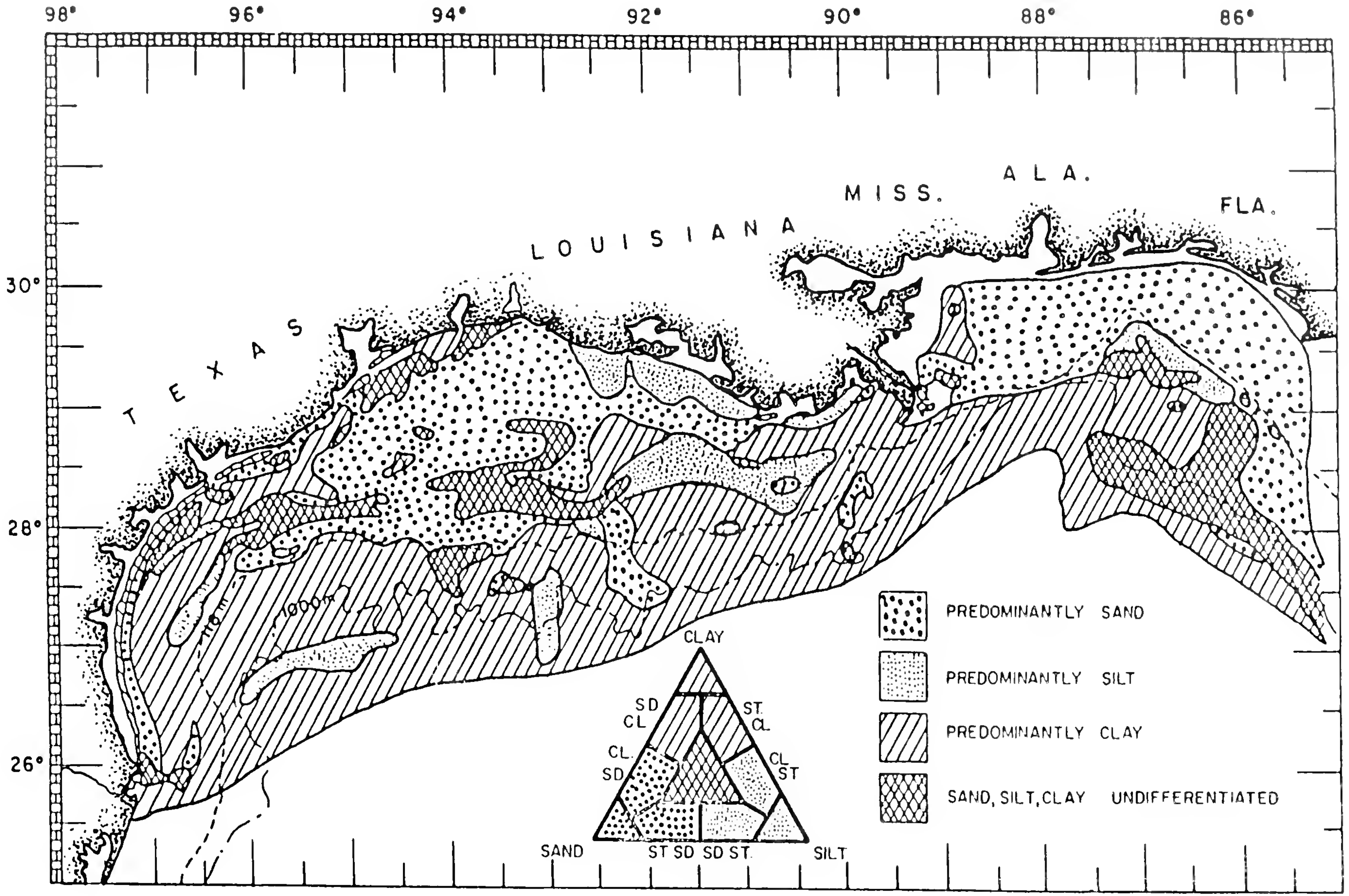


Figure 14. Distribution of sediment types in the northern Gulf of Mexico (based in part on Grady 1970 and unpublished data).

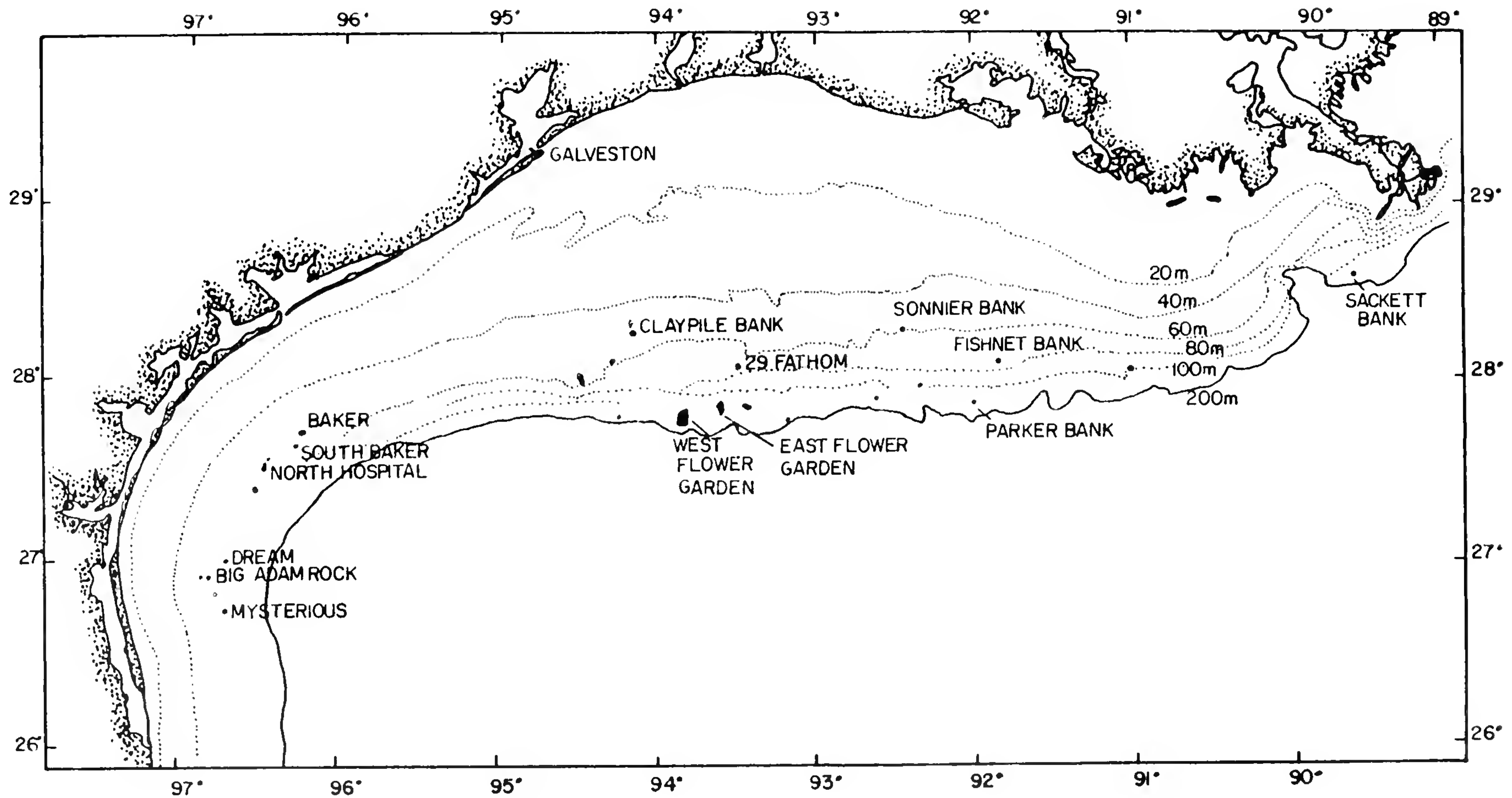


Figure 15. Distribution of submarine banks in the northern Gulf of Mexico.

outcrops or reefs occur in some nearshore areas, particularly off Louisiana. However, the best known of these natural nearshore reefs is, perhaps, Seven and One-Half Fathom Reef which is located offshore from Padre Island, Texas. As indicated by a comparison of Figures 1 and 15, artificial reefs in the form of petroleum platforms and shipwrecks provide most of the hard substrate habitat in nearshore waters, particularly offshore from Louisiana. Assuming the submerged portion of a typical petroleum platform consists of about 3,500 m^2, and that there are 3,342 of these structures in the gulf, these structures provide a total of about 1,500 ha of artificial reef habitat.

FAUNAL ASSEMBLAGES AND COMMUNITIES

Zoogeographic treatments of the Gulf of Mexico based upon benthic communities of the shelf of the northern gulf, have been treated by a number of authors (see Defenbaugh 1976 and Chittenden and McEachran 1976 for reviews based upon macroinvertebrates and fishes, respectively). Most of these studies are in general agreement that, although the faunal assemblages of the northern gulf basically represent an extension of the Carolinean Province of the Atlantic coast of the southern United States resulting from a Pleistocene connection across peninsular Florida, the eastern gulf fauna differs in a major way from that of the western gulf in that there is a stronger representation of Caribbean fauna in the eastern gulf. These differences appear largely attributable to (1) substrate differences (carbonaceous sediments east of the Mississippi River Delta and terrigeneous sediments west), and (2) circulation patterns and related hydrographic conditions (e.g. temperature, salinity, turbidity).

Considered as a whole, the Gulf of Mexico is often designated as a subtropical sea, but the surface waters over the inner shelf (to 20 m) of the northern gulf from just east of the Mississippi River Delta to Matagorda Bay are cold enough in winter to be considered warm-temperate (Parker 1960). Temperatures of the inner shelf waters change from warm, subtropical in the eastern gulf to cooler temperate waters in the central region, and back to warm subtropical on the southwestern coast near the Mexican border. As described above, starting at the Mississippi River Delta, salinity also increases on the shelf from the east to the west and southwest. This increase is largely a function of freshwater input which is, in turn, strongly correlated with climatic conditions. Parker (1960) classified the region from the delta to near Galveston, Texas as a Humid Zone, and from this point to Matagorda Bay as a Wet-Humid Zone. The region from Matagorda Bay to about Corpus Christi, Texas is labeled as Dry Sub-Humid changing southward of Corpus Christi to Semi-Arid.

Although the fauna of the Texas-Louisiana continental shelf is basically Carolinean, the above climatic and hydrographic conditions result in measurable faunal differences, leading some workers to subdivide the northern gulf into faunal provinces, ranging from two divisions by Deevey (1950) to 27 by Pequegnat (1973) which, in turn, are usually subdivided into depth zones (Parker 1960; Defenbaugh 1976). Pulley (1952) divided the Texas-Louisiana shelf into two provinces based upon bivalve distributions (Figure 16); Parker (1960), using a broader array of macroinvertebrates obtained mostly by grabs, separated the area into four provinces, also subdivided by depth zones (Figure 17). Parker (1960) and Gunter (1967) pointed out that the nearshore gulf between the delta and Sabine, Texas, is particularly notable because estuarine conditions extend offshore.

Basing his conclusions largely upon macroinvertebrates taken by trawling and using historical data, Defenbaugh (1976) determined that the Texas-Louisiana shelf was characterized by five faunal assemblages primarily zoned by depth (Figure 18). The primary depth zones were from 4 to 20 m, 20 to 60 m, and from 60 to 120 m. In his treatment of the shelf, Defenbaugh (1976) also included submarine bank assemblages (20 to 100 m) and a pro-delta fan assemblage (4 to 20 m).

Chittenden and McEachran (1976) described the zonation of the demersal fish assemblages of the Gulf of Mexico, noting that characteristic communities were associated with each of the major shrimp species, which, on a gulfwide basis, have distributions closely matching the major classes of sediment. White and brown shrimp (Penaeus setiferus and P. aztecus , respectively) occupy terrigenous muds which predominate in the western gulf while pink shrimp (P. duorarum) occur on calcareous sediments characteristic of the eastern gulf (Springer and Bullis 1954; Hildebrand 1954, 1955; Osborne et al. 1969). Williams (1958) showed that shrimp actively select these substrates, and similar sediment-associated distribution has been demonstrated for many demersal fish species (e.g. Hildebrand 1955; Miller 1959; Dawson 1964; Topp and Hoff 1972).

Chittenden and McEachran (1976) divided the white and brown shrimp ground demersal fish communities of the northwestern gulf bathymetrically, observing that the white shrimp ground assemblage extended from about 3 to 22 m and the brown shrimp ground fish assemblage was characteristic from 22 to 110 m. They noted that, inshore, the bathymetric distribution of the white and brown shrimp communities was not constant throughout, but was apparently affected by salinity and/or associated factors. The white shrimp assemblage was noted to be most developed and abundant offshore of Louisiana where estuarine conditions extend into the gulf and least developed and abundant west of the central Texas coast where climatic conditions become more arid (Chittenden and McEachran 1976 and references therein).

Although the pink shrimp community is best developed in the eastern gulf which is predominantly characterized by calcareous sediments, disjunct pink shrimp communities are scattered throughout the Texas-Louisiana shelf at depths of 45 to 64 m where appropriate

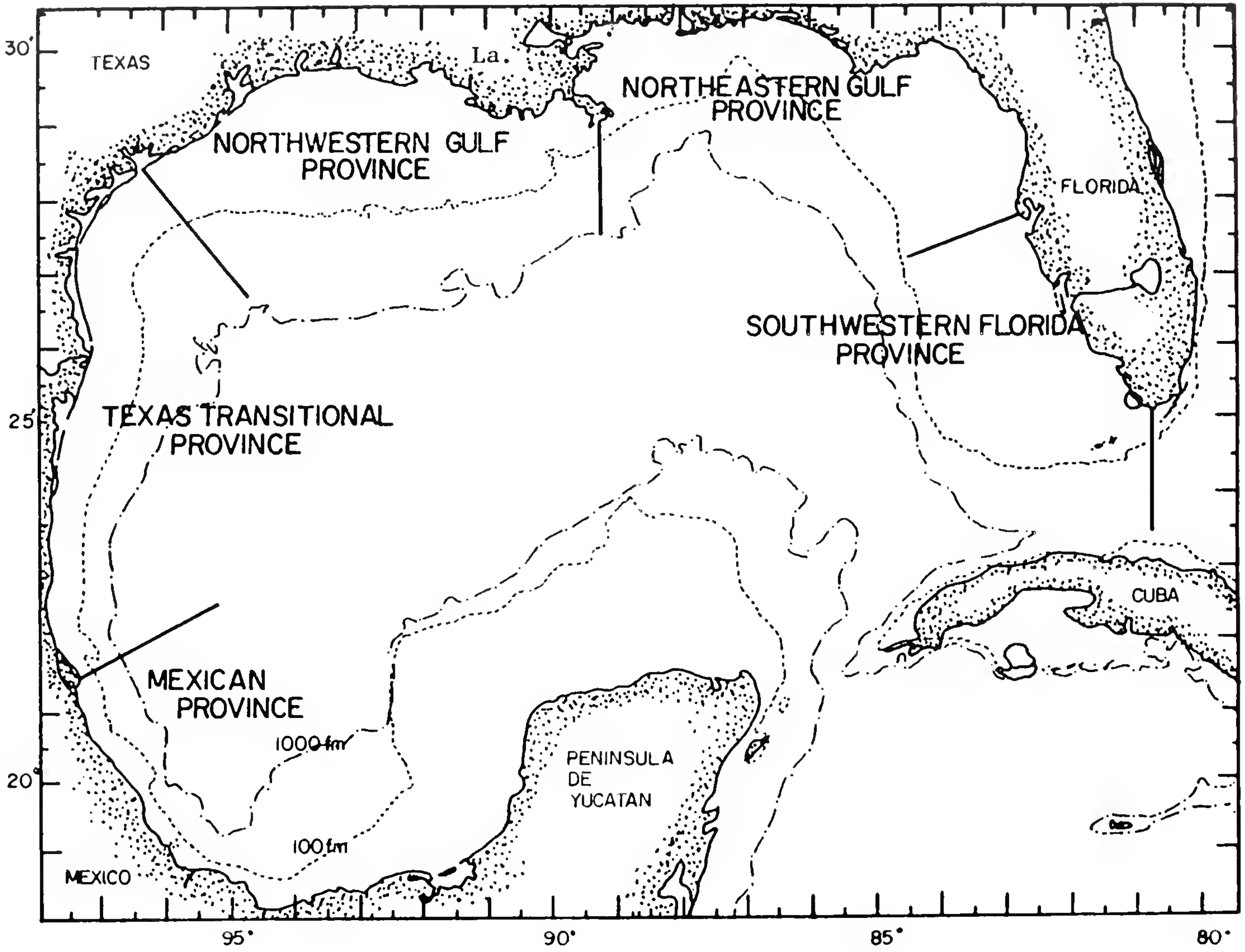


Figure 16. Faunal assemblages of the Gulf of Mexico (after Pulley 1952).

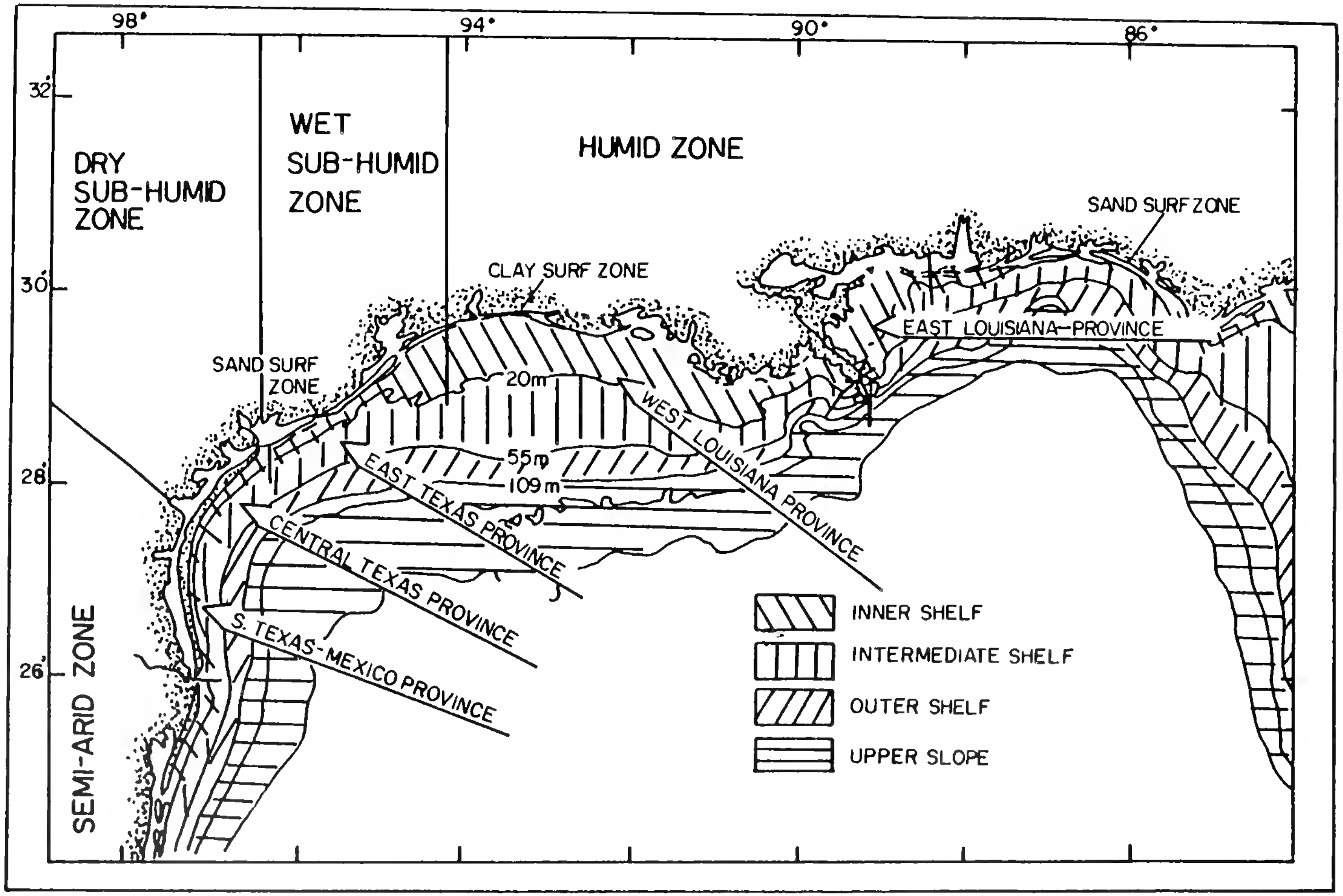


Figure 17. Faunal assemblages of the Gulf of Mexico (after Parker 1960).

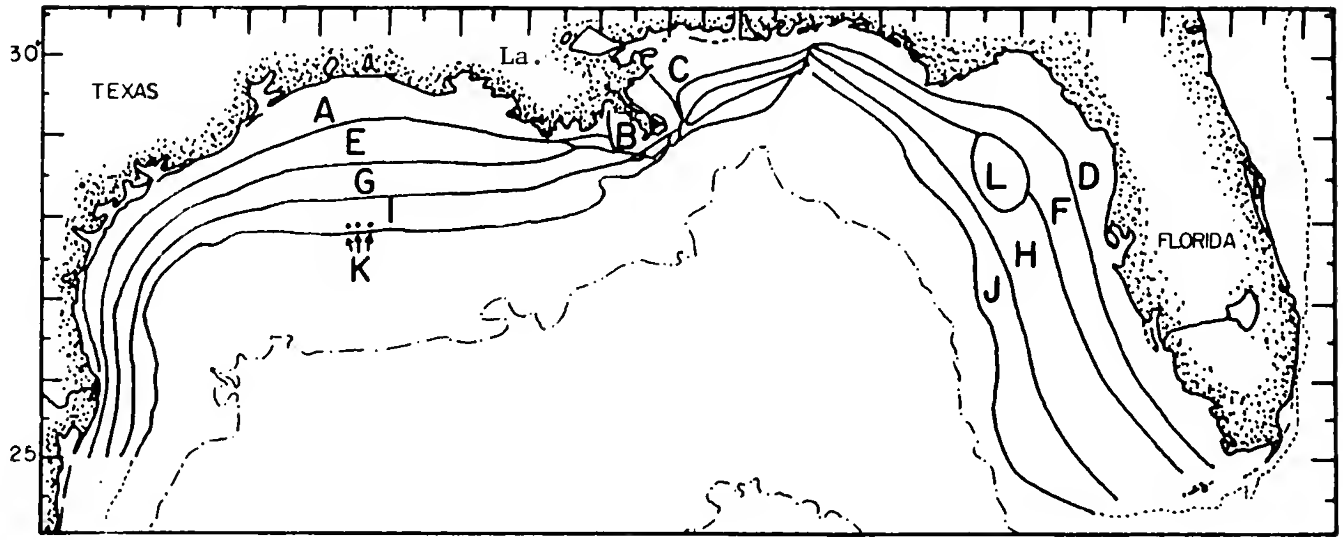


Figure 18. Faunal assemblages of the Gulf of Mexico (after Defenbaugh 1976). A. Inner shelf assemblage, Texas-Louisiana Shelf; B. Pro-delta fan assemblage; C. Pro-delta sound assemblage; D. Inner shelf assemblage, West Florida Shelf; E. Intermediate shelf assemblage, Texas-Louisiana Shelf; F. Intermediate shelf assemblage, West Florida Shelf; G. Outer shelf assemblage, Texas-Louisiana Shelf; H. Outer shelf assemblage, West Florida Shelf; I. Upper slope assemblage, Texas-Louisiana Shelf; J. Upper slope assemblage, West Florida Shelf; K. Submarine bank assemblages, Texas-Louisiana Shelf; L. Florida Middle Ground assemblage.

sediments occur (Chittenden and McEachran 1976). These authors also noted that areas of topographic relief in the northwestern gulf were characterized by distinctive assemblages which, in the southern gulf, corresponded (in part) to Robins' (1971) tropical insular fauna.

Most of the above studies draw largely upon studies of soft-bottom communities. However, hard bank communities are abundantly represented along the Texas-Louisiana continental shelf and include both natural and artificial habitats, the latter particularly dominated by petroleum platforms (see Figure 1). The communities characteristically utilizing these two classes of habitats consist of a sessile epifauna which provide habitat and/or food for an intimately associated cryptic fauna and food for an assemblage of fish which graze on epifauna. These assemblages are complemented by large aggregations of (1) plankton-feeding pelagic fishes and their predators, and (2) benthic reef fish (particularly snappers, Lutjanidae; and groupers, Serranidae). The latter two categories include both permanent residents and short-term, seasonal residents.

Results of studies performed offshore of Louisiana demonstrate that there is faunal zonation of reef communities related to depth. Sonnier et al. (1976) noted that a tropical fauna was characteristic of reefs located in depths of 90 to 180 m, but inshore, temperate species were characteristic. Gallaway et al. (1980) determined that there were three major platform or reef assemblages represented offshore Louisiana--a coastal assemblage (to about 27 m), an offshore assemblage (27 to 64 m), and a blue water or tropical assemblage (>64 m).

Nearly all of the zoogeographic treatments described above and references therein are in agreement that there is a distinct northwestern Gulf of Mexico nearshore faunal assemblage of Carolinean origin extending from the humid area of the delta towards the southwest where it is ultimately replaced by the "Mexican Province" fauna (Pulley 1952). There is no general agreement with respect to placement of the boundary between these two provinces, or how the transitional zone between them should be defined. For the assessment purposes of this paper, I follow the treatment by Pulley (1952), and define the boundaries of the system of interest as being the Texas-Louisiana shelf (out to 118 m) west of the delta to about Matagorda Bay (Figure 19). This area includes the humid and wet, sub-humid climatic zones of Parker (1960) and is greatly influenced by freshwater discharge from major river (primarily the Mississippi and Atchafalaya system) and low-salinity estuarine systems. South of this area, climatic conditions grade from dry, sub-humid to semi-arid; and river discharge is minimal which results in the estuaries becoming exceedingly more saline. The defined system of interest also appears to be delimited by temperature, and was classified by Parker (1960) as "warm-temperate" in contrast to most of the remainder of the shelf which he called "warm-subtropical." Although the major faunal assemblages of the defined system extend southward (and examples will be drawn from studies performed in this area), the region of about Matagorda Bay marks an area where species

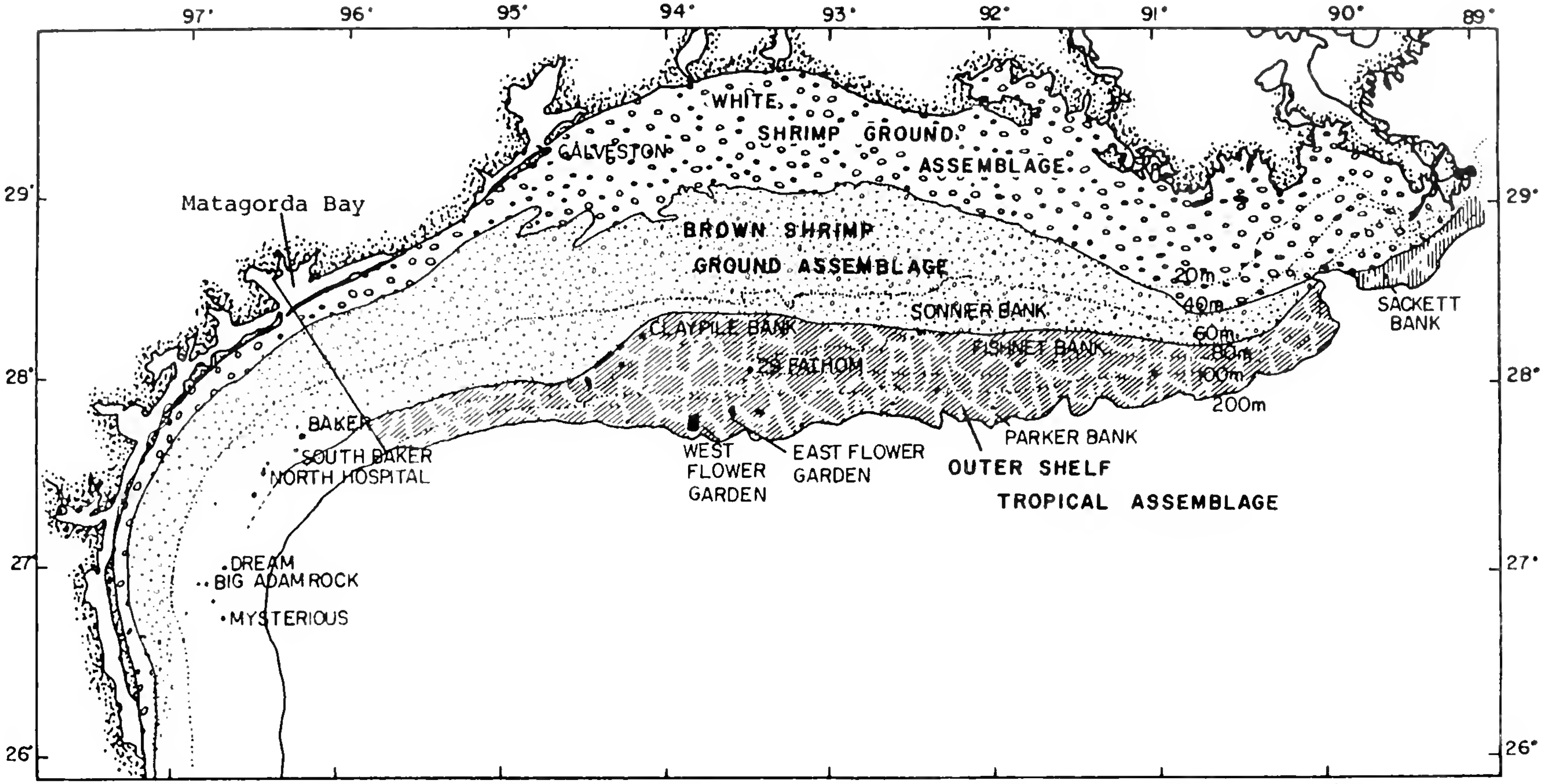


Figure 19. Faunal assemblages of the Texas-Louisiana continental shelf.

dependent upon hyposaline estuaries decline in abundance resulting in changes in the relative abundance of species within at least the nearshore community.

Within the Northwestern Gulf Province defined above, I believe (after reviewing data describing both soft- and hard-bank communities) that three characteristic faunal assemblages are represented on the Texas-Louisiana shelf--the white shrimp ground (inner shelf) assemblage, the brown shrimp ground (intermediate shelf) assemblage, and the outer shelf assemblage (Figure 19). Of these, the latter should be considered as representative of a separate province of a tropical nature. The estuarine-dependent white shrimp ground assemblage is considered to be generally delimited by the 20-m depth contour except near the Mississippi River Delta where the shelf is narrow and the community extends into deep water. This division (Figure 19) corresponds to the inner shelf assemblage of Parker (1960), and, generally, to the inner shelf assemblage plus the pro-delta fan assemblage of Defenbaugh (1976). The brown shrimp ground assemblage of the Texas-Louisiana shelf (Figure 19) is considered to extend from 20 to 60-m depths, corresponding to the intermediate shelf assemblages of Defenbaugh (1976) and Parker (1960). As indicated above, disjunct pink shrimp communities are represented within the brown and white shrimp grounds where appropriate sediments occur.

The outer-shelf, tropical assemblage is considered generally representative at depths greater than 60 m as shown by Figure 19. With the exception of some of the hard-bank communities, the outer-shelf assemblage is the least well-known of all the assemblages in terms of community composition and dynamics. Synoptic accounts of soft-bottom and hard-bank communities for each of the recognized assemblages are provided below. As with any effort of this nature, it should be kept in mind that these accounts represent generalized, broad-brush treatments and variation and exceptions are the rule rather than the exception.

White Shrimp Ground Faunal Assemblage

Pelagic and soft-bottom communities. The white shrimp grounds (particularly offshore of Louisiana) are characterized by high primary productivity as well as by high zooplankton consumer biomass levels--all greatly influenced by Mississippi River discharge. Fucik and El-Sayed (1979) reported results of phytoplankton ecological studies performed in the white shrimp grounds offshore of Louisiana. They found the diatoms to dominate phytoplankton populations over most or all of the year, particularly *Skeletonema costatum* during spring and fall months. They reported the surface standing crop of phytoplankton to be several times higher than in the open gulf, and integrated standing crop values to be double that normal for the gulf. In terms of primary productivity, the Louisiana white shrimp grounds were indicated to be more than an order of magnitude more productive than the oceanic gulf.

Marum (1979), also working in the white shrimp grounds nearshore of Louisiana, reported zooplankton biomass levels were high as compared to neritic waters of the gulf, and showed that this phenomenon was due to high primary productivity associated with Mississippi River runoff. Based upon characteristic copepod assemblages, the zooplankton community composition in this area was considered typical for the northern Gulf of Mexico.

A description of the species composition of the demersal macroinvertebrate fauna of soft bottoms of the white shrimp grounds is provided by Defenbaugh (1976) and references therein. Characteristic invertebrates include the epifaunal sea pansy (*Renilla muelleri*) and the white shrimp. Crustaceans, bivalves and gastropods have been shown to be particularly diverse (Parker 1960; Defenbaugh 1976).

Benthic mulluscan and crustacean infaunal populations in the white shrimp grounds off Louisiana were recently reported by Farrell (1979). Benthic communities were reported as diverse, with crustaceans (mainly decapods and amphipods), pelecypods, and gastropods being most numerous in his samples. In October 1972 and April 1973, benthic biomass at his offshore control station 17A was between 12 and 15 g/m^2, whereas during July, October, and January 1974, biomass levels were estimated ≤ 5 g/m^2. In the same general area, Waller (1979) reported infaunal communities at a control station to have been represented by 21 species (mainly polychaetes and crustaceans) having an estimated total biomass of 15.8+ g/m^2.

On a biomass basis, the demersal epifauna of the white shrimp grounds is dominated by fishes. For every volume of headed shrimp taken by the white shrimp fishery, an estimated 12 volumes of biomass are discarded and, in general, fish biomass closely parallels discard biomass (Chittenden and McEachran 1976). The demersal epifauna of the white shrimp community is characterized by estuarine-dependent forms as exemplified by the white shrimp. The dominant demersal fishes are mainly representatives of the family Sciaenidae with the Atlantic croaker (*Micropogon undulatus*) being the dominant species, representing about 30% of the fishes taken in shrimp trawls (Chittenden and McEachran 1976). Based upon shrimp trawl catches, other abundant fishes of the white shrimp community include Atlantic cutlass fish, *Trichiurus lepturus*, 14%; silver seatrout, *Cynoscion nothus*, 13%; star drum, *Stellifer lanceolatus*, 10%; sand seatrout, *Cynoscion arenarius*, 8%; Atlantic threadfin, *Polydactylus octonemus*, 5%; and sea catfish, *Arius felis*, 5%. Collectively these species comprise 85% of the fishes collected from the white shrimp community in shrimp trawls (Chittenden and McEachran 1976). The dominant pelagic species associated with this community in open waters are probably the Atlantic menhaden (*Brevoortia patronus*), mullets (*Mugil* spp.) and anchovies (Engraulididae), all plankton feeders; and the Spanish mackerel (*Scomberomorus maculatus*), a predator.

Reef communities. The hard substrate communities present on petroleum platforms within the white shrimp grounds offshore of Louisiana has been described by George and Thomas (1974) and by Gallaway et al. (1979). The biomass of sessile epifauna is dominated from the surface to about 8-m depths by small acorn barnacles (*Balanus amphitrite* and *B. improvisus*), which, in turn, are covered by a mat of macroalgae, hydroids, bryozoans, and encrusting sponges. The macroalgae component of the mat is restricted to zones near the surface (from 1 to 6 m deep) where growths may be luxuriant or sparse depending largely upon turbidity and season. Oysters are usually present but seldom abundant. Near bottom, hydroids dominate and a few dead barnacles and serpulid worm tubes are usually found.

The sessile epifauna of the nearshore platforms provides a low-relief habitat which influences the composition of the associated cryptic macrofauna. Although xanthid crabs and blennies are present, the motile fauna consists mostly of small species, particularly the amphipods *Corophium* sp., *Stenothoe* sp., and *Caprella* sp.

The sheepshead (*Archosargus probatocephalus*) is by far the dominant epifaunal grazer inhabiting coastal platforms, but is rivaled or exceeded in numbers (and biomass) by several pelagic species including spadefish (*Chaetodipterus faber*); lookdown (*Selene vomer*); blue runner (*Caranx chrysos*) and other jacks (Carangidae); and bluefish (*Pomatomus saltatrix*). Tropical reef fishes are sometimes encountered but seldom comprise a major component of the fauna. The gray snapper (*Lutjanus synagris*) is sometimes abundant at some of the more offshore of these platforms.

Brown Shrimp Ground Faunal Assemblage

Pelagic and soft-bottom communities. This assemblage is structurally similar to the white shrimp community but is generally characterized by lower levels of primary productivity and zooplankton consumer biomass. Diatoms dominate phytoplankton populations, and highest primary productivity occurs in spring and from fall through early winter (Kamykowski et al. 1976). As in the white shrimp community, *Skeletonema costatum* is often associated with seasonal blooms. In general, water column primary productivity in the brown shrimp community decreases from the north to the south, and with distance offshore. These differences have been attributed to freshwater runoff which, along with benthic nutrient regeneration, is considered to be a significant source of nutrients supporting primary production in shelf waters. Pequegnat (1976) has pointed out that highest phytoplankton biomass in gulf waters is, in many cases, associated with the bottom of the euphotic zones (50 to 110 m), pycnoclines or nitrate nutriclines, and that surface values are typically relatively low.

Park (1976) reported that zooplankton populations in south Texas exhibited a seaward increase which was greatly pronounced during the spring-summer periods of greatest abundance. Zooplankton were most productive in low-salinity, nearshore waters. Copepods were the most abundant zooplankters and were represented by assemblages considered typical for gulf waters. The benthic infauna over much of the brown shrimp grounds was sparse but diverse. Communities were dominated by polychaetes (40%), crustaceans (34%) and mollusks (19%), according to Holland et al. (1980). In the same study, benthic infaunal populations in nearshore waters of lower salinity were characterized by higher abundance than populations in high-salinity water offshore. Flint (1979) reported benthic infaunal biomass as about 4 g/m^2 in the south Texas brown shrimp grounds.

With the exception of a few forms (e.g. brown shrimp), epifauna of the brown shrimp community is not estuarine-dependent, although the young of many species move shoreward into the white shrimp ground for growth and development. As in the white shrimp grounds, the biomass of the epifauna is dominated by demersal fishes. For every volume of headed shrimp taken in the brown shrimp fishery, an estimated 11 volumes of biomass is discarded with fish biomass closely paralleling total discard biomass. Chittenden and McEachran (1976) found 23 species constituted 93% of the fishes represented in this community, with longspine porgy, Stenotomus caprinus , 39%; Mexican searobin, Prionotus paralatus , 8%; horned searobin, Bellator militaris , 6%; and dwarf goatfish, Upeneus parvus , 6%, dominating in shrimp trawl catches. The red snapper (Lutjanus campechanus) , mostly juvenile although not a dominant, was abundant on the brown shrimp grounds but was not represented in white shrimp grounds studied offshore from Texas.

Pelagic species of importance in the brown shrimp community include small schooling species such as the scads (e.g. Decapterus punctatus) and sardines (e.g. Harengula pensacolae); and large predators such as the summer abundant king mackerel (Scomberomous cavalla) , little tuny (Euthynnus alletteratus), and cobia (Rachycentron canadum) . In the more offshore areas, some tunas are well represented as are several species of billfishes.

As indicated earlier, pink shrimp communities occur in disjunct areas throughout the brown shrimp grounds where sediments are appropriate. Chittenden and McEachran (1976) have characterized the fishes associated with these communities. Dominant species include the tomtate (Haemulon aurolineatum) , bumper (Chloroscombrus chrysurus) , silver jenny (Eucinostomus gula), and others. In addition to the characteristic species, the pink shrimp communities usually have a strong admixture of species representative of the brown and/or white shrimp grounds.

Reef communities. The reef communities present at petroleum platforms offshore of Louisiana in the brown shrimp grounds have been described by Shinn (1974), Sonnier et al. (1976), and Gallaway et al. (1979). In contrast to the low-relief, barnacle-dominated white shrimp ground assemblage, bivalves dominate the sessile epifauna of brown shrimp ground platforms and the communities are of high relief. Near-surface areas are characterized by luxuriant growths of red and green algae in which the tree oyster (*Isognomon bicolor*) is often present in high densities. The bivalve *Chama macerophylla* and oysters (Ostreacea) are the typical biomass dominants to depths of 20 m and are complemented by octocorals (*Telesto* sp.) and solitary hard corals (*Astrangia* sp. and *Phyllangia* sp.) in addition to various hydroids and bryozoans. Below 20-m depths, colonial forms such as encrusting sponges (Homocoelidae), anemones (Zoanthidae) and ascideans (Ascidiarea) predominate. There appears to be a marked drop in biomass levels of sessile epifauna between 20- and 30-m depths. Biomass in the upper part of the water column ranges from 8 to 11 kg/m^2; below 20 m biomass levels are usually around 2 kg/m^2.

The sessile epifauna of the offshore platform assemblage is of high relief and supports a diverse cryptic fauna. Not only are small species such as microcrustaceans well represented, but relatively large species such as blennies, arrow crabs, stone crabs, oyster drills, and sea urchins are abundant.

The fish fauna of offshore platforms was described by Gallaway et al. (1979) as dominated by species such as spadefish, lookdown, bluefish, sheepshead, and gray triggerfish (*Balistes capriscus*) . These species were supplemented by many gray snapper, red snapper, blue runner and moonfish (*Vomer setapinnis*) . Large predator species such as barracuda (*Sphyraena barracuda*) , cobia and jack crevalle (*Caranx hippos*) were common. The platforms, particularly those in deeper waters, had a rich tropical fish fauna. Bermuda chub (*Kyphosus sectatrix*) were characteristically present and associated with the algal zone; blennies (Blennidae) of several species were abundant and several species of damselfishes (Pomacentridae), butterfly and angel fishes (Chaetodontidae) and tangs (Acanthuridae) were usually common.

Shinn (1974) described the general vertical zonation of fishes around Louisiana platforms. He listed spadefish, barracuda, lookdown, and sheepshead as characteristic of the upper water layers; red snapper and large groupers (*Epinephelus nigritus* , *E. itajara*) were described as predominantly bottom fish that spent some of their time in the mid-water layers; and restricted to the bottom were speckled seatrout (*Cynoscion nebulosus*) , sand seatrout (*Cynoscion arenarius*) , and flounders (*Paralichthys* spp.).

Sessile epifauna on petroleum platforms investigated offshore of Galveston in the brown shrimp grounds (Gallaway et al. 1980) differed greatly from that at similar depths on platforms investigated offshore of Louisiana. The major difference was that the large Mediterranean barnacle (*Balanus tintinnabulum*) was the perennial dominant. This species was estimated to occupy some 77% of the original platform substrate. Some individual barnacles attained basal diameters of 3 to 4 cm and heights of 6 to 8 cm. They characteristically grew in clusters forming a three-dimensional habitat, 10 to 15 cm thick. In contrast to epifauna on platforms offshore of Louisiana, bivalves comprised a relatively low proportion of the epifaunal biomass.

The dominance of the sessile epifauna by the Mediterranean barnacle was a major zoogeographic finding of the program. It has been reported as an incidental species in the gulf for some 20 years, and remains so on most platforms offshore of Louisiana. Observations indicate that this species may be the dominant barnacle on offshore platforms from Galveston to offshore of West Cameron, Louisiana, but it is seldom abundant on structures farther east (Gallaway et al. 1980).

The Mediterranean barnacle, a filter feeder on particulates and plankton, spawned during late spring or early summer and in fall, usually somewhat later than the other competing acorn barnacles which were seasonally abundant. The combination of the rapid growth and large size of the Mediterranean barnacle enabled it to settle on and overgrow the smaller acorn barnacles characteristic of Louisiana platforms.

The mat portion of the sessile epifauna on platforms offshore of Galveston was characterized by a virtually inseparable interspersion of macroalgae, sponges, bryozoans and hydroids. The macroalgae (mostly green and red algae) represented a relatively small percentage of the total standing crop biomass, and were more abundant in summer than in winter. The faunal component of the mat, however, bloomed during winter seasons (particularly the stalked bryozoan Bugula neritina , and the hydroid, Tubularia crocea), but declined markedly over short periods during spring resulting in the characteristic low levels of mat observed for summer and fall. The octocoral Telesto , characteristic on some Louisiana platforms in the brown shrimp grounds, was not represented on the Texas platforms.

Polychaetes and brittle stars dominated from a biomass standpoint although the numerical dominants of the cryptic assemblage associated with the biofouling community were represented by microcrustaceans, blennies, stone crabs, and pistol shrimp. Cryptic species which were dependent upon bushy hydroids and bryozoans as cover and/or food (microcrustaceans and brittle stars) also bloomed in winter and declined during warm seasons. In contrast, cryptic species dependent upon barnacles for habitat, and which did not outgrow the cover provided (e.g. pistol shrimp, polychaetes, and blennies), were characterized by stable seasonal population levels. Other cryptic species were apparently recruited to the barnacle substrate from the plankton, flourished and grew until they exceeded a size allowing use of the habitat as cover. They were then either harvested by predators or left the area before reaching a reproducing size (e.g. stone crabs). Principal epifaunal grazers and predators on microcryptic species were sheepshead, triggerfish, blennies and small reef fishes; sheepshead and triggerfish were principal predators on large cryptic species.

The biomass dynamics of the biofouling community by depth and biological season with respect to characteristic water column conditions offshore of Galveston in summer and winter were described by Gallaway et al. (1980). During all seasons, biomass levels near the bottom (<2 kg/m^2) were markedly lower than biomass levels in the upper water column (~20 kg/m^2). The depth of this biomass discontinuity appeared to coincide with the distribution of the year-round bottom nepheloid layer, and was mainly attributable to the absence of barnacles. Biomass levels in winter (~28 kg/m^2) were significantly higher than summer levels (~20 kg/m^2). Most of the observed seasonal change was attributable to the blooms of the mat community. High dissolved nutrient levels and phytoplankton blooms were also characteristic of the early winter season, and may have contributed to the increased biofouling levels.

The structure-associated fish fauna of the platforms offshore of Galveston was classified by Gallaway et al. (1980) as either seasonal transients or residents. The most important seasonal transients, at least from a fisheries standpoint, were the warm-season pelagic predators and their plankton-particulate feeding prey. The predatory species representing this group in the field included king mackerel, cobia, bluefish, little tuny, dolphin, sharks, blue runner, sharksuckers and jack crevalle. Prey species included Spanish sardine, scaled sardine, and rough scad. The attraction of the seasonal-transient assemblage of fishes appeared to be the structures _per se_ , but residence times at the structures for most of the species were believed to have been short.

According to Gallaway et al. (1980) the resident species in the field included (1) fishes which were directly dependent upon the biofouling community for both food and cover, and (2) those which apparently were attracted to the structures for cover alone; they exhibited little or no trophic dependency on the biofouling community. Category one included sheepshead (biomass dominant), blennies (numerical dominant), triggerfish, and amberjacks (_Seriola_ sp.); as well as small pelagic (damselfishes, butterfly fishes, angelfishes, small sea basses) and demersal (cubbyu, wrasses) "reef" fish. Category two included pelagic reef forms such as spadefish (usually the numerical and biomass dominant of the entire fish community) and tomtate, as well as benthic reef species such as red snapper and groupers. In contrast to fishes around platforms offshore of Louisiana, lookdowns and moonfish were seldom observed in the Texas field and were never seen in huge schools.

Outer Shelf Faunal Assemblage

Soft bottom communities. Levels of primary production and biomass of primary producers are lower on the outer shelf than in inshore areas.

Pequegnat (1976) and references therein report maximum concentrations of chlorophyll *a* at 50 to 110 m, often coinciding with the bottom of the euphotic zone, pycnoclines or nitrate nutriclines. Zooplankton assemblages probably represent a transition zone between the neritic and ocean zones as described by Pequegnat (1976) for the adjacent continental shelf. Parker (1960) and Defenbaugh (1976) described characteristic epifaunal invertebrates; the demersal fish community was characterized as similar to that of the brown shrimp assemblage by Chittenden and McEachran (1976) except near the hard banks where a tropical fauna is characteristic. Little has been published concerning the structure and dynamics of the soft bottom communities of the outer shelf.

Reef communities. Natural banks occurring on the outer shelf (Figure 15) exhibit much variability in their sessile epifauna; this variability has been variously attributed to depth, turbidity, nature of the basal substrate, proximity to the Mississippi River, and other factors. As recently reported by Dr. T.J. Bright (Texas A&M University, April 1981; pers. comm.), the natural banks can perhaps best be categorized biologically in terms of their biotic zonation defined with respect to reef-building activity. Dr. Bright recognizes seven zones:

I. *Diploria-Montastrea-Porites* Zone: A zone consisting of living, high diversity coral reefs.

II. *Madracis* Zone: A zone dominated by the small branching coral *Madracis mirabilis* , which is producing large amounts of carbonate substratum.

III. *Stephanocoenia* Zone: A zone consisting of living, low-diversity coral reefs.

IV. Algal-Sponge Zone: A zone dominated by crustose coralline algae actively producing large quantities of carbonate substratum (considered here to extend downward, past the depth at which algal nodules diminish in abundance, to the greatest depths at which coralline algal crusts are known to cover a substantial percentage of the hard substratum). This is the largest of the reef-building zones in terms of area of sea bottom.

V. *Millepora* -Sponge Zone: A zone where crusts of the hydrozoan coral *Millepora* share the tops of siltstone and claystone outcrops with sponges and other epifauna.

VI. Antipatharian Zone: A zone where limited crusts of coralline algae and several species of corals exist within a zone marked by sizeable populations of antipatharians. Banks supporting Algal-Sponge Zones generally possess a zone comparable to an Antipatharian Zone as a transition between the Algal-Sponge Zone and deeper, turbid-water, lower bank zones.

VII. Nepheloid Zone: A zone located at the bases of all banks wherein high turbidity, sedimentation, resuspension of sediments, and resedimentation dominate. Rocks and drowned reefs here are generally covered with veneers of fine sediment. Epifauna are depauperate and variable; deep-water octocorals and solitary stony corals are often conspicuous. This zone occurs in some form on lower flanks of all banks below the depths indicated for Zone VI, above.

Of the above zones, I-IV are considered to be characterized by major reef-building capabilities (Category A), Zone V by minor reef-building capability (Category B), Zone VI by some (but negligible) reef-building capability (Category C) and Zone VII by no reef-building capability (Category D).

Each of the seven characteristic zones were ranked on a scale of 1 to 8, based upon considerations of its reef-building attributes, biological diversity, aesthetics, rarity and areal extent. This was done to provide an index of their environmental priority. These indices were then used to assign a priority rating to each of the outer shelf banks by summing the respective indices for each zone represented on the bank in question. On this basis, the East and West Flower Garden Banks had the highest priority rating (Index value was 36, Figure 20) as Zones I-IV are all represented along with Zones VI and VII. With the exception of Sackett Bank near the Mississippi River Delta and characterized by Zones VI and VII only, the banks along the shelf edge had higher ratings (values ranged from ~11 to 17) than banks located more shoreward (values ranged from 6 to 8, Figure 20). The shelf edge banks other than the Flower Gardens were characterized by the presence of Zones III and/or IV in conjunction with Zones VI and VII. The more

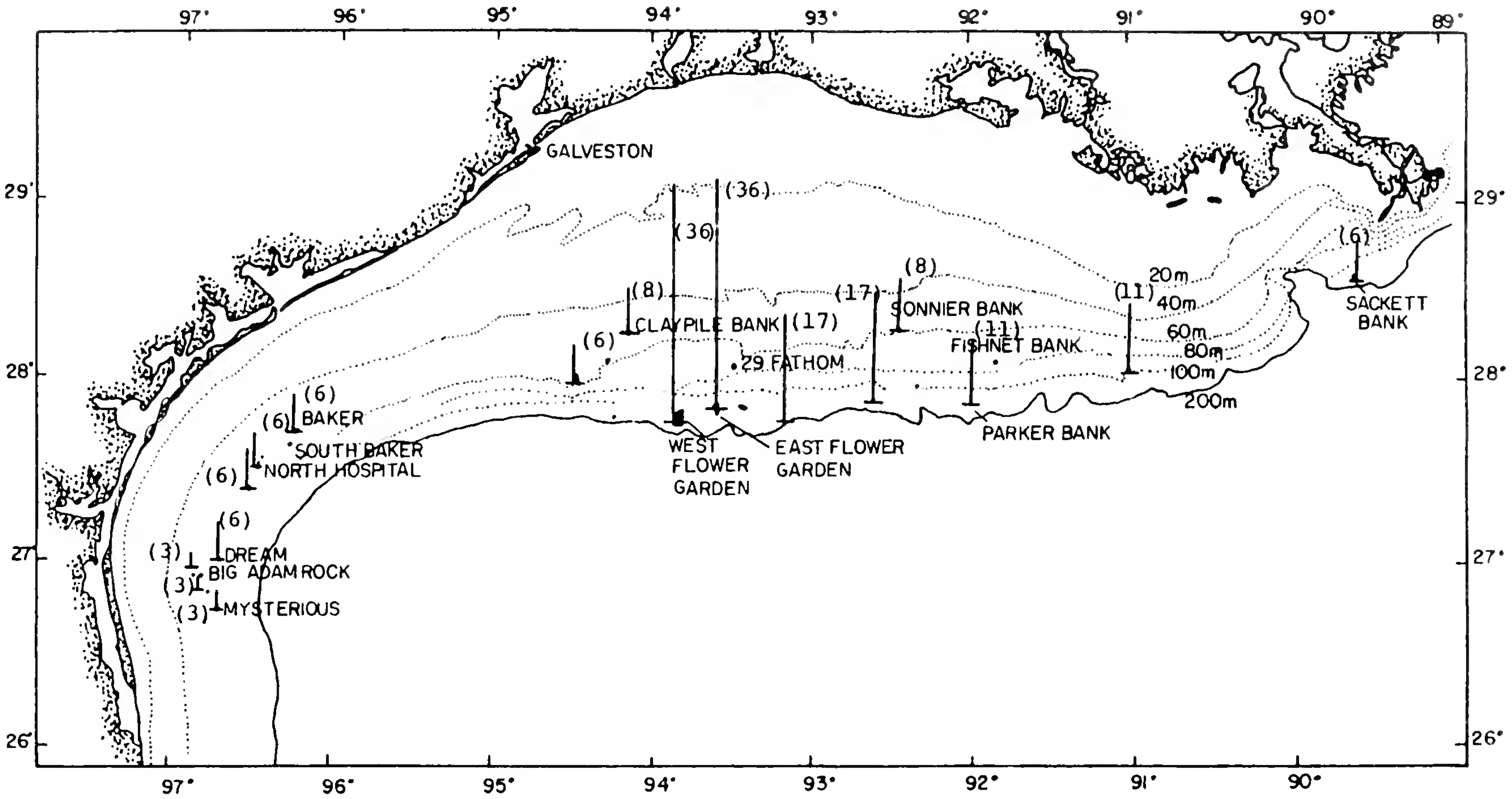


Figure 20. Relative priority rankings for representative banks on the outer continental shelf. See text for explanation of Index Scores represented above by the height of each bar with actual value shown in parentheses.

shoreward banks were characterized by the presence of V and VII or VI and VII. The South Texas banks having low values (3) were characterized by the presence of Zone VII only.

Abundant and common fishes characteristic for areas near the tops of banks on the outer shelf include barracuda, creole wrasse (*Clepticus parrai*) ; creole fish (*Paranthias furcifer*) ; several species of jacks (particularly the almaco jack, *Seriola rivoliana*); a number of species of angelfishes, butterfly fishes, damselfishes and parrotfishes (Scaridae); and other reef forms. In deeper zones, several species of the snapper-grouper assemblage predominate, including forms such as red snapper, groupers of the genera *Mycteroperca* and *Epinephelus* , vermilion snapper (*Rhomboplites aurorubens*) and cottonwick (*Haemulon melanurum*).

The sessile epifauna on platforms of the outer shelf that I have observed has been relatively little developed. Macroalgae and stalked barnacles were present at the surface of some of the structures while pelecypods and hydroids were found deeper. As at some of the offshore banks, spiny lobster (*Panulirus* sp.) are included in the fauna. The most striking feature of these platforms, however, is the dominance of the fish community by tropical reef forms. The barracuda is an abundant large predator and almaco jack and blue runner appear to be the dominant schooling pelagic species. The creole fish may be the dominant platform-associated fish. Spadefish and sheepshead are typically absent; gray triggerfish are abundant. Vertical members of these platforms are surrounded by swarms of tropical species. The damselfishes, angelfishes and tangs are abundant, but, on platforms I have seen, are overshadowed by the abundance of certain wrasses, particularly creole wrasse and Spanish hogfish (*Bodianus rufus*) . Other tropical species which I have observed here but not at any inshore platforms included the rock beauty (*Holacanthus tricolor*) , redspotted hawkfish (*Amblycirrhitus pinos*) and red hogfish (*Decodon puellaris*) . The platform fish assemblages are similar to those seen on the natural banks (Bright and Pequegnat 1974; Bright and Rezak 1978).

CONCEPTUAL MODEL AND SYSTEM PROCESSES

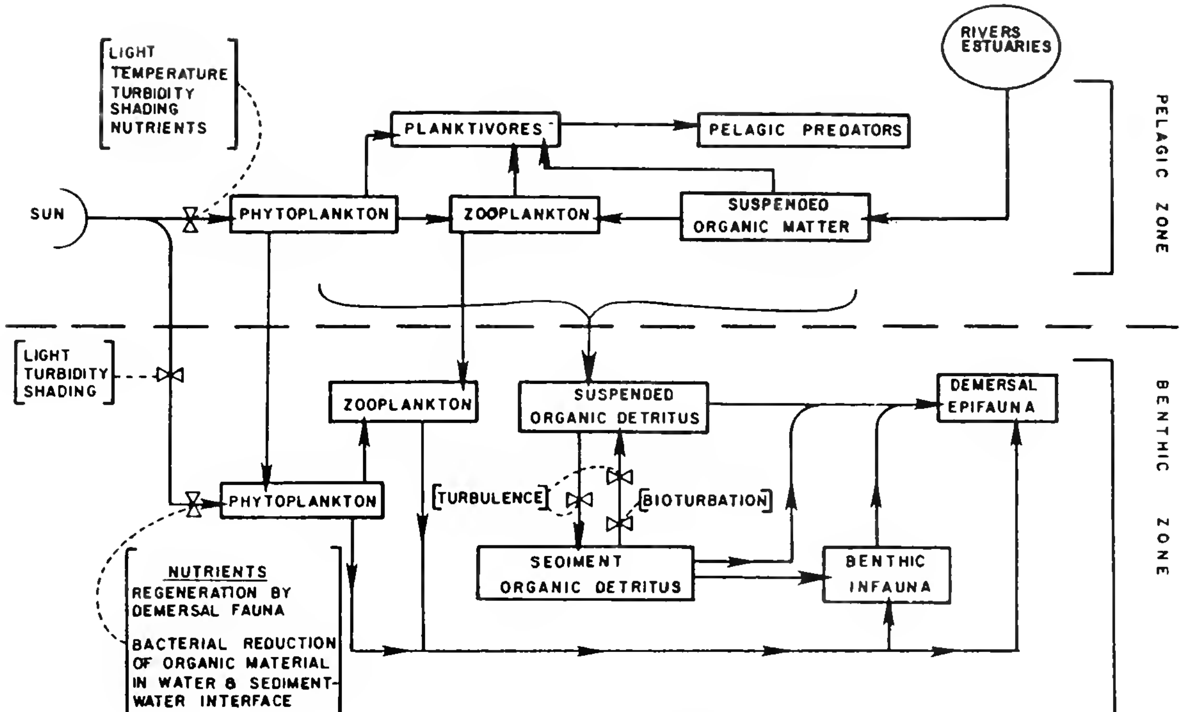
The two inner-shelf faunal assemblages defined above, while generally bathymetrically distinctive in terms of species composition, are similar in terms of their structure, function and trophic dynamics. Both are basically two-layered systems (pelagic and benthic) with the major biological resource being represented, in each case, by penaeid shrimps, a component of the soft-bottom benthic epifaunal community. The epifauna of the benthic community (the shrimps in combination with demersal fishes) likely dominates the system in terms of overall biomass. Characteristic species from both soft-bottom assemblages are characterized by (1) small size (most less than 20 cm long), (2) short life spans (1 to 3 yr), (3) high (90% or more) annual mortality rates, and (4) high fecundity and extended spawning seasons (Chittenden and

McEachran 1976; Gulf of Mexico Fishery Management Council [GMFMC] 1980a). Historically, these attributes are believed to have enabled the communities to withstand high rates of exploitation with little detrimental effect. Many of the commercially and recreationally important reef species and pelagic predators of the shelf assemblages are typically larger, longer-lived, and characterized by lower annual mortality rates than the forms described above, and are thus much more susceptible to over exploitation.

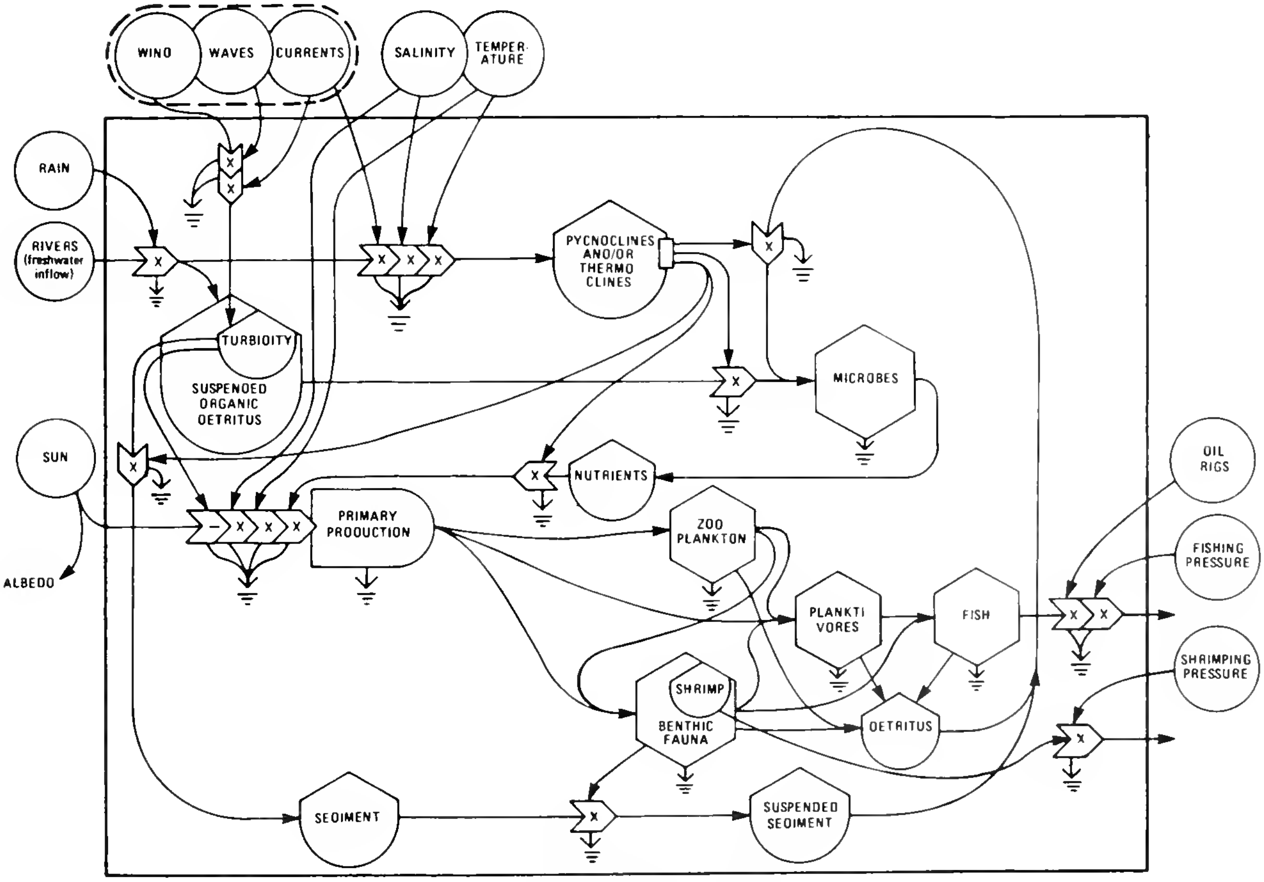
The demersal epifauna of the shelf and some pelagic and reef species of commercial importance (e.g. Gulf menhaden, red snapper) appear to be characterized by the same generalized life cycle. Spawning occurs at sea within the habitat of the adult, but the larvae are transported, or make their way to organic-rich, low-salinity, nearshore areas which serve as nursery grounds. The young animals develop in these areas, and then return to their respective marine habitats as subadults or adults (Pearse and Gunter 1957; Gunter 1967; Copeland and Fruh 1970; Gallaway and Strawn 1974). Species characteristic of the white shrimp ground assemblage (e.g. white shrimp, Atlantic croaker, Gulf menhaden, silver seatrout, star drum) and a few from the brown shrimp ground assemblage (e.g. brown shrimp) penetrate into the estuaries which are among the most productive and organic-rich of all ecological systems. Many estuaries and/or rivers, particularly those of the eastern Texas-Louisiana coast, are significant exporters of organic materials and nutrients to the nearshore shelf which is generally characterized by higher levels of organic materials and productivity than more offshore areas. These nearshore areas are used as nursery grounds by many species representative of the brown shrimp ground and outer shelf assemblages (Rogers 1977). The above described life history pattern has contributed strongly to the confusion over the placement of the bathymetric boundaries between the faunal assemblages represented on the Texas-Louisiana shelf.

A simplified conceptual model for the generalized shelf assemblage is shown in Figure 21. Boundaries between the pelagic and demersal components should not be considered as precise, particularly when the water column is well mixed. Flint (1979) points out that many nektonic species are pelagic as adults and larvae but have benthic eggs; and, conversely, numerous benthic species produce floating eggs which hatch into planktonic larvae and become dispersed by currents before settling permanently to the bottom. He further notes that motile epifauna such as demersal fish can (and do) swim into the pelagic zone to feed on plankton, but both the benthic epifauna, which lack strong swimming capability, and the benthic infauna depend upon the continued rain of organic materials from the overlying waters for nourishment.

The phytoplankton are depicted as the major primary producers in the system with productivity governed by levels of dissolved and suspended nutrients and toxins, and by levels of suspended solids which decrease the availability of sunlight. An important source of dissolved and suspended nutrients to the system is the discharge from rivers and



(a) BOX AND ARROW DIAGRAM



(b) ENERGY CIRCUIT DIAGRAM

Figure 21. Simplified conceptual model of the generalized shelf assemblage presented as both a box and arrow diagram (a) and as an energy circuit diagram (b).

estuaries, which typically also contain high levels of dissolved and particulate organic matter. Through the work of bacteria, organic material in the water column is converted to dissolved and suspended nutrients, a process requiring dissolved oxygen. Consumers in the water column also regenerate nutrients (which can stimulate production) as well as contribute directly to levels of suspended organic matter through excretion and death (Figure 21).

As with suspended solids, organic material in the water column tends to sink to the bottom, where it is either buried, or in the presence of oxygen, converted to nutrients by the work of bacteria and other reducers. There is considerable flux in water versus sediment levels of organic detrital materials and other suspended solids, particularly near the bottom. The recycling and release of nutrients and resuspension of organic materials are dependent upon current turbulence and the ease with which bottom sediments can be resuspended.

Primary productivity in the upper water column of the shelf usually peaks in spring with a smaller peak in fall in conjunction with freshwater runoff. Primary production apparently decreases from the east to the west and southwest of the Texas-Louisiana shelf, and with distance offshore (Fucik and El-Sayed 1979; Flint 1979). The decreases in productivity along these gradients are correlated with salinity increases, or conversely, with runoff. Apparent zooplankton production in the water column lags slightly behind primary production but follows a trend similar to that exhibited by the primary producers. The amount of pelagic biomass supported by primary production is unknown, but based upon the amount of zooplankton production would be expected to be small over most of the shelf (Flint 1979). Gulf menhaden, however, are commercially exploited in the eastern part of the Texas-Louisiana shelf. Commercial landings of Gulf menhaden over the period 1974-78 in the gulf averaged 2,046.9 x 10^6 lb valued at 69.9 x 10^6 dollars.

Based on studies performed in south Texas, Flint (1979) showed that only approximately 20% of the observed primary production would be required to support the estimated zooplankton production in shelf waters, leaving some 80% available to support demersal communities. Investigations of bottom waters during summer months showed that bottom waters not only appeared to support greater amounts of primary producers than surface waters, but also that they were characterized by the presence of a prevalent nepheloid layer and peaks of nitrogen (ammonia) in conjunction with the peak chlorophyll layers. Light transmission exceeded 1% and primary production was demonstrated. The high ammonia concentrations were considered as evidence of a considerable amount of nutrient regeneration.

Based upon standing crop biomass and turnover rates, the annual production of carbon was estimated for infaunal benthos, shrimp and other epibenthic species. The annual production by infaunal benthos (0.39 g C/m^2/yr) was not believed adequate (assuming a 10% transfer efficiency) to support the total epibenthic production of 0.06 g $C/m^2/yr$ (Flint 1979). This finding suggested that organic detritus was of particular importance to the trophic system.

Much of the organic detrital materials on the shelf are transported by the discharge of rivers and estuaries into the surface waters of the nearshore shelf during spring, promoting a spring bloom of primary production. These materials ultimately sink to the bottom, supplemented by organic materials produced in the surface water layers. The bottom serves as a nutrient reservoir and likely dampens the effects of the surface productivity cycles if bottom turbulence is sufficient to resuspend the material. The ease with which the bottom can be resuspended, enabling the nutrients to be recycled and released, may be greatly influenced by the amount of bioturbation from the infauna and epifaunal species which disturb or otherwise bioturbate the bottom.

Flint (1979) concluded that although the benthic infauna do not necessarily provide all of the direct food source for the benthic epifauna, they are important in that they supplement the diet of demersal consumers and indirectly provide alternative nutritional sources through their bioturbation activities. Results by Gallaway and Reitsema (1980) suggest that benthic infauna may be exceedingly important, not in the amount of food they represent, but in that they serve to accumulate and concentrate certain sterols and fatty acids which are required for sexual maturation by species such as brown and white shrimp.

A conceptual model for artificial reefs on the Texas-Louisiana shelf (mainly petroleum platforms) has been described by Gallaway et al. (1980). The physical presence of the platforms was presented as the major factor controlling, or accounting for, the three general biotic assemblages which aggregate at these sites--the biofouling, pelagic, and benthic reef fish communities. Of these, the biofouling community was the most complex. The diversity and biomass levels of the biofouling community that develops are controlled by the type of perennial shelled animal that dominates. Barnacles (or other shelled organisms) provide habitat diversity, space, and food for other organisms. Barnacles are preyed upon largely by fish such as sheepshead and triggerfish, species capable of crushing their protective shells. In their grazing, these fish do not always consume all the shellfish, and the remains are available to smaller predators such as blennies. Blennies, in turn, are sometimes taken by the epifaunal grazers as well as by other fish predators, such as amberjack or almaco jack. Even though cycling is undoubtedly high (Gallaway and Margraf 1978), the biofouling community probably obtains most of its food in the form of plankton and particulates flowing through the system. Some species are recruited to the biofouling community from outside the system (e.g. stone crab larvae, adult sheepshead). Losses from the biofouling community include those from reproduction, breaking-off and sloughing, as well as to man.

With the exception of a few plankton-particulate feeding pelagic species which apparently are platform residents, the pelagic predators (e.g. king mackerel, blue runner) and their prey (e.g. scaled sardine), essentially "drift" through the system as do suspended plankton and particulates, but the former are characterized by slightly longer residence times. The attraction of large predatory gamefish to structures is well-known, resulting in increased predation from the top predator--man. The benthic reef fish community (usually dominated by red snapper), is also subjected to increased predation by man. Red snapper aggregate at platforms, apparently only for purposes of cover since most of their diet is composed of organisms from the soft-bottom demersal fish and macrocrustacean community.

The trophic dynamics of the natural banks of the outer shelf reefs have not been adequately investigated. Corals are dependent upon plankton for food, but are greatly benefited by their symbiotic zooxanthellae, unicellular algae. The algal photosynthesis and concomitant respiration by the coral are mutually beneficial. In addition to the hermatypic corals, coralline algae also contribute to reef formation. Other primary producers of the coral reef community include leafy algae. Corals are preyed upon by numerous species; the most noticeable include parrotfishes and sea urchins. Reefs provide habitat for a large array of animals ranging from small plankton-feeding reef fishes to large snappers, groupers, and grunts. Many of the latter are believed to obtain most of their food from the surrounding soft-bottom communities. Coral reef habitats are unusually diverse and ornate. Their physical structure results in complex biological interactions having no rivals among other shelf systems.

THE ECOSYSTEM AS A RECIPIENT OF OIL AND GAS DEVELOPMENT ACTIVITIES AND EFFLUENTS

In the preceding sections, the Mississippi River has been suggested to be a dominant environmental factor acting on the Texas-Louisiana shelf ecosystem. In effect, the river sets the limits for community productivity and distributional patterns. The effects of man-made physical alterations of the river and contaminant discharges into the river have not been adequately addressed, but a case could easily be made suggesting that such activities already have had overriding effects on the Texas-Louisiana shelf ecosystem. For example, white shrimp landings peaked in the early 1940's at about 65,000 metric tons. The fishery declined markedly in the late 1940's, and catches have fluctuated erratically since that time (e.g. from 14,000 to 36,000 metric tons between 1957-65). The marked drop in white shrimp production also corresponds with the general period during which the low oxygen phenomenon offshore of Louisiana was first being discovered and rediscovered. Further, the present distributional and relative abundance patterns of white shrimp, based upon fishery landings (Klima, undated manuscript), reflect a low abundance of white shrimp in the area historically characterized by seasonal oxygen deficiencies (e.g. compare Figures 13 and 22). In any assessment of the Texas-Louisiana shelf, the effects of channelization and industrialization of the Mississippi River cannot be taken lightly, and possibly overshadow all other development activities.

EFFECTS OF STRUCTURES

One effect of oil and gas development activities on the shelf is immediately obvious--the addition of hard substrate extending from the bottom to above the water's surface. These substrates serve as focal points for rich and diverse biofouling communities and a complex assemblage of platform-associated macrobiota as described in preceding sections. Fish which would normally be found scattered throughout a large area are concentrated in the immediate vicinity of platforms, attracted to the food and/or shelter they provide. Such concentrations are commonly referred to in the literature as the "reef" or "artificial reef" effect of platforms.

The red snapper is one of the more important species attracted to petroleum platforms in that it supports sports and commercial fisheries. The life history of red snapper follows the generalized pattern

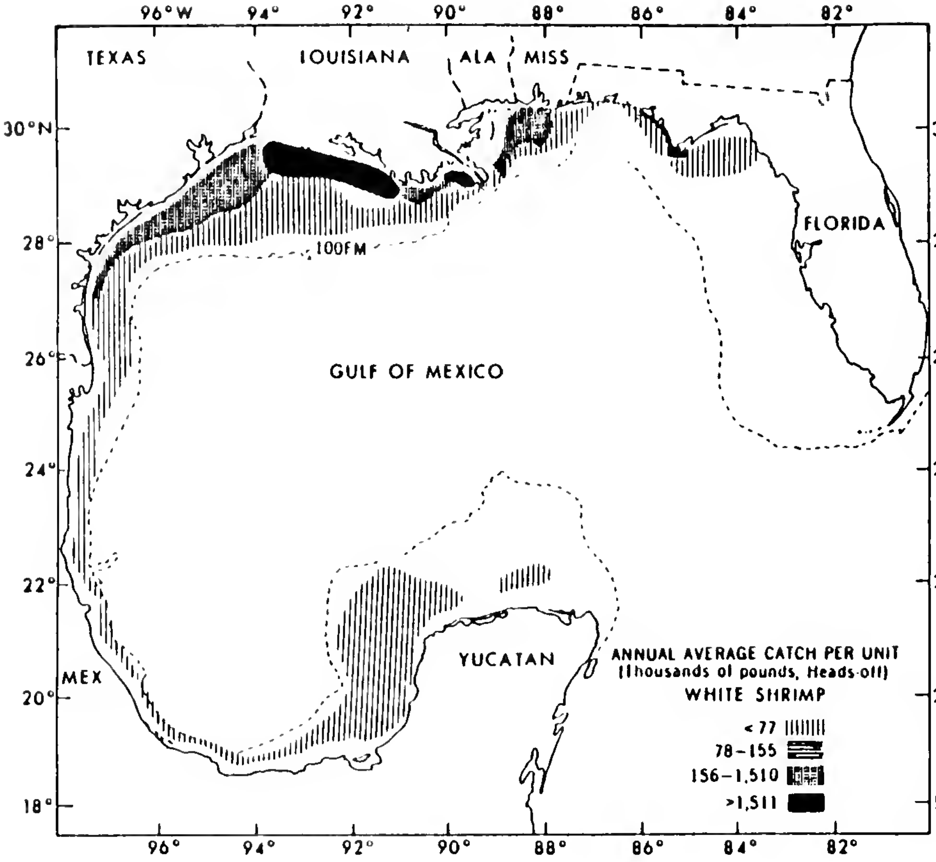


Figure 22. Distribution and relative abundance of white shrimp along the Texas-Louisiana shelf (Klima, undated manuscript).

described in a previous section. Adults spawn offshore; the young are transported, or move, inshore where they grow and develop, ultimately returning to natural and artificial reefs in deeper waters as reproducing adults. Preliminary evidence indicates that some fish may follow pipelines during the movement offshore, and thus be "funneled" to platforms. Tag return data from the Buccaneer Gas and Oil Field studies offshore Galveston indicated that once snapper were recruited to platforms, they did not move to other habitats. These results concerning lack of movement once recruited to a habitat are similar to the findings of Fable (1979). The combination of population estimates and tag return data indicated that most of the annual recruitment of red snapper to the structures was harvested mainly by sportfishermen before the fish attained sexual maturity. If pipelines in effect act as a "lead" and concentrate reef fish at offshore platforms, is there a related decline in red snapper stocks at natural reefs due to lack of adequate recruitment? As offshore platforms are easier to locate than are submarine structures, are stocks being overfished?

Gallaway et al. (1980) developed a simulation model of the recreational red snapper fishery at petroleum platforms offshore of Texas, based upon tagging observations, fishing pressure, and the biology of the species. The purpose of the model was to evaluate the observed fishing effort indicated at petroleum platforms in terms of its impact on the commercial fishery and snapper stocks in the Gulf of Mexico. The modeling produced projections of major red snapper stock declines. The declines were directly attributable to the recreational fisheries associated with petroleum platforms if as few as only 100 of these platforms received the same fishing pressure as a BGOF production platform. The Gulf of Mexico Fishery Management Council, GMFMC, (1980b) recently published data that also indicated red snapper stocks were being overfished, and that this condition was directly attributable to the recreational fishery as opposed to the commercial fishery.

This information, while providing a basis for some concern, does not rule out the possibility that red snapper populations at petroleum platforms may, in fact, represent surplus stocks which otherwise would not be available due to habitat limitation. For example, Fast and Pagan (1974) in studies comparing natural patch reefs to artificial tire reefs off Puerto Rico found some fish tagged at the natural reef moved to the artificial reef, but there was no observed movement from the artificial reef to the natural reef. This suggests relocation to a new habitat perhaps due to overcrowding.

Further evidence supporting the concept that petroleum platforms may result in increased stocks due to increased habitat can be derived from GMFMC (1980b) based upon habitat availability and distribution of apparently depressed stocks. According to calculations by the GMFMC (1980b), natural reef fish habitat in the Gulf of Mexico is represented by approximately 39,000 km^2 or only 5.7% of the total Gulf Fishery Conservation Zone. Assuming that there are 2,000 production platforms in snapper habitat in the gulf, and that the bottom area covered by each is 50 x 50 m, these structures might provide for another 5,000 km^2 of habitat. Most of the platforms in snapper habitat are offshore of Louisiana. Is it coincidence that nearly the entire nearshore gulf snapper habitat except that offshore from Louisiana is considered to be depressed, or do the structures, in fact, provide additional habitat enabling a larger stock?

However, there is a substantial decline of reef fish stocks in some areas of the Gulf of Mexico and a known factor contributing to this decline is overfishing by directed recreational and commercial users (GMFMC 1980b). Other possible factors contributing to the decline are destruction of habitat (natural and man-made), a large bycatch in other fisheries, and large-scale environmental changes (GMFMC 1980b). An insufficient data base exists to pinpoint the exact causes and magnitude of the decline. Of particular importance is determining the role of petroleum platforms (positive or negative) which may have either (1) caused an increase in overall standing stocks of habitat-limited reef fish due to increasing available habitat by about 13%; or contrastingly, (2) contributed to overfishing and resulting stock declines of reef fish.

Elevated levels of trace metals have been observed in the sediments, the biofouling community, and some fishes resident at platforms (Tillery 1980). However, marked bioaccumulation of trace metals has not been observed, at least when the elevated levels are compared to background levels. The sources of elevated trace metals characteristically observed in the environment in the vicinity of petroleum structures likely include the structures themselves, as well as the aqueous discharges emanating from some platforms.

DRILLING FLUIDS

The environmental fate and effects of drilling muds and cuttings have long been a controversial issue. Most recently the ongoing debate has culminated in a symposium conducted during January 1980. The resulting publication of the proceedings was in two volumes requiring 1,122 pages (Ayers et al. 1980a). The following paragraphs represent only a brief precis of some of the information available--all of which can be found in the referenced document.

The mechanics of drilling a well involve pumping drilling fluids (mud) down the center of a rotating string of drill pipe to the drill bit, where the mud exits through nozzles, picks up drill cuttings (rock fragments) and returns to the surface through the annulus between the drill string and the walls of the borehole and/or casings. The cuttings which come out of the well bore are suspended in a large volume of drilling fluids. These fluids are circulated through various mechanical devices (shale shaker, sand trap, hydrocyclones and centrifuge) that selectively separate most of the drilling fluids from the cuttings (Gettleson and Laird 1980).

Drilling fluids are circulated into the borehole during drilling activities to cool and lubricate the drilling bit and drill pipe, remove formation cuttings from the hole, insure controlled and efficient drilling through maintenance of well pressures and integrity of the borehole, permit logging and geological evaluations, and minimize corrosion. Drilling fluids are usually water-based, colloidal suspensions with additions of barite (barium sulfate) to increase density, bentonite to increase viscosity, and other components to control fluid loss, corrosion, and other mud properties. Barite and bentonite clays are the major components used in drilling fluids. The exact composition of the drilling fluids used varies with the depth of the hole and from site to site, depending on the formations and drilling conditions encountered. Normally, the initial 300 m of an offshore well are drilled with seawater and the natural formation clays. Seawater gel, consisting of added bentonite clay and minor amounts of barite, sodium hydroxide, mica flakes and cellulose fibers in seawater, is used below 300 m . From 1,200 to 1,520 m, the seawater gel drilling fluid is converted to a lignosulfonate mud by adding barite, lignosulfonate and other products. Freshwater is usually used with the seawater from 1,520 to 3,000 m and in place of the seawater below 3,000 m to maintain the desired properties of the drilling fluid. The percentage of barite and other components is normally increased with the depth of the well.

Although a typical well usually requires from 1 to 3 months to drill, depending on mechanical problems and hole depth, only 30% to 50% of the time is spent actually drilling. Drilling discharges may be divided into the categories of (1) cuttings with minor amounts of adhering drilling fluids and (2) drilling fluids. The cuttings, which are small pieces of the drilled formation produced by the drill bit, range in size from microns to a few centimeters. These cuttings with their adhering drilling fluids and additional minor quantities of fluids are discharged into the environment from the various mechanical devices used to separate the cuttings from the drilling mud. During drilling periods the discharge from the shale shaker is continuous, while that from the other devices is periodic. Discharges of drilling fluids without cuttings occur eight to ten times during the drilling of an offshore well (Offshore Operators Committee 1978) and usually originate from the mud tanks. Discharges normally result from mud changes at the time of cementing, at the end of drilling the well, and when excessive concentrations of colloidal solids build up in the drilling fluids.

Observations of the discharges as they enter the water column indicate that the large cuttings fall almost straight to the bottom with the adhering drilling fluids washing free during the descent. Flocculated clay spheroids appear to drift downward, while the drilling fluids and very fine cuttings form a plume of suspended clays that is diluted as it moves away from the discharge pipe (Ray and Shinn 1975; Zingula 1975; ECOMAR Inc. 1978). The effective differential settling velocities of individual or flocculated particles cause vertical motion within the plume. The motion is dependent on the particle grain sizes and may be negligible for the fines, but it does lead to a sorting of the material in the plume.

Ayers et al. (1980b) described the distribution of drilling muds in the water column for a well being drilled in 1978 in the nearshore gulf. In two experiments, 250 barrels (bbl) of mud were discharged at a rate of 275 bbl/hr, and 389 bbl of mud were discharged at a rate of 1,000 bbl/hr. The mud was a chrome lignosulfonate-clay type having a bulk density of 2.09 g/cc . Water samples were taken at the bottom, top, and most dense portion of the discharge plume using a rosette sampling array suspended from a helicopter. This novel sampling technique allowed rapid and almost continuous sampling of the plume. Transmittance, dissolved oxygen, temperature, and salinity were monitored as a function of depth and distance from the source using instruments suspended from the helicopter. Divers took samples and underwater photographs of the discharge plume close to the discharge source. Water samples were analyzed for solids content, barium, aluminum and chromium concentrations.

During both discharges, the mud formed a lower plume and an upper plume. The lower plume contained the bulk of the discharged material and descended quickly to the sea floor. As the lower plume descended, an upper, near-surface plume was generated by turbulent mixing of the lower plume with seawater. The upper plume was several meters thick, existed in the water column at the thermocline for a much longer time than the lower plume, and drifted away from the source with the current. All sampling and hydrographic measurements were made on the upper plume. Suspended solids and metal tracer concentrations in the plume reached background levels about 500 m from the discharge source during the 275 bbl/hr test and about 1,000 m from the discharge source during the 1,000 bbl/hr test. Transmittance was the only hydrographic variable affected by the discharge. All other hydrographic variables remained unchanged from ambient conditions within the monitored interval (40 to 1,500 m from the discharge point).

A comparison of these results with a previous experiment (Ayers et al. .1980b) at lower discharge rates indicated that transport time (distance/current velocity) required for suspended solids to reach background levels increased with discharge rate; however, even at high discharge rates background levels are reached in about 100 min. It was shown that most of the drilling mud settles rapidly and the material remaining in the water column (estimated to be 5% to 7% of the discharged material) had a minimal effect on ocean water quality.

Drill cuttings do not accumulate on the bottom in areas of high current velocity because they are either entrained within the shifting sediment or dispersed over a large area (Dames and Moore 1978; ECOMAR, Inc. 1978; Environmental Devices Corporation 1976). In areas of low current speed, such as the Gulf of Mexico, cutting piles are observed after drilling, but the size of a pile diminishes considerably with time, resulting in its eventual disappearance (Shinn 1975; Zingula 1975; Miller 1976; Zingula and Larsen 1977).

Like cuttings, drilling muds do not form significant accumulations on the bottom in areas of high current velocity (Environmental Devices Corporation 1976; Dames and Moore 1978; ECOMAR, Inc. 1978). However, in the Gulf of Mexico, accumulations do occur near drilling operations (Gettleson 1980, in press). The drilling mud probably accumulates in a layer of variable thickness on the sediment surface, depending on the hydrographic factors present at the time of the discharge.

Results of field studies have shown detrimental effects of drilling muds on bottom communities of the Texas-Louisiana shelf, but the effects have been generally restricted to areas within meters of the point of discharge (e.g. Fish et al. 1974; Perry 1974). Similar findings have been made in other marine systems. A study in Lower Cook Inlet, Alaska, showed no detectable effect of drilling fluid discharges on local benthic communities (Lees and Houghton 1980), although Crippen et al. (1980) found a decrease in the infaunal population in the immediate vicinity of a drilling island in the Beaufort Sea, and observed increased concentrations of heavy metals (primarily mercury) in the sediment and biota of the area. The latter study also found that increased sediment loads occasionally smothered benthic infaunal communities. Benech et al. (1980) found that pontoons on a submersible drilling rig supported different assemblages of fouling species, depending on their location relative to the drilling mud discharge point. The fouling community was particularly decreased in areas where mud particulates accumulated. Although very high concentrations of drilling muds have been used to retard coral growth, and coral growth in the Flower Garden Bank was determined by Hudson and Robbin (1980) to have decreased greatly beginning in 1957, it is unlikely that the decrease is in anyway associated with petroleum development. The area was not developed until 1974 and barium and chromium concentrations have showed no corresponding increase which would appear to be causative.

Laboratory analyses of drilling fluids have shown a wide range of biological effects which depend upon the type, concentration and method of preparation of the test material and upon the organism studied. Short term toxicity has been detected, but only at test solution concentrations far greater than those which occur in the environment outside the immediate vicinity of a discharge (see Ayers et al. 1980a for a review).

Usually, drilling muds appear relatively non-toxic at the concentrations encountered in the environment. Dilution of the plumes is rapid; and indirect or sublethal effects of discharged drilling fluids are virtually unknown, as are the long-term effects. In the gulf, the primary threat of significant detrimental effects from discharge of drilling muds appears related to coral reefs sited near drilling operations. Increased turbidity (decreasing light availability to coral zooxanthellae) and the remote possibility of direct smothering of the coral have been viewed as major concerns. Response to these concerns has been to require shunting of turbid drilling fluids to within 10 m of the bottom in areas near coral reefs which puts the fluids into the near-bottom turbid layer. The assimilative capacity of the Texas-Louisiana shelf ecosystem with respect to drilling muds (how much can be discharged before a measurable system-level effect threshold is reached) has not been addressed by any study. However, if development of the shelf proceeds as planned over the next decade, an average of 67,000 tons of mud solids a year will be discharged, approximately 0.02% of the amount of solids contributed annually by the Mississippi River (Department of the Interior/Bureau of Land Management, DOI/BLM 1981).

PRODUCED FORMATION WATER

The major effluent emanating from petroleum production platforms in the gulf is the briny water from the formation which is separated from the hydrocarbon products (oil, condensate, gas). The volume of this discharge varies considerably among formations and over time. An actively producing gas and oil production platform investigated during 1976-80 offshore of Texas averaged between 1,000 and 1,400 bbl/day (about 2.5/ℓ sec) discharge (Gallaway et al. 1980). Produced formation waters typically contain high concentrations of dissolved inorganic salts in which the principal cations are sodium, magnesium and calcium with chloride, sulfate, carbonate and bicarbonate being the principal anions. Concentrations of total dissolved constituents range up to 350,000 mg/ℓ. Hydrocarbons and other organic compounds are present in produced waters at parts per million levels. Dissolved oxygen levels are low at best (usually anoxic) and temperature of produced waters is high (30° to 40°C). Collectively, produced water and minor spills have been estimated to account for 2% of the six million metric tons per year of hydrocarbons discharged to the oceans (National Academy of Sciences 1975).

The nature and effects of produced water discharge were recently investigated at a gas and oil field offshore of Galveston, Texas. Produced waters were characterized in terms of alkanes, aromatics, volatiles, sulfur, and biocides by Middleditch and West (1980). They estimated the daily discharge of alkanes to average 382 g in produced waters, which represented 19% of the estimated 2 kg/day total of oil discharged from BGOF production platforms. The light aromatic fraction of hydrocarbons in produced water was represented by some 68 different compounds having an average total concentration of 104.2 parts per billion (ppb). Twelve normal, branched and cyclic alkanes were characterized in the analysis of produced water volatiles. Three aromatics, comprising 64% of the volatile components measured, were identified as benzene, toluene, and ethylbenzene.

In contrast to the low levels of hydrocarbons being discharged in produced water, some 207 kg of sulfur were estimated to have been discharged daily from BGOF production platforms. As sulfur has a specific gravity of about two and is insoluble in water, it may serve as the major transporter for oil through the water column and into sediments, if hydrocarbons can be adsorbed on sulfur particles. The acrolein biocide used to control microbial aggravated corrosion of pipes and vessels was not detected in produced water discharge samples. This biocide, while highly toxic, is quite labile.

As mentioned above, particulate sulfur was a major component in the produced water and, along with metal flakes from the platform, may have served as a transporter of hydrocarbons to the bottom. Hydrocarbon levels in sediments beneath the production platforms, although highly variable, were typically higher than levels in sediments in control areas. Another possible transporter of hydrocarbons to the bottom was oily sand which was sometimes present in the skim tank and discharged overboard.

With the exception of the large pieces of metal and barnacle shells, the residence time of particulates beneath the platform was presumably very short due to resuspension (waves) and transport out of the area (currents). The direction of sediment transport appeared controlled by seasonal current patterns. Dilution and/or biodegradation appears to reduce levels of contaminants to that of background conditions within short distances ($\lesssim$50 m) from the platforms.

The bacterial data provided evidence that the degree of hydrocarbon contamination emanating from the Galveston field was, indeed, minimal. Bacterial diversity and density levels in the BGOF were markedly similar to those in control areas. Although numerical densities and taxa represented in collections from the two areas were the same, the relative abundance of taxa was different between the BGOF and control areas. BGOF samples contained relatively more oil-degrading, sulfur-oxidizing, and sulfate-reducing bacteria than did samples from control areas outside the field. These data indicated chronic, low-level pollution was occurring, but not to the extent that population levels were significantly increased.

Produced water inhibited or retarded the growth of laboratory cultures of bacteria, but appeared to have either no effect, or a stimulatory effect, on isolates obtained from the BGOF. Both pure and mixed cultures of bacteria from the BGOF exhibited the ability to degrade significant portions of the n-alkanes in BGOF crude oil.

Tillery (1980) found that produced waters were enriched in barium and strontium, but characterized the levels of other trace metals in the discharge as being extremely low. These findings confirmed the previous work of Anderson and Schwarzer (1979), also performed in the BGOF.

Produced water was slightly toxic to marine organisms with crustaceans more sensitive than fish (Zein-Eldin and Keney 1979; ERCO 1980) as indicated in the following table.

Organism	Concentration (ppm) $\bar{x}$ 96-h LC50	$\bar{x}$ 48-h LC50	Concentration (%)
Brown Shrimp			
Larvae	-	9,500	1.0
Subadult	100,000	-	10.0
Adult	116,000	-	11.0
White Shrimp			
Subadult	68,000	-	6.8
Adult	70,000	-	7.0
Barnacle	83,000	-	8.3
Crested Blenny	269,000	-	26.9

The most sensitive organism among those tested was the larval brown shrimp which had a mean 48-h LC50 of about 9,500 ppm (1% produced water in seawater).

Gallaway et al. (1980) used two methods to project the concentrations of produced water in the receiving seawater. The first method was utilized by Environmental Research and Technology, Inc. (ERT) (1980) to establish an initial concentration for use in hydrodynamic models. Based upon dye studies by Workman and Jones (1979), the produced water (due to turbulent mixing beneath the platform) was assumed to completely mix in a volume of water approximately one-eighth of the volume occupied by the platform (Figure 23). The relative contaminant concentration (0.088%) projected by this method agreed well with the pollutant concentrations observed in waters beneath the platform (see Middleditch and West 1980; Tillery 1980) given the initial levels of contaminants in the produced water being discharged.

The second method employed was an analytic steady state approximation for diffusion from a continuous point source discharge having a mean advective component (ambient current) perpendicular to the dispersion. Eddy diffusion coefficients ($K_y = 0.1\ m^2/s$; $K_z = 0.01\ m^2/s$)

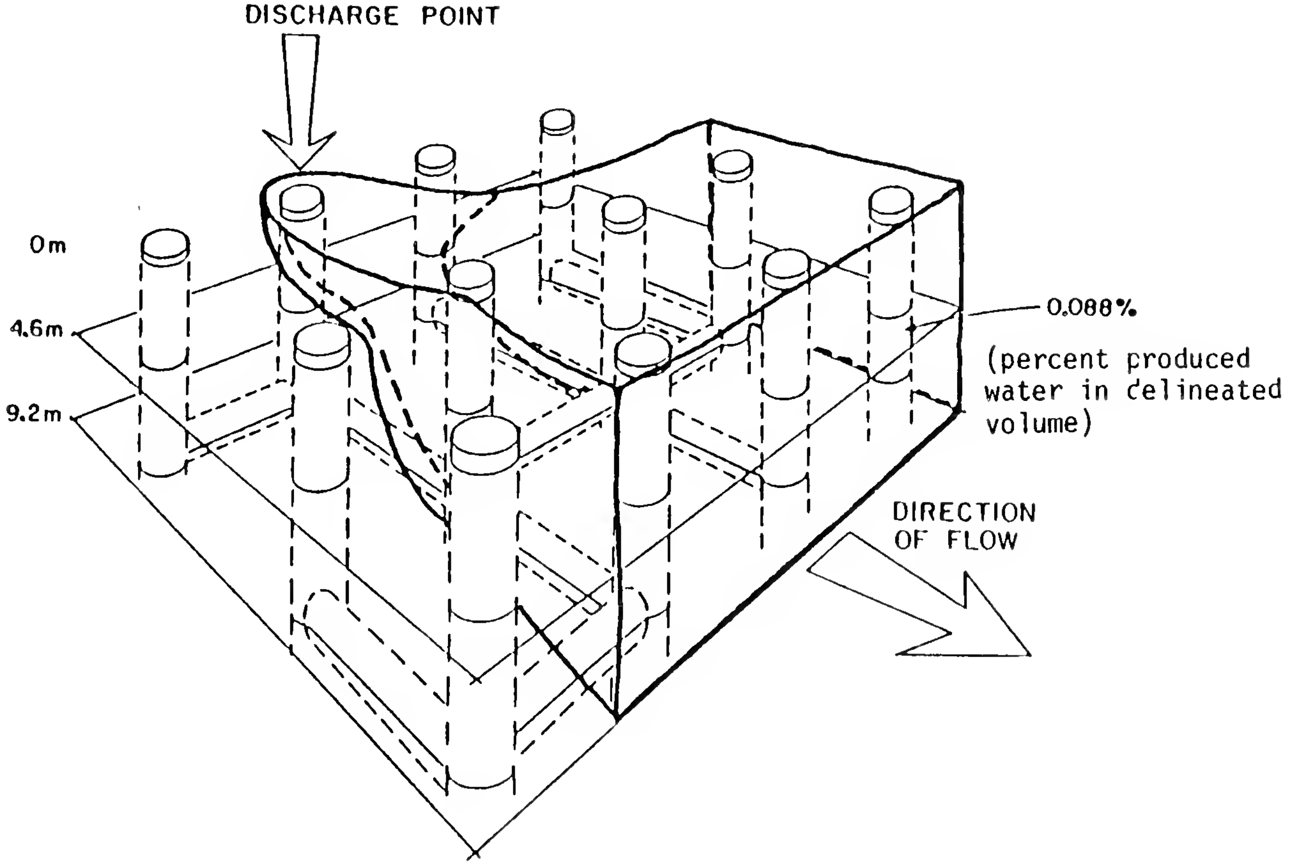


Figure 23. Hypothetical distribution of produced water in the water column.

were selected based upon Nichoul (1975) and, although considered typical for the mixed layer, represent the greatest uncertainty associated with the above model. Typical current velocities in the BGOF range between 0.05 and 0.25 m/s (Hazelton Environmental Sciences Corporation 1980) and were used in the model in conjunction with the average loading value at the point source (~ 2.5ℓ produced water/second) to project worst-case concentrations. The maximum zone of toxicity (assuming a 1% concentration of produced water in seawater to be toxic) was <1 m^3. Decreasing the diffusion rates each by an order of magnitude resulted in the "potentially slightly toxic" volume increasing up to 5 m^3, mostly in the direction of current flow. Increasing the diffusion rates resulted in a decrease in the potentially toxic volume, and in the limiting case, approximated results from method one described above.

The discharge of produced water had detrimental effects on the biomass levels and production rates of the BGOF biofouling community; but, using the 5% level to determine differences, significant alterations of the community were restricted to a vertical distance of about 1 m and a horizontal distance of less than 10 m. These results, which were obtained in-situ, agreed well with the projected zones of "toxicity" described above for worst-case conditions. The near-surface zones in the immediate vicinity of the outfall were characterized by the virtual absence of any living large barnacles but small (usually dead) barnacles were sometimes obtained in the collections taken there. Organisms colonizing this area may do quite well until worst-case hydrographic conditions occur. In addition, organisms colonizing this zone were probably periodically subjected to nearly 100% concentrations of produced water when they are exposed in the troughs of waves. Based upon recolonization information (Figure 24), worst-case conditions were apparently encountered more frequently in spring through fall periods than during winter. The surface effect of produced water on recolonization rates for spring to summer and summer to fall periods is readily apparent in Figure 24. However, production rates beneath the outfall at depths greater than 1 m were typically equal to, or greater than, production rates on control structures at the same depths during the same periods. Production rates at the surface beneath the outfall were even greater than rates at the surface station on the control structure during the fall to winter period. The fall to winter period was one of high energy and turbulent mixing prevailed. The winter to spring season was characterized by low production rates at all stations throughout the field and no significat differences were apparent.

Results of respirometry experiments indicated low rates of biofouling primary production and that a stress response (increased oxygen uptake) had been elicited from the communities subjected to treatment. In retrospect, the stress response was attributable to the fact that the concentration of produced water to seawater (10% to 25%) exceeded the 96-h LC50 value of most of the organisms being tested. For example, a common amphipod (*Jassa falcata*) of the biofouling community suffered 100% mortality when placed in a 10% produced-seawater mixture for 48 h.

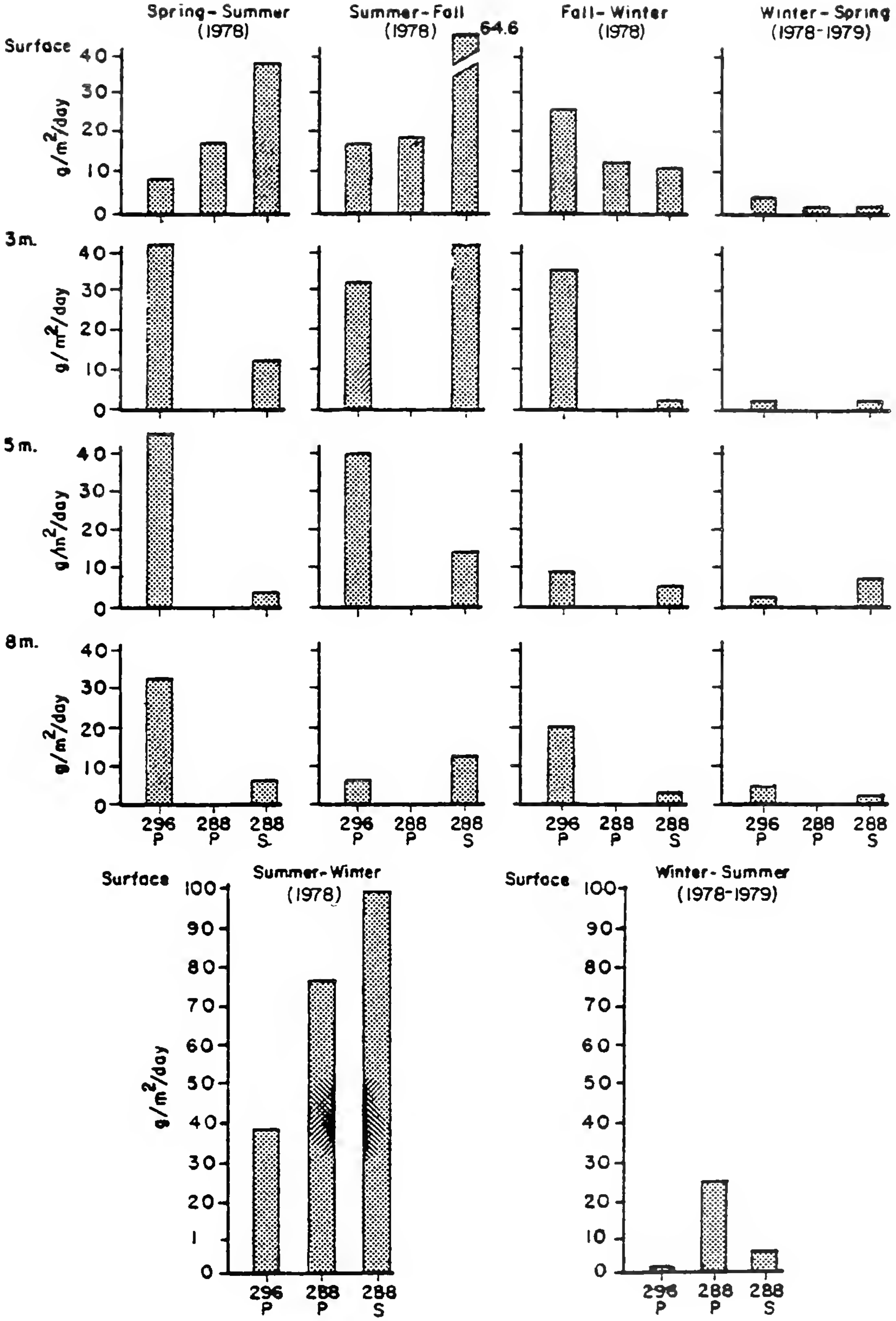


Figure 24. Recolonization biomass produced on Buccaneer Gas and Oil Field structures, 1978-79. P = Production platforms with surface discharges, S = Satellite well platform without discharge. After Gallaway et al. (1980).

The effects of produced water on the condition of the Mediterranean barnacle were reported by Boland (1980). Barnacles taken from locations as close as 1 m to the surface at the outfall were not significantly different in condition from those taken at control stations. He did find, however, that barnacles taken immediately below the sewage outfall were characterized by significantly better condition than barnacles taken in control areas. He also found that Mediterranean barnacles from the BGOF were characterized by significantly better condition than the same species collected from a structure offshore from West Cameron, Louisiana.

Barnacles did not contain measurable amounts of petroleum alkanes but the fouling mat in the immediate vicinity of the outfall was observed to have been oiled by direct exposure to produced water. The cryptic blennies, which were relatively insensitive to produced water (96-h LC50 = 27%) and which were apparently attracted to the area of outfall (Gallaway and Martin 1980), also showed evidence of marked petroleum contamination. The mean alkane concentration in this fish in 1978-79 was 6.79 ppm, considerably higher than levels found in any other fish. No evidence of any significant trace metal contamination of the biofouling community attributable to production activities was found during the BGOF investigations.

The effects of produced water on several species of platform-associated fish were also investigated in the BGOF program. Target species included the crested blenny and sheepshead, which rely upon the biofouling community for food; the spadefish, which takes most of its food in the form of plankton and particulates from the water column, and the red snapper, which feeds on epifaunal organisms from the soft bottoms away from the platforms.

Blennies exhibited an apparent attraction to the area of produced water discharge. Highest densities were observed on production platforms, and on these platforms, significantly higher densities were observed near the outfall than elsewhere. Based upon in-situ investigations, the effluent had no significant effects on recolonization rates of areas harvested of blennies, nor were there any significant effects on condition of blennies.

The apparent attraction to the outfall area may have been attributable to the combination of a greater level of habitat availability due to higher densities of both live and dead barnacles in these areas (Howard et al. 1980) and the apparent lack of sensitivity of the crested blenny to produced water (96-h LC50 was 269,000 ppm or about 27% produced water in seawater).

The crested blenny differed little from other BGOF fishes in terms of its bacterial flora. Species of _Vibrio_ were the most common taxa during each season; hemolytic _Vibrio_ were not isolated from fall specimens. *Moraxella* sp. were apparently a co-dominant with *Vibrio* spp. during spring. There was no marked difference in the bacterial flora of blennies taken from the production platform as compared to those collected at satellite jacket habitats. No diseased blennies were noted in any of the areas sampled.

The crested blenny was a "clean" fish in terms of histopathological anomalies. Other than a light infestation of microsporidean parasites, no significant histopathological anomalies were detected in the specimens examined. However, the average alkane concentration in this fish was 6.79 ppm, higher than the mean levels observed for any other fish from the BGOF (Middleditch and West 1980). Trace metal contamination of blennies attributable to BGOF operations was not indicated.

Sheepshead were found to be "structure-faithful" fishes, and density levels of sheepshead at platforms having contaminant discharges were similar to densities at non-discharging structures. The most notable histopathological finding with respect to sheepshead was the veritable absence of any anomalous condition in tissue samples taken from migrant specimens collected during the brief period of the spawning aggregation observed in the BGOF in April. Typically, sheepshead collected during other seasons (residents) exhibited five to seven different tissue anomalies, with each condition represented in 20% to 100% of the specimens collected. With the exception of gill hyperplasia, which was characteristic of all specimens collected during the summer and in four of five specimens collected at the production platform in fall, most of the anomalies in the tissues examined were lesions associated with a parasite (e.g. nematodes). If the fish collected during April were representative of a migrant population, it would appear that resident sheepshead were characterized by a higher degree of histopathological anomalies (or parasitism) than were sheepshead which migrated in and out of the study area for spawning purposes.

Comparisons of condition of sheepshead at the treatment and control structures were based upon specimens subsequently submitted for histopathological and bacterial flora analysis. The data set was reduced to the December 1978 and May 1979 collections, as the sheepshead represented during April were not considered resident fish, and weights were not obtained for the specimens analyzed from August. The length-weight regressions for fish from the two habitats had equal slopes, and although fish from the discharging platform were 10.6% heavier than fish from the control structure, the differences were non-significant.

Sheepshead were characterized by the presence of petroleum alkane contaminants in both liver (6.08 ppm) and muscle tissues (4.57 ppm). These levels were lower than that characteristic for blennies, but higher than levels observed for fishes not trophically dependent upon the biofouling community for food. No significant trace metal contamination related to BGOF operations was demonstrated (Tillery 1980).

Spadefish showed no evidence of either petroleum or trace metal contamination attributable to BGOF operations, and were characterized by the lowest levels of total alkanes of any fish tested (Middleditch and West 1980; Tillery 1980). Density levels of spadefish were equivalent among the various structure types in the field. Seasonal disease epidemics were observed but seemed best explained by natural phenomena. Whereas condition of spadefish was significantly lower during winter than during other seasons as might have been expected, condition did not differ significantly among the structures sampled during winter.

However, the possibility, although considered to be slight, remains that the winter disease epidemics may have been related to the chronic, low-level discharge of contaminants. Minchew and Yarbrough (1977) found that 96% of the mullet, Mugil cephalus , held in ponds subjected to a low-level oil spill (4 to 5 ppm) suffered fin rot whereas only 6% in a control pond developed eroded fins. The primary pathogen considered responsible for the fin erosion was a species of Vibrio . Subsequent laboratory work by Gilles et al. (1978) confirmed the above results and showed that chronic, low-level exposure of mullet to oil significantly altered the bacteria on the fish, allowing for a large population of potentially pathogenic Vibrio . They also suggested that the Vibrio , through utilization of the oil, may have acquired an enhanced virulence. The results of Gallaway et al. (1980) agree with the findings of the above pond and laboratory experiments in that fish exposed to chronic, low-levels of hydrocarbons in discharges developed external lesions and fin rot which may have been attributable to Vibrio sp.

Of the 34 red snapper from the BGOF examined for histopathological anomalies, 62% were characterized by gill hyperplasia and 47% by intestinal parasites, usually accompanied by intestinal inflammation, fibrosis and lesions. Gill parasites were believed largely responsible for the observed hyperplasia. No marked difference in the frequency of the various anomalies was observed for production platforms vs. satellite jacket populations or among seasons. Bacterial flora of red snapper varied seasonally with Vibrio sp. usually the dominant form on fish from each of the two habitats sampled. Hemolytic Vibrio spp., which include representatives of potential fish pathogens, were well represented on specimens from each structure during each season except fall 1978 when none were isolated from any of the samples. Aeromonas spp., which also include fish pathogens, were isolated from specimens taken at the production platform in summer 1978 (27% of the total 26 colonies isolated from snapper tissue were Aeromonas spp.) and in spring 1979 (15% of the total 47 isolated colonies). Aeromonas spp. were not isolated from red snapper specimens taken at the control structure during any season. No evidence of disease or red snapper in poor condition was observed at any location or during any season. Hydrocarbon contamination was variable (Middleditch and West 1980) but typically no significant trace metal contamination was observed (Tillery 1980).

Based upon studies in the BGOF, Gallaway et al. (1980) concluded that (1) produced waters are slightly toxic, but direct effects are generally restricted to within only a few meters of the outfall, and (2) that measurable uptake of contaminants is minimal and restricted to those species in the biofouling food chain.

Brent et al. (1979) found that producing platforms increased total organic carbon loading of the system from 2 to 4 mg/ℓ above background levels. The area affected by increased loading extended some 800 to 1,600 m from the platforms. They further pointed out that, given the naturally high organic load in waters of the Texas-Louisiana shelf and its effect on oxygen resources, this could be an area of some concern.

OIL SPILLS

The National Academy of Sciences (1975) estimated that the major sources of hydrocarbons into the world's oceans were from transportation (34.9%) and river runoff (26.2%). In contrast, offshore production activities were estimated to account for only 1.3% of the total hydrocarbon loading of oceans. Total volume of oil spilled in the Gulf of Mexico from offshore production activities (including pipeline failures) was 51,421 barrels (bbl) during 1971-75 (Danenberger 1976) and only 1,978 bbl were recorded to have been spilled from production activities during 1976-79 (DOI/BLM 1981). In comparison, Bedinger et al. (1980) estimated that the annual hydrocarbon input to the gulf from the Mississippi River may average about 151,000 bbl.

From 1974-79, 3,115 oil spills were recorded that were directly attributable to marine-transportation (other than pipelines, DOI/BLM 1981). Although most (97%) of these spills were less than 50 bbl (DOI/BLM 1981), one, the 1979 <u>Burma Agate</u> collision with a freighter, was estimated to have spilled 198,000 bbl of oil, of which 150,000 bbl burned in the ensuing fire (Kana and Thebeau 1980). Thus, as in the general case of the world's oceans, oil and gas production activities on the Texas-Louisiana continental shelf, particularly since 1971, appear to account for only a small portion of the total hydrocarbon input to the system.

Prior to 1971, only spills of major significance (>50 bbl) were recorded. Some of these spills were massive. Among the most spectacular were the Exxon pipeline break in 1967 (160,000 bbl), the 1970-71 Shell Timbalier blowout and fire (53,000-130,000 bbl), and the 1970 Chevron Main Pass incident (30,500 bbl). These last two incidents, in conjunction with the Santa Barbara blowout which occurred during the same period, drastically affected outer continental shelf (OCS) operations. The increased concern and scrutiny resulting from these high-profile accidents have led to greatly improved operating procedures and technology, and importantly, to a reduced number of spills on the OCS.

All of the spills on the Texas-Louisiana shelf have been dwarfed by the 1979-80 IXTOC blowout (3.3 million bbl) in the Bay of Campeche. Some of this oil reached the Texas-Louisiana shelf, but in a highly weathered state. An assessment of the impact of this event on the Texas-Louisiana shelf is currently being prepared based upon present studies being jointly conducted by NOAA and BLM.

The effects of oil spills on gulf ecosystems have not been determined with certainty. Surveys following the 1970 Chevron oil spill did not establish detrimental effects, nor have other accidents resulted in clear documentation of substantial impact. Mumphrey and Carlucci (1978) state in their regional status report for the gulf coast that the "short-term effects of oil spills include mortality and tissue damage to fishes and invertebrates but experience has shown that a year after the spills there is recovery of the biological resources."

The issue of whether or not any (or all) of the above-described and other petroleum spills have had an effect upon marine life in the Gulf of Mexico is an important management concern. It will be important for the reader to keep in mind that a number of terms are commonly used in descriptions of possible spill effects. For example, "long-term" effects are frequently differentiated from "short-term" effects in the literature, as are the roughly equivalent categories "chronic" vs. "acute." Typically, these expressions can be translated to mean either that immediate, obvious kill of visually dominant organisms (e.g. shorebirds, fish) occurred (short-term, acute) or that it did not, but that more subtle, long-lasting, demographic-type effects are to be anticipated in the form of reduced organism reproduction, lifespan, or the like (long-term, chronic). It is not clear whether the two classes of effects would best be considered a continuum as the occurrence of an acute effect may not necessarily indicate that a long-term, chronic problem will follow. For example, a massive kill of adults in a population whose larval recruitment is density-independent (and in which larvae are typically present in great excess) may not affect the size of the next year class at all if at least enough adults survive to produce young in adequate (if not excessive) numbers. This point has been amply demonstrated for many benthic organisms, which usually produce many more larvae than will survive to adulthood (Thorson 1966; Miliekovsky 1971). On the other hand, species which rely upon more conservative reproductive approaches to survival may be decimated by single catastrophic incidents or by sublethal, chronic effects at particularly sensitive periods in their life histories (Sarukhan 1979).

It must be emphasized that population-level information is wholly lacking for most marine organisms potentially impacted by oil spills in the gulf, and that the consequences of physiological, individual-level effects or population-wide effects are assessed almost entirely through the relatively crude measure of relative abundance. That is, the density or abundance of species or individuals of selected species may be measured before (by good chance, occasionally) and after a spill, mortality inferred, and predictive conclusions drawn (e.g. Michael 1979). These conclusions have been wrong as often as they have been right. The main reason that predictions have frequently failed is that natural variability in marine populations is enormous and, with or without spills, many species would show extreme seasonal and annual fluctuations in density. Furthermore, sampling methodology is not a small source of variability, and an apparent change in abundance may simply reflect gear or operator differences.

The reasons for the rather striking lack of correlative information linking spills with biological degradation (changes in abundance, tissue damage, etc.) are multiple. First, and perhaps foremost, is the sampling and natural variability problem. Given the level of natural variability in marine populations and the difficulty of sampling abundance adequately through time, it is extremely difficult to say whether or not a given set of samples indicate changes or trends in a single location, let alone over an entire region. Most marine organisms are patchy in distribution and a local increase or decrease may be insignificant from a community or population perspective. Furthermore, correlative information (e.g. petroleum high here, species "A" low here) is just that: correlative, not proof of any causal relationship. To establish a good correlation is a difficult goal and requires careful experimental design, including proper controls.

An adequate biological control area in the Gulf of Mexico is difficult to define either spatially or temporally. Hydrocarbons from both spills and from natural sources (Mississippi River, natural seeps) ultimately find their way to the sediments where they are intermingled and changed in nature, or weathered, by various reduction processes. Once in the sediments, the hydrocarbons can be either buried and/or variously resuspended and deposited as a function of bottom turbulence and currents. As part of the sedimentary cycle, the weathered hydrocarbons are distributed over broad areas in low, often uniform, concentrations. Selections of a control area for oil spill assessment studies must take hydrocarbon dispersal and weathering processes into account, both in terms of time and space.

Contamination of tissues of marine organisms often occurs when hydrocarbon levels are elevated. However, substantial evidence indicates that organisms exposed to high spill levels of hydrocarbons can rid themselves of the pollutants if these levels of exposure decrease (Koons et al. 1977; McAuliffe 1977; Teal 1977; all cited in Sharp 1979).

Large oil spills in the gulf undoubtedly kill many individuals of some susceptible species and may result in tissue contamination of many individuals which are exposed to elevated but sub-lethal concentrations. Both are seemingly short-term effects, but to extrapolate from a single event impacting a population that may be poorly known itself to a long-term prediction regarding that population's and the system's response is not possible given the kinds of data that are typically available (e.g. relative abundance, hydrocarbon levels, bioassay).

CUMULATIVE IMPACTS ON THE SYSTEM

As described above, most studies which have been performed with the goal of delineating oil and gas development activities on the shelf ecosystem have essentially been conventional baseline studies of the relative abundance of ecosystem components. Generally, these studies have attempted to relate observed biological differences to environmental variables, particularly specific contaminants such as hydrocarbons which can be toxic at elevated levels. Two important lessons have emerged from these studies. First, the ecosystem components have been found to be highly variable and difficult to measure; and, for assessment purposes, it has been, and is, exceedingly difficult to establish adequate controls. Second, even when biological differences have been determined and experimentally related to contaminant discharges, the significance of the findings has been difficult to evaluate at the population or system level as very little is known about the physical and biological processes which govern or regulate the nearshore, continental shelf ecosystem.

It would appear that the impacts of offshore oil and gas development activities on the shelf ecosystem *per se* have been minimal. Hydrocarbon loadings from these activities are small in comparison to other sources, and concentrations of discharged contaminants at toxic levels have been seldomly observed in the environment, except perhaps at the "end of the pipe" or in the cases of accidental, massive spills of hydrocarbons. Even in the case of a large spill, physical and microbial processes serve to quickly dissipate and reduce or change the nature and toxicity of hydrocarbons and other contaminants. Apparent recovery of affected areas is rapid, usually within a year.

The Texas-Louisiana shelf environment is highly variable and one which has long been exposed to hydrocarbon inputs through natural oil and gas seeps. The marked variability of the shelf environment has probably served to "temper" the system, resulting in a high degree of biological resiliency. Typical life cycles of system components are short and sexual maturity is attained rapidly. Characteristically, adults produce young in excessive numbers, and few adults are required to re-establish populations. Descriptions of species and size compositions of shrimp ground faunal assemblages provided by Gunter (1938, 1945) and Hildebrand (1954) are remarkably similar to more recent descriptions of these assemblages in the gulf by Chittenden and McEachran (1976). Such evidence suggests that the cumulative impacts from man's activities may have been minimal, at least to date.

However ecological systems are seldom characterized by gradual declines but, in contrast, change very rapidly when thresholds separating regions of no effect from effect are reached. Once a new condition or state is reached, a system often does not return to the original condition even when the disturbance is removed. The information which is most needed for the Texas-Louisiana shelf ecosystem is some estimate of its assimilative capacity (i.e. the amount of a given material that can be contained in a waterbody without producing an unacceptable impact on living organisms or non-living resources). Given the magnitude of organic and inorganic loadings to the shelf system from all sources, it is conceivable that the assimilative capacity of the shelf ecosystem can, and may soon, be reached. Conventional methods of impact assessment (assessment via baseline studies of system components) need to be replaced with studies of system processes because results of man's activities usually assert themselves as impacts through alteration of support processes, rather than through direct obliteration of components (populations). A characterization of process rates and mechanisms, rather than a compilation of baseline data about components, would enable scientists to project more effectively how oil and gas development may alter the system components.

The characteristics of processes are temporally and spatially more conservative than are characteristics of components. As a result of this relative constancy, process information is more broadly applicable than are conventional baseline data. Thus, information obtained for the Texas-Louisiana shelf system might consequently be more freely extrapolated to answer questions about development impacts in other areas (e.g. the eastern Gulf of Mexico).

REVIEW AND RECOMMENDATIONS

The major portion of the Texas-Louisiana shelf is presented as a reasonably discrete ecosystem, with the Mississippi River representing a dominant environmental force. The system is characterized by two major soft-bottom assemblages, each containing a highly-prized and commercially valuable species of penaeid shrimp. The pelagic community of the system contains few species which support commercial fisheries. The system is characterized by the presence of more artificial reef communities than any other shelf area of the United States (perhaps the world), and these reef habitats support recreational and commercial fisheries for species such as snapper and grouper. Some of the hermatypic coral reefs represented in the system are considered to be among the more valuable communities for the reason of uniqueness rather than commercial importance.

The information which is available for the Texas-Louisiana shelf ecosystem is largely descriptive. Structure of the system has been reasonably well-defined, and several large scale investigations dating from the early 1960's provide information characterizing annual variability in environmental attributes as well as abundance of dominant and/or valuable species. Recent information describing species composition and abundance of demersal epifauna compares favorably to descriptions obtained some four decades past.

Little information is available describing the processes which govern the fluctuations in abundance or status of important shelf species. The methodologies required to provide such information are only beginning to emerge. Given the overwhelming influence of the Mississippi River and its contaminant loads, many studies have been unsuccessful in delimiting effects of specific activities such as petroleum development from effects caused by natural forces, and the reductionist nature of most of the ongoing large investigative programs suggests that very little will be contributed in this regard in the near future. More information is needed regarding important processes to (1) be able to evaluate the results of man's activities vs. natural variations, and (2) estimate the assimilative capacity of the Texas-Louisiana shelf ecosystem as a recipient of man's waste products.

The estimate of the assimilative capacity of the Texas-Louisiana shelf should attempt to define how many increments of the total capacity are available for additional activities (or users) in light of the increments already being used by the natural system and existing activities. Examples of the existing users of say, dissolved oxygen, are the system consumers, other in-situ oxygen-demanding materials (natural seeps, deaths, excretion), the mainland (oxygen-demanding materials in riverine and estuarine discharges, direct run-off and erosion), oxygen-demanding materials from offshore production activities, and oxygen-demanding materials from marine transportation. Planned future users include activities such as the Strategic Petroleum Reserve (SPR) sites and offshore super tanker ports which will also discharge oxygen-demanding materials. Even though any specific activity may require only a small increment of the total capacity of the system, and be insignificant as compared to the demand of other activities (such as the natural system), only small, if any, increments may, in fact, be available. If the requisite process information was available, management plans could establish user priorities and meaningful regulations could be instituted. For example, a minor improvement in Mississippi River water quality resulting from regulatory actions might greatly benefit the system, whereas a major technological improvement required by regulation from a minor user (e.g. zero discharge of oxygen-demanding materials by offshore production platforms) might little benefit the system.

What specific information is needed? This question probably could best be addressed by attempting to develop an assimilative capacity model for the Texas-Louisiana shelf ecosystem during the course of a series of modeling workshops. The goal of the initial workshop would be to bound the system in time and space, select indicators that would reflect the health of the system in terms perceived important (e.g. commercial shrimp landings, commercial and recreational red snapper landings, coral standing crop, dissolved oxygen levels), develop process submodels describing the dynamics of each system indicator and integrate the submodels to provide a system model which concentrates on the system components of most concern. As the conceptual process models for each indicator were developed and translated to mathematical models, the specific information and data needs required for making the assessments would emerge. These needs could guide the planning of future research, insuring that all information obtained would be directly useful for environmental assessment purposes. Once the initial system model was constructed, various development scenarios could be evaluated, and would be based upon the best and most complete information available at the time.

After the initial workshop and following a period during which new information could be gathered, a second workshop could be conducted during which the model could be updated and revised based upon the results of the new information. Ultimately, through a series of information gathering periods and modeling workshops, a good model could emerge--one with reasonable prediction capabilities.

Several Federal and State agencies conduct and/or sponsor environmental studies in the Gulf of Mexico in a complementary, but little integrated fashion, due to the different mandates of various agencies. The above-defined approach could provide a clearly defined focus for all the research and monitoring programs being performed and enable integration of program results at a level heretofore unachieved. It is recommended that attempts be made to develop an assimilative capacity model for the Texas-Louisiana shelf ecosystem, and that this model be used for both assessment purposes and research planning by all agencies.

LITERATURE CITED

Agassiz, A. 1888. Three cruises of the U.S. Coast and Geodetic Survey steamer BLAKE in the Gulf of Mexico, in the Caribbean Sea, and along the Atlantic coast of the United States from 1877 to 1880. Bull. Mus. Comp. Zool. Harv. Univ. 14 & 15.

Anderson, J.B. and R.R. Schwarzer. 1979. Describe the fine sediments and nepheloid layer of the oil field, focusing upon their relationship to heavy metal absorption/determine levels, pathways and bioaccumulation of heavy metals in the marine ecosystem in oil field. In W.B. Jackson, ed. Environmental assessment of an active oil field in the northwestern Gulf of Mexico 1977-1978. Volume 3: Chemical and physical investigations. NOAA annual report to EPA. Project EPA-IAG-DS-E693-EO. NTIS Accession PB80107899. 722 pp.

Antoine, J.W. 1972. Structure of the Gulf of Mexico. Pages 1-34 in R. Rezak and V.J. Henry, eds. Contributions on the geological and geophysical oceanography of the Gulf of Mexico. Texas A&M University Oceanographic Studies, Volume 3. Gulf Publishing Co., Houston, Tex.

Armstrong, R.S. 1979. Describe seasonal circulation patterns in the oil field. In W.B. Jackson, ed. Environmental assessment of an active oil field in the northwestern Gulf of Mexico 1977-1978. Volume 3: Chemical and physical investigations. NOAA annual report to EPA. Project EPA-IAG-DS-E693-EO. NTIS Accession PB80107899. 722 pp.

Ayers, R.C., N.L. Richards and J.R. Gould. 1980a. Proceedings of a symposium. Research on environmental fate and effects of drilling fluids and cuttings. Washington, D.C. 1,122 pp.

Ayers, R.C., T.C. Sauer, D.D. Stuebner and R.P. Meek. 1980b. An environmental study to assess the effect of drilling fluids on water quality parameters during high rate, high volume discharges to the ocean. In R.C. Ayers, N.L. Richards and J.R. Gould. Proceedings of a symposium. Research on environmental fate and effects of drilling fluids and cuttings. Washington, D.C. 1,122 pp.

Bayer, F.M. 1961. The shallow-water octocorallia of the West Indian region. Martinus Nijhoff, The Hague. 373 pp.; 27 plates.

Bedinger, C.A., J.W. Cooper, A. Kwok, R.E. Childers and K.T. Kimball. 1980. Ecological investigations of petroleum production platforms in the central Gulf of Mexico. Volume 1: Pollutant fate and effects studies. Draft final report submitted to the Bureau of Land Management for contract AA551-CT8-17. 149 pp.

Benech, S.V., R. Bouker and R.A. Pimentel. 1980. The effect of long term exposure to fluids on the structure of the fouling community on a semi-submersible exploratory drilling vessel. Pages 611-631 in R.C. Ayers, N.L. Richards and J.R. Gould. Proceedings of a symposium. Research on environmental fate and effects of drilling fluids and cuttings. Washington, D.C. 1,122 pp.

Boland, G.S. 1980. Morphological parameters of the barnacle, Balanus tintinnabulum autillensis , as indicators of physiological and environmental conditions. M.S. Thesis. Texas A&M University, College Station. 69 pp.

Brent, C.R., H.P. Williams, W.A. Bergin, J.L. Tyroll and T.E. Myers. 1979. Organic carbon, inorganic carbon, and related variables in offshore oil production areas of the northern Gulf of Mexico. Pages 245-264 in C.H. Ward, M.E. Bender and D.J. Reish, eds. Effects of oil drilling and production in a coastal environment. Rice Univ. Stud. 65 (4 & 5). 589 pp.

Bright, T.J. and L.H. Pequegnat. 1974. Biota of the West Flower Garden Bank. Gulf Publishing Company, Houston, Tex. 435 pp.

Bright, T.J. and R. Rezak. 1978. South Texas topographic features study. Final report to BLM from the Texas A&M Research Foundation and Texas A&M University, Department of Oceanography. 772 pp.

Brongersma-Sanders, M. 1957. Mass mortality in the sea. In Treatise on marine ecology and paleoecology. Volume 1. Ecology. Geol. Soc. Am. Mem. 67:951-960.

Brucks, J.T. 1971. Currents of the Caribbean Sea and adjacent regions as deduced from drift-bottle studies. Bull. Mar. Sci. 21:455-465.

Caillouet, C.W., W.B. Jackson, G.R. Gitschlag, E.P. Wilkins and G.M. Faw. (In prep). Impacts of Buccaneer Gas and Oil Field in the northwestern Gulf of Mexico. Proc. Gulf Caribb. Fish. Inst.

Campbell, W.B., T.R. Jacobson and L.R. Pomeroy. 1980. Microbial associations with organic aggregates in the marine environment. Bacteriol. Proc. 80:172.

Causey, B.D. 1969. The fish of Seven and One-Half Fathom reef. M.S. Thesis. Texas A&I University, Kingsville. 110 pp.

Chittenden, M.E. and J.D. McEachran. 1976. Composition, ecology and dynamics of demersal fish communities on the northwestern Gulf of Mexico continental shelf, with a similar synopsis for the entire gulf. Texas A&M University, Sea Grant Publ. TAMU-SG-76-208.

Copeland, B.J. and E.G. Fruh. 1970. Ecological studies of Galveston Bay 1969. Final report to Texas Water Quality Board, Austin for contract IAC (68-69)-408.

Crippen, R.W., S.L. Hodd and G. Green. 1980. Metal levels in sediment and benthos resulting from a drilling fluid discharge into the Beaufort Sea. Pages 636-664 in R.C. Ayers, N.L. Richards and J.R. Gould. Proceedings of a symposium. Research on environmental fate and effects of drilling fluids and cuttings. Washington, D.C.

Dames and Moore. 1978. Drilling fluid dispersion and biological effects study for the Lower Cook Inlet C.O.S.T. Well. A report for Atlantic Richfield Company.

Danenberger, E.P. 1976. Oil spills 1971-75, Gulf of Mexico outer continental shelf baseline environmental survey 1977/1978. Final report to Bureau of Land Management, contract AA550-CT7-34. New Orleans, La: 4 volumes. Available from NTIS, Springfield, Va.: (1-A) PB-294-227/AS; (1-B) PB-294-228/AS; (2-A) PB299-686/AS; (2-B) PB299-687/AS.

Dawson, C.E. 1964. A revision of the western Atlantic flatfish genus Gymnachirus (the naked soles). Copeia 1964:646-665.

Deevey, E.S. 1950. Hydroids from Louisiana and Texas, with remarks on the Pleistocene biogeography of the western Gulf of Mexico. Ecology 31(3):334-367.

Defenbaugh, R.E. 1976. A study of the benthic macroinvertebrates of the continental shelf of the northern Gulf of Mexico. Ph.D. Thesis, Texas A&M University, College Station. 85 pp.

Department of Interior/Bureau of Land Management (DOI/BLM). 1981. Draft Environmental Impact Statement proposed OCS oil and gas sales 67 and 69. New Orleans OCS Office, New Orleans, La. 417 pp.

ECOMAR, Inc. 1978. Tanner Bank mud and cuttings study. A report for Shell Oil Company. Technical report, ECOMAR, Inc., Santa Barbara, Calif. 495 pp.

El-Sayed, S.Z., W.M. Sackett, L.M. Jeffrey, et al. 1972. Serial atlas of the marine environment. Folio 22. Chemistry primary productivity and benthic algae of the Gulf of Mexico. American Geographical Society. 29 pp.

Environmental Devices Corporation. 1976. Special water monitoring study, C.O.S.T. Atlantic G-1 Well. A report for Ocean Production Company.

ERCO, Energy Resources Company Incorporated. 1980. Crustacean and fish bioassay. In W.B. Jackson and P. Wilkins, eds. Environmental assessment of an active oil field in the northwestern Gulf of Mexico 1978-1979. Volume 3: Biological investigations. NOAA annual report to EPA. Project EPA-IAG-DS-E693-EO.

ERT, Environmental Research and Technology, Inc. 1980. Hydrodynamic modeling. In W.B. Jackson and P. Wilkins, eds. Environmental assessment of an active oil field in the northwestern Gulf of Mexico 1978-1979. Volume 2: Chemical and physical investigations. NOAA annual report to EPA. Project EPA-IAG-DS-E693-EO.

Etter, P.C. and J.C. Cochrane. 1975. A summary of water temperature on the Texas-Louisiana shelf. Institute of Applied Geosciences Texas A&M University, College Station. 51 pp.

Fable, W.A., Jr. 1979. Environmental studies of the south Texas outer continental shelf. Snapper/grouper. National Marine Fisheries Service. Southeast Fisheries Service. Panama City, Fla. 23 pp.

Farrell, D.H. 1979. Benthic mollusca and crustacean communities in Louisiana. Pages 401-436 in C.H. Ward, M.E. Bender and D.J. Reish, eds. Effects of oil drilling and production in a coastal environment. Rice Univ. Stud. 65 (4 & 5). 589 pp.

Fast, D.E. and F.A. Pagan. 1974. Comparative observations on an artificial tire reef and natural patch reef off southwestern Puerto Rico. Pages 49-50 in R. Stone and L. Colunga, eds. Proceedings of an international conference on artificial reefs. Houston, Tex. 20-22 March 1974. TAMU SG-74-103. 151 pp.

Fish, A.G., L.L. Massey, J.R. Inabinet and P.L. Lewis. 1979. A study of the effects of environmental factors upon the distribution of selected sandy beach organisms of Timbalier Bay, Louisiana. Gulf Universities Research Consortium. Appendix to report 138.

Flint, R.W. 1979. Ecology of the Texas Gulf of Mexico shelf. Pages 123-146 in P.L. Fore and R.D. Peterson, eds. Proceedings Gulf of Mexico coastal ecosystems workshop. U.S. Fish and Wildlife Service. FWS/OBS-80/30.

Fotheringham, N. and G. Weissberg. 1979. Some causes, consequences and potential impacts of oxygen depletion in the northern Gulf of Mexico. Offshore Tech. Conf. Proc., OTC 3611:2205-2207.

Fredericks, A.D. and W.M. Sackett. 1970. Organic carbon in the Gulf of Mexico. J. Geophys. Res. 75:2199-2206.

Fucik, K.W. and S.Z. El-Sayed. 1979. Effect of oil production and drilling operations on the ecology of phytoplankton in the OEI study area. Pages 325-354 in C.H. Ward, M.E. Bender and D.J. Reish, eds. Effects of oil drilling and production in a coastal environment. Rice Univ. Stud. 65 (4 & 5). 589 pp.

Gallaway, B.J. and F.J. Margraf. 1978. Simulation modeling of biological communities associated with a production platform in the Buccaneer Oil and Gas Field. Annual report to National Marine Fisheries Service, Galveston, Texas. LGL Limited-U.S., Inc., Bryan, Tex. 58 pp.

Gallaway, B.J. and L.R. Martin. 1980. Pelagic reef, and demersal fishes and macrocrustaceans. In W.B. Jackson and P. Wilkins, eds. Environmental assessment of an active oil field in the northwestern Gulf of Mexico. Volume 4: Biological investigations. NOAA annual report to EPA. Project EPA-IAG-DS-E693-EO.

Gallaway, B.J. and L.A. Reitsema. 1980. Shrimp and redfish studies in relation to Bryan Mound brine disposal site off Freeport, Texas, spawning site survey. Draft final report to National Marine Fisheries Service from LGL Ecological Research Associates, Inc. December. Bryan, Tex.

Gallaway, B.J. and K.S. Strawn. 1974. Seasonal abundance and distribution of fishes at a hot water discharge in Galveston Bay. Texas Contrib. Mar. Sci. 18:71-137.

Gallaway, B.J., M.F. Johnson, R.L. Howard, L.R. Martin and G.S. Boland. 1979. A study of the effects of Buccaneer oil field structures and associated effluents on biofouling communities and the Atlantic spadefish (Chaetodipterus faber) . Annual report to National Marine Fisheries Service, Galveston, Texas. LGL Limited-U.S., Inc., Bryan, Tex. 126 pp.

Gallaway, B.J., L.R. Martin, R.L. Howard, G.S. Boland and G.D. Dennis. 1980. A case study of the effects of gas and oil production on artificial reef and demersal fish and macrocrustacean communities in the northwestern Gulf of Mexico. Expo Chem 1980, Houston, Tex.

Garlo, E.V., C.B. Milstein and A.E. Jahn. 1979. Impact of hypoxic conditions in the vicinity of Little Egg Inlet, New Jersey in summer 1976. Estuarine Coastal Mar. Sci. 8:421-432.

George, R.Y. and P.J. Thomas. 1974. Aspects of fouling on offshore oil platforms in Louisiana shelf in relation to environmental impact. Final report, Offshore Ecological Investigations, Gulf Universities Research Consortium. 54 pp.

Gettleson, D.A. 1980. Effects of oil and gas drilling operations on the marine environment. In Marine pollution. Pergamon Press. In press.

Gettleson, D.A. and C.E. Laird. 1980. Benthic barium levels in the vicinity of six drill sites in the Gulf of Mexico. Pages 739-785 in R.C. Ayers, N.L. Richards and J.R. Gould. Proceedings of a symposium. Research on environmental fate and effects of drilling fluids and cuttings. Washington, D.C. 1,122 pp.

Gilles, R.C., L.R. Brown and C.D. Minchew. 1978. Bacteriological aspects of fin erosion in mullet exposed to crude oil. J. Fish. Biol. 13:113-117.

GMFMC, Gulf of Mexico Fishery Management Council. 1980a. Fishery management plan and proposed regulations for the shrimp fishery of the Gulf of Mexico, United States waters. Federal Register 45(218):74178-74308.

GMFMC, Gulf of Mexico Fishery Management Council. 1980b. Draft environmental impact statement and fishery management plan and regulatory analysis and proposed regulations, reef fish resources of the Gulf of Mexico. Report to Environmental Protection Agency, Washington, D.C. 147 pp.

Grady, J.R. 1970. Distribution of sediment types: northern Gulf of Mexico. NOAA Nat. Mar. Fish. Serv. Biol. Lab., Galveston, Tex. Map. 1 p.

Griffin, G.M. 1979. Evaluation of the effects of oil production platforms on the turbidity of Louisiana shelf waters. Pages 159-180 in C.H. Ward, M.E. Bender and D.J. Reish, eds. Effects of oil drilling and production in a coastal environment. Rice Univ. Stud. 65 (4 & 5). 589 pp.

Gunter, G. 1938. Seasonal variations in abundance of certain estuarine and marine fishes in Louisiana, with particular reference to life histories. Ecol. Monogr. 8:313-346.

Gunter, G. 1945. Studies on marine fishes. Publ. Inst. Mar. Sci., Univ. Tex. 1:1-190.

Gunter, G.G. 1952. Historical changes in the Mississippi River and the adjacent marine environment. Publ. Inst. Mar. Sci. 11(2):120-139.

Gunter, G.G. 1967. Some relationships of estuaries to the fisheries of the Gulf of Mexico. Pages 621-638 in G.H. Lauff, ed. Estuaries. Publ. 83. American Association for the Advancement of Science, Washington, D.C.

Harding, J.L. and W.D. Nowlin. 1966. Gulf of Mexico. Pages 324-331 in R.W. Fairbridge, ed. The encyclopedia of oceanography. Reinhold, New York.

Harper, D.E., Jr. and L.D. McKinney. 1980. Chapter V. Benthos. Pages 5-1 to 5-79 in R.W. Hann, Jr. and R.E. Randall, eds. Evaluation of brine disposal from the Bryan Mound site of the Strategic Petroleum Reserve Program. Final report of predisposal studies. Volume 1. Texas A&M University and A&M Research Foundation, College Station.

Harris, J.E. and W.M. Sackett. 1970. Spatial distribution of suspended matter in the Gulf of Mexico. Am. Geophys. Union Annu. Meeting.

Hazelton Environmental Sciences Corporation. 1980. Currents and hydrography. In W.B. Jackson and P. Wilkins, eds. Environmental assessment of an active oil field in the northwestern Gulf of Mexico 1978-1979. Volume 7: Chemical and physical investigations. NOAA annual report to EPA, Project EPA-IAG-DS-E693-EO.

Hedgpeth, J.W. 1954. An introduction to the zoogeography of the northwestern Gulf of Mexico with reference to the invertebrate fauna. Publ. Inst. Mar. Sci. Univ. Tex. 3:104-224.

Hildebrand, H.H. 1954. A study of the fauna of the brown shrimp, Penaeus aztecus Ives, grounds in the western Gulf of Mexico. Publ. Inst. Mar. Sci. Univ. Tex. 3:229-366.

Hildebrand, H.H. 1955. A study of the fauna of the pink shrimp, Penaeus duorarum Burkenroad, grounds in the Gulf of Campeche. Publ. Inst. Mar. Sci. Univ. Tex. 4:169-232.

Holland, J.S., J. Holt, S. Holt, R. Kalke and N. Rabalais. 1980. Benthic invertebrates, macroinfauna and epifauna. Chapter 13 in R.W. Flint and N.N. Rabalais, eds. Environmental studies, south Texas outer continental shelf, 1975-1977. Volume 3: Final report to the BLM by the University of Texas Marine Science Institute. Port Aransas, Tex.

Howard, R.L., G.S. Boland, B.J. Gallaway and G.D. Dennis. 1980. Effects of gas and oil field structures and effluents on fouling community production and function. In W.B. Jackson and P. Wilkins, eds. Environmental assessment of an active oil field in the northwestern Gulf of Mexico. Volume 6: Biological investigations. NOAA annual report to EPA, Project EPA-IAG-DS-E693-EO.

Hudson, J.H. and D.M. Robbin. 1980. Effects of drilling mud on the growth rate of the reef-building coral, Montastraea annularis . Pages 1101-1119 in R.C. Ayers, N.L. Richards and J.R. Gould. Proceedings of a symposium. Research on environmental fate and effects of drilling fluids and cuttings. Washington, D.C.

Jackson, J.R. 1979. Petroleum information package-compiled for American Petroleum Institute Exxon Co. U.S.A., Houston, Tex. Unpubl. collect.

Jacobs, M.B. and M. Ewing. 1969. Suspended particulate matter:concentration in the major oceans. Science 163:380-384.

Kamykowski, D.L., C. Van Baalen and W. Pulich. 1976. Phytoplankton and productivity project. Third quarterly report. Chemical and biological survey component of the environmental assessment of the south Texas outer continental shelf. University of Texas Marine Science Institute, Port Aransas. 760 pp.

Kana, T.W. and L. Thebeau. 1980. Draft Burmuh Agate report. Final report to NOAA/OMPA, Contract No. NA79 RAC 00033. Columbia, S.C.:RPI.

Kimsey, J.B. 1963. Currents on the continental shelf of the northwestern Gulf of Mexico. Annual report. Fiscal year 1963 of the Fishery Research Biological Laboratory, Galveston, Tex.

Kimsey, J.B. and R.F. Temple. 1962. Currents on the continental shelf of the northwestern Gulf of Mexico. Annual report. Fiscal year 1962 of the Fishery Research Biological Laboratory, Galveston, Tex.

Klima, E.F. (undated manuscript). The National Marine Fisheries Service shrimp research program in the Gulf of Mexico. Southeast Fisheries Center, Galveston, Tex. 12 pp.

Koons, C.B., C.D. McAuliffe and F.T. Weiss. 1977. Environmental aspects of produced waters from oil and gas extraction operations in offshore and coastal waters. J. Petrol. Technol. 29:723-729.

Lees, D.C. and J.P. Houghton. 1980. Effects of drilling fluids on benthic communities at the Lower Cook Inlet C.O.S.T. Well. Pages 309-346 in R.C. Ayers, N.L. Richards and J.R. Gould. Proceedings of a symposium. Research on environmental fate and effects of drilling fluids and cuttings. Washington, D.C. 1,122 pp.

Mackin, J.G. and S.H. Hopkins. 1962. Studies on oyster mortality in relation to natural environments and to oil fields in Louisiana. Publ. Inst. Mar. Sci. Univ. Tex. 7:1-131.

Marum, J.P. 1979. Significance of distribution patterns of planktonic copepods in Louisiana coastal waters and relationships to oil drilling and production. Pages 355-378 in C.H. Ward, M.E. Bender and D.J. Reish, eds. Effects of oil drilling and production in a coastal environment. Rice Univ. Stud. 65 (4 & 5). 589 pp.

McAuliffe, C.D. 1977. Dispersal and alteration of oil discharged on a water surface. Pages 19-35 in D.A. Wolfe, ed. Fate and effects of petroleum hydrocarbons in marine ecosystems and organisms. Pergamon Press, Inc., New York.

Michael, A.D. 1979. A "worst case" situation. In Oil and the sea. American Petroleum Institute, Washington, D.C. 23 pp.

Middleditch, B.S. and D.L. West. 1980. Hydrocarbons, biocides and sulfur. In W.B. Jackson and P. Wilkins, eds. Environmental assessment of an active oil field in the northwestern Gulf of Mexico. Volume 8: Chemical and physical investigations. NOAA annual report to EPA. Project EPA-IAG-DS-E693-EO.

Miliekovsky, S.A. 1971. Types of larval development in marine bottom invertebrates. Mar. Biol. 10:193-213.

Miller, D.K. 1976. A case study of special biological requirements, Mustang Island Block A-16, Lease OCS-G-3011, Well No. 1. A report for Cities Service Company. Tulsa, Okla.

Miller, R.J. 1959. A review of the seabasses of the genus Centropristes (Serranidae). Tulane Stud. Zool. 7:35-68.

Minchew, C.D. and J.D. Yarbrough. 1977. The occurrence of fin rot in mullet (Mugil cephalus) associated with crude oil contamination of an estuarine pond-ecosystem. J. Fish. Biol. 10:319-323.

Moore, G.T. 1973. Submarine current measurements, northwest Gulf of Mexico. Trans. Gulf Coast Assoc. Geol. Soc. 23:245-255.

Mumphrey, A.J. and G.D. Carlucci, Jr. 1978. Environmental planning for offshore oil and gas. Volume 5: Regional Status Report Part 3: Gulf Coast. U.S. Fish and Wildlife Service, Biological Services, Washington, D.C.

National Academy of Sciences. 1975. Petroleum in the marine environment. Report of a workshop on inputs, fates, and effects of petroleum in the marine environment. Washington, D.C.

Nichoul, J.C., ed. 1975. Modeling of marine systems. Elsevier Scientific, New York.

Oetking, P., R. Back, R. Watson and C. Merks. 1979. Physical studies of the near-shore continental shelf of south central Louisiana: currents and hydrography. Pages 119-144 in C.H. Ward, M.E. Bender and D.J. Reish, eds. Effects of oil drilling and production in a coastal environment. Rice Univ. Stud. 65 (4 & 5). 589 pp.

Offshore Operators Committee. 1978. Comments on U.S. Environmental Protection Agency Draft Document, "Permit conditions for NPDES permits at the Flower Garden Reefs, Gulf of Mexico, Outer Continental Shelf - August, 1978." Submitted to U.S. EPA Region VI.

Osborne, K.W., B.W. Maghan and S.B. Drummond. 1969. Gulf of Mexico shrimp atlas. U.S. Fish. Wildl. Serv. Circ. 312. 20 pp.

Park, E.T. 1976. Zooplankton project, third quarterly report. Chemical and biological survey component of the environmental assessment of the south Texas outer continental shelf. University of Texas, Marine Science Institute, Port Aransas. 760 pp.

Parker, R.H. 1960. Ecology and distributional pattern of marine invertebrates, northern Gulf of Mexico. Pages 203-337 in F.P. Shepard, F.B. Phleger and T.H. van Andel, eds. Recent sediments, northwest Gulf of Mexico. American Association of Petroleum Geologists.

Pearse, A.S. and G. Gunter. 1957. Salinity. Pages 129-157 in J.W. Hedgpeth, ed. Treatise on marine ecology and paleoecology. Geol. Soc. Am. Mem. 67.

Pequegnat, W.E. 1973. Western gulf hydrobiological zones. A.D. Little, Inc. Final report to U.S. Corps of Engineers, contract DACW-38-73-C-0027. U.S. Dept. Army, Vicksburg Distr. Corps Eng., Vicksburg, Miss. 146 pp.

Pequegnat, W.E. 1976. Ecological aspects of the upper continental slope of the Gulf of Mexico. Report prepared for the Bureau of Land Management for contract 08550-CT4-12. 305 pp.

Perry, A. 1974. A bottom/surface trawl and bottom grab study of areas of no production activity and areas of no activity in estuarine and offshore environments. Effect of platforms on biota (fishes) offshore. Gulf Universities Research Consortium. Appendix to Rep. 138.

Presley, B.J., J.H. Trefry and R.F. Shokes. 1980. Heavy metal inputs to Mississippi Delta sediments. Water Air Soil Pollut. 13(4):481-494.

Pulley, T.E. 1952. A zoogeographic study based on the bivalves of the Gulf of Mexico. Ph.D. Thesis. Harvard University, Cambridge, Mass.

Ragan, J.G., A.H. Harris and J.H. Green. 1978. Temperature, salinity and oxygen measurements of surface and bottom waters on the continental shelf off Louisiana during portions of 1975 and 1976. Prof. Paper Ser. (Biol.) 3. Nicholls State Univ., Thibodeaux, La. 29 pp.

Ray, J.R. and E.A. Shinn. 1975. Environmental effects of drilling muds and cuttings. Pages 533-550 in Conference proceedings on environmental aspects of chemical use in well-drilling operations. U.S. Environmental Protection Agency, EPA-560/1-75-004.

Reitsema, L.A. 1980. Biological/chemical survey of Texoma and Capline sector salt dome brine disposal sites off Louisiana, 1978-1979. Volume 2: Zooplankton. NOAA technical memorandum. NMFS-SEFC-16. 133 pp.

Richards, F.A. 1954. Oxygen in the ocean. Pages 185-238 in J.W. Hedgpeth, ed. Treatise on marine ecology and paleoecology. Geol. Soc. Am. Mem. 67(1).

Robins, C.R. 1971. Distributional patterns of fishes from coastal and shelf waters of the tropical Western Atlantic. Pages 249-255 in Symposium on investigations and resources of the Caribbean Sea and adjacent regions. Pap. Fish. Resource. FAO Fish. Rep. 71.2 FAO, Rome.

Rogers, R.M. 1977. Trophic interrelationships of selected fishes on the continental shelf of the northern Gulf of Mexico. Ph.D. Dissertation. Texas A&M University, College Station. 229 pp.

Sarukhan, J. 1979. Demographic problems in tropical systems. In O.T. Solbrig, ed. Demography and evolution in plant populations. Oxford-Blackwell Scientific Publication.

Sharp, J.M. 1979. The cumulative effects of petroleum drilling and production in coastal and near-shore areas. Pages 3-15 in C.H. Ward, M.E. Bender and D.J. Reish, eds. The Offshore Ecology Investigation, Rice University Studies, Rice University, Houston, Tex. 589 pp.

Shinn, E.A. 1974. Oil structures as artificial reefs. Pages 91-96 in L. Colunga and R. Stone, eds. Proceedings of an international conference on artificial reefs. Center for Marine Resources, Texas A&M University, College Station.

Shinn, E.A. 1975. Effects of oil field brine, drilling mud, cuttings and oil platforms on the offshore environment. Pages 243-255 in Marine environmental implications of offshore oil and gas development in the Baltimore Canyon region of the Mid-Atlantic coast. Estuarine Research Federation 75-1.

Smith, N.P. 1980. Hydrograhic project. Chapter 2, in R.W. Flint and N.N. Rebalais, eds. Environmental studies, south Texas outer continental shelf, 1975-1977. Volume 3: Study area final reports. University of Texas Marine Science Institute, Port Aransas. 648 pp.

Sonnier, F., J. Teerling and H.D. Hoese. 1976. Observations on the offshore reef and platform fish fauna of Louisiana. Copeia 1976:105-111.

Springer, S. and H.R. Bullis. 1954. Exploratory shrimp fishing in the Gulf of Mexico. Summary report for 1952-54. Comm. Fish. Rev. 16(10):1-16.

Steele, J.H. 1974. The structure of marine ecosystems. Harvard University Press, Cambridge, Mass. 128 pp.

Teal, J.M. 1977. Food chain transfer of hydrocarbons. Pages 71-77 in D.A. Wolfe, ed. Fate and effects of petroleum hydrocarbons in marine ecosystems and organisms. Pergamon Press, Inc., New York.

Temple, R.F., D.L. Harrington and J.A. Martin. 1977. Monthly temperature and salinity measurements of waters of the northwestern Gulf of Mexico, 1963-65. NOAA Tech. Rep. NMFS 55RF-707. 26 pp.

Thorson, G. 1966. Some factors influencing the recruitment of marine benthic communities. Neth. J. Sea Res. 3:267-293.

Tillery, J.B. 1980. Trace metals. In W.B. Jackson and P. Wilkins, eds. Environmental assessment of an active oil field in the northwestern Gulf of Mexico. Volume 9: Chemical and physical investigations. NOAA annual report to EPA, Project EPA-IAG-DS-E693-EO.

Topp, R.W. and F.H. Hoff. 1972. Flatfishes (Pleuronectiformes). Fla. Dept. Nat. Resources, Mem. Hourglass Cruises. Volume 4. Pt. 2:1-135.

Uchupi, E. 1967. Bathymetry of the Gulf of Mexico. Trans. Gulf Coast Assoc. Geol. Soc. 17:161-172.

U.S. Army Corps of Engineers. 1973. Crude oil and natural gas production and other mining operations in navigable waters along the Louisiana coast. U.S. Corps of Engineers, Army Engineer District, New Orleans, La. 403 pp.

Waller, R.S. 1979. Pelagic, epibenthic, and infaunal invertebrates of Timbalier Bay and offshore environment. Pages 529-536 in C.H. Ward, M.E. Bender and D.J. Reish, eds. Effects of oil drilling and production in a coastal environment. Rice Univ. Stud. 65 (4 & 5). 589 pp.

Ward, C.H., M.E. Bender and D.J. Reish. 1979. Effects of oil drilling and production in a coastal environment. Rice Univ. Stud. 65 (4 & 5). 589 pp.

Williams, A.B. 1958. Substrates as a factor in shrimp distribution. Limnol. Oceanogr. 3:283-290.

Workman, I.K. and C.E. Jones. 1979. Determine effects of oil field discharges on species composition and abundance of pelagic fishes and demersal fishes and macrocrustaceans in the oil field. In W.B. Jackson, ed. Environmental assessment of an active oil field in the northwestern Gulf of Mexico, 1977-1978. NOAA annual report to EPA. Project EPA-IAG-DS-E693-EO. NTIS accession PB80165970.

Zein-Eldin, Z.P. and P.M. Keney. 1979. Crustacean and fish bioassays. Pages 2.3.4-1 to 2.3.4-25. In W.B. Jackson, ed. Environmental assessment of an active oil field in the northwestern Gulf of Mexico, 1977-1978. Volume 2: Data management and biological investigations. NOAA annual report to EPA. Project EPA-IAG-DS-E693-EO. NTIS accession PB80165970.

Zingula, R.P. 1975. Effects of drilling operations on the marine environment. Pages 433-450 in Proceedings of a conference on environmental aspects of chemical use in well-drilling operations. U.S. Environmental Protection Agency, EPA-560/1-75-004.

Zingula, R.P. and D.W. Larsen. 1977. Fate of drill cuttings in the marine environment. Offshore Technology Conference, Paper 3040:553-556.

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. FWS/OBS-81/27	2.	3. Recipient's Accession No.

4. Title and Subtitle
An Ecosystem Analysis of Oil and Gas Development on the Texas-Louisiana Continental Shelf

5. Report Date
August 1981

6.

7. Author(s)
Benny J. Gallaway

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
LGL Ecological Research Associates, Inc.
1410 Cavitt Street
Bryan, Texas 77801

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.
(C) 14-16-0009-80-058
(G)

12. Sponsoring Organization Name and Address
U.S. Fish & Wildlife Service and Bureau of Land Management
Office of Biological Services Branch of Offshore Studies
U.S. Department of the Interior
Washington, D.C. 20240

13. Type of Report & Period Covered

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

The Texas-Louisiana shelf ecosystem in the Gulf of Mexico is described in terms of its physiographic, oceanographic, and biological characteristics and as a recipient of oil and gas development activities and effluents. The northeast sector of the ecosystem is influenced by Mississippi River discharge, whereas high-salinity Caribbean water affects the southwest sector. Soft-bottom communities are prominent, characterized by economically valuable penaeid shrimps. The coral reef communities are more important than would normally be assumed. Pelagic communities are little known and harbor only a few commercially valuable species. It is surmised that much of the primary productivity from the pelagic community is used by the benthic communities.

Observed effects of oil and gas development activities and effluents are described. Data from most field studies indicate that direct effects are limited in space, but the effects over time are unknown. Particular concern is expressed relative to increased organic loading of the system and the apparently related low dissolved oxygen levels characteristic of specific sites during warm seasons. Future research should be directed towards defining key processes governing the ecosystem, with modeling workshops serving as the focus for these research and monitoring programs.

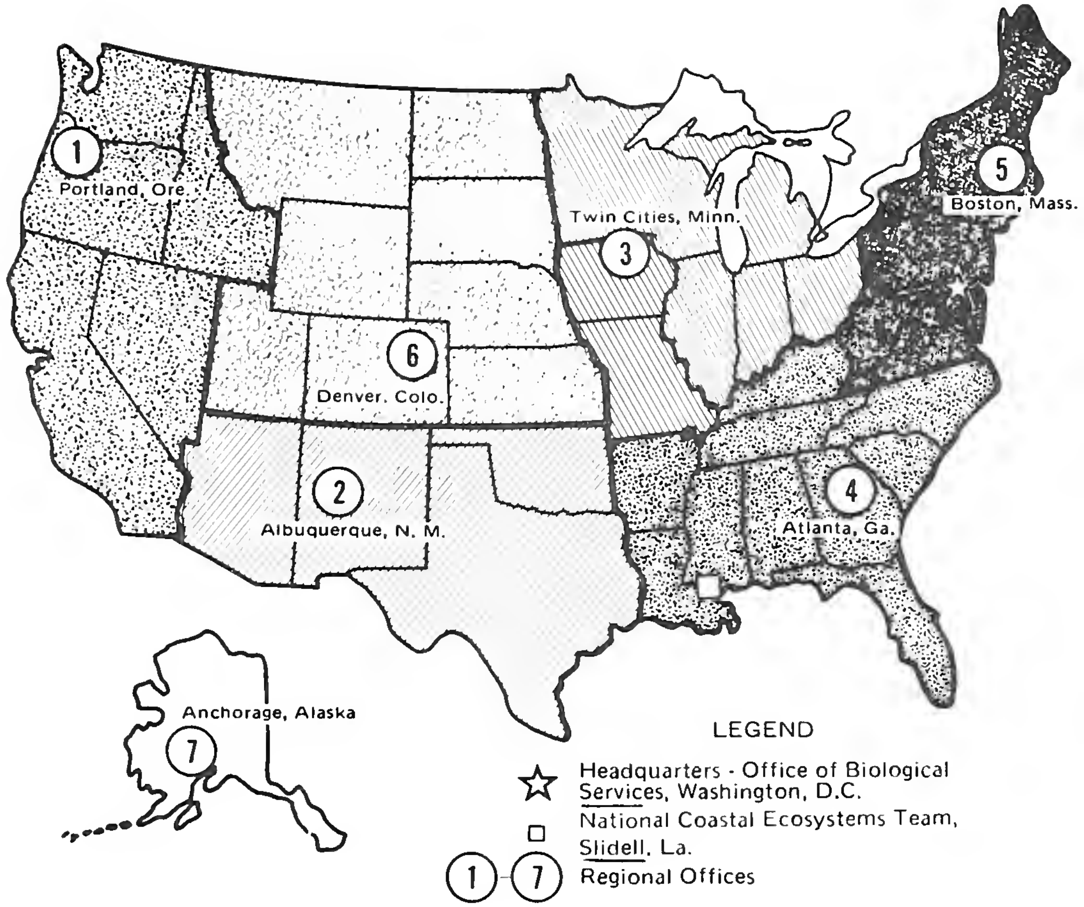
17. Document Analysis a. Descriptors

Continental shelves, Offshore drilling, Shrimps, Aquatic biology, Salinity, Water pollution

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

18. Availability Statement Unlimited	19. Security Class (This Report) Unclassified	21. No. of Pages 97
	20. Security Class (This Page)	22. Price



U.S. FISH AND WILDLIFE SERVICE
REGIONAL OFFICES

REGION 1
Regional Director
U.S. Fish and Wildlife Service
Lloyd Five Hundred Building, Suite 1692
500 N.E. Multnomah Street
Portland, Oregon 97232

REGION 2
Regional Director
U.S. Fish and Wildlife Service
P.O. Box 1306
Albuquerque, New Mexico 87103

REGION 3
Regional Director
U.S. Fish and Wildlife Service
Federal Building, Fort Snelling
Twin Cities, Minnesota 55111

REGION 4
Regional Director
U.S. Fish and Wildlife Service
Richard B. Russell Building
75 Spring Street, S.W.
Atlanta, Georgia 30303

REGION 5
Regional Director
U.S. Fish and Wildlife Service
One Gateway Center
Newton Corner, Massachusetts 02158

REGION 6
Regional Director
U.S. Fish and Wildlife Service
P.O. Box 25486
Denver Federal Center
Denver, Colorado 80225

REGION 7
Regional Director
U.S. Fish and Wildlife Service
1011 E. Tudor Road
Anchorage, Alaska 99503

DEPARTMENT OF THE INTERIOR
U.S. FISH AND WILDLIFE SERVICE