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ENVIRONMENTAL RESEARCH NEEDS IN THE GULF OF MEXICO (GOMEX)

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GULF OF MEXICO WETLANDS:

VALUE, STATE OF KNOWLEDGE AND RESEARCH NEEDS

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ABSTRACT

We present a brief overview of the distribution and functional role of coastal wetlands along the northern Gulf of Mexico and discuss some of the research needs on these habitats. Because of the large degree of variability, both within and between wetland habitats, this paper is not meant to be a detailed accounting of our state-of-knowledge of these systems. It is evident, however, that tidal marshes, mangrove forests, and seagrass meadows, possess characteristics common to one another that are significant to the functioning of adjacent areas, and that many "black boxes" and data gaps exist in our knowledge of Gulf coast wetlands.

Approximately 50% of the commercial and recreational fishes in the Gulf and 80-90% of the fishery landings are estuarine-dependent. Coastal wetlands provide habitats and food resources that make estuarine-nearshore zones vital spawning, nursery and feeding areas for aquatic species. Although there is a great deal of information on plant species in Gulf wetlands, little quantitative data exist on mixed species communities and submergent species and on the factors regulating growth and production of most wetland plants. There is a general paucity of quantitative data on the abundance and distribution of faunal components, including forage species and meiofauna, and on growth and mortality rates of juvenile fishes, age-specific utilization, and resource partitioning within wetland habitats. One of the most important, yet poorly understood, aspects of wetland ecology is the production, decomposition, utilization, and export of detrital material from Gulf wetlands. When one considers that about 75% of the total plant production in Gulf estuarine-wetland areas is derived from macrophytes, the importance of developing a sound information base on the decomposition process is obvious. Intensive long-term studies on a few systems and extensive short-term studies on many systems on a regional basis within the Gulf are needed to understand natural variability among organisms and their habitats, as well as the range of conditions and variability of wetland ecosystems.

1. INTRODUCTION

Along the Gulf of Mexico, approximately 48% of the 103 species of finfish and shellfish that make up the bulk of the commercial fishery organisms and 45% of the 60 recreational finfish species are estuarine-dependent. These estuarine-dependent species, however, compose 90-97% of the commercial landings biomass (McHugh, 1976; Lindall and Saloman, 1977) and 80% of the recreational biomass in the Gulf of Mexico (McHugh, 1976). Gulf menhaden, penaeid shrimp, blue crabs, and mullet compose about 86% of the estuarine-dependent commercial poundage, while spotted seatrout, red drum, sand seatrout, tarpon, and black drum make up about 80% of the recreational fishery biomass.

There is a scientific basis for this estuarine-wetland dependency. Included in our definition of estuarine-dependent organisms are those that live totally within estuaries, use them as breeding or nursery grounds, or move into estuaries seasonally for extended periods to feed (McHugh, 1976). These coastal estuaries and wetlands provide habitat and food resources that make the estuarine-nearshore coastal zone a vital spawning, nursery, or feeding ground for aquatic organisms; they also provide avenues for migration of anadromous and catadromous species.

Marine fisheries habitats comprise riverine, estuarine-nearshore, and continental shelf zones that are integrally linked through flowing water, cycling of nutrients, and production of organic matter. In regions where estuaries are small or few in number, but where rich fisheries exist, such as on Georges Bank or along the Gulf of California, upwelling and turbulence provide an abundance of nutrients that result in high levels of phytoplankton. This phytoplankton-based food web leads primarily to a high-level carnivorous fishery community. Upwelling, however, is not a predominant phenomenon along the Gulf coast; rich fisheries do exist there and have been correlated with wetland areas.

Where estuarine systems are well developed, they abound in living resources year-round. In regions rich in estuaries and wetlands such as the Gulf of Mexico, phytoplankton production is complemented by estuarine-produced detrital material from marshes, mangroves and seagrasses. In fact, total macrophyte production represents an estimated 75% of the total plant production in the estuarine-wetland complex of the Gulf coast. The energy produced by these wetland and phytoplankton organisms leads to a detritus-omnivorous based fishery community, having only a small top-level resident carnivore component.

The purpose of this paper is to review briefly the value of wetland habitat types in the Gulf of Mexico and research needs in wetland ecology. The wetland habitat types selected, i.e., marshes, mangroves, and seagrasses, have characteristics common to one another that are significant to the functioning of adjacent areas. We will not concern ourselves with waterfowl and furbearing organisms that utilize these systems; this subject has been the concern of several reviews (e.g., Palmisano, 1973). Ours is by no means an in-depth review; rather, we provide an overview of the function and value of coastal wetlands from both quantitative and qualitative studies throughout the U.S., with an emphasis on the Gulf of Mexico. This approach is necessitated not only by the enormity of the subject, but also by the extensiveness of available information on certain aspects of Gulf wetlands. Nevertheless, there is a paucity of information on many aspects of wetland ecology in the Gulf (particularly on synthesis aspects), some of which have been documented and synthesized for similar systems elsewhere. In fact, members of Federal agencies responsible for commenting on permit proposals and environmental impact statements have indicated that in many instances they are dependent upon ecological information derived from non-Gulf research because data for the Gulf are either nonexistent, too site-specific, or too widely scattered (and unsynthesized) in the scientific literature. The establishment of a general overview of the value of these habitat types provides a stronger framework from which to discuss research needs.

2. GENERAL DESCRIPTION OF GULF WETLAND HABITATS AND PLANT SPECIES

The Gulf of Mexico estuarine area is the largest in the United States, excluding that of Alaska, with 207 estuaries. The total open-water area of estuaries at mean high water is about 7.9 x 10^6 acres with a volume of 57.9 x 10^6 acre-ft (Lindall and Saloman, 1977). Louisiana contains 43%, Florida 26%, Texas 19%, Mississippi 6%, and Alabama 5% of the acreage (Fig. 1A). The entire region is dominated by warm subtropical waters and generally small tidal ranges. From Apalachee Bay, Florida, southward tides range from 0.6 to 1.2 m, while to the west, tidal amplitude generally is < 0.6 m (Brooks, 1973; Christmas, 1973; Diener, 1975). Heavy rainfall over much of the area (except south Texas) brings sediment from a broad coastal plain, resulting in generally high turbidity estuaries with predominantly terrigenous sediments.

The 15.5 x 10^3 mi shoreline of the Gulf is dominated by tidal marshes, mangroves and submergent seagrass beds. Coastal marshes and mangroves form an interface between marine and terrestrial habitats, while seagrass beds occupy a transition zone between emergent vegetation and unvegetated estuarine and coastal bottoms. These habitats may occupy narrow bands or vast expanses and can consist of sharply delineated zones of different species, monotonous stands of a single species, or mixed plant species communities.

The total area of tidal marsh along the Gulf coast is about 6 x 10^6 acres, or 63% of the tidal marshes in the United States (Lindall and Saloman, 1977). Louisiana contains most of the Gulf's tidal marsh (64%), followed by Texas (16%), Florida (9%), Mississippi (1%), and Alabama (0.6%) (Fig. 1B). This habitat is probably the most intensively and extensively studied wetland type in the Gulf.

The number of plant species that comprise marsh communities is large and varied. For example, in a Mississippi marsh, Gabriel and de la Cruz (1974) identified 34 species, and this did not represent the entire flora of the marsh. On the Gulf coast of Florida, *Spartina alterniflora* (smooth cordgrass) is the dominant species and occurs from mean sea level up to the level of the highest predicted tide (Humm, 1973). *Juncus roemerianus* (black needlerush) represents about 28% of the Florida Gulf marshes and dominates the zone just landward of Spartina. Distichlis spicata and S. patens occur above the high tide line. Along the coasts of Mississippi and Alabama, Juncus represents 92% and 52%, respectively, of the total marsh (Eleuterius, 1976); S. alterniflora, S. cynosuroides, S. patens, and D. spicata also are present. The dominance by Juncus may be attributed to the outflow of large quantities of freshwater and to raised marsh levels in these areas (Crance, 1971; Eleuterius, 1973). Brackish water marshes dominated by S. patens represent about 45% of the tidal marshes in Louisiana, while marshes dominated by S. alterniflora at low elevations and grading into Salicornia sp. and Juncus represent about 30% (Perret et al., 1971). Along the Texas coast, the best developed marshes are in the Sabine Lake and Galveston Bay areas and are dominated by S. alterniflora and S. patens.

Mangrove communities generally are restricted to a lower temperature limit of -4°C and are conspicuous coastal wetland elements below 25°N latitude. There are an estimated 4.5 x 10^5 acres of mangroves along the Gulf coast, the largest proportion occurring in Florida (Fig. 1C); the 10,000 islands area of Florida shows the best development of mangroves. Four species are native to the United States: red (Rhizophora mangle), black (Avicennia germinans), and white (Laguncularia racemosa) mangroves, and buttonwood (Conocarpus erectus). Only black mangroves are continuous from the Dry Tortugas to the islands of the Mississippi Delta (Humm, 1973) and also occur in Texas (Duncan, 1974). Mangroves exhibit a zonation of species, with reds generally found in deepest waters along shorelines; landward are black mangroves and buttonwoods. White mangroves are the least abundant species and generally grow landward of black mangroves (McNulty et al., 1972). Factors involved in zonation are disputed, but are considered to be the degree and duration of inundation and the soil and water salinity (Lugo and Snedaker, 1974).

There are an estimated 8 x 10^5 acres of submergent seagrasses within Gulf estuaries, approximately 95% of which are found in Florida and Texas (Fig. 1D) where they occupy about 20% of the bay bottoms. Although often considered continuous around the entire periphery of the Gulf, a combination of low salinity and high turbidity results in only narrow bands or scattered patches from Louisiana to Copano-Aransas, Texas; in the Louisiana area, grass beds are well developed around the Chandeleur and Breton Islands. Six species occur in the Gulf: Thalassia testudiunum, Halodule wrightii, H. beaudettei, Syringodium filiforme, Halophila engelmanni, and Halophila baillonis. Ruppia maritima, which generally is not included in lists of true seagrasses and has its best growth at low salinities, has been reported for all Gulf coast states. Seagrasses display vertical zonation, with Halodule able to penetrate into the intertidal zone, and Thalassia, Syringodium, and Halophila from the low-water spring tide level. While Thalassia is the most abundant Gulf submergent, Halodule predominates in Mississippi and Alabama, and Ruppia predominates in Louisiana waters. Light, salinity, temperature, substrate type, and currents are locally important factors that affect distributional patterns (Ferguson, Thayer and Rice, In press).

3. A FUNCTIONAL VIEW OF GULF COAST WETLANDS

This section is a modification of a review that we recently published on the value of marine coastal wetlands (Thayer et al., 1979), which did not emphasize any one geographic area. Our modification will emphasize Gulf coast systems.

Although extensive information exists on tidal marsh and mangrove plant species structure and distribution in the Gulf and on commercial species such as shrimp, quantitative studies on the distribution and abundance of submergent plants and on wetland infauna and fishes are scarce. Our understanding of the function of these ecosystems has only recently received significant consideration; this appears to be the result of a continued and increased multiplicity of demands being placed on these habitats. Wood, Odum, and Zieman (1969) presented a scheme describing the functional role of seagrasses that can equally apply to marshes and mangroves:

1. Organic productivity is relatively high, and for some species, it rivals or often exceeds that of subsidized agricultural crops.

2. There are high standing crops, and few organisms feed directly on the plant. As a result, wetlands produce large quantities of detritus, which play a major role in the dynamics of the particular system and the estuary of which they are a part.

3. Leaves, stems, and prop roots present surfaces for epibiotic organisms. This increases both the primary and secondary productivity of the habitat, and the epibiota may be significant food sources for fish and invertebrates.

4. Roots, stems, and leaves reduce current velocity, thus promoting sedimentation of both inorganic and organic matter. Entrained allochthonous and autochthonous material decomposes, thus recycling nutrients within the system.

5. The root system generally binds sediments and retards erosion.

6. The presence of above-substrate vegetation and lateral zonation presents a wide variety of habitats for protection and growth of fish, birds, and invertebrates.

3.1 Primary Production

It is generally concluded that coastal wetlands are among the most productive natural systems in the world; those in the Gulf are no exception. Where data are available on a national scope, values range from about 200-2000 g C m^{-2} y^{-1} for salt marshes (Turner, 1976), about 400 g C m^{-2} y^{-1} for mangroves and 100-900 g C m^{-2} y^{-1} for seagrasses (Thayer et al, 1979). Kirby and Gosselink (1976) report a yearly value of about 1300 g C m^{-2} for *Spartina alterniforna*, while Hopkinson et al. (1978) report values ranging from about 700-3000 g C m^{-2} for various species in Louisiana marshes (Table 1). In one of the few studies on a mixed species marsh, Gabriel and de la Cruz (1974)

TABLE 1. ORGANIC PRODUCTION (g C m^{-2} y^{-1}) BY REPRESENTATIVE GULF COAST SALT MARSH, MANGROVE AND SEAGRASS SPECIES WHERE NECESSARY DRY WEIGHT VALUES HAVE BEEN CONVERTED TO CARBON, ASSUMING A CARBON:DRY WEIGHT RATIO OF 1:2.

HABITAT	SPECIES	PRODUCTION (g C m^{-2} y^{-1})	LOCATION	SOURCE
Salt marsh	*Spartina alterniflora*	200-2000	East and Gulf Coasts	Thayer et al. (1979)
		1300	Louisiana	Kirby and Gosselink (1976)
	Distichlis spicata	1600	Louisiana	Hopkinson et al. (1978)
	Spartina cynosuroides	670	Louisiana	Hopkinson et al. (1978)
	Spartina patens	3000	Louisiana	Hopkinson et al. (1978)
	Juncus roemerianus	1700	Louisiana	Hopkinson et al. (1978)
	Mixed species	500	Mississippi	Gabriel and de la Cruz (1974)
Mangrove	*Rhizophora mangle*	400	Florida	Heald (1969)
	Mixed species	4.8-7.5 gCm^2 $.d^{-1}$	Florida	Carter et al. (1973)
	Avicennia germinans	2.8 gCm^2 $.d^{-1}$	Florida	Lugo et al. (1975)
Seagrass	*Thalassia testudinum*	580-900	Florida, Texas	Brylinsky (1967)
				Jones (1968)
				Zieman (1968)

computed an annual rate of about 500 g C m^{-2} in Mississippi. Although photosynthetic rates appear controlled closely by light intensity, factors regulating growth are poorly understood. Gosselink et al. (1977) state that on the east coast 90% of the variability in yield of S. alterniflora could be predicted by a combination of soil and tissue nutrients, while poor predictability was found in Louisiana. They further state that salinity over a broad range and soil Eh appear critical, but the role of the latter is unclear.

Few measurements of the biomass and productivity of mangroves and seagrasses in the Gulf are available. Mangrove biomass values, exclusive of litter, range from 390-8700 g C m^{-2} with litter ranging from 15-4900 g C m^{-2} (Lugo and Snedaker, 1974). Production averages about 400 g C m^{-2} y^{-1} (Table 1), with red mangroves exhibiting the highest values, followed by black and white mangroves and buttonwoods (Lugo et al., 1975). Factors governing production and growth (e.g., nutrients, freshwater inflow, salinity and soil conditions) are unclear, but fringing dwarf mangroves, which may be nutrient limited, display the lowest rates of production. Biomass values for seagrasses range from a low of 23 g C m^{-2} for Syringodium and 93 g C m^{-2} for Halodule beaudettei in Texas to in excess of 1500 g C m^{-2} for Thalassia in Florida and Texas (McRoy and McMillan, 1977). Productivity of Thalassia ranges between 580 and 900 g C m^{-2} y^{-1} (Table 1). Iverson (R.L., Fla. State Univ., pers. commun.) indicates an average seagrass production of 300 g C m^{-2} y^{-1} for the eastern Gulf. Only recently have factors regulating seagrass production and success been studied; sediment and water column nutrients, temperature, light, currents, and salinity appear to be key factors. Thalassia tends to show locally reduced photosynthetic rates under reduced salinities; net productivity values decrease rapidly at temperatures less than about 28°C or in excess of 30°C (McMillan, 1974; Zieman, 1975; Ferguson et al., 1979).

Production estimates presented in Table 1 are conservative because below-ground portions of the plant, which may represent in excess of 50% of the total biomass for marsh species, 40% of mangrove biomass, and 80% of Thalassia biomass, are not included. Production of underground plant material and its contribution to the cycling of nutrients in Gulf coast wetlands have been studied on only a limited basis (Hackney and de la Cruz, 1978; Pamatmat and Skjoldal, 1979) and really are unknown. Based upon limited Atlantic coast studies, however, their contribution should be considered significant.

These macrophytes are not the sole producers of primary organic material in wetlands. In addition to phytoplankton production in the water column and microalgae on the mud surfaces, epiphytic algae and macrobenthic algae are common components. All too often, the contribution of these floral elements, which may be significant (Penhale, 1977), is overlooked; macroalgae and epiphytes may contribute 25% or more of the total production of a wetland habitat (Thayer et al., 1979). In addition to contributing to the production of primary organic matter in these habitats, micro- and macro-algae provide food and increase the surface area available for use by animals. Phytoplankton chlorophyll and production values for Gulf coast estuaries appear fairly high, averaging about 7 mg Chl a m^{-3} and about 300 C m^{-2} y^{-1}, respectively (Sykes, 1970; Estabrook, 1973; Johansson, 1975); there is not a plethora of data on phytoplankton production and controlling factors in Gulf coast estuaries, however.

If we assume that the average production values presented are realized for all Gulf wetland systems, we can estimate the total contribution from each. Average values were estimated to be 1300, 400, 500, and 350 g C m^{-2} y^{-1}, respectively, for marshes, mangroves, seagrasses, and phytoplankton. Based upon total estimated acreage and open estuarine water area, total plant production for wetland-estuarine habitats in the Gulf approximate 45 x 10^{12} g C m^{-2} y^{-1}, of which about 75% is contributed by macrophytes.

3.2 Detritus: Production and Export

Of the many functional aspects of coastal wetlands, the presence and formation of detritus probably have received the greatest attention (e.g., Day et al., 1973; de la Cruz and Gabriel, 1973; Hackney, 1978). This emphasis has arisen from the recognition that little of the living plant is utilized directly and that much of the suspended matter in estuarine and nearshore waters is of coastal macrophyte origin (Day et al., 1973; Thayer et al., 1979). Our information base on detrital formation in Gulf wetlands and on aspects such as utilization and export, however, is relatively small.

The scale factors discussed by Odum and Heald (1975) that relate mangroves to estuaries are appropriate for all coastal wetland types: (a) the size and shape of the system is related to the absolute amount of production available, (b) the size of the receiving body of water influences the degree of dilution of the photosynthate, and (c) tidal fluctuations (which are generally low in the Gulf) and channels connecting the wetland to the estuary control migration routes to the system and export out of the system. As a result of the flushing of tides and migration of animals, the actual boundaries of the habitat do not occur at the physical wetland edge. As discussed by Odum et al. (1973), although the specific details and rates may vary, there are three fundamental processes involved in the degradation from large to fine detrital fractions: (a) an initial rapid loss of soluble organic compounds, (b) a colonization of the substrate by bacteria, fungi, and protozoans, and (c) physical and biological fragmentation. Most of the studies have been done with litter bags and only recently has effort been placed on the processes of senescence, leaching, and microbial colonization. Little really is known about the factors involved in leaching and microbial colonization of detrital particles; the importance of microbes and meiofauna in the decomposition process simply has not been quantified. In addition to organismal intermediates, the rate of decomposition will depend upon whether the leaf material ends up in freshwater, brackish water, or seawater, or on the shore (Heald, 1969).

The nutritional quality of detritus may play a significant role in the utilization of detritus by animals. Russell-Hunter (1970) suggested that a C/N ratio of 17/1 or less is adequate for good detritivore nutrition; this value is based on raminant studies and its validity in aquatic system is unknown. Numerous studies have shown an increase in the C/N ratio of coastal salt marsh, mangrove, and seagrass detritus during the initial decay stages, which is followed by a decrease in the C/N ratio often to < 15/1. This nutritional improvement has been attributed to an increase in microorganism biomass on the detrital particles. Newell (S.Y., Mar. Inst., Univ. Ga., pers. commun.) and Ustach (unpubl.) have shown for Juncus, however, that the C/N ratio is still in excess of 30/1 after a year of decomposition on the marsh surface, and Newell's work shows that fixation by cyanobacteria contributes to the high carbon levels; in both studies, C/N values did decrease.

The actual fate of the primary production in wetlands (e.g., internal degradation and utilization, and export as particulates, dissolved organics, and living biomass), is one of the most important, yet poorly understood, aspects of wetland ecology. Export may occur as dissolved organic matter (DOM) and/or living and dead particulate matter. DOM release has been shown for each wetland plant type, and Gallagher (1978) suggests that since DOM is readily consumed by microbes, it probably represents a more important contribution than the absolute rate of release might suggest. The contribution of DOM may be a major factor of importance in black mangrove systems (Heald, Odum, and Tabb, 1974). Just how much is produced, how it is utilized, and its role in these systems are unanswered questions.

Hackney (1978) points out that estimates of particulate matter export range from near 50% net export to net imports, and that no single factor explains why some marshes are net exporters while others are importers. Few direct transport studies have been undertaken, and they show export to be sporadic. Hopkinson et al. (1978) estimated the annual disappearance of dead D. spicata from a Louisiana marsh equal to 98% of its annual production, with values of 91%, 91%, and 85% for Juncus, S. alterniflora, and S. patens, respectively. There is no indication, however, of where or how this material is lost (i.e., to export, internal utilization, or incorporation into animals and marsh sediments). Day et al. (1973) estimated that 51% of the above-ground production in a Louisiana salt marsh was exported as detritus and that 80% of this flowed out into coastal waters, while Hackney (1977) found that a Mississippi Juncus marsh was a particulate matter importer most of the year. Newell (S.Y., Mar. Inst., Univ. Ga., pers. commun.) has calculated a net carbon exchange value for a Florida Juncus marsh of 28 g C m^{-2} y^{-1} exported to the estuary, while there was a net gain of nitrogen by the marsh of 0.2 g m^{-2} y^{-1}.

Little quantitative data is available on export from mangrove and seagrass systems. Heald (1969) indicated that greater than 80% of the detritus in North River, Florida, was from red mangroves, and Carter et al. (1973) estimated that 57 to 80% of the total energy budget of Fahkahatchee and Fahka Union Bays, Florida, was supported by exports from mangrove forests. In yet another Florida mangrove system, Newell (pers. commun.) computed a net export of carbon of 146 g m^{-2} y^{-1} and a net import of nitrogen of 0.6 g m^{-2} y^{-1}. We know of no published export/import studies on Gulf seagrass systems, although Zieman et al. (1979), Bach and Thayer (in prep.), and Iverson (R. L., Fla. State Univ., pers. commun.) have indicated significant export in tropical and temperate grass bed systems. Zieman (J.C., Univ. Va., pers. commun.), who is currently working in Florida Bay, has shown export of Thalassia and

Syringodium to both open Gulf waters and adjacent mangrove systems. This communication between wetland systems, also noted on the east (pers. obs.) and west coasts (Gallagher, J.L., Univ. Ga., pers. commun.) may be significant in the cycling of nutrients within these habitats.

Regardless of the wetland type, organic material exported from these systems is a nutritional contribution to adjoining estuarine and coastal systems, and when material is exported, it may form a nutritional buffer to the normal seasonality exhibited in phytoplankton production and abundance. Even if some marshes export little of their own production as suspended organics, they are significant in the regulation of overall export from estuaries (Hackney, 1978) and, in addition, provide a diversity of habitats and food supply, both of which are exploited by aquatic organisms.

3.3 Animal Utilization of Gulf Coast Wetlands

To be of significance as a nursery, feeding, or reproductive zone, a habitat must provide adequate protection from predators, a substrate for attachment of sessile stages, and a food source that is both varied and concentrated. Coastal salt marshes, mangroves and seagrass meadows provide all or most of these requirements. There are numerous data sources that demonstrate large population sizes, particularly of juvenile life-history stages, in wetland habitats, yet most studies have emphasized commercial species, e.g., shrimp, crabs, oysters and finfish, and not the abundant forage species. Although many unknown factors are involved, Turner (1977) and Faller (1979) have computed a highly significant positive relation between the yield of commercially valuable quantities of penaeid shrimp and the area of intertidal vegetation for Louisiana and Texas waters. Efforts along these lines should be encouraged for other commercial and forage species, the latter of which generally are more abundant than either sport or commercial organisms.

The fauna of coastal wetlands can be categorized according to major habitats within the system they occupy. Within marshes, there are three primary habitats -- subtidal channels, the intertidal zone, and the upper marsh. Gulf coastal marshes with their relative shallowness and dense stands of vegetation provide ideal protection from predators for juvenile fish, while the network of channels common to marshes provides ready access to food resources for both fish and crustaceans. While many ecological equivalents are found when species from the Gulf, Atlantic, and Pacific coasts are compared, quantitative data on species composition, feeding habits, and resource partitioning among the many species using these habitats simultaneously are poorly documented. Few species use the marsh over their entire life cycle; for many, wetlands serve as nurseries for postlarvae and juveniles. A few of the important commercial or recreational species common to marshes are presented in Table 2. Herke (1971), Parker (1971), and Conner and Truesdale (1973) have shown Gulf marshes to be nursery grounds for a variety of fish and invertebrates, and Hackney (1978) has discussed faunal data for Gulf estuaries in relation to some environmental factors. All too frequently, however, extensive fish and invertebrate surveys are carried out with little effort expended regarding the question of how and when organisms utilize the varied habitats present.

TABLE 2. PARTIAL LIST OF COMMERCIAL OR SPORT FISH AND SHELLFISH THAT UTILIZE SALT WATER MARSHES AS NURSERIES. (TAKEN FROM THAYER ET AL., 1979)

ORGANISM	REFERENCE
Sand sea trout (*Cynoscion arenarius*)	Herke (1971), Conner and Truesdale (1973)
Weakfish (*C. regalis*)	Wass and Wright (1969)
Croaker (*Micropogon undulatus*)	Herke (1971), Parker (1971), Wass and Wright (1969)
Spot (*Leiostomus xanthurus*)	Herke (1971), Parker (1971), Wass and Wright (1969)
Menhaden (*Brevoortia* spp.)	June and Chamberlain (1959), Herke (1971), Conner & Truesdale (1973)
Striped mullet (*Mugil cephalus*)	Herke (1971), Dahlberg (1972)
Bay anchovy (*Anchoa mitchilii*)	Herke (1971)
Striped bass (*Morone saxatilis*)	Wass and Wright (1969)
White perch (*M. americanus*)	Wass and Wright (1969)
Silver perch (*Bairdiella chrysura*)	Dahlberg (1972), Thomas (1971)
Summer flounder (*Paralichthys dentatus*)	Clark (1967)
Brown shrimp (*Penaeus aztecus*)	Herke (1971), Conner and Truesdale (1973)
White shrimp (*P. setiferous*)	Herke (1971), Conner and Truesdale (1973)

Mangroves also provide a diversity of habitats for aquatic and terrestrial animals: tree canopies, rot holes in branches, soil and root surfaces, interstitial spaces of soil, permanent and semi-permanent pools, and water channels. Few studies of animals that use Gulf mangrove habitats are available in the literature. This scarcity is probably related to quantitative sampling problems associated with this habitat; the most widely referenced studies are those of Odum (1969) and Heald (1969). Thayer et al. (1979) have summarized some of the organism-habitat associations common to mangroves. Soil and roots provide surfaces for support of both sessile and crawling invertebrates (Fig. 2A), a large proportion of which are considered to feed on detritus and ultimately serve as food sources for nekton. Even organisms associated with the tree canopy are part of a food chain originating with mangrove detritus (Fig. 2B).

Seagrasses also provide a variety of microhabitats; animal and plant niches may be found on (1) the leaf or stem surfaces, (2) on or in the sediment, and (3) in the water above or below the leaf canopy. Figure 3 shows some of the relationships within tropical seagrass beds and Table 3 provides a listing of some of the representative fish, invertebrates, and waterfowl that utilize grass beds. Studies by Hoese and Jones (1963), Carr and Adams (1973), and Weinstein and Heck (1979), to list a few, also provide evidence of the utilization of Gulf seagrass systems by marine fauna. These and other published studies suggest that the dense blades of grass afford protection from predation and water currents and that there is an abundance of suitable food supplies; the diets of most of the fish and invertebrate species, however, are known only to a limited degree.

There is overwhelming evidence that the predominant food pathway within coastal wetland systems is through the detrital food chain, yet there is some recent evidence that several marsh plants contain compounds which actually inhibit detrital feeding (Valiela et al., 1979). Our information base on utilization of detritus and/or its microbial community, the role of microbes and meiofauna in the decomposition process, and the entire question of detrital production and availability within Gulf wetlands has received relatively little attention. Although many structural aspects of wetland habitats are well described, invertebrate communities and actual quantitative data on fish species present within each habitat in the Gulf still require study.

4. RESEARCH NEEDS IN GULF COAST WETLANDS

Along a 50-mile-wide band adjacent to the Gulf from Florida to Texas, the current growth rate is 23.7 people per 100 per year. The growth rate for the U.S. as a whole is only about 30% of that occurring along the Gulf. During 1975, approximately 5.06 million people inhabited this region, and at the current growth rate, the population can be expected to double in less than 30 years (pers. commun., Census Bureau, U.S. Dept. Comm.). As the population grows and expands into coastal areas, demand for fish and shellfish as well as other uses of wetland habitats will grow. The impact of man's presence and environmental modification of essential fishery habitat can be expected to accelerate as the population grows. Degradation of these critical areas unfortunately is cumulative, and a reliable information base is required to make rational management decisions regarding these habitats.

Recent publications have documented many of the alterations to wetland systems in this region (e.g., Thayer et al., 1975; Hackney, 1978; Lindall et al., 1979). As pointed out by Lindall et al. (1979), some of the most insidious pertubations include construction and maintenance of navigation channels; dredging and filling; ditching, draining, and impounding of wetlands; petroleum exploration and production; and pollutants from domestic, industrial, and agricultural discharges. In the Gulf, more than 4,400 mi of navigation channels exist, are under construction, or are planned, and currently about 152 million yd^3 of sediment are removed yearly and deposited in open estuaries and sound and bay waters, on wetlands, or in upland areas. Coupled with spoil islands from dredging of navigation channels, over 13.8 x 10^4 acres of Gulf estuaries have been filled. Health authorities have closed almost 8 x 10^5 acres (10% of the available area) of Gulf shellfishing areas because of pollutants. Over 5.6 x 10^3 acres of Louisiana marsh between 1975 and mid-1977 were lost because of dredging and filling for petroleum exploration and production; there is an accelerated deterioration of surrounding marsh areas resulting from canal side sloughing and interference with normal drainage and sheetflow patterns. Childress et al. (1975), McConnell (1976), Hackney (1978), and others have documented the loss of habitat and decrease in fishery resources resulting from water diversion projects in the Gulf, particularly in Texas.

Throughout this review, we have stressed generic aspects of wetlands, and it is evident that there is a large degree of variability both within and between wetland ecosystems as a result of variations in geological, hydrological, and climatological factors that have a significant influence of ecological processes in estuarine wetlands. It is essential that care be used not only in applying results from one ecosystem to another, but also in designing field research within these habitats. Although there are numerous site-specific research needs, we attempt to summarize briefly below more generic needs alluded to in the foregoing discussion; these gaps can be considered in terms of structural and functional aspects.

4.1 Research Needs on Structural Parameters

Each Gulf coast state has participated in and published a Gulf of Mexico Estuarine Inventory that describes wetland habitats to varying degrees; none have been published since 1975 and most information presented is pre-1970. Lists or maps of the major emergent species and their general distributions are provided, but with few exceptions, there are no data presented on standing crops of plants and their seasonality (data do exist, however, in other publications), or the extent of mixed species associations; the contribution and value of mixed species and edge habitats are unknown. Our knowledge of the distribution and abundance of submergent macrophytes is considerably less than that of low marsh and mangrove species. Emphasis must be placed on high marsh plants, which no longer can be considered to have little ecological value to marine systems. Frequently, distributional information has been derived from planimetry of topographic maps, and there still is a need for detailed habitat type inventories. Mapping of coastal wetlands, particularly submergent habitats, is a difficult problem and is probably best accomplished through a combination of satellite and aerial

TABLE 3. LIST OF REPRESENTATIVE SPECIES OF COMMERCIAL AND RECREATIONAL ORGANISMS USING SEAGRASS BEDS (THE MAJOR GEOGRAPHIC HABITAT (A = ATLANTIC, P = PACIFIC, G = GULF, T = TROPICAL FLORIDA) AND LIFE HISTORY STAGE (A = ADULT, J = JUVENILE, L = LARVAE, E = EGGS, M = MIGRATORY), IF REPORTED, ALSO ARE SHOWN) (TAKEN FROM THAYER ET AL., 1979)

COMMON NAME	SCIENTIFIC NAME	RANGE	LIFE STAGE
Spotted seatrout	Cynoscion nebulosus	A,G	J
Mullet	Mugil cephalus	T	J
Sea bream	Archosargus rhomboides	A,G	A,J
Spot	Leiostomus xanthurus	A,G	A,J
Pinfish	Lagodon rhomboides	A,G	J
Pigfish	Orthopristis chrysopterus	A,G	J
Gag grouper	Mycteroperca microlepis	T	J
Gray snapper	Lutjanus griseus	T	A,J
Sheepshead	Archosargus probatocephalus	T	A,J
Holbrooks porgy[1]	Diplodus holbrooki	A,G	J
Halfbeak[1]	Hyporhamphus unifasciatus	T	J
Pacific herring	Clupea harengus pallasi	P	E
Red drum	Sciaenops ocellata	T	L,J
English sole	Parophrys retulus	P	J
Striped seaperch	Embiotoca lateralis	P	J
Thread herring[1]	Opisthonema oglinum	A	J
Permit (pompano)[1]	Trachinotus falcatus	A,G	J
White grunt	Haemulon plumieri	A	J
Silver perch	Bairdiella chrysura	T	J,A
Mojarra	Gerres cinereus	G	J
Green sea turtle	Chelonia midas	T	A
Queen conch	Strombos gigas	T	A
Bay scallop	Argopecten irradians	A,G	A,J,L
Pink shrimp	Penaeus duorarum	A,G	A,J
Blue crab	Callinectes sapidus	A,G	A
Brant	Branta bernicla	A	M
Black brant	Branta nigricans	P	M
American wigeon	Anas americana	P	M

TABLE 3. LIST OF REPRESENTATIVE SPECIES OF COMMERCIAL AND RECREATIONAL ORGANISMS USING SEAGRASS BEDS (THE MAJOR GEOGRAPHIC HABITAT (A = ATLANTIC, P = PACIFIC, G = GULF, T = TROPICAL FLORIDA) AND LIFE HISTORY STAGE (A = ADULT, J = JUVENILE, L = LARVAE, E = EGGS, M = MIGRATORY), IF REPORTED, ALSO ARE SHOWN) (TAKEN FROM THAYER ET AL., 1979) (Cont'd)

COMMON NAME	SCIENTIFIC NAME	RANGE	LIFE STAGE
Scaup	*Aythya marilataffinis*	A,G,P	M
Canada geese	*Branta canadensis*	A,G,P	M
Redhead duck	*Aythya americana*	A,G,P	M

[1] Reported for *Ruppia* beds in Florida (Carr and Adams, 1973)

photographic techniques. Faller (1979) has described some of the approaches that he has employed for the coast of Louisiana.

There is an overall need for quantitative information on abundance and distribution of faunal components, including meiofauna and forage species, within each wetland type. All too often, surveys consider only commercial species and are carried out in estuarine-nearshore areas with little consideration of the potentially available habitats that the organisms may use. Thus, it is very difficult to answer such questions as what is the amount and quality of habitat required by an organism for spawning, rearing and growth, protection, or food. This is compounded by the fact that high species diversity may not be indicative of environmental stability, since wetland habitats are dominated by juveniles whose physiological requirements change as they grow and are constantly moving and responding to environmental cycles (Hackney, 1978). There also is a need to provide accurate, unbiased estimates of fishery abundance, data which can be gained only by establishment of good gear efficiencies developed through comparative habitat and life-history studies. Even with commerical species, e.g., penaeid shrimp, the validity of catch and effort statistics and abundance data has been severely questioned (Etzold and Christmas, 1977).

4.2 Functional Aspects

As noted, research on functional aspects of Gulf wetlands generally has taken a "backseat" to structural parameters until relatively recently. Thus, there is a large gap between our levels of understanding of these two aspects, not only for the Gulf, but for wetlands as a whole. Research needs on functional aspects fall into three general categories: (1) production and factors governing success of plant species, (2) internal utilization of the habitat by organisms, and (3) detritus and mineral cycling and export.

Although production of low marshes in the Gulf is fairly well documented, there is a paucity of data on high marshes, mixed species marshes, mangroves, and seagrass (mono- and mixed-species) meadows. To determine such factors as the water requirements for germination, reproduction and growth, and the substrate characteristics governing plant establishment and growth, research efforts need to be directed toward physical, chemical, and biological factors that regulate these processes. Unknown, also, are the optimum or minimum freshwater inflow requirements necessary to sustain present levels of plant productivity; this is of particular importance when evaluating the potential impacts of freshwater impoundments, river diversions, and interruptions of sheetflow over emergent wetlands. Large stocks of roots and rhizomes exist in these wetlands, but the live portion, its production and metabolic activity, remain largely unknown. As pointed out by Pamatmat and Skjoldal (1979), this information is required for assessment of energy or carbon budgets of a wetland. The release of oxygen and exudates by below-ground portions of the plant influences oxidative state of the sediments, the solubility of metals, dissolved organic matter cycles, and bacterial and faunal activities.

Once having entered estuaries, postlarvae have a mosaic of distinct habitats to utilize for nutrition and protection. When the nursery role of estuaries and particular habitats within estuaries is considered, however, it becomes increasingly clear that there is a dearth of information on age-specific utilization of habitats and just how the habitat is utilized. In addition, there is only limited information on food habits of the abundant juveniles of estuarine-dependent species; the occupancy of various habitats by many juvenile species simultaneously poses problems regarding partitioning of the habitat's resources, problems to which the answers can only be estimated at present. There also is a general lack of growth and mortality rate data, especially for juvenile fishes. Meiofaunal invertebrates, which have high turnover rates and may serve as important food sources in estuarine wetlands, generally are overlooked when studies are designed. Additional quantitative research is required on benthic invertebrate populations in wetland habitats, since the composition of the benthic community and the transfer of energy within it can influence the structure and productivity of fishery organisms (Mills, 1975). Also of importance and generally unknown is the quantitative importance of forage organisms produced in wetlands as food resources for successive trophic levels in adjacent estuaries and wetlands. To this list should be added research on the optimum or minimum inflow requirements to sustain fishery production. There is a great deal of evidence (e.g., Chapman, 1966; Childress et al., 1975; McConnell, 1976; Hackney, 1978) that levels of discharge influence fishery harvest (Fig. 4), and that low-flow years can alter invertebrate and vertebrate population structure.

We pointed out earlier that one of the most important, yet poorly understood, aspects of wetland ecology concerns the production, decomposition, utilization, and export of detrital material. There are several "black boxes" and major data gaps that should be addressed to critically evaluate the importance of wetland-derived detritus to detritus-based estuarine food webs. Within each wetland type, data gaps exist on rates of detritus formation, and efforts must be placed on processes of plant senescence, leaching, and microbial colonization. In addition, research efforts should be directed toward gaining information on the influence of meiofauna on microbial colonization of detrital particles and on the role of these two groups in the decomposition process. The ability of organisms to utilize DOM leachates derived from detritus and detrital particles themselves also is a universal problem. In regard to detrital utilization, recent evidence suggests that some wetland plant species contain compounds that may inhibit detrital feeding; is this universal and to what extent is there inhibition? The nutritional quality of detritus also is important, and the question arises as to whether C/N ratios or some other chemical parameter (e.g., amino compounds) are the most appropriate measures. Present usage of a 17/1 ratio for good detrital nutritional value is arbitrary, being based primarily on studies with ruminants.

The role of Gulf coast wetlands as exporters of detrial material is speculative at best, although the work of Turner (1976) and Faller (1979) suggest that wetland acreage and detrital export are significant to the yields of penaeid shrimp. Several published studies show a net export from Gulf wetlands, while other studies show net import functions; most data are for marsh systems and there is little available information on mangrove and seagrass systems. If one considers that an estimated 75% of the total plant production in Gulf estuarine-wetland areas is derived from macrophytes, the importance of developing a sound data base on the export functions of these systems is obvious; by necessity, there will be a need for sound hydrological studies along with the export research. Export studies should be designed to consider not only the transport of particulate detritus, but also DOM and living biomass. Since wetlands function in elemental nutrient cycles, effort should be expended in evaluating net transport of nitrogen and phosphorus fractions.

This review is not meant to provide a detailed accounting of our state-of-knowledge of estuarine-wetland areas in the Gulf. Rather, we intend it to be an overview of the value of these habitats upon which generalized gaps in knowledge can be assessed. It is evident that one can no longer consider wetlands solely from the point of view of being suppliers of detrital material, for their value to estuaries and the nearshore coastal zone and their habitats is multifaceted. There are overall needs for intensive long-term studies on a few systems in order to identify how they function, to identify controlling factors, and to establish natural variability among organisms and their habitats. In addition, extensive short-term studies of many systems would provide invaluable information on the range of conditions and variability of wetland ecosystems on a regional basis within the Gulf.

The value of extensive short-term studies and in particular, intensive long-term studies in providing necessary information to develop a framework for planning and management of wetland systems, has been demonstrated in a recent publication by Livingston and Loucks (In press). In this paper, the authors not only provide a review of wetland functional relations, but more importantly, they present a summary of data from an eight-year intensive study of two north Florida Bay systems - Appalachicola Bay and Apalachee Bay. Unfortunately, a great deal of the background data pertinent to this case study is not published at this time. This notwithstanding, this valuable contribution points up that climatic cycles are a strong determinant of biological functions in wetland systems and that cyclic reactions of biological systems may be an adaptive response by populations to long-term trophodynamic changes in the system. The report also emphasizes, as we have done in this review, that the scientific community is not yet able to predict the long-term consequences of human modification of wetland systems and that for rational management of these systems, we must have a comprehensive understanding of their functioning.

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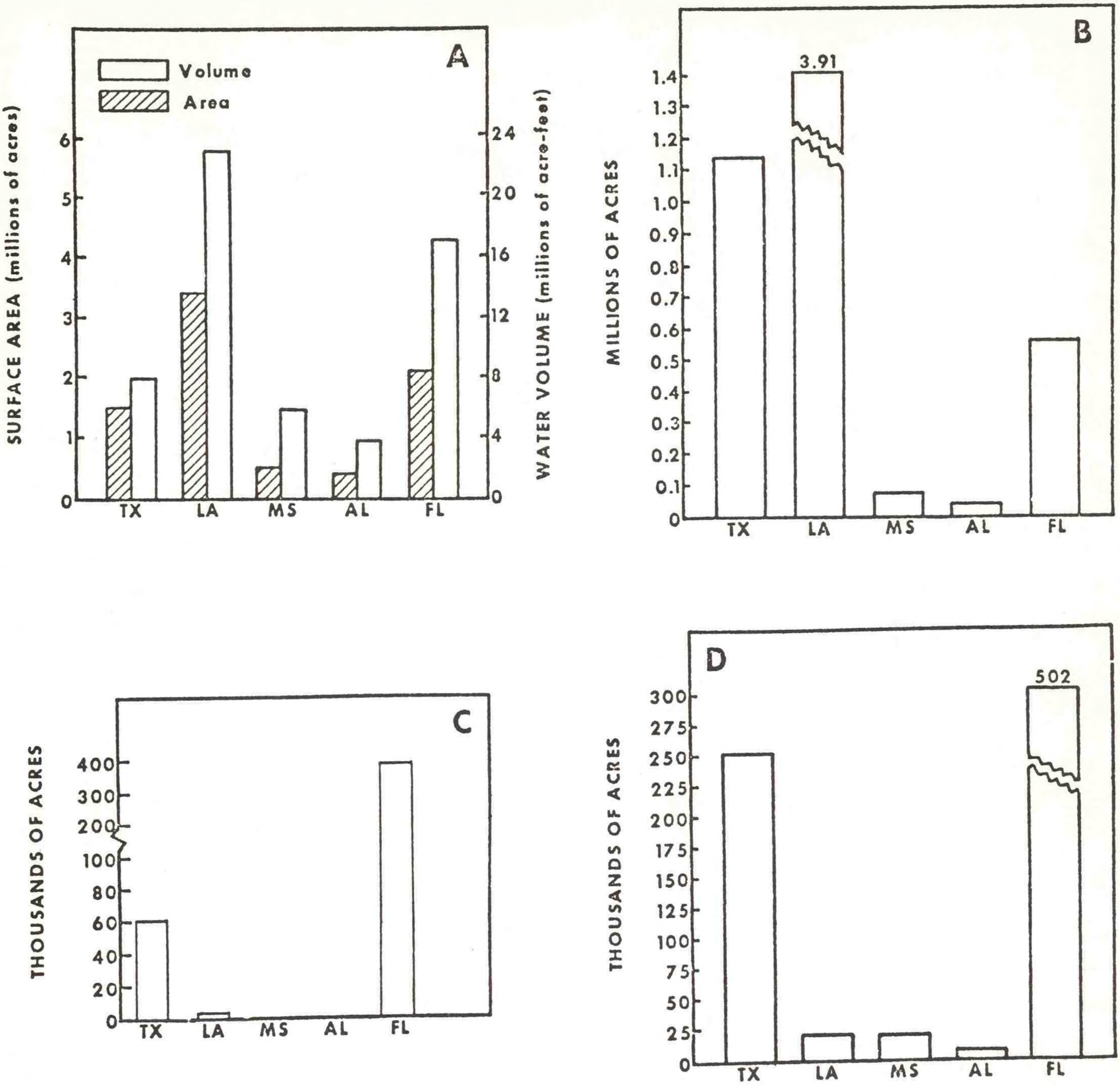
FIGURE LEGENDS

Figure 1. A. Surface area and volume of open estuarine water by Gulf coastal state; B. acreage of Gulf tidal marshes by state; C. acreage of Gulf mangroves by state; D. acreage of seagrass beds in the Gulf by state. Figure 1A and D are taken from Lindall and Saloman (1977), and Figure 1B is modified from Lindall and Saloman (1977).

Figure 2. Top: Diagram of the vertical distribution of representative organisms inhabiting mangrove forests (taken from Glynn, 1964). Bottom: Diagram of the flow of energy from mangrove leaf material to carnivore levels in a black mangrove system (taken from Tabb, Drummond, and Kenney, 1974).

Figure 3. Diagram of animal-plant associations in a tropical seagrass community. (Redrawn from an original in J. C. Ogden, Fairleigh Dickinson University, West Indies Laboratory, St. Croix, U.S.V.I.).

Figure 4. Diagram showing the commercial harvest of estuarine-dependent fishery resources from Texas waters during wet and dry years between 1956-1962. (Taken from Chapman, 1966.)



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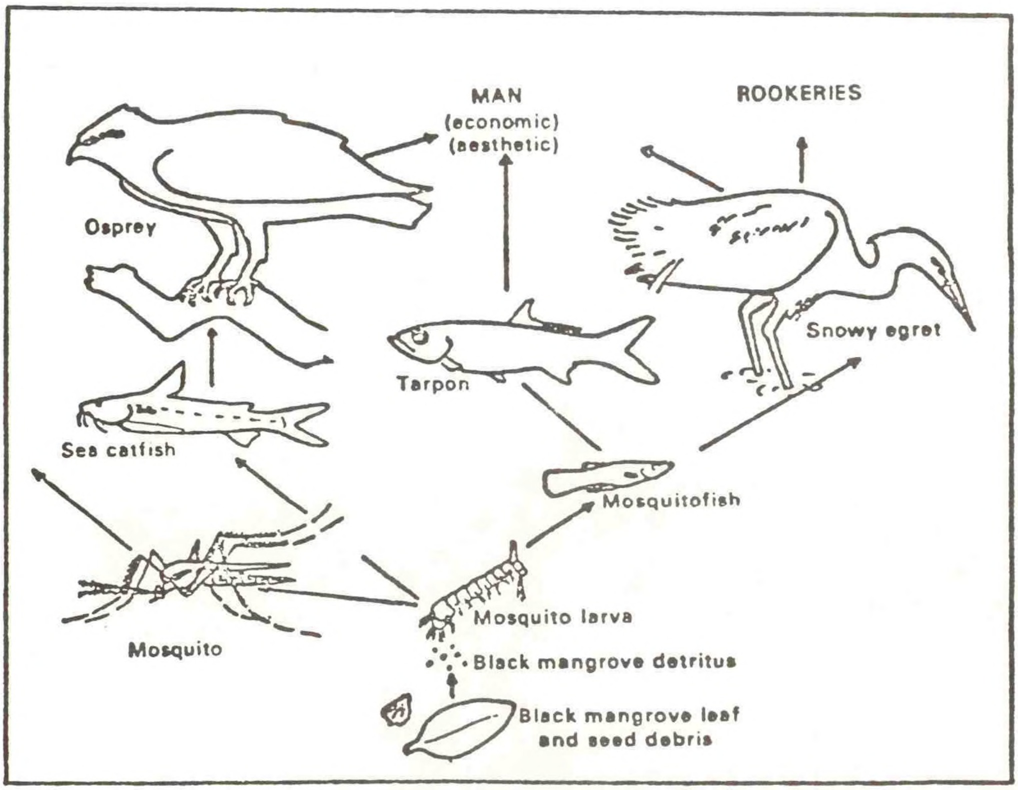

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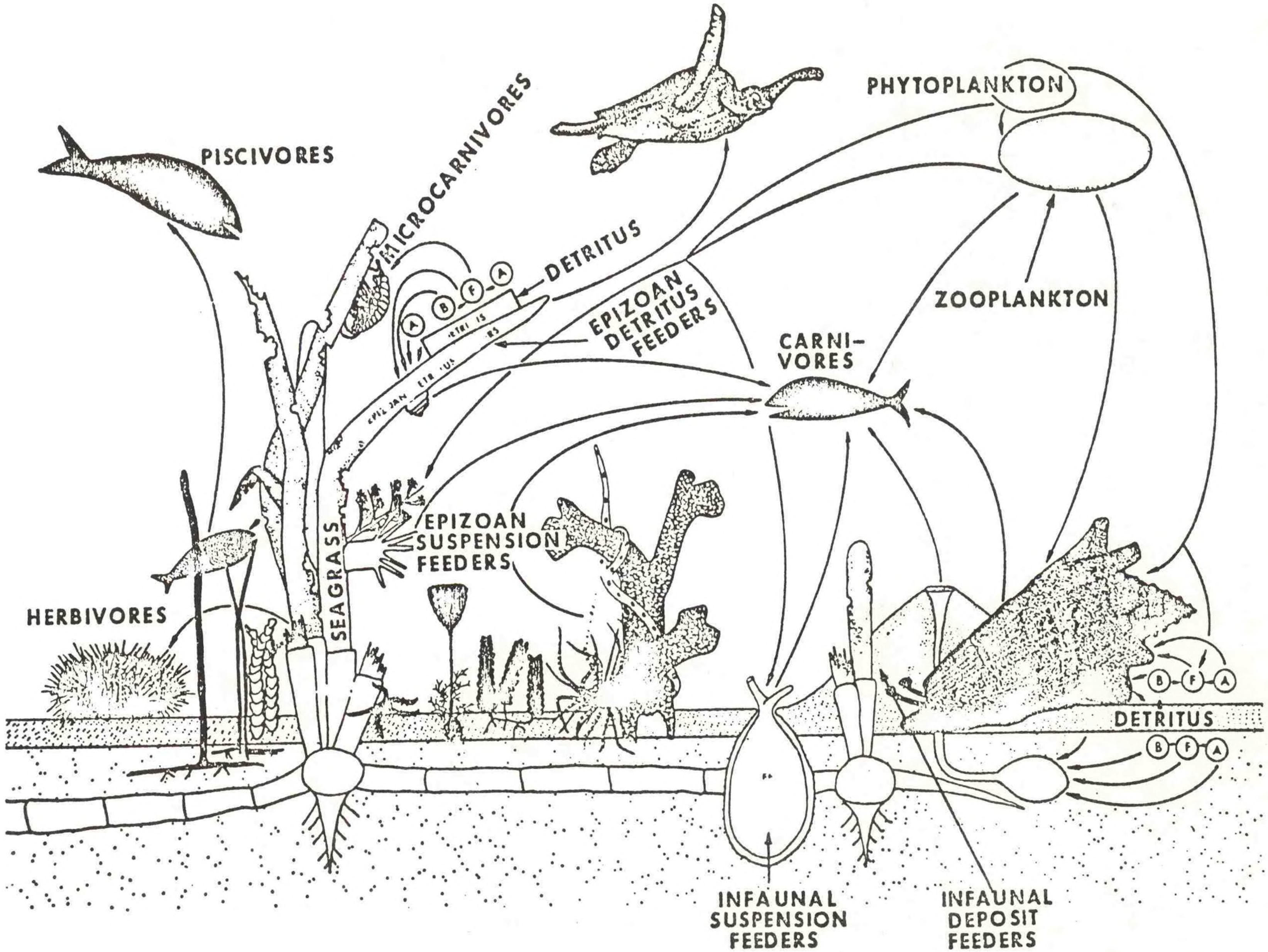

Fig. 3. Diagram of animal-plant associations in a tropical seagrass community. (Redrawn from an original by T. Taxis in Ogden (1980), Fairleigh Dickinson University, West Indies Laboratory, St. Croix, U.S.V.I.).(Reprinted with permission of Garland Publishing Inc.)

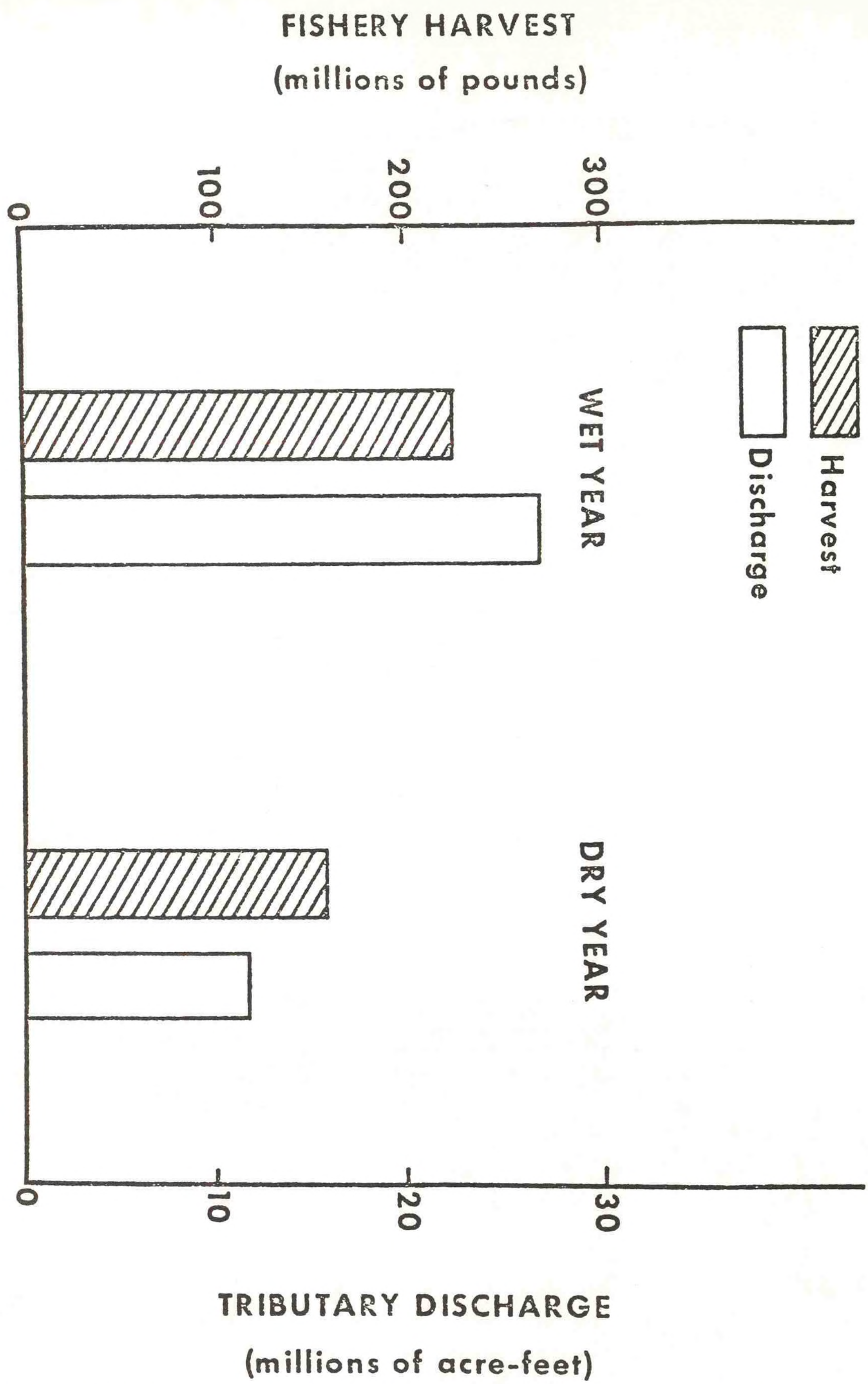

Fig. 4. Diagram showing the commercial harvest of estuarine-dependent fishery resources from Texas waters during wet and dry years between 1956-1962.

(From Chapman, 1966, reprinted with permission of the American Fisheries Society.)

LITERATURE SEARCH ON THE SOFT-BOTTOM BENTHOS OF THE OPEN WATERS OF THE GULF OF MEXICO

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1. INTRODUCTION

It is possible to view research on a marine benthic habitat as progressing through levels of increasingly detailed understanding. Conceptually, and often historically, qualitative descriptions of the fauna (often biogeographic in nature) occur first. They are followed by quantitative descriptive studies of community structure and autecological studies of particular species. At a third level, spatial and temporal variability of the communities are incorporated into these descriptions. Research designed to determine community function occupies a fourth level. Such studies include investigations of the participation of physical factors and biological interactions in community control. Also at this level are studies of energy and material flows within the community. We have used this conceptual framework to structure our presentation.

The study of the nonestuarine soft-bottom communities of the Gulf of Mexico appears to be in its infancy. Substantial work has been done in the more readily accessible estuarine areas, but the benthos of the continental shelf, continental slope, and abyssal regions has been neglected. Much of the literature consists of taxonomy or accounts of local biotas. The latter provide a general description of the communities of Gulf of Mexico soft-bottom habitats, although the detail of the description decreases dramatically as deeper habitats are considered. Few investigations have considered functional (level four) aspects of community organization. Both species and the species-environment relationships are virtually unknown. There is little quantitative information on standing crop, production, and energy pathways. Knowledge of how a community functions is critical as a basis for management decisions, because it is this level of understanding that encompasses the control of the community, its behavior under stress, and the nature and magnitude of its connections to adjacent habitats. In the treatment of specific habitats which follows, we attempt to show the information that is available and make suggestions for research that appears to be required to support management decisions involving each habitat.

Survey work on the Gulf of Mexico macrofauna[1] was initiated in the late 1800's with the cruises of the Blake and the Albatross (see Galtsoff, 1954; Geyer, 1970; and McCaffrey, 1977, for reviews of the early explorations). Work on the collections from these cruises resulted in a series of primarily taxonomic papers. These early works were followed by a long, seldom disturbed hiatus before there was a renewal of research activity in the 1950's.

Systematic reviews on many of the common taxa found in the Gulf of Mexico were given in the first compendium of knowledge on the Gulf (Galtsoff, 1954). Since its publication, much new taxonomic information has been published and has been incorporated into a number of comprehensive studies.

[1]Benthic ecologists group animals by size class. Macrofauna are retained by a sieve with 0.5 mm mesh opening. The macrofauna includes most of the polychaetes, isopods, and amphipods, for example.

The most useful studies include: Wass (1955), Provenzano (1959), Williams (1965), Abele (1970), Manning and Chace (1971), Chace (1972), and Wood (1974) for decapod crustaceans; Shoemaker (1933), Steinberg and Dougherty (1957), Barnard (1969), Culpepper and Pequegnat (1969), McCain (1969), Bousfield (1973), and McKinney (1977) for amphipod crustaceans; Menzies and Frankenberg (1966) and Schultz (1969) for isopod crustaceans; Manning (1969) for stomatopod crustaceans; Abbott (1954) and Andrews (1971) for mollusks; Hartman (1951) and Day (1973) for polychaetes; Phelan (1970) and Downey (1973) for echinoderms; and Hoese and Moore (1977) for fishes.

Major literature reviews and lists of bibliographic references to supplement these studies include Geyer (1950) and Saloman (1975) for the general Gulf of Mexico and the west coast of Florida, respectively; Hulings (1967) for ostracods; Perkins and Savage (1975) for polychaetous annelids; Powers (1977) for brachyuran crustaceans; and Topp and Ingle (1972) for fishes.

General checklists and annotated species descriptions for various taxa have been produced for many areas surrounding the Gulf; these include Briggs (1958), Springer and Woodburn (1960), Tabb and Manning (1961), and Menzel (1971) for Florida; Swingle (1971) for Alabama; Walker (1955), Moore (1961), and Richmond (1962, 1968) for Mississippi; Behre (1950), Dawson (1966), Perrett (1971), and Barrett et al., (1978) for Louisiana; and Gunter (1945, 1950), Pulley (1952), and Hoese (1958) for Texas.

Bottom communities of the Gulf of Mexico have been briefly described by Hedgpeth (1953, 1954), Collard and D'Asaro (1973), and Lyons and Collard (1974); nearshore and estuarine benthic habitats have been well documented by Odum et al., (1974). In this report, we summarize the existing information on these benthic habitats and their associated faunas: Sandy beach intertidal (0--1 m), soft-bottom continental shelf (~1-200 m), and the soft-bottom continental slope and deep sea (200-4000 m).

2. SANDY BEACH

In the Gulf of Mexico, Price (1954) estimates that 52% of the shoreline is occupied by sandy beaches. General reviews of this habitat in the Gulf of Mexico include Hedgpeth (1953, 1954, 1957), Collard and D'Asaro (1973), Horlick (1974), and Riedl and McMahan (1974). The consensus of these authors is that, although an extensive literature exists on the physical processes related to beach formation and maintenance, little biological information has been produced.

Qualitative descriptions of the Gulf sand beach macrofauna include checklists for several locations: Grand Isle, Louisiana (Behre, 1950; Dawson, 1966); Horn Island, Mississippi (Richmond, 1962, 1968); Mississippi Sound and its barrier islands (Moore, 1961); and Apalachee Bay and St. George Sound, Florida (Menzel, 1971). LaFleur (1940) surveyed the macrofauna of Grand Isle, Louisiana, while Warren (1942) described the polychate assemblages of the island. Gunter (1950) presented annotated species lists of the motile macrobenthic invertebrates taken along the Texas coast, including beach seine collections. In addition, he discussed general seasonal patterns and the effects of salinity and temperature on distributions of the dominant taxa. General surveys of the sandy beach mollusk communities of the Texas coast are detailed by Ladd (1951) and Rosso (1952).

Sandy beach macrofaunal assemblages have been described quantitatively from the coasts of Louisiana (Horlick, 1974), Florida (Horlick, 1974; Saloman and Naughton, 1977, 1978), Texas (Keith and Hulings, 1965), and Mexico (Dexter, 1976). A strikingly high number of similar genera and species appear on beaches of the Gulf of Mexico, as well as around the world (Hedgpeth, 1957). Among the dominant taxa found in the Gulf studies are Donax, Emerita, Haustorius, and Scolelepis along the northern, warm-temperature beaches and Excirolana and Scolelepis on tropical, southern beaches of Mexico.

Dexter (1976) compared the sandy beach fauna of the Pacific and Gulf coasts of Mexico. While the Gulf fauna was impoverished compared with other tropical American beaches, it was significantly more abundant than the comparable Pacific coast fauna. Horlick (1974) and Saloman and Naughton (1978) have described spatial and temporal distribution patterns in macrofaunal assemblages on several northern Gulf beaches.

Autecological studies of macrofauna have been done on a very limited number of the conspicuous species; these include: the beach clam, Donax (Edgren, 1959; Loesch, 1957; Tiffany, 1968); the ghost crab, Ocypode (Haley, 1969, 1972); the mud shrimp, Callianassa (Phillips, 1971); and the hermit crab, Isocheles (Caine, 1974). In general, these studies concentrate on various aspects of species' growth patterns, reproductive cycles and larval development, burrowing behavior, and feeding morphology.

Studies of the interstitial[2] component of the sand beach fauna in the Gulf include the quantitative works of King (1962) and Bennett (1974). King (1962) found differences in species composition and relative abundance of nematodes between a high and low energy beach at Alligator Harbor, Florida. He attributed the differences to substrate particle size, organic content, and specific feeding strategies of the species. Bennett (1974) examined the influence of physical parameters on the distributions of several interstitial species with depth and position relative to the waterline. Reduced dissolved oxygen diffusion rates with increased depth appeared to limit penetration into the sediments. Landward distribution was governed by dryness, temperature extremes, and low salinity caused by local rainfall, while seaward distributions appeared to be limited by wave-associated turbulence.

Fishes of the surf zone and nearshore waters have been studied along the coasts of Florida (Springer and Woodburn, 1960; Finucane, 1969; Naughton and Saloman, 1978) and Texas (Gunter, 1945, 1958; McFarland, 1963b). Pompano

[2]The interstitial fauna live in the pore water between the sand grains. They are highly adapted for life in this region, generally displaying small size, vermiform body shape with contractile ability, cement glands, and a strong cuticle or other means of protection from abrasion.

(Trachinotus), mullet (Mugil), and sardines (Harengula) were among the dominant fishes collected. The limited seasonal information suggests abundance peaks in the surf zone during the spring and summer. At the level of community function, McFarland (1963a, b) has cursorily examined the role of phytoplankton in the maintenance of fish populations in the surf region. Also, Finucane (1969) studied the feeding habits of pompano and permit (Trachinotus spp.); juveniles fed on a variety of organisms including small crustaceans and Donax while adults fed primarily on Donax.

From this survey, it seems clear that in a few localities the sand beach community and a portion of its variability have been described and a beginning has been made toward an understanding of the role of physical factors in controlling the spatial extent of the community. Further research should expand on this base with studies of physical and biological aspects of community control. These studies should be coupled with work on energetics to determine the interconnection of the sand beach with adjacent habitats. Finally, to judge the degree to which results from one location might apply to another, an additional biogeography should be done to delineate regions of similar community composition.

3. CONTINENTAL SHELF

In contrast to that on the sandy beach, qualitative information on continental shelf, soft-bottom fauna of the Gulf of Mexico is extensive (see bibliographic references listed by Saloman, 1975). Quantitative information on infaunal macrobenthic assemblages of the shelf is much more limited; no investigations of the benthic meiofauna[3] have been reported.

Among the most extensive of the qualitative surveys was that of the R/V Oregon. Between 1950 and 1955, trawl samples of fishes and macroinvertebrates were taken from 35-135 m at various stations throughout the Gulf. Springer and Bullis (1956) listed crustaceans, mollusks, and fishes collected from these samples and included general station descriptions of temperature, bottom type, and depth. These data provide a basis for a rough characterization of the species composition of major habitats in this region of the continental shelf. Studies of the fauna associated with the white and brown shrimp grounds (Hildebrand, 1954) of the northwestern Gulf of Mexico (5-80 m) and the pink shrimp grounds (Hildebrand, 1955) in the Gulf of Campeche (10-30 m) added considerably to our biogeographic understanding of the shelf. Unfortunately, all collections were taken aboard commercial shrimp trawlers with little attention paid to quantification of fishing effort or collection of environmental parameters.

Hulings (1961) qualitatively sampled the nearshore macrofauna (10-30 m) between Long Beach and Port St. Joe, Florida, with a dredge; 53 decapod and 8 barnacle species were observed, primarily associated with scallop

[3] The meiofauna are small, multicelled animals, which, by definition, pass a 0.5 mm mesh sieve, but are caught on a 0.062 mm mesh screen. Important meiofaunal taxa include nematodes, harpacticoid copepods, and turbellarians.

(*Aequipecten gibbus*) beds. In trawl/dredge sampling off the coast of Mississippi between 18 and 90 m, Franks et al., (1972) collected 129 species of fishes and 50 species of invertebrates, primarily decapod crustaceans. *Micropogon* was the dominant fish species collected; *Renilla* was the most conspicuous invertebrate. Seasonal changes in depth distributions of various species appeared correlated with onshore/offshore migrations. Soto (1972) examined decapod crustacean assemblages across the shelf from 18-180 m between Cape San Blas, Florida, and the Mississippi Delta. He recognized six general faunal groups with only five species (4%) belonging to the assemblage endemic to the Gulf shelf.

The Hourglass cruises, sponsored by the Department of Natural Resources of the State of Florida (Joyce and Williams, 1969), were conducted on the continental shelf of western Florida at depths of 9-72 m. Publications based on these collections included taxonomic and life-history works on scyllarid lobsters (Lyons, 1970), flatfishes (Topp and Hoff, 1972), brachiopods (Cooper, 1973), rock shrimp (Cobb et al., 1973) and stomatopod crustaceans (Camp, 1973).

Fishes of the Gulf of Mexico have received considerable attention, yet primary focus has been directed toward the estuarine assemblages. Ichthyofaunal surveys of the continental shelf have been reported from the southwestern Florida coast (Moe and Martin, 1965), the northwestern Gulf coast of Mississippi, Alabama and Florida (Miles, 1951; Lewis and Yerger, 1976; McCaffrey, 1977), the northwestern Gulf coast of Louisiana and Texas (Miller, 1965; Moore et al., 1970; Chittenden and McEachren, 1976; Chittenden and Moore, 1977), and the southwestern coast off Campeche (Sauskan and Ryshov, 1977).

The industrial bottomfish fishery in the northern Gulf of Mexico has been reviewed by Roithmayr (1965), Gutherz et al., (1975), and Gutherz (1976). Russell (1977) has attempted to correlate river discharge with the distribution and landings of industrial bottomfish in the northern Gulf; he attributed increased annual production to increased nutrient availability and nursery area.

Quantitative sampling of infaunal and epifaunal animals in the Gulf appears to have begun with the publications by Parker (1956, 1960) and Parker and Curray (1956) on the macrofauna of the Mississippi Delta and the northwestern continental Gulf shelf. Collections with Van Veen and orange-peel grabs accompanied by trawl samples revealed a series of depth-related assemblages from the inshore marshes to the edge of the continental shelf and slope. Species distributions appeared to follow ranges of bottom temperatures and to separate according to major sediment types. Depth *per se* was not a critical factor, although a general decline in both numbers of species and individuals was noted with increasing depth.

Sediment characteristics have been shown to play a role in governing species distributions on the shelf. Hulings (1958) noted distinct "biozones" in recent ostracod assemblages off the west coast of Florida; water depth and substrate type appeared to be influential in governing species patterns. Keith and Hulings (1965) found different polychaete, crustacean, and mollusk groups inhabiting sandy and muddy substrate stations off Texas. In contrast, Rice and Kornicker (1965) found that mollusk distributions in the deeper water of the Campeche Banks (30-240 m) were not greatly affected by gross substrate differences. Farrell (1974) observed substrate differences to be a primary factor in regulating species patterns in the offshore water from Timbalier Bay, Louisiana; species distributions were less affected by sediments at inshore sites. Flint (1979) recently observed four distinct macroinfaunal zones across the shelf (0-27 m, 30-100 m, > 100 m, and a ubiquitous species group). Using a multivariate statistical approach, he found sediment texture, sediment organic content, bottom temperature and salinity, and primary production to be useful in characterizing the component species "niches."

Because of their commercial importance, our knowledge of penaeid shrimp biology is more extensive than our understanding of other components of the shelf fauna (see bibliographic references in Perez Farfante, 1969, and Saloman, 1975). In addition to the studies on the fauna of the offshore shrimp grounds (Hildebrand, 1954, 1955) in the western Gulf, various surveys have dealt specifically with the distribution, migrations, and general life history of the shrimp of the family Penaeidae, primarily the genus Penaeus (Burkenroad, 1934; Lindner and Anderson, 1956; Hoese, 1960; Iverson and Idyll, 1960; Eldred et al., 1961; Costello and Allen, 1966, 1968; Perez Farfante, 1969; Brusher et al., 1972). Penaeid distributions have been found to be influenced by rainfall along the Texas coast (Hildebrand and Gunter, 1953; Gunter and Hildebrand, 1954), sediment characteristics (Grady, 1971), and offshore overwintering populations (Gaidry, 1974), as well as by temperature, salinity, available nursery area, river discharge, and the number of hours of water temperature below 20°C (Barrett and Gillespie, 1973, 1975; Barrett and Ralph, 1976, 1977).

Exchanges of energy and materials between shelf benthos and adjacent habitats occur. Both invertebrate (e.g., penaeid shrimp) and vertebrate populations migrate between the shelf and estuarine areas. Nutrients appear to be transferred from sediment pore waters to the water column. Fanning and Carder (personal communication) have data that suggest that this movement occurs when storms or near-bottom turbulence erode the surface sediment layers.

More research on the continental shelf benthos is needed at all levels. Although extensive qualitative information has been gathered, communities in most regions of the Gulf require quantitative descriptions that should include the meiofauna. Although some studies have indicated the importance of sediment characteristics to faunal distributions, their role in community control is far from clear and should be further examined. Data on other physical variables, e.g., temperature, salinity, depth and current patterns, should be examined as well. Little information exists on biological interactions within the continental shelf communities. Feeding and resource partitioning have been examined for selected demersal fishes (Rogers, 1977; Ross, 1977), but no comparable information exists for invertebrates. Similarly, no information is available on the role of competition or predation in regulating communities. Exchanges of energy and materials need to be identified and their magnitude assessed. Migrations of both invertebrates (e.g., penaeid shrimp) and fishes (e.g., trout, spot, croaker) are often reported, but how these migrations affect the material and energy budgets of these areas is unclear.

4. DEEP SEA

The deep sea in all of the world's oceans remains poorly known because of its great area and relative inaccessibility. Much of the work in the Gulf of Mexico consists of taxonomy and qualitative descriptions of faunal components. Springer and Bullis (1956) list macrofaunal species from collections by the R/V Oregon from depths of 315-540 m; the collections consist primarily of larger crustaceans, mollusks and fishes. Parker (1960) discusses the mollusk fauna of the upper continental slope between 125 and 1080 m; he includes a list of the common macrofauna in his collections. Deep-sea fishes of the Gulf of Mexico have been listed by Rass (1972). Pequegnat and Chace (1970) compile qualitative biogeographic information from deep areas of the Gulf. Studies of taxonomy and depth distributions of decapod crustaceans include the carideans (Pequegnat, L. H., 1970), brachyurans (Pequegnat, W. E., 1970), and anomurans (Pequegnat and Pequegnat, 1970, 1971). In addition, Pequegnat et al., (1971) give distribution maps for selected decapod species in the deep Gulf.

Quantitative studies of the Gulf of Mexico deep sea have been restricted to a few investigations; Rowe (1966), Kennedy (1976), and Roberts (1977) examined benthic assemblages over the range of depths from the shelf margin (200 m) to the abyssal plain (> 3256 m). There was a general decrease in both the number of individuals and the number of species of macrofauna with increasing depth. Biomass estimates of the deep-sea fauna in the Gulf (Rowe and Menzel, 1971; Rowe et al., 1974) indicated a reduction in standing crop as biomass decreased exponentially with increasing depth. Further, animal abundance and biomass on the Sigsbee Plain were one-tenth the values observed at comparable depths on the Atlantic continental rise. A general lack of correlation between declining benthic macrofaunal biomass with depth and sediment organic carbon was noted. A puzzling inverse relationship, however, was found between animal biomass and an observed east-west gradient in plant-derived detritus. A complex pathway of energy flow to the deep-sea bottom, initiated by primary production and including the slow rain of detrital particles, was suggested, but with little supporting evidence. Feeding habits of deep-sea demersal fishes have been reported by Bright (1970) and Rohr and Gutherz (1977); small benthic and epibenthic crustaceans and polychaetes, as well as some fishes, comprised the bulk of the diets of those species examined.

Our knowledge of the benthos of the deep sea in the Gulf of Mexico consists mainly of qualitative descriptive information. The quantitative studies of biomass variability have been informative, but, in general, no community in this habitat is known in terms of its quantitative structure. Community energetics as well as the roles of physical and biological factors in community control are unknown. There is an immediate need for a representative site to be chosen so that a quantitative description of a Gulf deep-benthic community can be produced. This work should be coupled to measurements of in-situ metabolic rates as a first step toward an understanding of the community energetics.

5. POLLUTION IN THE GULF OF MEXICO

Extensive work on environmental pollution in the Gulf of Mexico has been done; yet, as is the case with general ecological information, the majority of the studies have been performed in the shallow nearshore and estuarine regions. These areas are closest to the sources of contamination and report the highest concentrations of pollutants. Few investigations have focused on the fates and effects of environmental contaminants in faunas of the Gulf continental shelf, continental slope and abyssal plain. This report does not purport to summarize the existing pollution literature in the Gulf of Mexico, but points out some of the major areas of work conducted in the deeper habitats.

Considerable research effort has been expended on the problems associated with the offshore petroleum industry. St. Amant (1971) briefly summarized various aspects of oil drilling in the Gulf; he discussed seismic exploration activities, mechanical and physical effects of drilling platforms, and potential adverse environmental impacts. Field studies conducted in the vicinity of drilling rigs operating under normal conditions tend to indicate no ill effects (Farrell, 1974; Horlick, 1974; Sharp and Tyson, 1975; Mertens, 1976; Oppenheimer, 1977). Mertens (1976) reported no adverse responses of species diversity; no change in size, growth or reproductive activity of various organisms; and no biomagnification of petroleum fractions in food webs. Meyers (1978) observed hydrocarbon contamination in penaeid and stomatopod shrimps from sites around drilling platforms before, during, and after drilling operations; hydrocarbon fractions were incorporated into the tissues and persisted up to six weeks after removal of the drilling rig.

Laboratory findings have indicated detrimental effects of petroleum hydrocarbons on a variety of organisms, e.g., amphipods (Lee et al., 1977) and polychaetes (Rossi and Anderson, 1978). Barite, the principal component of drilling muds, was shown to affect the community composition of laboratory microcosms by reducing the larval settlement of polychaetes (Tagatz and Tobia, 1978). The authors suggest that community composition in areas of offshore drilling discharges could be affected.

Pesticides, polychlorinated biphenyls, and phthalate ester plasticizers have been reported from nearshore Gulf macrobenthos (Giam et al., 1972, 1974, 1978). Highest concentrations were reported from the nearshore sample sites with the highly polluted Mississippi Delta area having the highest concentrations of all contaminants. Levels of DDTs and PCBs from samples reported in the 1978 study appeared to be considerably lower than those reported in the 1972 survey.

Heavy metals have been examined for some components of the Gulf of Mexico benthos (Bright, 1973; Reimer and Reimer, 1975). Horowitz and Presley (1977) reported trace metal concentrations and partitioning among various tissues from macrofauna of the outer Texas continental shelf. Shrimp had enhanced concentrations in the exoskeletons relative to muscle tissue. Detoxification and/or adsorption processes from seawater were suggested as possible mechanisms for this enrichment.

Effects of thermal effluents from power plants on the macrobenthos have been studied in connection with the steam generating plant near Crystal River, Florida, (Grimes, 1971; Grimes and Mountain, 1971). Only shallow inshore stations appeared affected, with abundances of fishes significantly decreased during summer months. The invertebrate faunal components, on the other hand, showed no effects from the heated effluent (Lyons, et al., 1971).

Little information is available on the general distribution and dynamics of contaminants in either the fauna or the environment of the continental shelf, continental slope, and abyssal plain. Baseline information is needed for a variety of organisms over a wide range of pollutants to assess the extent of contamination in the offshore waters and to determine potential problem areas. Pollutant effects on individual species growth, reproduction, and survival are unknown from the deeper habitats of the shelf, slope, and abyss; effects on community structure and functions also remain unknown. Collection of such data could be coupled with qualitative and quantitative studies (first- and second-level investigations) of the macrofauna that are urgently needed from the deep Gulf of Mexico. Later, work on pollutant biomagnification and movement through food webs could accompany studies of feeding patterns and energy pathways.

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ECOLOGY AND MANAGEMENT OF CORAL REEFS AND ORGANIC BANKS

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1. INTRODUCTION

Coral reefs have been recognized by naturalists and ecologists since the time of Darwin as unique and fascinating marine communities. They have a long geologic history, but recent human activity has made serious inroads on their vitality. Management of coral reefs is an important need; however, few agencies have implemented effective programs toward this end. In this paper, we hope to define real and potential problems, note the current jurisdiction in American continental shelf waters, and suggest a coherent management policy combined with research needs.

2. DEFINITION

Goreau et al. (1972) describes a coral reef as a "localized shallow water wave resistant carbonate structure built up by lime-secreting organisms unconformably deposited on an underlying platform from which it is morphologically distinct." Wells (1957a) adds, "the coral reef....essential fauna and flora consists of corals and calcareous algae which dominate in numbers and volume and provide the ecological niches essential to the existence of all other reef dwelling animals and plants." Odum (1971) states that coral reefs are probably the most biologically productive of all natural communities, marine or terrestrial.

3. GEOGRAPHICAL DISTRIBUTION AND NATURE OF ATLANTIC REEFS IN U.S. WATERS

Western Atlantic coral reefs are discontinuously distributed from Bermuda to Rio de Janeiro, throughout the Caribbean, and in the Gulf of Mexico. The region of Florida from Palm Beach southwestward to Dry Tortugas harbors the only nearshore complex of shoal water coral reefs bordering North America (Figs. 1, 2, 3, 4, 5, and 6).

Reefs from Miami to Palm Beach, Florida, have been studied by Duane and Meisburger (1969), Goldberg (1970, 1973), Raymond (1972), and Courtney et al. (1974). In general, these reefs are not so extensive nor so well developed as reefs found off the Florida Keys; however, the dominance and density of octocorals are greater off Palm Beach; a square meter may contain 60 or more colonies (Goldberg, 1970, 1973; Wheaton, personal communication).

From West Palm Beach to at least Cape Canaveral, Florida, *Oculina* reefal assemblages are found along the margin of the continental shelf (Figs. 1, 7, and 8). These deep reefs are difficult to study using conventional methods; the Harbor Branch Foundation is using a small submersible for this purpose. Low-relief hard-banks, referred to as "live-bottoms," occur between 18 and 145 m off the South Atlantic states from Cape Hatteras to Miami. These banks are inhabited by tropical and subtropical fishes, coralline algae, octocorals, a few hard corals, sponges, hydroids and other attached and mobile forms (Huntsman, 1976; Johnston, 1976). Although some hermatypic corals occur as far north as Onslow Bay, North Carolina, the reefal or hard-bank assemblages north of Palm Beach, Florida, cannot be classified as tropical coral reefs.

In the eastern Gulf of Mexico (West Florida Shelf), coral communities (organic banks and bioherms) are sparsely distributed in depths of 10 to 60 m over a wide area (Lyons and Collard, 1974; Figs. 1, 3, and 9). While individual coral colonies are found as far north as Panama City, the northernmost reported coral bank assemblages are at the Florida Middle Grounds, an area of high topographical relief (Smith and Ogren, 1974; Fig. 1). A deep coral bank composed of Lophohelia prolifera was reported off the Mississippi coast by Moore and Bullis (1960).

The Texas-Louisiana Outer Continental Shelf bears a series of topographical prominences, two of which (the East Flower Garden and the West Flower Garden) are capped by tropical Atlantic coral reefs of the submerged variety (Figs. 1, 10, and 11; Bright and Pequegnat, 1974). Shelf edge banks to the east of the Flower Gardens are occupied by algal-sponge assemblages (Figs. 1, 2, 12, and 13) with sparse populations of hermatypic corals (Bright et al., 1976). Mid-shelf banks are occupied either by Millepora-Sponge associations, such as those at Stetson Bank and Three Hickey Rock (Figs. 14, 15, and 16), or by a deep-water epibenthic assemblage typified by corallive algae, large antipatharian whips, sponges, crinoids, and various other species also found on the lowermost parts of the Flower Garden Banks (Figs. 10, 11, 17, 18, and 19; Bright and Rezak, 1976). Along the eastern Mexican coast, the reefs are emergent features with typical Acropora shoal zones (Moore, 1958; Logan, 1969; Rannefeld, 1972).

Coral reefs in Puerto Rico and the U.S. Virgin Islands are basically the same as those in the Florida Keys and Dry Tortugas, except that the emergent portions of the reefs tend to be closer to shore (Figs. 20, 21, and 22). In Puerto Rico, the regions of greatest reef development are on the east (windward), south, and southwest coasts (Almy and Carrion-Torres, 1963). Ogden (1974) states that coral reef development in St. Croix is better than that of the other Virgin Islands. In St. Croix and nearby Buck Island, the emergent reefs are best developed on the windward east, northeast, and southeast coasts.

4. GULF OF MEXICO REEFS

4.1 Northeastern Gulf of Mexico

This region includes the waters off the west coast of Florida, from the Everglades north to Cape San Blas on the Florida panhandle. The best known and most important area in this region is a 1536-km^2 (338-nmi^2) area of irregular relief northwest of Tampa known as the Florida Middle Ground (FMG; Fig. 1). The FMG is characterized by steep-profile limestone escarpments and knolls rising 10-13 m (33-43 ft) from the surrounding sand and sand-shell substrate, with overall depths varying from 26-48 m (85-157 ft; Smith, 1976). Brooks (1962) attributed the relief to underlying Pleistocene relict reefs which flourished during the last interglacial epoch. At present, live corals contribute little to the configuration of the area (Smith, 1976), so that it is best to use the term "hard bottom" rather than coral reef to describe it. This point is underscored by noting the absence of the hermatypic brain corals (Montastrea and Diploria (Smith et al., 1975)) characteristic of the Flower Garden reefs discussed below.

The dominant scleractinians in the FMG include Madracis decactis, Porites divaricata, Dichocoenia stellaris, D. stokesii, and S. lacera. Octocorals, a relatively minor component of other Gulf reefs considered below, become prominent on the Middle Grounds; dominant forms include Muricea elongata (orange Muricea), Muricea laxa (delicate Muricea), Eunicea calyculata (warty Eunicea), and Plexaura flexuosa (sea rod) (Grimm and Hopkins, 1977). Additions to the latter paper have been made available by Wheaton-Smith (in preparation). It is of interest to note that several genera of octocorals (Plexaura, Eunicea, Pseudopterogorgia, etc.) usually considered typical of tropical areas occur this far north.

A faunal zonation pattern exists on the Florida Middle Grounds with overlap between adjacent zones. Grimm and Hopkins (1977) describe a Muricea-Dichocoenia-Porites zone at 26-28 m (85-92 ft). From 28-30 m (92-100 ft), the dominant forms are Dichocoenia (eye coral) and Madracis. Millepora (fire coral) dominates from 30-31 m (100-103 ft) but become co-dominant with Madracis, from 31-36 m (103-118 ft).

A second shelf region with notable coral communities is bounded by the waters off Tampa Bay on the north and Sanibel Island on the south and has been investigated and reported by the Florida Department of Natural Resources in their Memoirs of the Hourglass Cruises. The so-called "Hourglass region" (Fig. 1) consists of a variety of bottom types. Rocky bottom occurs at the 18 m (59 ft) contour where sponges, alcyonarians, and the scleractinians Solenastrea hyades (stump coral) and Cladocora arbuscula are especially prominent (Joyce and Williams, 1969). Smith (1976) notes additional "patch reefs" (hard bottoms) which occur off Sarasota, Florida. Cairns (1977) published an analysis of the stony corals of the Hourglass samples. While it is apparent that the distribution of corals in this region is irregular, a considerable diversity of scleractinians and octocorallians occur here and are listed among those recorded from the Eastern Gulf of Mexico. Dominant species were Siderastrea radians, Cladocora arbuscula, Solenastrea hyades, Phyllangia americana, Oculina diffusa, and Oculina tenella; twelve other species were rare (Jaap, 1979; personal communication).

As in the FMG, the Hourglass region octocoral fauna shows the presence of Carolinian elements in addition to those of West Indian affinity. This Leptogorgia/Lophogorgia assemblage is found in some abundance in the vicinity of Naples, Florida (Wheaton-Smith, in preparation), and persists sporadically to Cape Sable, Florida (Tabb and Manning, 1961).

In addition to the FMG and Hourglass areas, the eastern Gulf region also includes abundant hard bottom communities (Causey, 1979, personal communication). Woodward-Clyde Consultants (1979) described the biological associations of these areas, in which Oculina robusta is particularly abundant.

4.2 Northern Gulf of Mexico

This region is bounded on the east by an arbitrarily fixed border off St. Josephs, Florida, and on the west by the Mississippi Delta. Although there is relatively little information available for this area, the shallow nearshore region appears to be a transition zone between hard-bottom communities to the east and southeast and localized hard-bank communities to the west. The area is influenced by the Mississippi River outflow. Although some solitary corals (Manicina areolata rose coral at 34 m (112 ft) depth; Jaap, 1979; personal communication) and inshore hard bottoms have been reported 3-11 km (1.6-5.9 nmi) offshore between Panama City, Florida, and the Choctawatchee Bay entrance (Brooks, 1974), most coralline areas are restricted to the outer edge of the continental shelf in this region.

The shelf edge lying in the area between the Mississippi Delta and northwest Florida contains a number of discontinuous mounds, hills, and pinnacles at depths of 80-168 m (262-550 ft). Ludwick and Walton (1957) studied a section of these prominences off Mobile, Alabama (depth, 80-110 m or 262-360 ft; mean temperature, 18.3^{o}C or 63^{o}F), which were found to be Pleistocene rock composed chiefly of calcareous algae. Their relief averages 9 m (30 ft) above the surrounding terrain, and although no evidence of modern reef construction was found, a number of scleractinians and octocorals (in addition to the antipatharian Cirripathes sp.) were obtained by dredge and grab.

4.3 Northwestern Gulf of Mexico

The principal coral communities on the U.S. outer continental shelf in the northwestern Gulf of Mexico (west of the Mississippi River Delta, the Mexican border) are localized on the hard banks occurring on the seaward half of the shelf (Fig. 1). These banks usually originate in waters 40-100 m (131-330 ft) deep and are covered with filamentous and leafy algae (Bright, 1977; Giammona, 1978). Bright (1977) has grouped these banks into three categories based on their biota and depth of origin, as described in Table 1 and Fig. 23. The first and third of the above groups rise to crest depths of generally less than 25 m (82 ft), while those of the second group usually crest between 58-70 m (190-230 ft). Epibenthic assemblages on these banks fall into at least six biotic zones, all of which are faunally linked and occupied by organisms known to occur at the two Flower Garden Banks (Bright, 1977).

Two banks (Stetson and Sonnier) in the first group (those originating between the 50-60 m (163-196 ft contour)) are dominated by the fire coral Millepora alcicornis and various sponges (Giammona, 1978; Bright, 1977). Stetson Bank, in particular, has been described in some detail by Bright and DuBois (1974; Fig. 14). This bank occupies about four hectares of bottom composed primarily of a soft claystone, which rises from a mud bottom at roughly 49 m (161 ft) to a crest at about 20 m (66 ft). A wide variety of benthic organisms are associated with the bank. The most common invertebrates include the sponge Neofibularia sp. and the rock-boring bivalve Jouannetia quillingi.

Few scleractinian and no gorgonian corals are found at Stetson Bank. Stephanocoenia michelinii (also reported as S. intersepta by some researchers) occurs with occasional encrustations of Madracis decactis (Bright and DuBois, 1974). Edwards (1971) reported the presence of Siderastrea sp. (starlet coral) and the brain corals Montastrea annularis, Madracis asperula, and Diploria strigosa on Stetson Bank, but these were not encountered by the former authors despite extensive SCUBA and submersible operations.

Another bank within Group 1 is the Sonnier Bank (formerly known as the Three Hickey Rock). This bank is a mid-shelf structure composed of siltstone

Table 1. Classification of Gulf of Mexico Banks Based on Depth Contour of Origin. (After Bright, 1977.)

Group 1 Origin between 50-60 m (163-196 ft) contour		Group 2 Origin between 60-60m (196-262 ft) contour		Group 3 Origin between 100-200 m (330-660 ft) contour	
Stetson Bank	Claypile Bank	Mysterious Bank	North Hospital Bank	East Flower Garden Bank	Ewing Bank
Sonnier Bank (3 Hickey Rock)	32 Fathom Bank	Blackfish Ridge	Aransas Bank	West Flower Garden Bank	Parker Bank
		Big Adam Rock	South Baker Bank	Bright Bank	18 Fathom Bank
		Small Adam Rock	Baker Bank	Bouma Bank	28 Fathom Bank
		Dream Bank	29 Fathom Bank		
		Southern Bank	Fishnet Bank		
		Hospital Bank			

outcrops. The crest of Sonnier at 20-21 m (66-69 ft) is almost entirely encrusted with Millepora sp. (fire coral), which persists to 40 m (132 ft), along with the sponges (Neofibularia nolitangere and Ircinia sp. Although a specimen of Agaricia sp. (lettuce coral) was recovered at 52 m (170 ft), the only scleractinian of note was Stephanocoenia sp. at 36-41 m (118-135 ft; Fig. 12).

The base of Sonnier lies at about 52 m (170 ft), where rubble gives way to a mud bottom at 58 m (190 ft). The antipatharian black corals Cirripathes sp. and Antipathes sp. were noted from 47-58 m (153-190 ft) adjacent to the bank, but not on it. Bright (1978) considers the structure, environment, and biota of Sonnier to be similar to Stetson Bank (described above).

The second group of banks, of which Southern Bank (Fig. 17) is typical, does not rise as close to the surface as either of the other two groups and is characterized primarily by antipatharians of the genus Cirripathes. Also present are scattered encrustations of coralline algae and gorgonians of the genera Hypnogorgia (Muricea ?) and Thesea (Bright and Rezak, 1976). It is worth noting that nearby Dream Bank (also in group 2) has a more diverse octocoral fauna when compared with the rest of the South Texas Banks. Bebryce cinerea Deichmann, Scleracis guadalupensis Duchassaing and Michellotti, Thesea nivea Deichmann, and T. parviflora are all known from here at depths of 63-83 m (207-271 ft; Giammona, 1978). In addition, Muricea pendula Verrill has been taken on Baker and Aransas Banks (60-62 m; 196-203 ft), Nicella flagellum (Studer) is known from Hospital Rock (depth unspecified), and Placogorgia tenuis Verrill has been recovered from South Baker Bank at 76 m (250 ft; Giammona, 1978).

Scleractinian corals, while not abundant, are represented by populations of Agaricia sp. (lettuce coral), Madracis brueggemanni, and an unidentified solitary species (Bright and Rezak, 1976). Cairns (1978) lists several additional ahermatypic corals from the shelf banks of this region. The physical conditions which characterize these hard banks are not conducive to the development of coral communities. The South Texas Banks, in particular, are subjected to frequent instrusions of coastal water masses with their attendant thermohaline fluctuations. Bright and Rezak (1976), for example, state that bottom temperatures can vary from 12-16^{o}C (53 to 61^{o}F) and salinities can change abruptly. In addition, the upper levels of the banks are subjected to periodical inundation by nepheloid layers (turbid water layers), which overlie the predominantly soft bottom of the Texas-Louisiana outer continental shelf (Bright, 1977). The community characterized as the "antipatharian zone" is apparently adapted to these conditions, although the tops of the banks, which are frequently above the nepheloid layer, are biotically more diverse than the lower parts of the banks (Bright, 1977).

The third group of Gulf banks classified by Bright (1977) includes the outer shelf structures originating at depths of 100-200 m (330-660 ft). These are typified by the East and West Flower Garden Banks, except for the large number and diversity of scleractinians that are found in abundance only in their shallowest zones. Located in clear, oceanic waters over 200 km (108 nmi) south-southwest of Galveston, Texas, these two banks bear the most complete and complex coral communities on the northwestern Gulf of

Mexico continental shelf. Zonation patterns at the banks resemble those observed in the Florida Reef Tract but begin at much greater depths. The greater reef crest depths at Flower Gardens, compared with Florida reefs, apparently are not favorable for Acropora sp. (Bright, 1979, personal communication).

Geologically, the Flower Garden Banks are salt dome structures that have been colonized by coralline algae and reef-building corals (Levert and Ferguson, 1969). Because at least some of the relief has been contributed by hermatypic corals, it seems appropriate to refer to these salt dome structures as a special variety of coral reefs. Accordingly, Bright and Pequegnat (1974) classify the Flower Gardens as a submerged reef-bank with coral prominences cresting at a depth of approximately 20 m (66 ft).

The coral assemblages and habitat at the East and West Flower Garden Banks comprise a unique resource. The coral reefs on these banks are the northwestern-most reefs in the Gulf of Mexico. The biota are climatologically near the limits of existence, are at least partially isolated from the gene pool, and are susceptible to collapse should existing populations be destroyed. Geographically, they are of particular research interest. The biotic zonation at the Flower Gardens has been described as one of the most extensive of all Gulf of Mexico banks. Potential threats to the reefs may result from increased oil and gas drilling in the area, close proximity to major shipping lanes, and increased recreational use.

West Flower Garden Bank is composed of large, closely spaced coral heads up to 3 m (10 ft) or more in diameter. The resultant topography is quite rough with much growth in the form of ledges and overhangs (Bright and Pequegnat, 1974). The principal growth zone of the reef, found over an area of 40 ha (100 a) at a depth of 24-49 m (78-160 ft), is dominated by Montastrea annularis (small star coral), Diploria strigosa (brain coral), Montastrea cavernosa (large star coral), Colpophyllia natans (moon coral), and Porites astreoides (finger coral), in that order of adundance. Bright and Pequegnat (1974) refer to this as a "Diploria-Montastrea-Porites Zone" (Fig. 10). The acroporids, the dominant hermatypes in other coral reefs in the southern Gulf and Caribbean, are entirely absent from the Flower Garden Reefs and other localities in the Gulf north of Veracruz, Mexico (Moore, 1958). The reasons for the absence of this and other groups of hermatypic corals may include the seasonal temperature range between 20-30^{o}C (68-86^{o}F; Bright and Pequegnat, 1974), combined with recruitment difficulties presented by the great distance between the Flower Garden Banks and other coral gene pools of south Florida and the southern Gulf. East Flower Garden Reef is somewhat smaller (28 ha or 70 a) than West Flower Garden and has a similar pattern of zonation (Fig. 11). In addition to the Diploria-Montastrea-Porites zone, however, the eastern bank also possesses a biotic zone of Madracis mirabilis and a zone of fleshy algae on the uppermost peaks (Bright, 1977).

The deeper portions of both banks contain a sponge-coralline algae zone followed by a deeper (70 m or 230 ft) antipatharian zone similar to, but deeper than, that found on the south Texas fishing banks described above in group 2 (Bright, 1977). On the Flower Gardens, gorgonian corals of the type characteristic of West Indian reefs are not present on the reef crest (Bright and Pequegnat, 1974). Giammona (1978) lists a number of deep-water gorgonian species taken largely below the zone of active reef growth.

Several other topographic highs on the Louisiana continental shelf also fall in this third group: Bright, Bouma, Ewing, Parker (not figured), and 18 Fathom Banks (Figs. 2, 13, 24, 25, and 26; Bright, 1978). All five are shelf-edge features supporting a community structured largely by populations of coralline algae. All possess features of zonation, generally similar to those seen at Flower Garden Banks (except for the noted lack of scleractinian diversity and number). The algal-sponge zone (coralline algae - Neofibularia sp.) at 50-70 m (165-230 ft) is developed on all five banks, usually associated with Madracis sp. followed by an antipatharian zone at 70-80 m (230-263 ft) (Cirripathes sp. and Antipathes sp.). In addition to these zones, 18 Fathom Bank is capped with a zone composed of the scleractinians Montastrea cavernosa, Stephanocoenia sp., and Agaricia sp., plus the hydrozoan Millepora sp. This coral zone, the only one of its kind in the banks described here, is found in patches from 43-47 m (140-154 ft). It is worth noting that lettuce coral Agaricia sp. is also found on Bright and Bouma Banks, M. cavernosa is known from Bright Bank, and the solitary coral Oxysmilia sp. is reported from both 18 Fathom and Ewing Banks (Bright, 1978).

Octocorallians are only preliminarily described for these regions, but 18 Fathom Bank is reported to have four species: Bebryce cinerea, Nicella flagellum, Nidalia sp., and dense populations of a whiplike Ellisella sp. at 62-73 m (203-240 ft; Bright, 1978). Nicella scmitti and Nidalia occidentalis are reported from Ewing Bank.

A final Gulf bank not fitting the above biotic classification is Sackett Bank (Bright, 1978). The area in which this bank is located is chronically beset with stresses associated with variations in turbidity and salinity due to its proximity to the Mississippi River. It is not occupied by extensive coral or coralline algae communities, except that at 70-80 m (230-263 ft) the Cirripathes zone becomes developed (Fig. 18). At 80-88 m (263-288 ft), Antipathes sp., Nidalia occidentalis, an unidentified paramuriceid, and the solitary scleractinian Oxysmilia sp. are all found but disappear below 90 m (295 ft) due to the development of a mud surface.

4.4 Deep-water Corals

Information concerning deep-water corals is exceedingly sparse. In most instances, the information is not complete enough to make assessments as to the abundance of the stocks. With respect to the condition of the stock (i.e., mortality versus replacement rates) and overall stock stability, it is not possible to make an informed assessment. In one sense of the word "condition," however, the lack of exploitation and other damaging development activities in deep-water areas (except for limited collection and damage by research dredging) implies that the stocks should be in a pristine state.

For the Gulf of Mexico, the three principal studies of deep-water corals are Cairns (1979), Giammona (1978), and Moore and Bullis (1960). Cairns described the zoogeography of scleractinians throughout the management area; Giammona reviewed available information on Octocorallia in the Gulf of Mexico and relates his distributional information to habitat types; Moore and Bullis (1960) reported a "deep water coral reef" from 420-510 m (1350-1700 ft) on the continental slope 70 km (37.8 nmi) east of the mouth of the Mississippi River. In the first such area reported from the Gulf (other areas mentioned below have been reported in the Atlantic), a single trawl produced about 100 kg (220 lbs) of corals, including Lophelia prolifera (Pallas) and Caryophyllia sp. (Moore and Bullis, 1960).

In the Atlantic, similar structures have been reported along the margins of the Straits of Florida off Miami, Palm Beach, and points farther north (Squires, 1963; Neumann and Ball, 1970). One such mound observed from a submersible in 825 m (2700 ft) of water on the Miami Escarpment was described by Neumann and Ball (1970) as "small mounds of muddy sand capped by thickets of branching, deep water ahematypic corals." The uncollected species were possibly of the genera Lophelia, Madrepora, and Dendrophyllia. Cairns (1979, personal communication) reviewed unworked collections at the Smithsonian Institution and has hypothesized that deep-water banks may possibly occur commonly along the Atlantic continental slope within the coral management area--particularly around the 600-800 m (1980-2640 ft) depth contour. If this is true, associated deep-water corals, including Enallopsammia (which Cairns believes to be the Dendrophyllia reported by earlier investigators) and Lophelia, may be relatively abundant in many localized areas.

Also identified within the Atlantic coral management area are "bump areas" (Stetson, et al., 1962; Squires, 1963) located in a broad area about 370 km (200 nmi) southeast of Charleston, South Carolina, in 720-970 m (2350-3200 ft) of water. Here, a 5145 km^2 (1130 nmi^2) area contains thousands of "bumps" (hummocks of low relief) hypothesized to represent accumulations of coral material. As in the Straits of Florida, the corals were predominantly the branching corals Lophelia prolifera and Enallopsammia profunda.

In both the Gulf and Atlantic portions of the management area, solitary corals may also occur along the shelf flank, slope, and plain. Although solitary deep water corals have occasionally been collected from a single trawl in numbers exceeding several hundred individuals, such collections are rare and fit no discernible pattern.

5. ECOLOGICAL REQUIREMENTS

Coral reef communities exhibit relatively high species diversity and productivity as well as stable community structure, but are stenotopic in ecological requirements. Recent evidence indicates that reef communities can tolerate most natural environmental fluctuations imposed on them; however, beyond certain limits stress and/or community upheaval can occur. Temperature requirements are generally 18 to 30°C (optimum ca. 26°C), salinity ranges from 26 to 40% (optimum 36%; Wells, 1957b), and adequate light is a very important requirement for reef development.

Bathymetric limits are imposed by the depth of light penetration and substratum characteristics. In many Caribbean areas, hermatypic corals can be found to a depth of 80 m; in contrast, reef building off the Florida Keys appears limited to depths of less than 40 m. This shallower limit in the north is probably due to availability of suitable substrata and latitudinal influences on limits of light penetration, and temperature.

Hermatypic corals contain, within their endodermic tissues, endosymbiotic dinoflagellate algae (zooxanthellae) from which they presumably can obtain much of their sustenance. Calcification and growth are also enhanced by the actions of zooxanthellae. Johannes et al. (1970) speculated that active feeding on zooplankton by corals provides certain micronutrients; however, the bulk of energy requirements come from photosynthetic pathways dependent on the zooxanthellae.

Shallow reef flats that are emergent or near-emergent exist under environmentally unpredictable conditions (Slobodkin and Saunders, 1969). Elevated temperature, altered salinity, storm waves, and desiccation may strongly influence their biotic communities. Deeper, seaward reef zones occupy less rigorous environments and are thus more accommodated to, or controlled by, biological factors.

Due to their northern latitude, shoal water coral reefs off Florida are exposed to environmental unpredictability not encountered in more tropical regions of the western Atlantic. Recruitment and survival of scleractinian corals appear to be significantly lower in Florida than in Jamaica (Dustan, personal communication). Growth is not as rapid in Florida; annual growth of staghorn coral (*Acropora cervicornis*) ranges from 4 to 11.5 cm/year in Florida (Vaughan, 1915; Shinn, 1966; and Jaap, 1974); ranges in Jamaica are 26 cm/year and in Barbados 14 cm/year (Lewis et al., 1968; Figs. 5 and 27). More growth rate studies are needed to determine whether massive corals such as *Montastrea annularis* behave in a similar fashion (Figs. 6 and 28).

Dahn et al. (1974a) devised a preliminary coral reef ecosystem model. Even at the conceptual, theoretical level, this model defined 95 compartments. Other models have been suggested for energetics, carbon flow, nitrite, nitrate, ammonia, phosphate, oxygen, carbon, carbon dioxide, and phosphous.

6. CORAL REEF LITERATURE

The amount of literature devoted to coral reefs is massive. The citations listed below should ultimately lead interested readers to the most recent contributions.

Coral reef review literature includes: Wells, 1956, 1957a, and 1957b; Newell, 1959, 1971 and 1972; Yonge, 1963 and 1973; Stoddart, 1969a; and Sachet, 1974. For bibliographies refer to: Pugh, 1950; Sachet and Fosberg, 1955 and 1971; Ranson, 1958; Thomas, 1963; and Milliman, 1965.

Symposia and special journal literature of coral and coral reef interest include: Atoll Research Bulletin; United States Geological Survey Professional Paper 260; Philosophical Transactions Royal Society, London vol. B-260, 1971; Field Guide to Some Carbonate Rock Environments, Florida Keys and Western Bahamas, Multer (compiler), 1971; Regional Variation in Indian Ocean Coral Reefs, Stoddart and Yonge, eds., 1971; Hydro-lab Journal vols. 1-3, Wicklund, ed., 1972, 1973, 1975; Symposium on Corals and Coral Reefs, Mandapam Camp, Mukundan and Pillai, eds., 1972; Results of the Tektite Program, Collette and Earle, eds., 1972, and Earle and Lavenberg, eds. 1975; Helgolander Wissenshaftliche Meeresuntersuchungen 24 (1-4) (man in the sea - in situ studies on life in the oceans and coastal waters), Kinne and Bulnheim, eds., 1973; Animal Colonies: Development and Function Through Time, Boardman, Cheetham, and Oliver, eds., 1973; Bulletin of Marine Science (papers in honor of T. F. Goreau, coral reef project), 23 (1-2), R. A. Smith et al., eds., 1973; Biology and Geology of Coral Reefs, 4 volumes (vol. 4 in press), Jones and Endean, eds., 1973 - 1976; Biota of the West Flower Garden Bank, Bright and Pequegnat, eds., 1974; Reefs in Time and Space, LaPorte, ed., 1974; Guidebook to the Geology and Ecology of Some Marine and Terrestrial Environments, St. Croix, U.S. Virgin Islands; Multer and Gerhard, compilers and eds., 1974; Proceedings of the Second International Symposium on Coral Reefs, 2 vols., Cameron et al., eds., 1974; Coastal Ecological Systems of the United States, Vol. I, Coral reefs, DiSalvo and Odum, 1974. Thomas Goreau, a giant in coral reef research, published 40 scientific papers between 1947 and 1970; John Wells has contributed greatly to the systematics of the stony corals and his 1956 and 1957 publications.

7. CORAL REEF ECONOMIC VALUE

The economic value of coral reefs is significant. The primary utilization of coral and coral reef resources is for recreational purposes. It is estimated that the economic value of coral reefs to Florida alone from boating, fishing, diving, tropical fish collecting, mariculture, and educational expenditures is upwards of $40 to 50 million annually. This does not reflect the income from peripheral businesses such as restaurants, service stations, hotels, trailer parks, campgrounds, and souvenir shops that parallel the main roads. No person or firm is totally economically dependent upon harvesting or harvested coral community species, but numerous businesses derive significant portions of their income from coral activities (i.e., boat rentals, gear sales).

The nearshore coral reefs off the Florida east coast are certainly the most exploited in U.S. waters due to their easy access and their proximity to large population centers (lighthouses and navigation markers are found on most major reefs from Miami to the Dry Tortugas).

The offshore reefs in the Gulf of Mexico figure significantly in the head-boat and commercial snapper and grouper fisheries. But because of the paucity of sizeable assemblages off other Gulf states and because of their distance from the mainland, they are visited by relatively few sport or scientific diving parties. A visit to the Flower Garden Banks off Texas requires a 10-hour trip from the nearest port (Port Arthur). Far more diving in nearshore zones is conducted around oil rigs, shipwrecks, and other artificial reefs than coral assemblages per se. Off Texas, for example, artificial underwater structures collectively have accounted for more fishing use than natural reef or bank sites, even though the latter areas were fished in approximately 87% of all trips (Ditton et al., 1978).

7.1 Park Facilities

By far the major reef utilization is concentrated in Monroe County, Florida (Keys). One and a quarter million tourists visited the Keys in 1978 (Rogers, 1979, personal communication). A recent Skin Diver Magazine market analysis indicated that the sport diving activity centered around the Florida Keys reef may be upward of $30 million annually. This is due in large part to the offshore reefs, John Pennekamp Coral Reef State Park, and Key Largo Marine Sanctuary. This vicinity is dependent upon coral resources. The area supports 34 boat ramps, 22 marinas, 13 dive shops, and 22 dive boats. John Pennekamp Park facilities can accommodate up to 529 dive/snorkel/glass bottom boat customers per day (U.S. Dept. Commerce, Office of Coastal Zone Management, 1978). Most visitors who use the area's facilities spend at least several days shopping in adjacent business districts and utilize camping facilities, local hotels, motels, and restuarants. Similar though smaller pockets of coral-related industries exist near Marathon and Key West, Florida. Although the total monetary benefit from visitors to the area has never been assessed, it is undoubtedly very significant to local, county, and occasionally even state economies.

In 1978, 368,000 persons passed through the entrance of John Pennekamp Coral Reef State Park. Many of these visitors utilized the park's facilities. Statistics from the dive shop in the park for the period March 1 to August 31, 1978, appear below:

	Scuba Trips /	Snorkeling Tours /	Discovery Undersea Tour (Glass Bottom Boat)
Users	3,507	14,525	431,803
Cost/person	$15.00	$12.00	$6.00 adults/ $3.00 under 12.

The park also has an all-day sailing, diving trip which had 381 users.

These statistics reflect only those visitors who utilized the park's accommodations and do not include those visitors who utilized private boats or services of businesses outside the park. In addition, these statistics do not reflect visitor utilization during the peak season from January to Easter.

Dustan (1975) estimates that between 100 and 300 thousand people dive in the John Pennekamp Coral Reef State Park reef annually. Thirty to fifty boats visit Molasses Reef every day and an estimated 90 to 150 divers descend to the reef daily. Reefs outside the park also have heavy diving pressure; in areas where reefs are sparse, boat traffic is congested. Guides who take tourists to Looe Key reef (off Big Pine Key) estimate that this reef alone is worth $500,000 annually. Within U.S. Atlantic waters, it is probable that only Buck Island reef, because it is a focal point for sport dive charter operations out of Christiansted, St. Croix, and the U.S. Virgin Islands, experiences diving pressure comparable to that on the reefs of the Florida Keys. However, impacts of diving activities at the compact Buck Island locality are much more effectively controlled by the National Park Service and the Charter boat operators than is the case for the numerous and widespread Florida reefs.

7.2 Fisheries

Despite the absence of a domestic coral harvesting industry, corals are directly related to numerous commercial fisheries. Sport and commercial fishing make heavy use of the reefs. Foremost among individual fisheries is the spiny lobster catch in southern Florida, an industry that was valued at $8.6 million in 1976 (U.S. Dept. Commerce, 1978). Mackerel, yellowtail snapper, and some grouper are also taken from patch and coral reef areas. On hard grounds, shrimp are the major fishery. Sponges are collected for market from grounds in the Dry Tortugas. According to Florida Landings, Annual Summary, 1976, issued by the Department of Commerce, dockside values of finfish landed in Monroe County were approximately:

Spanish Mackerel	$1,080,607
Yellowtail Snapper	618,739
King Mackerel	509,934
Snapper (five species)	201,286
Groupers and Scamp	631,210
Total	$3,041,776

In addition to commercial fisheries users, four primary coral user groups, encompassing both consumptive and non-consumptive activities, were identified: coral wholesale and retail outlets (importation/distribution/sales), tropical specimen enterprises (fish and invertebrate collection/distribution/sales), dive shops and schools (recreation/instruction), and charter boat operators (recreational diving and fishing). Educational and research users are another significant, and currently growing, industry sector.

7.3 Coral Sales

The nearby presence of domestic corals also plays an important role in generating interest in shell shops throughout the management area, but especially in the Florida Keys. Both tourists and residents purchase shells, corals, and other marine specimens from the numerous small shops situated in coastal areas. Most companies import raw corals from the Pacific (primarily the Philippines) or Haiti, clean the pieces, and sell them. Some sea fans are collected and sold legally within the Florida coral law (Causey, 1979, personal communication). Interest in domestic corals may be a major reason for such coral-related businesses. Income generated from coral sales varies according to the volume and the type of coral sold. Corals also vary in price depending on the species and size of the piece. The aesthetic factor doubtless also is involved in price setting.

7.4 Tropical Fish

Throughout many coral communities, tropical fish constitute another important fishery. Tropical specimen collectors depend very heavily (50-90 percent of the catch) upon "coral areas" (i.e., coral reefs, hard bottoms, solitary corals) for their collections. Bright (1979, personal communication) estimates this industry to be in excess of one million dollars. Within the purview of the Florida coral law and the Florida Department of Natural Resources, some tropical fish collectors also collect and sell live and dried gorgonians (other than sea fans) for aquaria (Causey, 1979, personal communication; Feddern, 1979, personal communication).

7.5 Recreational

Offshore areas along the coast are becoming increasingly popular for a wide range of SCUBA and snorkeling activities. Outside Florida, dives to coral habitats still appear to be limited. Florida and other Gulf states do serve as main domestic staging points for dive trips abroad throughout the Caribbean region (San Salvador, the British Virgin Islands). However, most firms surveyed indicated that these trips do not contribute significantly to their total income, especially when compared to equipment sales.

7.6 Charter Boats

The major component of all vessels utilizing corals for part or all of their monetary and non-monetary income are the diving, snorkeling, and sight-seeing boats that visit coral and patch reefs. Offshore fishing boats that visit reef areas may also be included. Most of these activities are concentrated in the Florida Keys and, to a lesser extent, on the Texas coast near offshore banks.

In Texas, where the Flower Garden Banks are located, over 200 km (108 nmi) offshore, dive boats with about 40 passengers charge $100 per person for a two- or three-day trip (Blood, 1978, personal communication). Where corals are nearer shore, as in the Florida Reef Tract, charter fees average about $20 but reach $40 per person for a daily trip. Snorkelers are usually charged about $10 to $20 for a half-day trip. Scenic glass-bottom boat cruises average $3 to $10 for a three-hour trip. At these rates, many shops carry 20 to 100 charter divers to the reefs each day during the peak seasons of December to April and June through September. Such shops may operate two or three boats simultaneously. Charter boat users also generate considerable income spinoff effects in the process of preparing for charter boat trips, especially where they remain beyond one day, e.g., consumption at hotels, restaurants, and equipment shops.

8. STRESSES AFFECTING CORAL REEFS

8.1 Natural

Natural and man induced stresses described below possess the capability of temporarily or permanently depressing coral health and stability. Some of the more common responses to stress include polyp retraction altered physiological or behavioral patterns, and modified energy cycles; the latter may be difficult to observe or quantify but it is a significant component of overall coral health.

Reefs act as buffers to storm waves and so directly affect coastal development. Munk and Sargent (1954) estimated windward that reefs at Bikini atoll dissipate 500,000 horsepower of wave energy. Nevertheless, damage by hurricanes or cyclones is considered to be the most devastating natural event affecting reef communities (Stoddart, 1969b, 1970). Hurricane damage to Florida reefs has been reported by Springer and McErlean (1962), Ball et al. (1967), Perkins and Enos (1968), and Shinn (1972). In many cases, entire reefs have been redistributed following coral colony fragmentation and dispersion (Shinn, 1972). Approximately one year after hurricanes Donna (1960) and Betsy (1965), reef recovery at Key Largo Dry Rocks was almost total (Shinn, 1972). In contrast, after Hurricane Hattie (1961), recovery of devastated reefs and caves off northern Belize, British Honduras, progressed very slowly (Stoddart, 1962, 1963, 1965, 1969b, 1974). Cyclone damage to reefs in the Pacific and Indian Oceans is widespread (Barnes et al., 1971; Blumenstock, 1961; McIntire and Walker, 1964; Moorhouse, 1936; Pillai, 1971; Stephenson and Wells, 1956; and Stephenson et al., 1958).

"Exposure of reefs to brackish silt-laden water has historically probably been the greatest cause of reef destruction" (Johannes, 1972 and 1975). Damage of this nature is restricted in most cases to coral reef ecosystems in close proximity to high-relief land masses. Coral reefs off peninsular Florida are not subject to this problem; it is, however, a threat in the

Virgin Islands, Puerto Rico, Hawaii, and Pacific Trust atolls. An extreme case occurred in Stone Island, Australia, in January 1924, when a lens of fresh water ten feet deep and extending eight miles from the coast killed all nearshore reefs in the area (Hedley, 1925). Hurricane Flora (1963) deposited 550 mm of rain on Port Royal, Jamaica, resulting in a massive zooxanthellae expulsion by shallow-water hermatypic reef organisms (Goreau, 1964). Silt-laden runoff from heavy rains is cited as a contributing factor in the demise of coral reefs in Kaneohe Bay, Hawaii (Banner, 1968; DiSalvo, 1972). Flood runoff from the Rio Jampa and Rio Popaloapan Rivers periodically dilutes the salinity and reduces the visibility around Enmedjo reef near Vera Cruz, Mexico; disappearance of living reef corals in the upper Acropora palmata zone (less than 8 m) was attributed to a flood of the Rio Papaloapan in the summer of 1970 (Rannefeld, 1972).

Thermal elevation and tidal emergence adversely affect shallow reef communities. Zooxanthellae expulsions and mortalities occur during periods of low tides at or near midday in conjunction with calm wind conditions (Vaughn, 1911; Mayer, 1918; Yonge and Nicholls, 1931; Shinn, 1966; Glynn, 1968, 1973a; Loya, 1972; Jaap, 1979).

Central nearshore west Florida shelf coral communities were devastated by recent red tides (population explosions of the dinoflagellate alga, Gymnodinium breve). Smith (1975) reported that red tides can cause irreversible extirpations of reef communities. Metabolic toxins and anoxic water related to red tides devastated reef communities; Smith's monitoring indicated that recovery proceeded very slowly or not at all.

Vaughan (1911) reported that "black water" (possibly a lens of fresh water and associated periphyton bluegreen algae from the Everglades; Feinstein et al., (1955) caused catastrophic mortalities among the Acropora cervicornis reefs in the Dry Tortugas during 1879. According to Vaughan, the destruction could be measured in terms of square miles. However, Acropora reefs are extensive in the Tortugas today.

Shinn (1975) suggested that cold water intrusion onto the Atlantic shelf from Florida Bay caused scleractinian mortalities at Hens and Chickens reef off Plantation Key, Florida. Dustan (unpublished) speculates that occasional cold water intrusions into reef areas may have an effect on the population dynamics and growth of reef corals off north Key Largo. Glynn and Stewart (1973) cited cold water upwelling as a factor causing reduced coral growth on the Pacific side of Panama. Although a lesser threat in the Atlantic-Caribbean region, volcanoes and earthquakes have been cited as causes of reef damage in the Indo-Pacific.

The East and West Flower Gardens and the Florida Middle Grounds (Fig. 1) are, because of their depth and substantial distance from shore, largely protected from many of the natural stresses experienced by coastal reef communities (low salinity, turbid water, drastic temperature changes, emergence, red tides, black water, and perhaps even hurricane damage).

Natural gas seeps have been detected and examined on several of the reefs and banks off Texas, i.e., Fishnet, 28 Fathom, East and West Flower Gardens, Southern, Hospital, and Baker Banks (Fig. 2). Two-hundred to 600 million cubic meters of natural gas per year may be released into the water column and air directly above the East Flower Garden. Bernard et al. (1976) suggest that most of such gas seeps are produced by microbial degradation of organic material in anoxic deposits some distance below the sea bottom and do not represent deep petrogenic deposits of commercial interest. Whether biogenic or petrogenic, the natural gas mixture is composed of over 99 percent methane. Localized effects of such gas seepage on coral health and growth are not known.

Biological agents of reef destruction include a host of animals, plants, and bacteria. The best known and documented is the crown of thorns starfish (Acanthaster planci) that have devastated many reefs in the Pacific (Endean, 1973). Although A. planci does not presently occur in the Caribbean or Atlantic, it will feed on western Atlantic scleractinia (Porter, 1972). If the crown of thorns were introduced to the region, it could become a major problem.

Oscillatoria submembranacea, a blue-green alga, has been documented as a natural agent of coral mortality in Florida and Belize (Antonius, 1974; Dustan, unpublished). The alga apparently gains a foothold through damaged coral coenosarc tissue. The conspicuous trademarks of the pathogen are an expanding band of algae leaving behind a zone of white skeleton (Fig. 29).

Workers in Bermuda have noticed a coral disease apparently bacterial in nature (Garret and Dudelow, 1975). The bacteria Beggiatoa and Desulfovibrio were suspected of killing the brain coral Platygyra in laboratory experiments involving the addition of crude oil, copper, potassium phosphate, and dextrose to the water.

An apparent pathogenic condition referred to as "white death" by several workers (Dustan, 1976) is fairly common in the Caribbean and the Florida Keys.

The polychaete Hermodice carunculata (Pallas, 1766) has been reported as a predator of several species of stony corals. Antonius (1974) suggested that H. carnuculata may be a biological control agent of Acropora cervicornis (Lamarck) in Florida (Fig. 30). Marsden (1962) and Glynn (1962) reported Hermodice as a predator on other stony coral species in the Caribbean.

Bivalves, gastropods, crustaceans, barnacles, polychaetes, sipunculids, sponges, echinoids, asteriods, and ichthyofauna are predatory coralivores, and/or bioeroders of reef corals. In general, large conspicuous coralivores are well known but microbial pathogens are poorly understood.

8.2 Man Induced

8.3 Dredging and Sediment Damages

Poorly planned and managed dredge operations have been responsible for the demise of many reefs. Physical-mechanical damage can destroy reefs. High turbidity associated with dredging operations affects the penetration of solar radiation and removes dissolved oxygen from the water column above reefs (Johannes, 1975). Depletion of oxygen may be a significant factor, since reef organisms under high rates of sedimentation are more stressed physiologically and may be placed in oxygen debt at night. The reef may well depend upon oxygen gained from photosynthetic zooxanthellae pathways, which are directly related to light penetration. Silt created by dredging is a chronic problem that remains for many years after the actual operation has ended (Johannes, 1975). Levin (1970) reviewed the literature on dredging and coral reefs.

The ability of the coral polyp to remove sediment from its surface is a function of wave action, current patterns, sediment particle size, and polyp morphology. Silt-size material is most easily removed, and corals possessing large fleshy polyps bearing cilia tracts are most efficient at sediment removal (Hubbard and Pocock, 1972; Hubbard, 1973; Kolehmainen, unpublished report, Puerto Rico Nuclear Center, Mayaguez, Puerto Rico). Cavernicolous coral reef biota are more susceptible to sediment burial and choking than are more errant forms (Endean, 1976).

Terrigenous sedimentation due to poor land management is probably the biggest pollution threat to coral reefs (Johannes, 1972 and 1975). Kaneohe Bay, Hawaii, exhibits a classic example of this type of reef destruction. Erosion of upland terrain, which had been cleared for agriculture and development, has deposited 1.5 m of material on the bay bottom since 1927, and the shore has progressed up to 2 km across the reef flat (Johannes, 1975). Kaneohe Bay reef problems have been documented in a film, "Cloud over the Coral Reef," and in an atlas of the bay, "A Reef Ecosystem under Stress" (S. V. Smith et al., 1973).

Coral communities in Lindberg Bay, St. Thomas, U. S. Virgin Islands, have been destroyed by sedimentation caused by bulldozing, construction, and surfacing of land that drains into the bay (van Eapael and Grigg, 1970). Dredging has destroyed corals in Water Bay, St. Thomas. TerEco Corp. (1973) surveyed the coral reefs and other sublittoral epibenthic communities of the south coast of St. Croix, U. S. Virgin Islands, and reported that emergent and submerged reefs appeared healthy everywhere except in the immediate vicinity of an industrial area consisting of an oil refinery and an aluminum plant where, in 1963-64 and again in 1966-67, channels were blasted and dredged through the adjacent reefs. Most of nearby Long Reef was totally destroyed and damage has occurred to benthic epifaunal communities just seaward of Long Reef. Recovery does not seem to have progressed far (Figs. 31, 32, and 33).

Dredging in the Florida Keys has been cited as a source of reef damage (Fig. 34). Griffin (1974) monitored a canal dredging operation in Key Largo and found that turbidity created from the dredging could not be separated from ambient sediment levels in the water column at a distance of 0.5 nautical mile from the dredging. He found, however, that fine silt was resuspended after every storm, and water in the bottom of the dredged canals was anoxic. On the basis of the study, ten recommendations (Appendix A) were put forward as ways of minimizing damage to the marine environment (Griffin, 1974).

Aller and Dodge (1974) and Dodge et al. (1974) correlated reduced growth rates in Montastrea annularis with resuspended sediments in Discovery Bay, Jamaica.

Beach renourishment projects and pipeline excavations on the sea floor are potential threats to coral reefs off Florida. Courtnay et al. (1974) noted that sand being shuttled ashore in a beach renourishment program near Hallandale, Florida, buried a small reef, smothering benthic invertebrates and choking some fishes (Fig. 35).

Since dredging represents a severe threat to coral reefs, regulatory agencies responsible for permits should be aware of its potential hazards and should require environmental impact statements giving the locations of coral reefs in the dredging area. Efforts should be made to use turbidity curtains, and preliminary cores should be taken to insure that clay or other sediments that may be particularly harmful to coral reefs do not underlie the surface.

8.4 Oil Pollution and Petroleum Industry Activities

Oil pollution threatens reefs in several ways, the most direct being tissue damage. Chronic oil pollution also affects reproductive functions; dissolved oxygen is consumed by the oil-degrading bacteria, and reduced gas exchange at the air/sea interface can affect metabolism. Oil slicks and sheens reduce light penetration. Benthic algal diversity and productivity are enhanced within the reef community by the degrading oil. Those commercial reef species that survive a spill may become unpalatable, their value may be lost due to the public's unwillingness to purchase marine protein harvested from an oil spill area.

Crude oil, Bunker C, and other nonvolatile petroleum fractions cause little or no damage to corals when floating above the reef for short durations (Grant, 1970; Rützler and Sterrer, 1970; Reimer, 1975; Jaap, unpublished). Volatile fractions and oil spill dispersant chemicals, however, have caused stress to reef corals under experimental conditions (Lewis, 1971; Eisler et al. 1974; Elger-shuizen and de Kruijf, 1975). Birkeland et al. (1976) noted mortalities and reduced coral growth rates due to exposure to crude oil for 1.5 hours; results were dependent upon species and experimental conditions.

Emergent reefs are more susceptible to oil pollution, since oil adheres to tissues and substrata. Less tolerant species display extensive damage (Johannes et al., 1972). Massive damage occurred to an emergent reef flat in the Gulf of Eliat following an oil spill at or near noontime (Loya, 1975, 1976). Loya concluded that a subsequent lack of community recovery was probably the result of reproductive failure, decreased viability of larvae, and substratum alteration. By comparison, a reef having no oil exposure but suffered damage from tidal emergence recovered to become a community similar to its original structure.

Birkeland et al. (1976) found an increase in algal diversity and productivity on reef flats subjected to Bunker C and diesel fuel exposure.

Bacterial oil degradation requires vast amounts of oxygen. Blumer (1971) calculated that one gallon of crude oil required all the dissolved oxygen in 320,000 gallons of saturated seawater in order to complete bacterial degradation. This demand for oxygen could upset the community's metabolism, since most reef organisms live very close to their lower limits in regard to oxygen requirements. Wells et al. (1973) used in situ metabolism studies to show that several species of stony corals possess maximum production/respiration ratios greater than one, implying that the zooxanthellae symbionts are producing oxygen in excess of the metabolic needs of the corals. Porter (personal communication) reported that foliaceous corals to a depth of 30 m receive 100% of their energetic and carbon requirements through the autotrophic metabolism of zooxanthellae. Under experimental conditions, photosynthesis was terminated when corals were exposed to hydrocarbon solutions (J. M. Wells, 1976, personal communication). Oil films and slicks may reduce both oxygen transfer at the air/sea interface and solar radiation.

Jaap (1975) studied a Bunker C oil spill that occurred off the Florida Keys on July 20 and 21, 1975. The spill was of a 20,000-50,000 gallon magnitude and came ashore from Key West to Bahia Honda. Oil passed over offshore reefs at Sand Key; Eastern, Middle, and Western Sambo; and Looe Key. Diving reconnaissance revealed few visible effects on the reefs. Histopathological analyses conducted on several of the more conspicuous reef flat corals revealed no anomalies in the tissues.

Tanker traffic in the Caribbean is quite heavy and there is a concentration of vessel traffic through the Straits of Florida adjacent to the Florida Keys reef tract. Evidence of vessel discharge is documented by the tar residue found on many of the rubble islands along the reef tract and on inshore mangrove islands. The July oil spill occurred in what was considered international waters; hence, legal charges were dropped. The extension of the coastal zone jurisdiction to 200 miles may allow better control of vessel pollution. Although monitoring of vessel discharge is difficult, methods exist that can "fingerprint" the oil and determines its origin. This technological capability, coupled with expanded jurisdiction, may help minimize oil discharge at sea.

Possible impacts on reefs due to offshore drilling and production operations include mechanical damage due to anchoring, drilling, or pipeline construction; effects of oil spillage; effects of blowouts or well fires; and effects of drilling- and production-related effluents discharged into the sea (sewage, deck drainage, produced formation water, produced sand, drill muds, drill cuttings, well treatment materials, etc). The proprietary drilling of oil wells on or near reefs is controversial. For example, one incomplete transcript of testimony given to a Royal Commission on Oil Drilling on Australia's Great Barrier Reef runs to 10,771 pages.

According to the U.S. Bureau of Land Management (1976), approximately 190,000 gallons of oil were spilled in the Gulf of Mexico between October 1974 and June 1975. On the average, approximately 33,000 gallons of oil were produced for every gallon spilled. Sackett (1975) estimates that offshore production in the northwestern Gulf of Mexico resulted in the release of 1500 metric tons of light petroleum hydrocarbons between 1964 and 1974. He also indicated that the predicted maximum levels of soluble petroleum components in the area's surface waters are in the range observed by Brooks (1975) to inhibit primary productivity (.01 to 10 parts per billion).

Federal regulations currently require that persistent oil slicks and oil spills be reported to the U.S. Geological Survey. Oil spillage guidelines for certain everyday offshore drilling effluents have been established by the Environmental Protection Agency (EPA). They limit chlorine in sanitary discharges and restrict the average daily amount of oil and grease discharged to 30 milligrams per liter of produced water or deck drainage released into the sea.

Although elaborate "blowout preventers" have been used during offshore drilling operations, at least two blowouts occurred on the Texas outer continental shelf during 1975 and 1976. The possibility of a blowout near one of the reefs or fishing banks is real. Such an event conceivably could result in massive oil or gas spillage and mechanical damage to reef communities. The physiological effects on coral communities of locally high concentrations of dissolved methane in the water are not known.

The other drilling effluents are primarily drill cuttings and drill mud. Historically, this material has been dumped at the sea surface. Visual observations (E. A. Shinn, personal communication) indicate that larger cuttings drop nearly straight to the bottom beneath the drill rig, whereas fine sedimentary particles form a downcurrent plume. At least one plume that was slightly over a mile in length has been measured (Bright et al., 1976). Smith (1976, personal communication) (Florida Dept. Natural Resources, unpublished report) observed a drill rig during active drilling at the Florida Middle Grounds and noted that during surface disposal of drilling spoils, there was a turbidity plume extending about 0.5 mile down-current. Diving observations revealed that the drill spoil flocculent fraction was deposited over a wide area, while larger fragments remained near the base of the drill rig.

McDermott (1973) listed nearly 150 possible chemical and particulate ingredients used in drill muds. Land (1974) and Robichaux (1975) reviewed the toxicity of drill mud components. Thompson and Bright (1977, an unpublished report) have subjected the corals Montastrea annularis and Astrangia sp. to in situ and static treatments with various drill mud components. The corals are generally able to rid themselves of sizeable doses of the individual solid components, such as barium sulfate and Glen Rose Shale, through pulsing of the covered portion of the colony, ciliary action, and mucous secretion. This clearing behavior is seriously impaired by the addtion of chemical drill mud additives. According to Land (1974), compounds used for adjusting pH elicit specific toxicities. Certain emulsifiers and thinners may be toxic to aquatic animals at low concentrations if they possess ionizable chromium. Lubricants and detergents are toxic to fish at <100 ppm, but they are not used extensively in muds. Preliminary experiments performed by Bright and Thompson (unpublished report) on the coral Oculina diffusa with a chlorinated phenol biocide used in drill muds obtained mortalities between 5 and 10 ppm of the biocide.

In view of the well-documented, deleterious effects of sedimentation and prolonged high turbidity on coral communities, and in response to concern expressed by reef biologists during public hearings, the U. S. Bureau of Land Management (BLM) has required in several instances that drill cuttings and associated effluents be shunted through a downspout to depths well below the lowermost portions of nearby reefs or fishing banks in the northwestern Gulf of

Mexico (Fig. 36). This seems to have worked since no trace of cuttings or drill mud has been found on reefs near regions of recent drilling operations and reef biota do not seem to have been affected.

Insofar as drilling near reefs in the northwestern Gulf of Mexico is allowable, there is a rather urgent need to know the behavioral, physiological, and lethal effects that drill mud components (particularly barium sulfate, certain tannins, chromium compounds and various biocides), specific petroleum hydrocarbons, and even high concentrations of dissolved natural gas components have on at least the several species of major hermatypic corals.

8.5 Offshore Dumping

Ocean dumping is a potential hazard to organic banks in the Gulf of Mexico, and currents conceivably could carry dumped materials onto coral reefs in the Florida Keys. Regulations now require an EPA permit to dump at sea. Florida has successfully objected to the issuance of dumping permits. Materials that have been dumped in the past have included sludge, acids, heavy metals, chlorinated hydrocarbons, nerve and mustard gases, old military ordnance, and aviation fuels.

The Gulf of Mexico receives runoff from over twenty major river systems draining an excess of 1.5 million square miles of the continental United States and over half of Mexico. In comparison with the annual yearly flux of certain heavy metals into the Gulf of Mexico from the Mississippi River, the yearly input of similar industrial wastes to the Gulf through ocean dumping from barges is small (Trefry and Presley, in press). Sackett (1975) calculated gross inputs of DDT, chlorinated hydrocarbons, and petroleum to the western Gulf.

The EPA, which has had regulatory control over ocean dumping since 1973, has allowed large amounts of chlorinated hydrocarbons and other industrial chemical wastes to be dumped at a prescribed chemical waste dump site approximately 43 miles southwest of the Flower Gardens. According to Hann et al. (1976), chemical waste has been dumped in the same general area off Texas since the early 1950's. The National Academy of Sciences (1975) published figures indicating that during 1973, the EPA issued permits allowing the dumping of nearly 11,000 metric tons of chlorinated hydrocarbons southwest of the Flower Gardens. The EPA has, however, recognized the uniqueness of the Flower Gardens and other nearby hard banks and has specified in its permits that barges carrying waste must navigate around the Flower Gardens by a radius of 15 miles, and around Stetson and Claypike Banks by radii of 5 miles. Moreover, in a move to further protect the Flower Gardens, the EPA relocated the prescribed Texas Chemical Ocean Dumping site by making its southern boundary its new northern boundary (Fig. 1). This maneuver, in effect, moved the dump site 16 miles farther to the southwest. EPA intends to control dumping of oil and gas drilling effluents around the Flower Gardens by issuing NPDES permits in 1980.

8.6 Coastal Water Pollution

Sewage and water pollution can afflict coral reef ecosystems through increased nutrients, turbidity, toxic metals; decreased dissolved oxygen in the water column and sediment; and alteration of plankton, infaunal, and epifaunal communities. Effluent from agricultural activities adds fertilizer, herbicides, and pesticides to the environment. Toxic heavy metals from industrial wastes, engine emissions, power and desalinization plants, and solid and liquid waste disposal threaten coral reefs. Chlorine used in sewage and power and desalinization plants is another potential threat to reefs.

Sewage has been cited as a contributing factor in the demise of coral reefs in Kaneohe Bay, Hawaii. Sewage altered infauna communities from aerobic to anaerobic and lowered redox potentials of the sediment. Increased nutrients stimulated the explosive growth of Dictyospheria cavernosa (green bubble alga) that overgrew corals. Transplanted corals soon died in the bay. Death was caused by toxic substances in the sediments; predation by platyhelminthes; and competition for space for ascidians, sponges, oysters, polychaetes and bacteria (S. V. Smith et al., 1973).

Some Florida reefs are already threatened by sewage pollution. The six-county South Florida region (St. Lucie County to Monroe County) has a resident population of approximately 2.7 million, along with a large tourist population of 20,000 and a total of 62,000-64,000 persons in the county at any given time (Florida Dept. Natural Resources, 1974). Growth in the South Florida region from Palm Beach to Key West has been so rapid that waste disposal units, particularly liquid waste treatment facilities, have been overburdened. In 1969, many hotels on Miami Beach pumped their untreated liquid wastes a short distance offshore. Key West, the largest city in the Keys, pumps untreated sewage 1.4 miles offshore into Hawk Channel (landward of the reefs).

With the exception of a subdivision on Vaca Key, the vast majority of urban Monroe County is dependent on septic tanks for sewage treatment; 95 percent of the Key Largo area homes have septic tanks. Soils in the Keys are unsuited for septic tanks because the porous limestone and oolite substrata do not retain the sewage long enough for decomposition. The water table is so high in many places that holes must be put into the bottom of the septic tanks, or they will float. Sewage package plants serving the motels and high-density areas are inefficient and are operated by untrained personnel (Florida Dept. Natural Resources, 1974). Effluent from these sewage plants is added to surface waters or is pumped into subsurface wells. In either case, the effluent is introduced to marine ecosystems bordering the Keys.

To the north, Dade County pumps 146.4 million gallons of sewage waste daily into adjacent waters (Baljet, 1971). The county's main sewage plant is located on Virginia Key in close proximity to the reef tract; expansion plans for the plant on Virginia Key have begun. The outfall will bring additional material to the reef tract. Current patterns are such that material coming out of Biscayne Bay may be caught in a nearshore current running counter to the northward flow of the Florida Current (Gulf Stream) and carried to the reefs southwest of Miami (Manker, 1975). Manker also noted a plume of heavy metals that appears to originate near Virginia Key. Ocean outfall liquid waste disposal is the most common method used by cities along the Florida east coast. Outfalls are seldom far enough offshore for effluent to be placed in the flow of the Gulf Stream. An outfall off Palm Beach terminates just inshore from the reefs (Jaap, personal observation).

Manker's (1975) study of heavy metals in sediments and living and dead corals indicates that mercury, zinc, lead, cobalt, and chromium are present in the sediments of the bays and reefal regions off southeast Florida. Highest concentrations were found offshore of high density urban areas; most of the heavy metals were thought to have come from urban sewage, industrial wastes, power plants, and automobile emissions. Tested corals were high in chromium in comparison with corals from the Florida Middle Grounds (Betzer, personal communication). Lead and mercury in the 4-micron-size bottom sediments of Tavernier Key and the John Pennekamp Coral Reef State Park marina are approaching values that should cause concern (Manker, 1975).

Manker's study indicates that Hens and Chickens reef is an area of deposit for heavy metals and that this reef may have succumbed to heavy metal or sewage pollution. The community structure would indicate that a drastic change has occurred. A rich assemblage of sponges is now found in the area. Sponges appear to increase in response to particulate organic enrichment in the tropics (Dong et al., 1972; Johannes, 1975).

Some coral reef ichthyofauna have high concentrations of chlorinated hydrocarbons and polychlorinated biphenyls. McCormick (personal communication) suggested that high incidences of carcinomas, lesions, and fin and scale rot in Pomacentridae (damselfishes) from reefs in John Pennekamp Coral Reef State Park were caused by chlorinated hydrocarbons. McCloskey and Chesher (1971) found high concentrations of DDT, DDE, PCBs, and dieldrin in the reef coral Acropora cervicornis; they noted that exposure to organochloride decreased production/respiration ratios and increased the light compensation level.

A domestic detergent at a concentration of 0.05 percent killed the scleractinian coral Montastrea annularis in Jamaica (Barnes, 1973). Industrialization of the southeast coast of Puerto Rico is cited as a potential threat to nearby reefs (DiSalvo and Odum, 1974). TerEco Corp. (1973) and Dahl et al. (1974) cited problems with reefs in St. Croix, U.S. Virgin Islands, due to industrial wastes. Effluents flowing into the industrial harbor on the south coast of St. Croix seem to have killed most of what was left of the coastal red mangrove forest after construction of the harbor (Fig. 37). These effluents move out of the harbor, westward along the shore toward Southwest Cape, and out to sea. At one point, water flowing directly into the ocean over a beach at the western boundary of the industrial area was observed to be extremely hot. Present plans are to pipe the effluent offshore to some depth just below the shelf edge. If this obviously toxic waste has a tendency to rise, it could be carried by the westward-flowing longshore current from the offshore outfall directly onto some of the most healthy shelf edge coral reefs on the island, with possible disastrous results.

In the Pacific, dumping of sugarcane wastes has been documented as being a threat to nearshore reefs off Hawaii (Johannes, 1975) and Queensland, Australia (Endean, 1976). There is a definite need for more research on the effects of coastal water pollution on coral reefs.

8.7 Electric Generating and Desalinization Plants

Pollution from electric generating and desalinization plants can be detrimental to coral reef ecosystems. Thermal addition, hypersaline effluent, chlorine antifouling chemicals, heavy metal emissions, oil spills, and nuclear leakage could threaten coral reefs in the vicinity of such operations.

Thermal addition in tropical waters can have serious consequences if proper site planning is not undertaken (Zieman and Wood, 1975). Power plants had a severe effect on coral reef biota at Kahe, Hawaii (Jokiel and Coles, 1974; Coles, 1973, 1975), and Tanguisson, Guam (Jones et al., 1976). Discharges of chlorine and copper and a mean temperature increase of 7°C were cited as the degrading elements in Guam. It should be noted that most tropical marine organisms live within a few degrees of lethal upper thermal limits during summer (Mayer, 1914). An increase of five or ten degrees centigrade can be sufficient to cause death or reproductive failure. Thus, chronic thermal pollution can effectively eliminate coral reef communities.

Desalinization plants can discharge nickel, copper, chlorine, and hypersaline heated effluent. Metallic ions are retained in the sediments nearby and considerable biological perturbation can result (Chesher, 1975). Thorough studies are needed before site approval can be given for generating and desalinization plants in coral reef areas.

8.8 Shipwrecks

In the past two years, several ships have been wrecked on reefs in John Pennekamp Coral Reef State Park, and, recently, another ship was wrecked on Looe Key Reef. On November 3, 1974, a large sailboard ran ground on Key Largo Dry Rocks, cutting a swath through the elkhorn coral (*Acropora palmata*) zone of the reef. Several of the large elkhorn colonies were broken from the reef platform. Dating indicates that these colonies were 180 to 190 years old (Dustan, personal communication). Fiberglass and antifouling paint had been impregnated into the coral skeletons.

The *Ice Fog*, a 70-foot tug, and an accompanying barge loaded with molasses were wrecked off the Florida Keys in February, 1973. The tug sank in 130 feet of water, but the barge went aground on the reef (ironically called Molasses Reef), spilling molasses into the adjacent waters. Fortunately, seas were heavy and most of the molasses was carried away and dispersed.

On January 5, 1976, the 110-foot vessel, *Lola*, ran aground on Looe Key (Fig. 38). It rested atop a spur formation for 18 days, during which time sewage, garbage, engine oil, and other materials were deposited over and on the reef. In May, 1976, the BLM funded a preliminary study to ascertain the extent of damage from this wreck. As a member of the investigating party, Jaap noted approximately 344 square meters of damaged spur top (Fig. 26); several colonies of *Diploria strigosa* and *Montastrea annularis* had been dislodged from the side of the spur. Twelve pieces of structural steel covered the top of the damaged area, along with pipe and steel plate. A fiberglass housing, batteries, tool holders, and a cutting torch tip were found in the groove channel. The team recommended that the site be monitored for at least a year to note changes in community structure and succession. Small-scale transplants were suggested as a possible way to speed recovery. Removal of steel from the reef flat during calm weather could be attempted. A lighted navigational marker near the reef would reduce the potential threat of future shipwrecks.

The 60-foot shrimpboat Captain Allen went aground on Middle Sambo reef flat during the winter of 1973-74. The hull was gutted by salvors and left to the elements. By March, 1976, the hull was almost completely washed away; a few large steel stay bars were all that remained of the vessel. This accident might have been avoided had there been a lighted marker near the reef.

With the expected advent of supertankers visiting Texas ports, there exists a very real possibility that devastating mechanical damage accompanied by massive oil spillage could occur if one of the larger tankers, some of which draw 82 to 98 feet (25 to 30 m) (Bragg and Bradley, 1971), were to go aground on either of the Flower Gardens or STETSON BANK (crest depths of 65 to 85 feet {20 to 26 m}). The west Flower Garden Bank is located only 11 km (6 nmi) from the Gulf Safety Fairway, a major east-west corridor for tankers and cargo vessels into and out of Texas ports. Newer deep draft tankers have drafts too deep to pass over some of the northwestern Gulf hard banks or the reefs along the Florida Keys. It is obvious that marker buoys need to be maintained at these banks. Buoys were placed by the U.S. Coast Guard in 1973, but they have since been removed.

We appear to have come full circle: lighthouses were originally intended to protect vessels from the reefs; now we suggest that the reefs might be spared damage from the ships if the reefs were adequately marked. Most of the wrecks in recent years have involved small vessels; hence, the damage has not been severe. If a large ship (supertanker or bulk carrier) were to wreck on a reef, damage to the reef might be disastrous.

8.9 Salvage Operations

Cockrell (Coral Reef Workshop, Miami, October 21-22, 1974) stated that the most commonly employed technique used to uncover historical shipwrecks in the Florida Keys is the propwash method. Cylindrical ducts direct the propeller turbulence, blowing the sediment away. Many of the older shipwrecks in the Keys are near reefs, since the ships struck the reefs and then sank close by. The propwash technique creates considerable turbidity, and reefs in the area can be affected. The Continental Shelf Coral Protection Act was used by BLM to terminate salvage operations near Coffins Patch Reef off Fat Deer Key. Salvage operations should be regulated to avoid any possible reef damage, and alternatives to the propwash sediment-removal and air lift method should be pursued.

8.10 Anchor Damage

The only clearly demonstrable impact of man on offshore coral reefs and attendant clear water communities in the northern Gulf of Mexico is mechanical disruption, primarily due to anchor damage (Fig. 39). There are numerous hearsay reports of merchant vessels anchoring at the Flower Gardens to pump bilges or clean tanks. The extent of such activities is unknown, but we have frequently seen anchor scars during SCUBA dives and from research submersibles. Typically, the damage is manifested in overturned, broken coral heads or in arrow-shaped scars in the algal module-covered terraces below the reef. We have seen such scars at the East and West Flower Gardens and at 28 Fathom Bank.

Damage has occurred to biota of the hard carbonate sea bottom at 50 m depth surrounding a concrete mooring block for a Coast Guard buoy on the East Flower Garden. The sea floor was scoured clean of algal modules and other biota for a radius of 15 m, due to the excessive length of the mooring cable, which dragged the bottom continually. The buoy has since been removed. Better planning and consultations among reef ecologists could have prevented such damage.

Small boat anchoring on reefs off Florida damage coral formations. Fragile colonies are torn from their attachments and numerous scars appear to be the result of anchoring. A consequence of this scarring is that the exposed wound may become infected with Oscillatoria or some other coral pathogen.

Shrimp trawlers and bottom fishing boats anchoring behind the northwest side of Loggerhead Key, Dry Tortugas, to escape storms cause significant damage to the Acropora cervicornis beds. Anchors crush and break corals and the anchor lines cut swaths of considerable length through the reefs. The vessels also deposit trash and junk on the reefs. Anchor damage to the reef face at Pulaski Shoal, Dry Tortugas, was noted during recent field studies. Davis, Jaap, Robbin, and Wheaton noted at least 14 large anchors (ca. 100 lb. each). Anchors and ground tackle are lost when the anchor lines were cut by the reef face. Corals and other benthic organisms were broken and damaged in the process. As noted at Loggerhead Key, the reef at Pulaski has become a deposit area for discarded junk, primarily from the shrimp trawlers. Education is a most important aspect of management in reducing small boat anchor damage.

8.11 Fishing

Most net fishing in the Florida Keys is for shrimp or pelagic fishes and their fisheries are located away from the reefs. However, damaged nets are occasionally discarded by vessels at anchoring grounds near Dry Tortugas, and others are put onto Florida reefs as a result of shipwrecks. A large net found on a spur formation on western Sambo Reef in 1973 may have been from a nearby shipwreck. Damage was minor in that instance, but it can occasionally be severe. Hook-and-line bottom fishing is concentrated in coral reef areas in the Keys. Hooks may tear and break corals, but seldom to the extent of concurrent anchor damage.

Spearfishing activities on reefs outside John Pennekamp Coral Reef State Park selectively remove large snappers (Lutjanidae), hogfish (Labridae), grouper and jewfish (Serranidae) and a few other large species, although some spear-fishermen, primarily novices, are less discriminate. Removal of large predatory carnivores from the reef could increase the incidence of sick fish that the predators would otherwise consume. Afflicted and diseased fish not so removed may infect other reef fishes. Bahamian spearfishing regulations prohibiting use of SCUBA and allowing only Hawaiian slings and pole spears may more effectively protect larger carnivorous fishes from over-exploitation and thus insure more stable reef communities.

8.12 Lobstering

Considerable lobstering in Florida is centered around reef environments. Traps are frequently dropped on corals, and trap recovery in areas of prolific coral growth (i.e., Acropora cervicornis beds) can cut a swath through the reef. Divers inadvertently and sometimes intentionally damage corals while catching lobster. Moderately sized heads of Diploria spp. (brain coral) are overturned, and corals may be damaged by metal implements used in sport lobstering. Efforts to exclude commercial and sport fishing from the Pennekamp sanctuary have been unsuccessful.

Beardsley et al. (1975) noted a great disparity between size frequencies of lobster populations in protected areas of Ft. Jefferson National Monument, Dry Tortugas, and the Florida commercial fishery. Most fishery researchers consider the Florida spiny lobster fishery a totally exploited resource. Catch per unit effort has dropped continuously over the past decade as greater effort has been exerted upon the fishery.

Following the precedent of the United States action to protect stocks of the American lobster (Homarus americanus) from foreign exploitation, the Bahamas in 1975 declared the spiny lobster (Panulirus argus) a creature of their shelf waters and excluded non-Bahamian action fishing interests from the resource. The Bahamian action has increased trapping efforts off southeast Florida. Many displaced fishermen have moved their operations to Monroe County, where fishing pressure has increased markedly. Exploratory fishing has not located new commercially exploitable lobster stocks. Enactment of similar laws by other Caribbean countries to protect their fishery resources would probably add more pressure to the southeast Florida fishery.

Recent developments in plastic trap design have produced lobster and crab traps impervious to rot and decay; wood traps left on the bottom decay rapidly. If plastic traps are put into large-scale use, significant numbers will be lost and will continue to attract lobsters, crabs, and fishes that may die and attract additional animals. These highly durable devices should be regulated to include some degradable element such as wood or cotton panels that will decay after a relatively short period.

8.13 Diving Activity

An increase in sport diving as a hobby has had an effect on the vitality of the coral reefs off southeast Florida. Boats grounded on shallow reef flats, careless anchoring, divers breaking and damaging coral in quest of lobster and fish, and the removal of reef biota by collectors adversely affect the reefs.

Dustan (1975) cited diver damage and anchoring as the two most severe problems for the coral reefs in John Pennekamp Coral Reef State Park. He estimated that 15,000 persons descend annually on each of the more popular park reefs. Anchors and divers injure coral, allowing coral pathogens a foothold via coral wounds. Many such unintentional acts can severely damage a reef. A large number of the visitors are novices to reef diving and are unaware of the fragile nature of the reefs. An information program is needed to protect the reefs from diver damage.

8.14 Marine Collecting

Collection of marine specimens is a popular hobby and a growing commercial enterprise. Commercial collectors land marine specimens valued in excess of one million dollars annually in Florida (Florida. Dept. of Natural Resources, unpublished data). Since many of the harvested species are reef inhabitants, rapid growth of the tropical aquarium business could drastically reduce certain key reef species. For instance, symbiosis is highly prevalent in the coral reefs (Johannes and Betzer, 1975), and removal of the symbiotic cleaners (gobies, shrimp) may cause severe biological repercussions for the fish fauna of the reef. Endean (1976) also speculated that removal of predatory Charonia tritonis (giant triton snails) from the Great Barrier Reef off Australia was a contributing factor in the population explosion of Acanthaster planci (crown-of-thorns starfish).

There is widespread use of chemicals in collecting marine specimens. Some of the more severe toxicants used include sodium cyanide (Ireland and and Robertson, 1974), Lindane, Dieldrin (Endean, 1976), and sodium hypochlorite (Johannes, 1975). Because sodium hypochlorite is available as laundry bleach, it has gained wide usage as a collecting agent. Chlorine is also used as an antifouling agent in power and desalinization plants. Chlorine is a fertilization inhibitor of marine invertebrates (Muchmore and Epel, 1973), and lethal to marine fish (Alderson, 1972). J. M. Wells (personal communication) noted depressed photosynthesis in algal communities exposed to sodium hypochlorite. A cave exposed to chlorine bleach on the south coast of Oahu, Hawaii, caused devastion for fish, lobster, sponges, and ascidians, and showed only marginal recovery a year after the bleaching (Johannes, 1975). Campbell (personal communication) states that bleaching "wipes out the whole biota."

Jaap and Wheaton (1975) studied effects of a rotenone derivative (toxicant) and a quinaldine-aceton solution (anesthetizing agent) on Florida octocorallian and scleractinian reef corals (Fig. 40). Qualitative observations indicate that rotenone caused severe tissue damage to stony corals (Scleractinia) and quinaldine-acetone caused minor damage; octocorallian corals were not adversely affected by either chemical.

Florida requires a permit for use of chemicals to collect marine specimens. In Fiscal Year 1974-75, when 192 permits were issued, quinaldine was the most frequently used chemical.

8.15 Coral Collecting

Historical quantitative data on coral collecting in the Keys is difficult to obtain. The Florida Department of Natural Resources Marine Patrol estimates that twelve full- or part-time coral collectors were active in the Key West area from 1964 to 1973. Collecting pressure was heaviest on elkhorn (Acropora palmata), staghorn (A. cervicornis), brain corals (Diploria spp., and Meandrina sp.), and pillar coral (Dendrogyra cylindrus) (Fig. 41). Extrapolating the Marine Patrol figures, yearly harvest may have been from 468 to 1560 tons, having a value of $18,720 to $624,000.

Florida's first statute pertaining to coral collection, enacted in 1973, placed limitations on collection of three species of stony corals and two species of soft corals. The law was expanded during subsequent years, limiting collection of all species of stony corals (Scleractinia and Milleporina) and sea fans (*Gorgonia* spp.). This law also forbids sale of coral collected in Florida waters. A 1976 amendment prohibits all coral collection in Florida waters. Recently, BLM, acting under authority of the 1953 Continental Shelf Act, banned collection of all living and dead coral seaward of the 3-mile state limit. If Federal and state regulations are enforced, the threat of coral collection to Florida's reefs should be minimal.

Many shell and coral shops have been allowed to sell their existing stocks of coral but have not been permitted to collect any additional coral. In the year following the ban on commercial collection, there was apparently little decrease in the sale of coral. Since imported coral is required to be invoiced from its point of origin, and many countries (including the Bahamas, Netherland Antilles, and Belize) have protected their coral reefs with laws banning coral collection, it is possible that some of the coral in the curio shops was illegally collected in Florida.

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10. JURISDICTION - FEDERAL PROGRAMS

10.1 Marine Sanctuaries Program

The Office of Coastal Zone Management's (OCZM) Marine Sanctuaries Program is an important federal program. This program was authorized under Title III of the Marine Protection Research and Sanctuaries Act (MPRSA) of 1972. Its purpose is preserving or restoring the conservation, recreational, ecological, or aesthetic values of localized areas "...as far seaward as the outer edge of the continental shelf,...(and in) other coastal waters where the tide ebbs and flows..." (MPRSA, Section 302a). In effect, the Marine Sanctuaries Program is a coastal water counterpart to the more familiar national park, forest, wildlife refuge, and wilderness systems. Individual attention is accorded to each designation and a separate set of sanctuary-specific regulations are tailored to the protection needs of each area. Regulations are placed only on those activities within the sanctuary boundaries judged to be incompatible with the sanctuary's purpose.

Actual site management and administrative responsibility for a particular sanctuary may either be retained by OCZM or delegated with necessary funding support to other appropriate management units.

The Marine Sanctuaries Program is particularly interested in protecting outstanding coral reef areas. One of the three existing sanctuaries--the Key Largo Coral Reef Marine Sanctuary off Key Largo, Florida--complements state efforts at John Pennekamp State Park by protecting a 343 km^2 (100 nmi) section of the Florida Reef Tract. Looe Key, Florida received marine sanctuary status during the summer of 1980. The next sanctuary in the program's recent expansion efforts may well be the Flower Garden Banks which includes the northernmost well-developed coral reef in the northwestern Gulf of Mexico (Office of Coastal Zone Management, 1979). The interest in coral reefs by the Marine Sanctuary Program is a logical application of the program's authority and will likely continue in the future.

The purpose of the proposed Flower Garden Bank Marine Sanctuary is "...to protect and preserve the bank's ecosystems in their natural state and to regulate uses within the Sanctuary to insure the health and well being of the coral and associated flora and fauna and the continued availability of the area as a recreational and research resource..." (U.S. Dept. Commerce, Office of Coastal Zone Management, 1979). The activities proposed for regulation address, among others, deliberate harm of coral, dredging, trawling, and oil and gas operations.

OCZM is currently completing a management plan for the Key Largo Coral Reef Marine Sanctuary. It is designed "...to provide the protection necessary to preserve the coral reef ecosystem in its natural state..." The draft management plan addresses public education, environmental monitoring, and regulatory enforcement needs at the site (Office of Coastal Zone Management, 1978).

Enforcement is conducted cooperatively by the Florida Department of Natural Resources (Marine Patrol) and the U.S. Coast Guard.

10.2 National Parks and Monuments

Another site-specific management program with applicability to coral protection is the system of national parks and monuments operated by the National Park Service (NPS) within the Department of Interior. In the broadest terms, the purpose of the NPS units are to "...preserve for all times scenic beauty, wilderness, native wildlife, indigenous plant life and areas of scientific significance and antiquity..." (16 USG §1). Although the National Park System includes several marine areas, their distinctly land-based orientation makes them somewhat less likely to include new marine areas within their system. Nevertheless, two areas operated and managed by the NPS include significant coral resources---the Biscayne National Monument north of Key Largo, Florida, and the Fort Jefferson National Monument in the Dry Tortugas, Florida. Both the statement of management for the Fort Jefferson National Monument (U.S. Dept. of Interior, National Park Service, 1977) and the general management plan for Biscayne National Monument (U.S. National Park Service, 1978) include as major management objectives the protection of natural resources (including corals) within their boundaries. At the Fort Jefferson Monument, all areas within the Monument's administrative boundaries (with the exception of Garden Key) are classified as an outstanding natural area under the National Park Service's land classification system. Prohibited activities include commercial fishing and the taking of lobsters while allowed uses include sport fishing and non-consumptive recreational activities. Under NPS management, the coral resources at the Fort Jefferson National Monument appear to be well protected (Jaap, 1979, personal communication).

According to the general management plan for the Monument, the Biscayne Monument is "...designed to facilitate the existing recreation activities in a compatible manner with the physical and biotic environment, and (to) provide mechanisms for detecting areas of existing or potential environmental degradation" (U.S. National Park Service, 1978). Recognizing that recreational use often creates a certain level of coral damage, some of the management provisions at this monument include: (1) monitoring to detect destruction of an area at early stages (to allow initiation of corrective measures); (2) improvement of monument boundary, channel, and depth warning markers at critical locations; (3) establishment of activity areas; (4) enforcement of regulations prohibiting tropical fish collecting and "pot hunting" (use of fish or lobster traps); (5) the establishment of mooring stations near corals to reduce anchor damage; and (6) establishment of monitoring stations to detect natural fluctuations in environmental factors such as temperature, salinity and wind. In addition, special studies are planned in cooperation with the state of Florida to determine what types of commercial and sport fishing will be allowed, in what magnitude, and what regulatory actions will be necessary.

In the Virgin Islands, the National Park Service has jurisdiction over a large portion of the coral reefs on the coasts of St. John and Buck Island. Apparently, however, only the Army Corps of Engineers exercises authority over marine environmental matters in the U.S. Virgin Islands outside the parks, particularly in relation to coastal dredging and construction. The questions of jurisdiction over coral reefs outside established reserves in U.S. Trust Territories has apparently not been addressed.

10.3 Outer Continental Shelf Oil and Gas Leasing

The Secretary of the Department of Interior (DOI) is charged with administering mineral exploration, development and removal on the OCS, pursuant to the Outer Continental Shelf Lands Act (OCSLA), as amended in 1978 (43 USC § 1331 et seq.). The Secretary of Interior has been limited to conservation rules and regulations of corals only as related to mineral leases. This responsibility has been delegated to two offices within the Department: the Bureau of Land Management (BLM) and the U.S. Geological Survey (USGS). The BLM serves as the administrative agency for leasing submerged Federal land. Federal law requires that unique and valuable biotic communities be protected from damage due to such activities. The USGS is charged with supervising mineral development operations on the OCS. It performs licensing and enforcing functions relating to offshore drilling and may act as an intermediary between BLM and the oil companies.

The Secretary of Interior can withdraw tracts from proposed OCS mineral lease sales for lack of information, aesthetic, environmental, geologic, or other reasons. The presence of coral reefs, hard bottoms, or other marine areas containing significant resources could be reasons for withdrawing tracts. Further, the OCSLA (43 USC § 1341) also provides for permanent disposition from leasing; Key Largo coral reef was provided such protection by President Eisenhower, through Proclamation No. 3339 (25 CFR 2352) which established the Key Largo Coral Reef Preserve on March 17, 1960. Ths disposition served as a precursor to the present Key Largo Coral Reef Marine Sanctuary. The Secretary of Interior's authority to issue rules and regulations including ones of conservation applies only in connection with the administration of OCS mineral leases and not the authority to promulage conservation measures regulating other activities.

With respect to oil and gas tract withdrawal, BLM has demonstrated an awareness and interest in preserving coral communities and other significant resources. Several potential lease tracts nominated by oil companies have been withdrawn due to the presence of significant bottom habitats, including some containing coral. For example, the Secretary of Interior rejected oil company bids for a tract off the Georgia coast (Tract #41) in the 1978 South Atlantic OCS Sale #43. The deletion was based on the perceived need to preserve a "live bottom cummunity" (i.e., hard bottom) documented to exist there. Similarly, the recent OCS Sale #48 in the Gulf of Mexico has prohibited drilling directly over several coral-encrusted hard banks located on salt domes, including areas directly over the East and West Flower Garden Banks (U.S. Dept. of Interior, Bureau of Land Management, 1978). Further, BLM lease stipulations require that drilling operations adjacent to these banks must shunt their drilling discharges directly to the bottom nepheloid layer (a dense water mass of high turbidity) to minimize potential impacts from surface discharges that might otherwise affect bank corals and other bank biota.

The Secretary of Interior's ability to delete lease tracts from oil and gas development and BLM's ability to require certain drilling techniques which minimize environmental damage through lease stipulations represent an important OCS habitat protection authority for protecting localized coral habitats. Further, the USGS must ensure oil company compliance with regulations and lease stipulations once a lease is sold, also represents a key management authority for ensuring protection of coral communities. Although these authorities are not comprehensive, they are significant because of the widespread interest in current OCS oil and gas development and its potential impact on corals.

10.4 Fish and Wildlife Service (FWS), DOI

The ability of the FWS to affect the management of coral is based primarily on the Endangered Species Act and the Fish and Wildlife Coordination Act. Although no coral species have been listed as endangered or threatened under the Endangered Species Act, one--the pillar coral (Dendrogyra cylindrus)--has been recommended for listing. If listed, protection against the taking of the listed species and disruption of its critical habitat would be forthcoming. Under the Fish and Wildlife Coordination Act, the FWS reviews and comments on proposals for work and activities in or affecting navigable waters that are sanctioned, permitted, assisted, or conducted by Federal agencies. The review focuses mainly on potential damage to fish and wildlife, and their habitat, presumedly including coral.

10.5 Environmental Protection Agency (EPA)

EPA may provide protection to coral communities through the granting of National Pollutant Discharge Elimination System (NPDES) permits for the discharge of pollutants into ocean waters, and the conditioning of those permits so as to protect valuable resources. EPA has extended its authority to control dumping of oil and gas drilling effluents by issuing NPDES permits beginning in 1980. Consideration of ecosystem integrity in the granting of ocean dumping permits may also foster the protection of corals.

10.6 Corps of Engineers (COE), Department of the Army

COE jurisdiction over the disposal of dredged material, pursuant to both the Clean Water Act and the MPRSA, could be exercised in a manner protective of coral resources. Proposals to dispose of materials during the construction of artificial reefs, for example, are assessed to assure that the disposed materials do not pollute or physically alter the environment.

10.7 United States Coast Guard (USCG), Department of Transportation (DOT)

The Coast Guard's prime management jurisdiction emanates from the Ports and Waterways Safety Act, as amended in 1978, under which it may regulate shipping in the waters offshore the U.S., in part, to protect the marine environment.

USCG may establish and operate shipping lanes and other vessel traffic services, and also establish vessel design and operation standards, all of which may attenuate the impacts of commercial shipping on coral resources. Under various environmental statutes, including the FCMA, USCG is charged with enforcement responsibility to prevent damage to the marine environment. Also, the Coast Guard, along with EPA, administers the National Oil and Hazardous Substance Pollution Contingency Plan. As part of that plan, USCG has final authority over the procedures and equipment used to clean up oil spills.

10.8 Fish and Wildlife Service (FWS), DOE, and Customs Service (CS), Treasury Department

A special management institution involving the Customs Service of the U.S. Department of Treasury and the Fish and Wildlife Service of the U.S. Department of the Interior coordinates the importation of corals. Regulations have been implemented concerning duty percentages for various products and lega ports of entry, among other subjects.

11. JURISDICTION - STATE PROGRAMS

Because significant coral communities within state waters appear to be limited to the southernmost portions of Florida, detailed discussion of site-specific state programs is limited to those actually protecting coral habitat in Florida. The programs identified to be of primary concern include the state's Aquatic Preserve and Park Systems.

11.1 Florida Aquatic Preserve System

By special legislative action, the Florida Aquatic Preserve Act of 1975 (Florida Statutes, Sections 258.35 - 258.44) was created to establish a direct means of permanently preserving submerged, state-owned lands. The Act defined an aquatic preserve as a "biologically, aesthetically or scientifically...exceptional area of submerged lands and its associated waters set aside for maintaining the area essentially in its natural or existing condition" (Florida Statutes, Sections 258.37 - 258.38).

The Aquatic Preserves created under this Act include only lands and water bottoms owned by the state (Florida Statutes, Section 253.03) and other lands or water bottoms that another government agency might authorize for preservation. No privately owned lands or water bottoms are included in the Act unless by special agreement with that private owner. Other specific exclusions from the Aquatic Preserves are areas altered by channel maintenance of other public works projects and, lastly, lands lost by avulsion or artifically induced erosion.

The Aquatic Preserve System is administered by the Florida Department of National Resources. Limitations on usage (discussed in Section 258.42 of the Florida Statutes) control: sale, lease, and transfer of preserve lands; water relocation or bulkheading; dredging or filling except a required minimum; drilling for oil or gas; or mineral excavation. Private owners bordering the preserve retain certain riparian rights to construct docks and protect their shoreline, if those actions are deemed necessary.

Although each preserve was to have its own set of rules and regulations to protect water quality and aquatic resources, no preserve rules have yet been developed. In process, however, are rules for the Biscayne Bay Aquatic Preserve which could provide a prototype set of rules for other designated preserves.

The original Florida Aquatic Preserves Act of 1975 outlined boundaries for 31 Aquatic Preserves. Although most of these are in inshore waters such as rivers and estuaries, ocean areas may also be included. At least three preserves in the Florida Keys probably include coral habitats--the Coupon Bight Aquatic Preserve adjacent to and south of Big Pine Key, Florida; Lignumvitae Key Aquatic Preserve to the south of Key Largo, Florida; and Biscayne Bay Aquatic Preserve in Biscayne Bay, Florida.

11.2 Florida State Park System

The relevance of the State Park System is due principally to the John Pennekamp Coral Reef State Park on and off Key Largo, Florida. This outstanding park adjacent to Key Largo Coral Reef Marine Sanctuary contains significant coral reef habitats. The park is managed to (Florida Dept. of Natural Resources, Division of Recreation and Parks, 1971):

1. Seek a true balance between preservation of natural conditions and the permitting of various recreational pursuits.

2. Emphasis in recreational use is on passive varieties.

3. Management program emphasis is on interpretation and appreciation of the natural attributes--aesthetic, educational, and scientific.

4. Development is geared toward providing convenient access to and within the park; recreational facilities should be spaced reasonably and balanced with access and competitive land use; development is limited to not more than 20 percent of the land area.

The John Pennekamp State Park was established in 1959 and includes over 125 km^2 (36 nmi^2) of state waters.

Within John Pennekamp Coral Reef State Park (Figure 1) and several other state parks containing reefs in Monroe County, the Florida Department of Natural Resources (FDNR) Division of Parks, along with the Division of Law Enforcement Marine Patrol, enforces state rules and regulations concerning reef use. The Marine Patrol also enforces pertinent rules and regulations in state waters outside state and federal parks, monuments, and refuges.

Florida has a 10-1/2 mile limit on its Gulf coast and a 3-mile limit on the Atlantic. However, there are small islets farther than three miles off Key Largo, Key West, and areas between which are considered Florida land, even though they barely break the sea surface. The reefs surrounding these low islets are also under Marine Patrol surveillance.

Although these state agencies attempt to enforce the strict Florida laws concerning exploitation and damage to coral reefs, their field staff is limited in terms of personnel and funds. For example, the Marine Patrol consists of 200 offices distributed in 11 enforcement districts and is responsible for enforcing laws over 8300 miles of coastline (Lt. Harding, 1980, personal communication, FDNR Division of Law Enforcement Marine Patrol, St. Petersburg, Florida).

11.3 Other Site-Specific Protection Programs

In addition to the above listed active habitat protection efforts, several other government programs which could or might be expected to have relevant area specific coral protection authorities have also been considered: state Natural Area Programs; the Outstanding Florida Water System; the Federal Estuarine Sanctuaries Program within the Office of Coastal Zone Management; the Geographic Areas of Particular Concern segment of developing state Coastal Zone Management Programs; and the National Wildlife Refuges operated by the U.S. Fish and Wildlife Service.

State Natural Area Programs have not been considered in detail because, with the exception of Florida, no significant coral communities have been identified in any other state waters. The Florida Outstanding Florida Waters classification, which took effect January 1, 1979, is the newest aquatic protection initiative mandated by the state of Florida. Since waters so designated presently include only surface waters within existing national and state parks, monuments, aquatic preserves, recreation areas, environmentally endangered lands, and similar systems, and since it is still too early to project how this new classification might relate to coral protection, it is not discussed in detail.

Several estuarine sanctuaries have been considered and established along the coast. Estuaries, however, are not typically suitable sites for extensive coral communities. Thus, the relevance of estuarine sanctuary designations will be limited primarily to the extent that they can improve or assure high quality coastal water drainage and not their ability to preserve specific aquatic habitats. High quality coastal drainage is important so as to reduce pollution stress to coastal open water marine habitats including important coral habitats.

As mentioned above, the only state in the management area believed to have jurisdiction over important coral habitat areas is Florida. The coastal zone management program of the state, now being restructured and redirected, has limited its identification of geographic areas of particular concern to areas already established by the state legislature (i.e., Aquatic Preserves, State Wilderness Areas, Areas of Critical State Concern, Environmentally Endangered Lands, and Coastal Shore Front Areas). None of these areas, however, included special provisions to protect corals or coral habitats. Only the above mentioned Biscayne Bay Aquatic Preserve and the Florida Keys Areas of Critical State Concern contain coral habitats.

Finally, three National Wildlife Refuges are located in the Florida Keys which undoubtedly contain coral habitats: the National Key Deer Refuge, the

Great White Heron National Wildlife Refuge, and the Key West National Wildlife Refuge. These areas are operated by the U.S. Fish and Wildlife Service. These areas, however, rely on the coral permitting authority of the State of Florida to protect the corals (Shinn, 1979).

12. MANAGEMENT AND RESEARCH RECOMMENDATIONS

The importance of coral ecosystems and closely associated habitats has been well documented by numerous studies and symposia (Jones and Endean, 1973, 1976; Bright and Pequegnat, 1974; Taylor, 1977). Many emphasize the complex structure of coral ecosystems, the importance of coral for habitat, the sedentary life-style, the wide geographic and bathymetric distributions and the many behavioral, physiological, ecological and physical associations that combine to yield an exceedingly intricate functional unit. Most corals inhabiting our nation's continental shelf, especially the hermatypic species which are less temperature tolerant, are at the very limit of their geographic range.

It is very important to implement rational policies to minimize man-induced stresses on coral reef ecosystems. The remoteness and diversity of the resource, however, make it impossible to enact general regulations that would offer universal management criteria. Suggestions to improve management and guide future research on coral ecosystems appear below.

Regional management procedures could be adopted which would give each ecosystem the specific protection needed. Agencies in existence can take the responsibility with adequate support and funding. Reefs adjacent to coastal states should be entrusted to those states, provided they have the willingness, expertise, and manpower to accomplish the task. Reefs found in insular or remote regions on the continental shelf not presently under effective management should be watched over by BLM, the United States Coast Guard, NOAA, or some other federal enforcement agency or combination of agencies in a cooperative sense. Pacific Trust territories require special consideration due to their remoteness, unique fauna and recent rapid human population growth. There is apparently little attention being paid to reef environments near some of these islands.

In all cases, the pertinent management-regulatory arms of the agencies involved should be located near the reefs in question, have a staff of qualified persons and be able to react quickly to natural or man-made reef catastrophies. Management agencies should support local educational-information programs to minimize man-made damage to the reefs. There is a need for regional organizations to coordinate research, collect and maintain pertinent literature and data in central locations, sponsor regional meetings, monitor reef usage and act as clearing houses for questions concerning local coral reefs.

On the national level, general relief for all coral reefs could be accomplished by enacting laws banning the sale of coral in the United States and providing funding for coral reef research and management in the appropriate states, commonwealths and trust territories.

Since most of the information required for meaningful decision-making on coral reef management is either poor or unavailable, research is a primary need.

At a research coordinating meeting in Miami on October 13, 1975, the following research needs were accepted by many of the scientists present: (1) synoptic mapping to locate and define reefs (including aerial mapping, sidescan sonar profiles and ground truth); (2) resource inventory (including quantitative sampling of selected groups of key reef biota, physical and chemical oceanography, pollution ecology), and (3) study of resource stress factors (including water and air pollution, dredging, user activities).

12.1 South Florida Reef Track

Past management practices pertaining to Florida's reefs are enlightening in reference to current and future problems. From the time of Spanish exploration until the establishment of the Key Largo Coral Reef Preserve (John Pennekamp Coral Reef State Park) in 1959, activities in the reef areas were governed by a laissez faire policy. The establishment of 75,130 acres as a marine park has had mixed consequences. The reefs have been protected from specimen collecting and spearfishing, but the heavy influx of tourist divers has created difficulties in maintaining the pristine nature of the sanctuary.

State and federal attempts to act on reef problems have been well meaning but difficult to enforce. Some of the more important policies that have directly or indirectly affected the coral reefs include:

1. Establishment of John Pennekamp Coral Reef State Park, off Key Largo.

2. A temporary moritorium on all dredging in Monroe County.

3. Declaration proclaiming Monroe County an area of critical state concern, with state participation in zoning and establishment of guidelines for land and water management.

4. Federal establishment of the Biscayne National Monument to include coral reefs north of John Pennekamp Coral Reef State Park.

5. Enactment of suits by the U.S. Corps of Engineers against illegal development in the Florida Keys; builders at fault were required to return land to its original condition.

6. Enactment of coral protection legislation on the state and federal level.

7. Sponsorship of two coral reef workshops to establish liaison and determine research needs in the Florida reef tract.

8. Participation of the Smithsonian Institution with a private institution (Harbor Branch Foundation) to conduct coral reef research in John Pennekamp Coral Reef State Park.

9. Investigation, by state and federal field teams, of environmental damage to the reefs.

10. Establishment of a Federal Marine Sanctuary adjacent to John Pennekamp Coral Reef State Park.

11. Sponsorship of reef research in the Dry Tortugas by the National Park Service.

A coastal zone management study (Florida Dept. Nat. Res., 1974) of Monroe County brought to light numerous problems and made a strong recommendation that "An immediate intensive research effort should be established to ascertain physiological stresses of the Florida Keys coral reefs as a system. Such an effort should be designed to serve as a basis for active management of the reefs as a valuable public resource and should include provisions for monitoring their vitality over time." Reef research needs have since been better defined, however, there has been no commitment to implement the program. After the October 1974 coral reef workshop, the Florida Department Natural Resources Marine Research Laboratory was designated as the agency responsible for monitoring environmental conditions in the Florida coral reef tract (Florida Dept. Nat. Resources, Coastal Coordinating Council, 1974). The Governor and state cabinet signed the workshop document on February 17, 1975; their signing and recommendation of the 1974 Monroe County Coastal Zone Management Study were accepted as a sign of support for reef conservation. However, funds have not been available for the Marine Research Laboratory to initiate the program, and research efforts have been limited to small, less comprehensive activities and reaction to reef catastrophes.

The National Science Foundation, approached during 1974 for information on submission of grant proposals by FDNR for support of the Florida reef tract program, responded that NSF would not consider funding such a project submitted by a state agency.

Recent trends in coral reef research funding need examination. The Cooperative Investigations of Tropic Reef Ecosystems (CITRE) was to be an International Decade of Ocean Exploration (IDOE) coral reef research program; CITRE never got beyond the planning stages. The Smithsonian Institution conducts a limited amount of coral reef research through their Investigations of Marine Shallow Water Ecosystems (IMSWE). The NOAA Manned Underseas Science and Technology Office (MUS&T) now fund coral reef research at Hydro-Lab, a small undersea habitat off Grand Bahama. Thirty research articles appeared in the Hydro-Lab Journal; there were numerous unpublished reports, and some analyses are still in progress. Hydro-Lab is now operating in St. Croix, U.S. Virgin Islands.

Currently, we have a multitude of state and federal agencies and bureaus with legal responsibilities in the coral reef ecosystems (Table 1). Very few of these have funds to operate or manage their defined areas. When offshore drilling leases were let in the eastern Gulf of Mexico, there was competition among EPA, USGS, NOAA, BLM and USF & WS for administration of associated environmental studies. Until BLM was given jurisdiction, investigators were unable to determine who the regulatory agency was.

Appendix 2 outlines research priorities particularly applicable to the South Florida reef tract which, if pursued, would provide much of the management-related information necessary to insure the perpetual well-being of this valuable regional resource.

AGENCIES	air & water quality	bulkhead lines	dredge & fill	beach construction setback	aquatic preserves	wetlands protection	aquaculture	game & fish management	hurricane flooding	land use control	utilities control & management	law enforcement	solid waste disposal
I. FEDERAL													
A. Dept. of Commerce	o	o	o		●	o	o	●	●	●		o	
B. Dept. of Defense	o	●	●			o			o	o	●	o	
C. Environmental Protection Agency	●	o	●			●		o		o	●	o	●
D. Dept. of Interior	o		o			o		●	o	●	o	o	
E. Dept. of Transportation	●									o	o	●	●
II. STATE													
A. Dept. of Administration	o					o				●			
B. Bureau of Coastal Zone Management	o	o	o	o	o	o	o	o	o	o	o	o	o
C. Dept. of Natural Resources	●	o	o	●	o	●	o	●		●		●	o
D. Dept. of Environmental Regulation	●	o	●	o	o	●	o	o		●	●	o	●
E. Dept. of State										o			
III. REGIONAL & LOCAL													
A. Central & Southern Florida Flood Control District	●					●				o	●	o	
B. South Florida Regional Planning Council										●			
C. Florida Keys Aqueduct Authority											●		
D. Monroe County	●	●	●						●	●	●	●	●
E. City of Key West	●	●	●						●	●	●	●	●
F. City of Layton		●	●						●	●		●	
G. City of Key Colony Beach	●	●	●						●	●	●	●	●

Legend

Primary Responsibility - ● Secondary Responsibility - o

12.2 Offshore Reefs and Banks

With the exception of the U.S. Bureau of Land Management and the U.S. Geological Survey, authority to promulgate regulations prohibiting damage to coral by gases or others engaged in operations substantially related to mineral activities, management of offshore reefs in the northern Gulf of Mexico has been non-existent. Increased accessibility and use of these reefs will follow the installation of petroleum production platforms near them (exploratory wells are now being drilled within three miles of the East and West Flower Gardens).

A reasonable long-term environmental monitoring program at selected offshore reefs in the northern Gulf of Mexico is necessary to (1) quantitatively assess apparent changes in reef communities due to human activity against a background of natural variation in reef populations and the effects of coral pathogens and other natural destructive agents, and (2) monitor hydrography, water quality and environmental levels of chemical contaminants.

Most of the research priorities presented in Appendix 2 apply to offshore reefs as well as coastal reefs. Some of the more obvious information needs relating to management of offshore reefs are:

1. The distribution of reefal communities on offshore banks (reefs should be mapped).

2. The toxic effects on reef building corals and other reef organisms of chemical and particulate wastes entering the Gulf through rivers, ocean dumping, or as offshore drilling effluents.

3. Details of water movements on the continental shelf (particularly near reefs and banks) of characteristics of dispersal and sedimentation processes affecting contaminants released near the banks.

4. Nature and extent of naturally occurring pathological conditions affecting corals on offshore reefs.

5. Effects of hurricanes and severe storms on the reef communities.

6. Extent and impact of mechanical damage to reefs due to anchoring and diver use.

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APPENDIX A

RECOMMENDATIONS CONCERNING FUTURE DREDGE PROJECTS IN THE FLORIDA KEYS

(From Griffin, 1974)

Because dredging of the entrance canal at Basin Hills appears to have had no detectable impact on the coral patch reef 0.48 miles to the NNE or on the remaining grass flat areas, it seems reasonable that future dredging regulations in the Keys and other coral reef areas could use this project as a minimum model, at least until it is proved that the system can tolerate greater stresses. Based on this general philosophy, it is suggested that future regulations include consideration of these criteria prior to approval:

I. Significant reefs composed of hermatypic corals, and more than 20% alive, within one nm of the proposed canal must be located and mapped by diving scientists. Canals and related temporary or permanent spoil areas should be positioned so as to approach no closer than 0.5 nm to such reefs in order that they be protected from excess sedimentation. The more or less continuous linear zones of low (less than 1 foot high) non-reef-forming *Porites divaricata* and other similar corals that occur within several hundred yards of shore should not be included in this restriction.

II. Locations where the surface of the nearshore bottom is composed predominantly of bare limestone bedrock should be favored for entrance canals, and areas of significant *Thalassia* will continue to aid in water clarification.

III. Also, to aid in sediment trapping and water clarification, a fringe of red mangrove should be preserved along the shoreline, and care must be taken to preserve its vitality during and after dredging. The width of this zone should be determined by future research; for the present, it is suggested that it be at least 100 feet, or no less than the preexisting width if that should be less than 100 feet. (The natural width of the mangrove fringe along Key Largo varies from approximately 60 feet to several hundred yards; it is easily discerned on color aerial photos.) All spoil shall be deposited no closer to the coastline than the width of this fringe. There should probably be no objection to stilt or catwalk structures, or piers over parts of this fringe zone, so long as they do not involve removal of vegetation or otherwise interfere with healthy growth of the mangrove.

IV. The number of dredged entrance canals should be limited so as to avoid excessive turbidity during dredging, and also to avoid the low-level turbidity that persists after dredging. A periodicity averaging one entrance canal per linear mile of coast seems reasonable, with the actual canal site selected so as to avoid the live coral reefs and grass flats, which must be mapped, as prescribed in I above.

V. Between entrance canals, perimeter canals, separated from the coast by the mangrove fringe described in No. III above, seem on the whole to be a desirable alternative to an excessive number of entrance canals. However, legislation seems necessary to force perimeter canal owners to allow new connections into them by adjacent developments. Perhaps entrance and perimeter canals should be dedicated for public use in the same way as streets in inland subdivisions.

The allowable depth of perimeter canals should be dictated by the depth requirement for adequate water exchange with adjacent natural open water bodies. Otherwise, the perimeter canals quickly become oxygen depleted, with resulting fish mortality and diminished recreational usage. Also, adequate number of vents to open water must be provided for oxygen ventilation. It is suggested, in lieu of further research, that vents be provided every 200 linear feet of perimeter canal, and that these be open channels 3 feet deep and 10 feet wide to allow limited passage of small boats. These vents should not extend more than approximately 50 feet seaward of the mangrove fringe.

VI. No additional artificial "cross-key" waterways should be allowed between the Atlantic side of the Keys and the Florida Bay, Barnes Sound, and Card Sound side. This restriction would prevent greater influx of the more turbid bay waters into the reef tract area. In addition to higher turbidity, the bay waters also undergo much greater seasonal temperature and salinity fluctuations than the Hawk Channel waters, and all of these factors are detrimental or even lethal to growth of coral and other sensitive organisms of the reef track area.

VII. The hard-rock dredge techniques described earlier, as employed at Basin Hills, produce much less turbid water than hydraulic dredging. Therefore, it is recommended that no other type of dredging be permitted in the Keys or similar areas elsewhere.

Also, because the rates of effluent generation and dispersal are important in assessing effects on water clarity and possible biologic damage, it is recommended that, in lieu of further research, the rate of dredging in the Keys be restricted to that at Basin Hills, i.e., approximately 570 cubic yards per 8-hour working day. In addition, the total rate of fallout should be monitored by sediment traps 100 feet away on both sides of the canal extension, and limited to a maximum 200 $mg/cm^2/day$, averaged over a one week period. If the total fallout exceeds this amount, dredging should pause for one week, to allow the natural dispersive forces to clear the organisms of sediment.

VIII. Turbidity diapers seem beneficial only if the dredge operator repositions them frequently, so as to close gaps. Attention to this seems especially necessary in the final phase when one of the parallel spoil fingers has been completely removed, leaving a large potential opening. Also, gross leaks were frequently observed at anchor points in the corners of the diaper. This suggests that a redesign of diapers is needed to eliminate the depression of the corners.

The diaper allows suspended matter to settle to the bottom instead of being dispersed immediately as a turbid plume. However, no permanent benefit is obtained from this unless the entrance canal is dredged deeply enough to form an effective sediment trap; otherwise, natural waves and currents and boat wakes will resuspend the fines whenever the diaper is removed. Therefore, it is suggested that regulations requiring a diaper, to be effective in reducing turbidity permanently, must be coupled with a requirement that the canal be dredged to several feet below the effective base of the expected disturbances. The minimum required depth would have to be determined by further research, but is probably at least on the order of 8 to 10 feet. This depth would exceed the maximum of 6 feet previously recommended by the Florida Department of Pollution Control (1973) for all canals. Perhaps, the previous recommendation should be re-examined and possibly applied only to perimeter and other interior canals.

IX. Lastly, it is recommended that research into the technology of dredging and its potential effects continue. At present, there is insufficient quantitative knowledge of at least five points: (a) the tolerance limits of organisms to increased sedimentation and turbidity; (b) the width of mangrove fringe and/or *Thalassia* beds necessary to provide adequate natural suspended sediment traps (i.e., natural water clarification); (c) the ultimate depositional site of the excess particles generated by the dredge; (d) the optimum methods of providing oxygen bearing water to the perimeter and other interior canal systems; and (e) the size-distribution of the dredge effluent, and the possible effects of changes from the natural size distribution on the respiration of some of the important organisms of the inshore area.

APPENDIX B

CORAL REEF RESEARCH PRIORITIES

I. Mapping of the coral reef tracts.

Aerial photography of the entire Florida reef tract with water penetration film is being undertaken. Numerous overlays are currently available, and some ground truth data have been taken. Completion of photography and basic ground truth acquisition to define fundamental biotopes is of utmost importance. Similar programs should be established for the U.S. Virgin Islands.

II. Resource inventory.

Existing aerial photography should be used to ascertain locations of patch and fringing reefs. Study sites should be established at selected patch and fringing reefs in four geographical areas of the Florida reef tract: the northern, mid, and lower tract, as well as Tortugas. These sites would provide a broad coverage of existing Florida reef environments. Similar sites should be established off Texas and in the U.S. Virgin Islands. The following studies should be conducted at selected sites:

A. Baseline data gathered along permanently installed multiple transects in selected reef areas.

1. Biological assessment including species composition, distribution, diversity and community affinity of the scleractinian and octocorallian faunas.

2. Assessment of the reef ichthyofauna.

    a. An *in situ* SCUBA census of dominant reef species along designated transects. Species selected should be numerically abundant, easily identified, and otherwise amenable to census methods. Particular attention to certain parrotfishes (Scaridae) is suggested because their diet includes coral polyps.

    b. Surveys of ectoparasites of particular taxa are suggested. Changes in relative incidences of such parasites could relate to changes in abundance of cleaner organisms (such as shrimps and gobies), which could relate to changes in the coral reef itself.

3. Assessment of algal and possibly seagrass stocks, and their contribution to the reef community.

4. Possible assessment of other invertebrate taxa, including poriferans, actiniarians, and echinoids.

B. Specialized studies to be initiated concurrently with or after the baseline inventories at the same sites. These studies are necessary to determine population dynamics of coral, *i.e.*, recruitment rates, growth rates, living space competition, predators and pathogens.

1. Recruitment studies should be conducted by establishing "clear off" sites, then monitoring coral colonization. These will provide information on how long an area will require to become recolonized after a major disturbance.

2. Growth studies should be conducted within the same study sites to provide data on the time required for an actual coral community to re-establish itself after a major disturbance.

3. Studies on organic cover of a reef should be conducted within the same sites to determine which organisms compete with coral for living space.

4. Studies of natural predators of coral should be conducted. These will provide an understanding of natural destruction of reef versus externally induced destruction.

5. Studies on certain "pathogens," e.g., *Oscillatoria*, *Desulfovibria*, *Beggiatoa*, "white death," and others, should be conducted to determine normal background levels, relationships to fish abnormalities, etc.

6. Studies on other organisms not *directly* associated with corals but responsive to the same sensitive environmental conditions should be conducted. Suggested organisms include chaetodonts (butterfly fishes), scarids (parrot fishes), and selected gastropod mollusks such as *Strombus* (Queen Conch) and *Cerithium litteratum*.

C. Physiochemical inventory - These studies are basic to detecting causes of alteration or change in community structure. It would be impossible to determine the cause of a reef decline or even catastrophe without having knowledge of the physical and chemical factors influencing the reefs.

1. Studies of water chemistry (to include constant monitoring of temperature and salinity), water exchange, and wave energy should be conducted. These studies might possibly be coordinated with ERTS overflights, giving a broad base of information at which to aim specialized data needs.

2. Assessment of heavy metals, pesticides, hydrocarbons, and industrial chemical waste (in sediments, the water column, and selected organisms) should be made. Having delimited normal levels of these elements, any increase can be monitored for possible reef damage.

3. Assessment of terrestrial runoff and sewage discharge should be made. Present levels will be delimited and future assessment of problems will be possible.

D. Geological inventory - A geological inventory is necessary mainly in reference to sedimentation. Light is one of the fundamental factors governing reef development. High levels of sedimentation have been shown to be detrimental to coral viability.

III. Resource monitoring should be conducted to relate cause and effect of observed changes.

A. The fauna or flora assessed in the baseline studies should be periodically resurveyed to determine any changes in their relative stability as members of the reef community.

B. Those parameters assessed during the physiochemical inventory should be monitored to document any drastic changes that might be detrimental to the reefs.

IV. Measurement of user pressure on the resource should be made. All factors of a resource that are used to any extent are somewhat depleted by that use. How much and how often it is used should be documented to facilitate precise management of that resource.

A. Commercial pressures on the resource such as fishing, lobstering, and coral harvesting should be monitored to insure that such activities do not exceed the ability of the resource to maintain itself.

B. Recreational pressures on the resource, such as sports fishing, diving, and attendant anchor damage to the reef, should be monitored.

V. Management of the resource must be conducted.

A. A program of education and information dissemination should be main- so that the users may be well informed about the resource.

B. Research being undertaken on Florida, Texas, and U.S. Virgin Island reefs must be coordinated to insure that the best possible information is developed for sound management of the resource. An organization must be appointed or created to: (1) store and retrieve data; (2) sponsor meetings for exchange of information and ideas; (3) generate funding; (4) review proposals to avoid duplication of effort; and (5) inform investigators of work currently in progress that might relate to their own.

APPENDIX C

OFFSHORE CORAL REEF AND HARD-BANK RESEARCH PRIORITIES, TEXAS-LOUISIANA

I. Obvious problems

A. Ocean dumping
B. Drilling and oil and gas transport
C. Waste discharge from rivers

II. Concerns

A. Coral reefs and attendant communities
B. Other fishing banks

III. Management needs

A. Information leading to resonable predictability of the effects of specific contaminating or damaging activities on biotic communities of concern.

B. Information to provide the basis for assessment of actual effects of such activities during their progress and after they take place.

IV. Major gaps in knowledge

A. Details of water movements on the continental shelf, particularly on a small scale over short time periods.

B. Dispersal rates of contaminants.

C. Settling and sedimentation rates of contaminants.

D. Specific effects of contaminants on key marine organisms.

E. Normal ranges of variation in population dynamics of communities of concern.

F. Growth rate, mortality, and life cycle studies for predominant coral and coralline algal species.

G. Long-term effects of contamination on communities of concern.

V. An approach

A. Establishment of long-term, hard-bank monitoring sites on the outer continental shelf.

1. East Flower Garden Bank
2. Stetson Bank
3. Hospital Rock

B. Objectives at long-term monitoring sites.

1. Determine the nature and magnitude of seasonal and other natural variations in certain important components of biotic communities. Reason: to provide the population dynamics background against which supposed effects of contamination on communities can be effectively evaluated over time.

   a. Hard banks

      Epibenthos
      Groundfishes

   b. Soft bottoms near banks

      Trawl-caught benthos
      Meiobenthos
      Macroinfauna

2. Determine variability of other pertinent and biologically important hydrographic conditions such as temperature, salinity, and turbidity, from surface to bottom.

3. Determine details and variability of small-scale (several miles) water movements over long periods of time at each locality from surface to bottom.

4. Experimentally determine dispersion rates, settling and sedimentation rates for supposed contaminants under various conditions of water movement.

5. Periodic determination of concentrations of selected chemical entities in selected biota and substrata.

C. Attendant pertinent laboratory and field studies.

1. Effects of specific expected contaminants on adults of key organisms from each community of concern.

   a. Hard banks

      Species of reef building corals

      Millepora alcicornis
      Montastrea annularis
      Diploria strigosa

      Lithothamnium--coralline algae
      Spondylus americanus--Americal thorny oyster
      Chromis enchrysurus--Yellowtail reef fish

b. Soft bottom near banks

An array of meiobenthos as a unit
Micropogon undulatus--Atlantic croaker
Stenotomus caprinus--Longspine porgy
Penaeus setiferus--White shrimp
P. aztecus--Brown shrimp

2. Life histories and growth rates of these same key organisms, followed by studies of effects of contaminants on various critical stages in ontogeny.

3. Coral growth rate and mortality studies at selected localities.

4. Assessment of extent and effects of coral diseases, bioeroders, and coralivores.

5. Monitoring of extent and effects of chronic mechanical damage due to anchoring or other activities.

VI. Advantages of the approach

A. Regardless of initial problems in establishing the required base of knowledge in the face of imminent impacting industrial activities, after a few years a highly practical and managerially functional system would be developed to monitor and assess long-term effects of all types of ocean contamination relating to the outer continental shelf hard-banks in the northern Gulf of Mexico. The functionality of the approach, therefore, goes far beyond an immediate interest in effects of ocean dumping and petroleum industry operations.

B. Within the framework of the program, responsible and dedicated researchers could answer a number of very basic questions concerning the nature and magnitude of effects of pollution and other human impacts on key offshore reef organisms and biotic communities.

Figure 1. Coral reefs and organic banks in Florida and the Gulf of Mexico (stars). Prescribed ocean dumping areas for chemical industrial wastes off Texas and Louisiana (squares). State and Federal areas include reefs in the Florida Keys and Dry Tortugas (arrows).

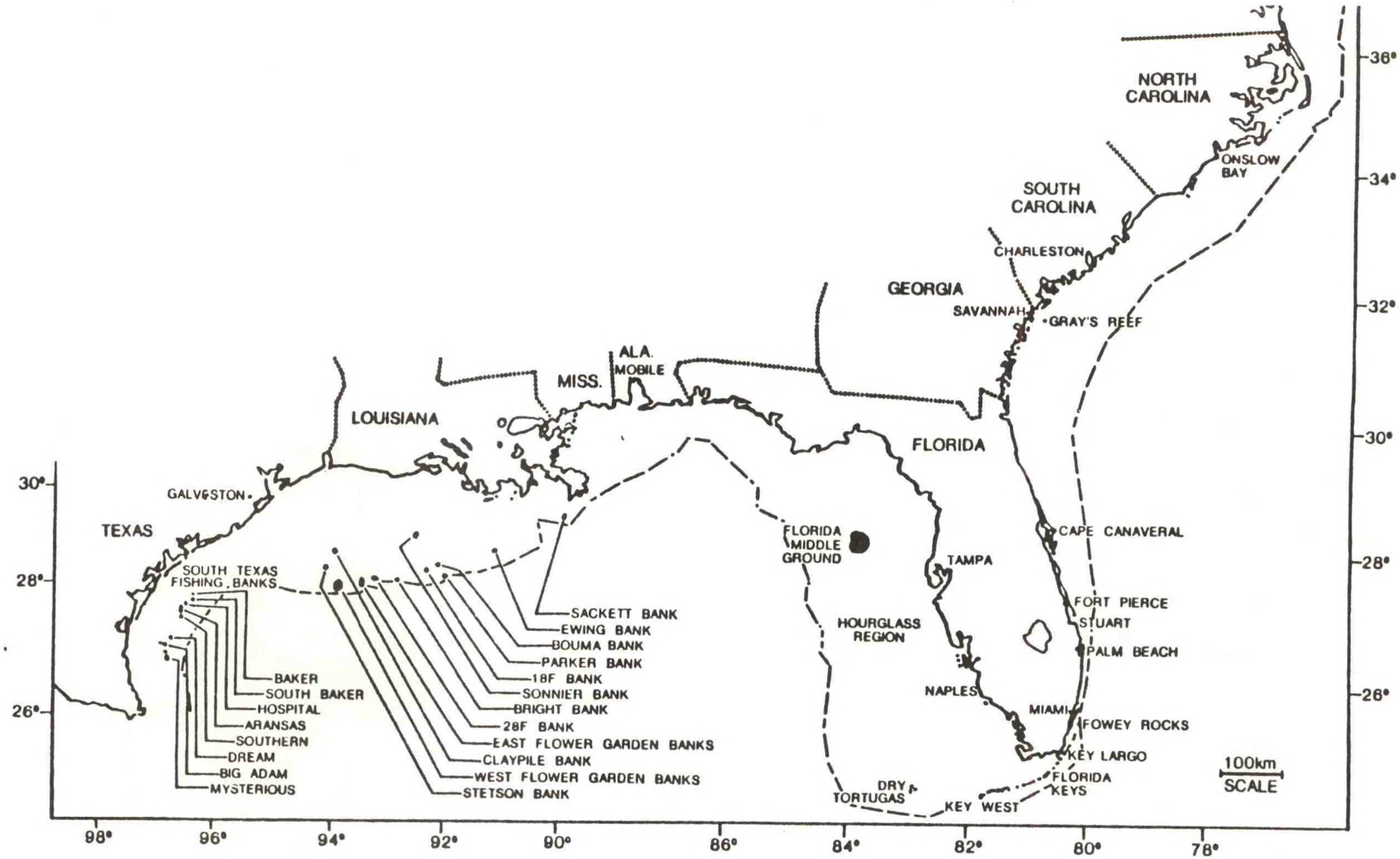

Figure 2. Distribution of hard banks and prominent hard bottoms in the Gulf of Mexico and South Atlantic regions. Broken line denotes edge of the continental shelf at 200 m (660 ft.).

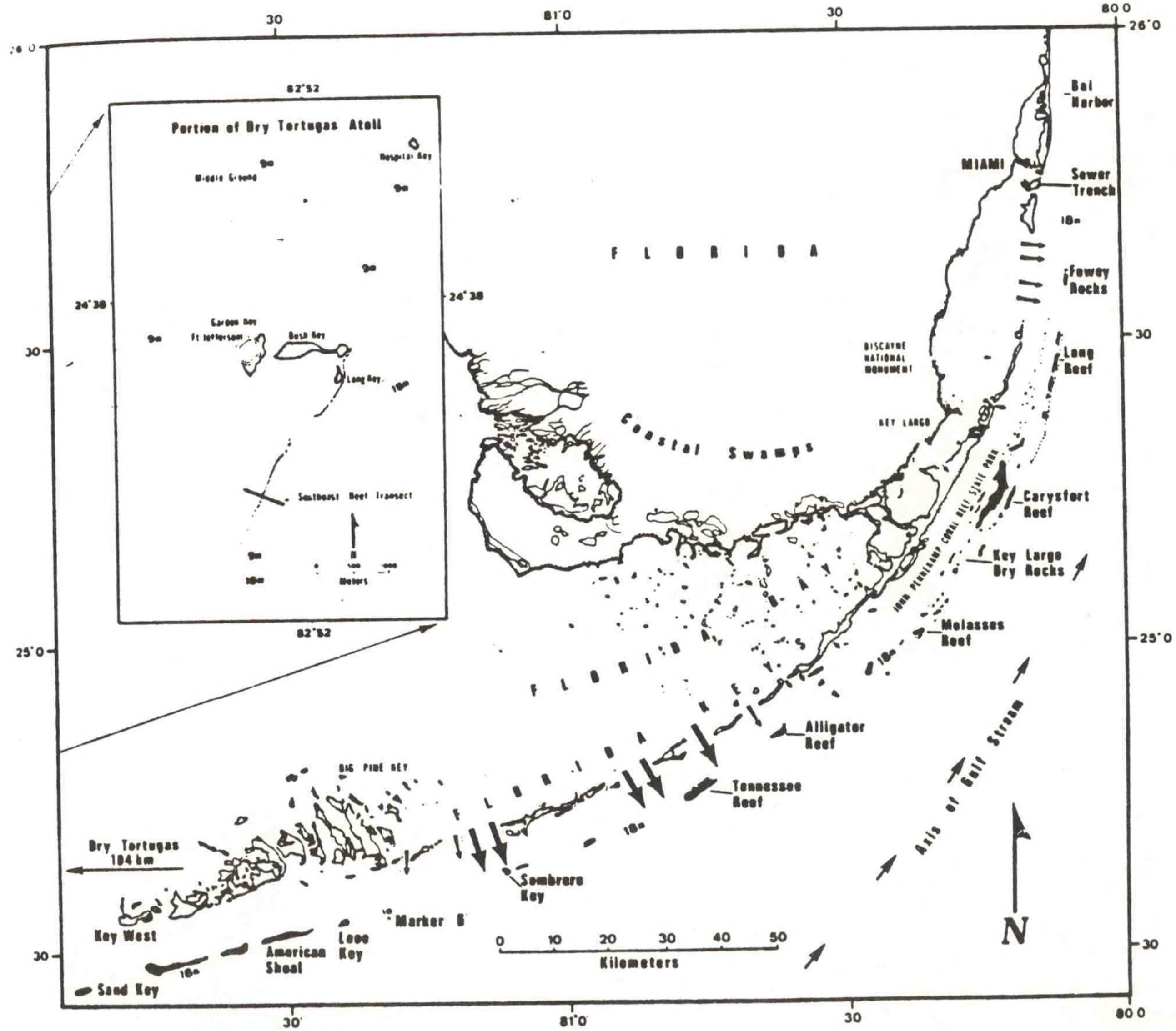

Figure 3. The Florida Keys. Arrows indicate major passes for bay water exchange (From Shinn et al., 1977, with permission of the author.)

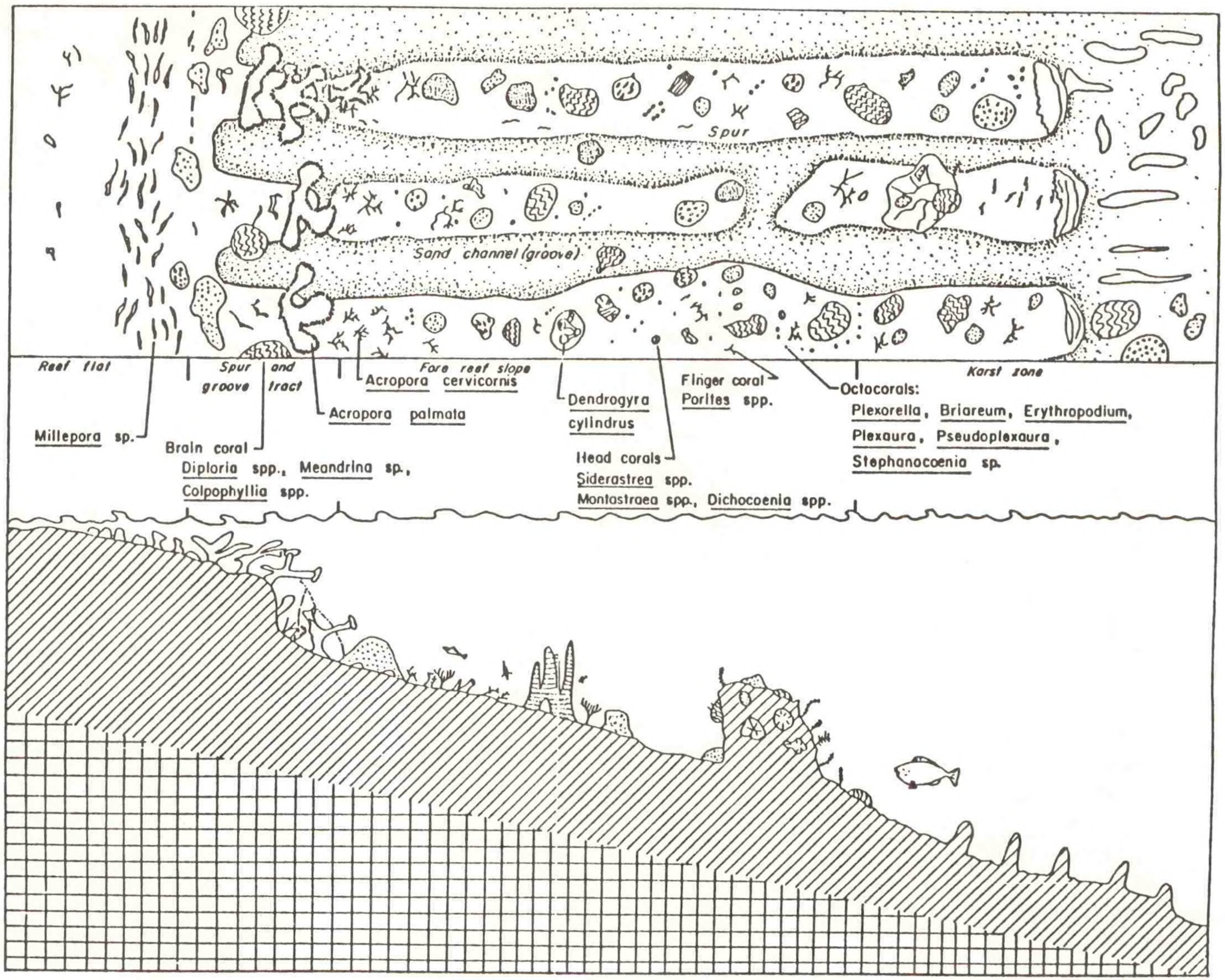

Figure 4. Composite diagram showing conspicuous features of coastal coral reefs in Florida.

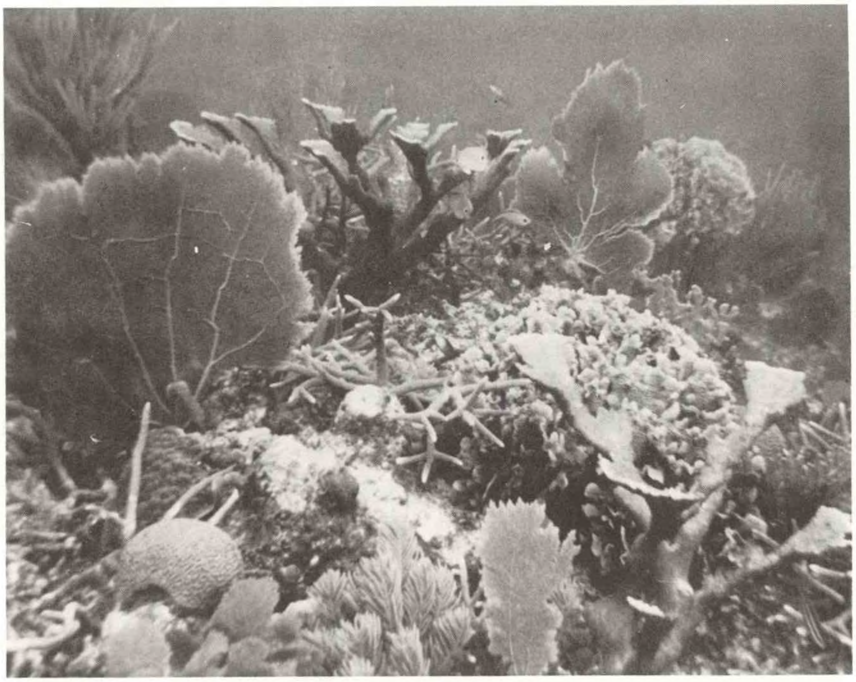

Figure 5. Elements of a typical emergent Atlantic coral reefs. Alcyonarian corals are represented by sea whips and sea fans; hydrozoan corals by hard, bush-like growths of Millepora (upper right); madreporarian corals by branching Acropora palmata (top center and lower right) and Acropora cervicornis (center), and by a small massive brain coral head (probably Diploria) in the lower left with a Porites colony just above it. The bush-like growth in the right center appears to be Agaricia, a madreporarian.

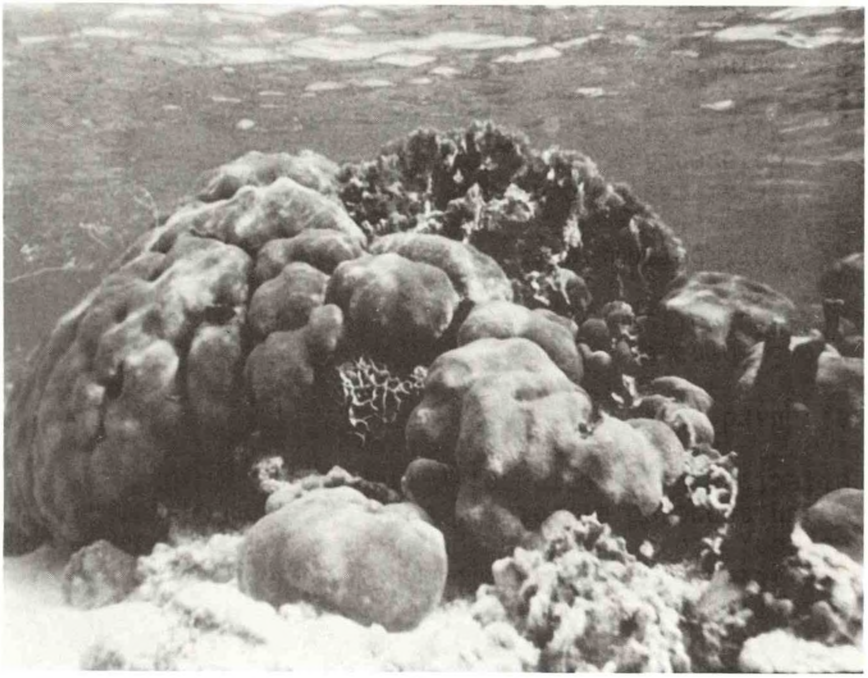

Figure 6. Head of Montastrea annularis with attendant growths of Millepora (upper right) and Agaricia (center). Typical of emergent Atlantic coral reefs.

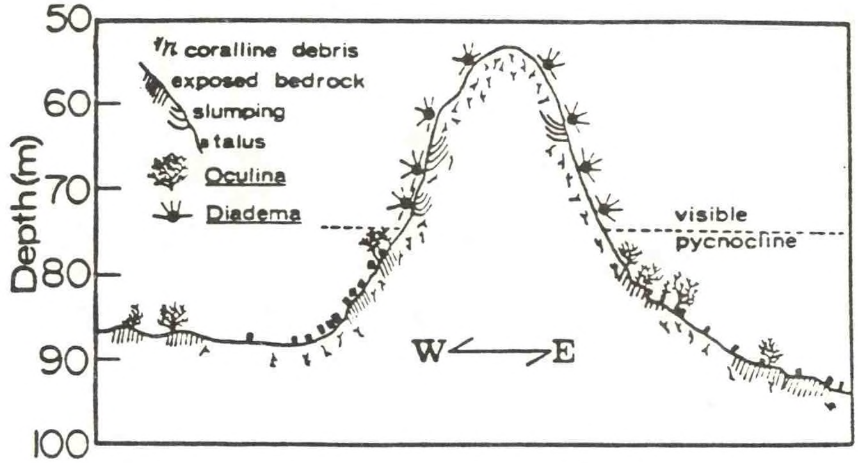

Figure 7. Diagrammatic representation of Oculina reefal assemblage found off eastern Florida from West Palm Beach to Fort Pierce. Courtesy of Robert Advent, Harbor Branch Foundation.

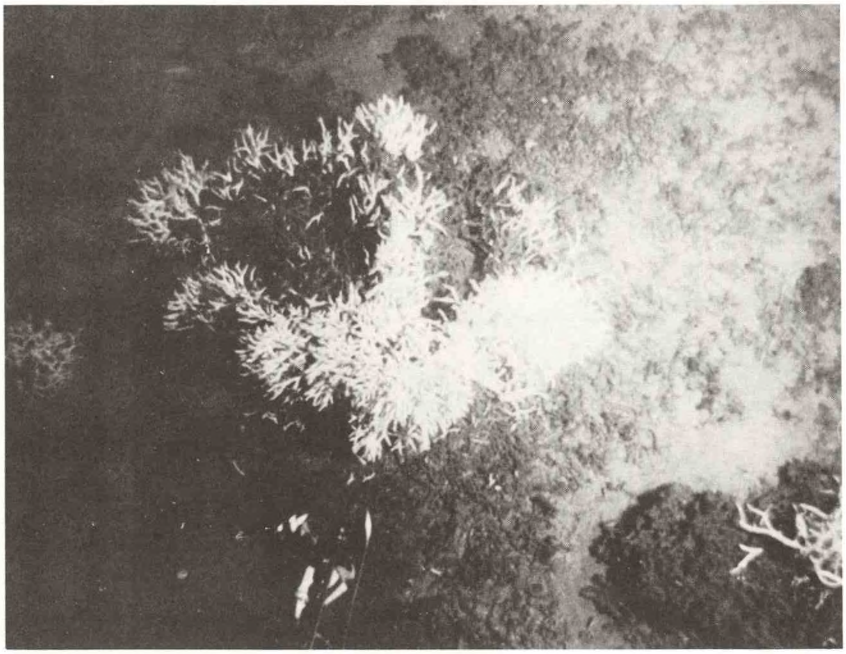

Figure 8. Oculina on one of the reefs diagrammed in Figure 5. Photograph taken from Harbor Branch Foundation research submersible.

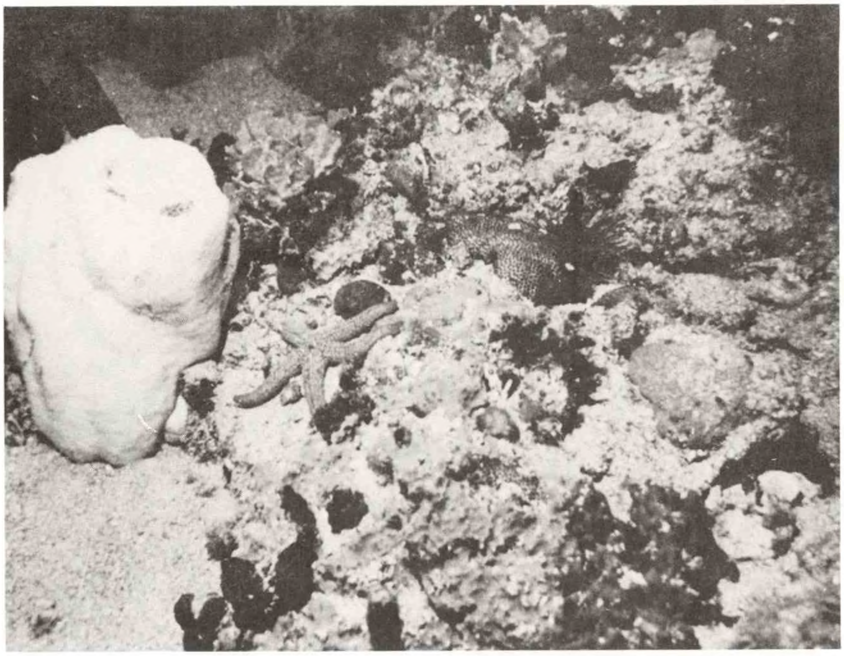

Figure 9. Sponges, corals and echinoderms of an organic bank on the western Florida continental shelf.

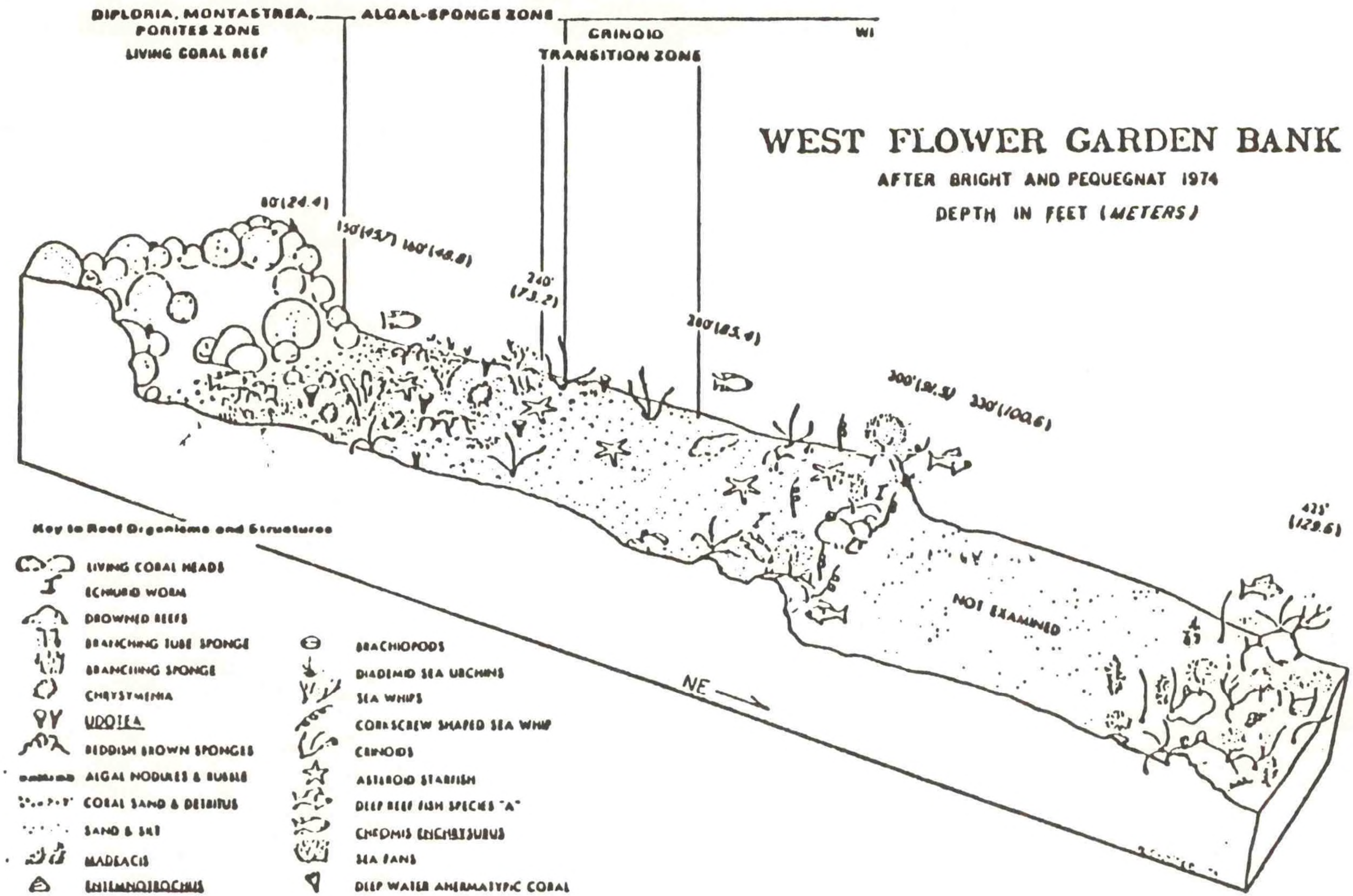

Figure 10. West Flower Garden coral reef (25 m depth). Note the total absence of shallow water alcyonarians and branching species of Acropora.

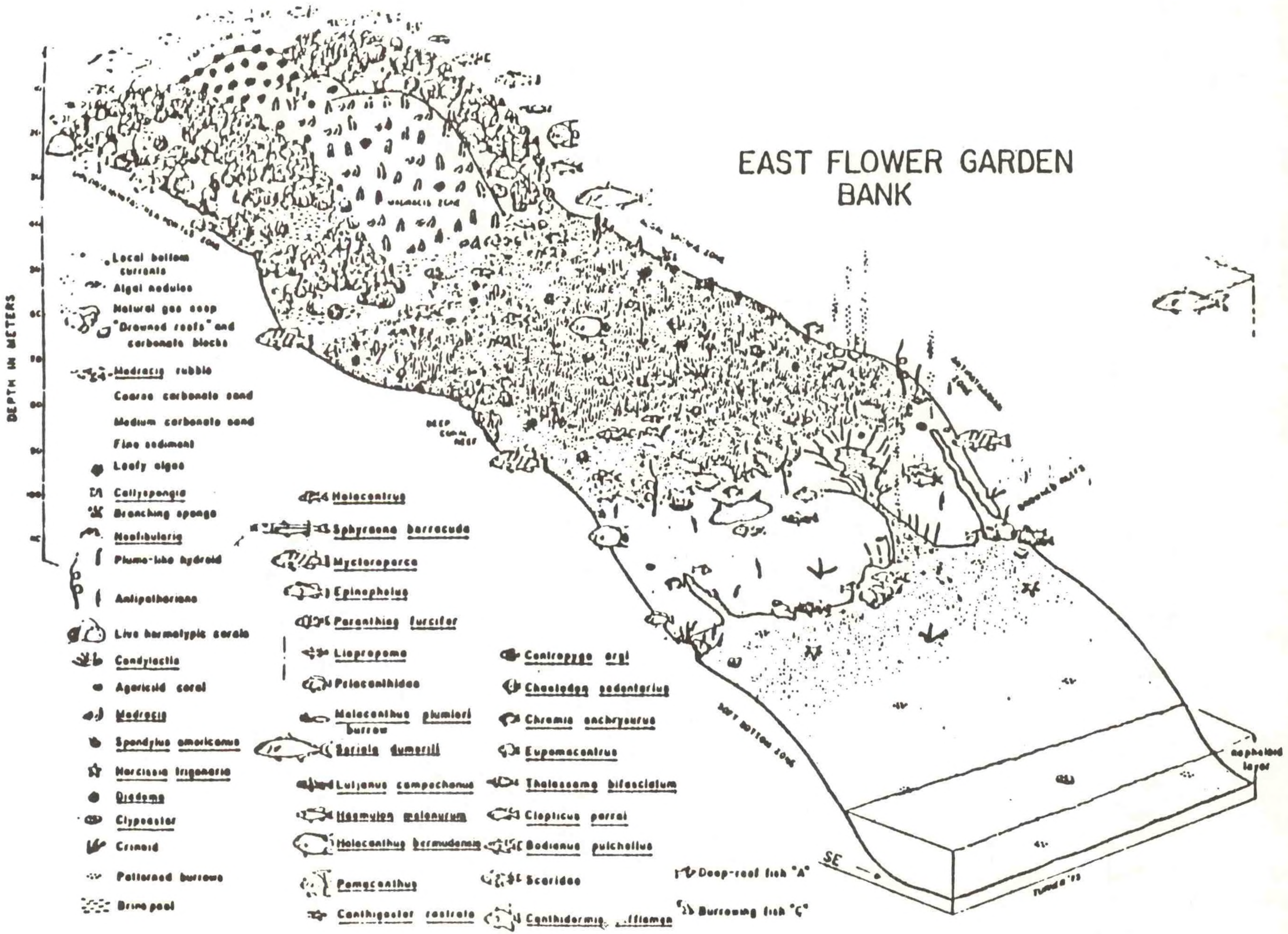

Figure 11. East Flower Garden coral reef and hard, carbonate bank. Based on observations made from Texas A&M Oceanography department research submersible DIAPHUS (after Bright, 1978).

SONNIER BANK

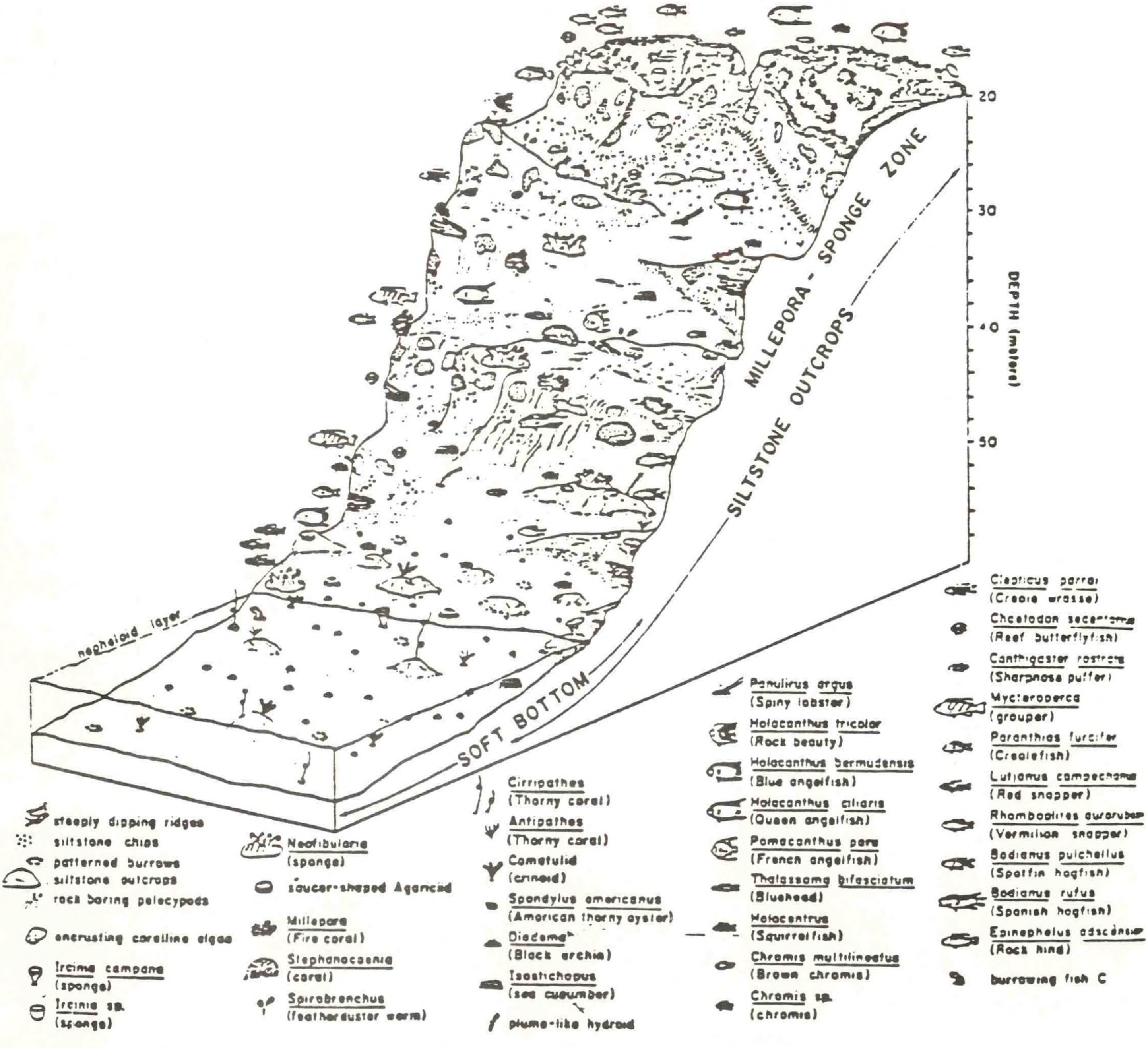

Figure 12. Based on observations made from Texas A&M research submersible DIAPHUS (after Bright, 1978.)

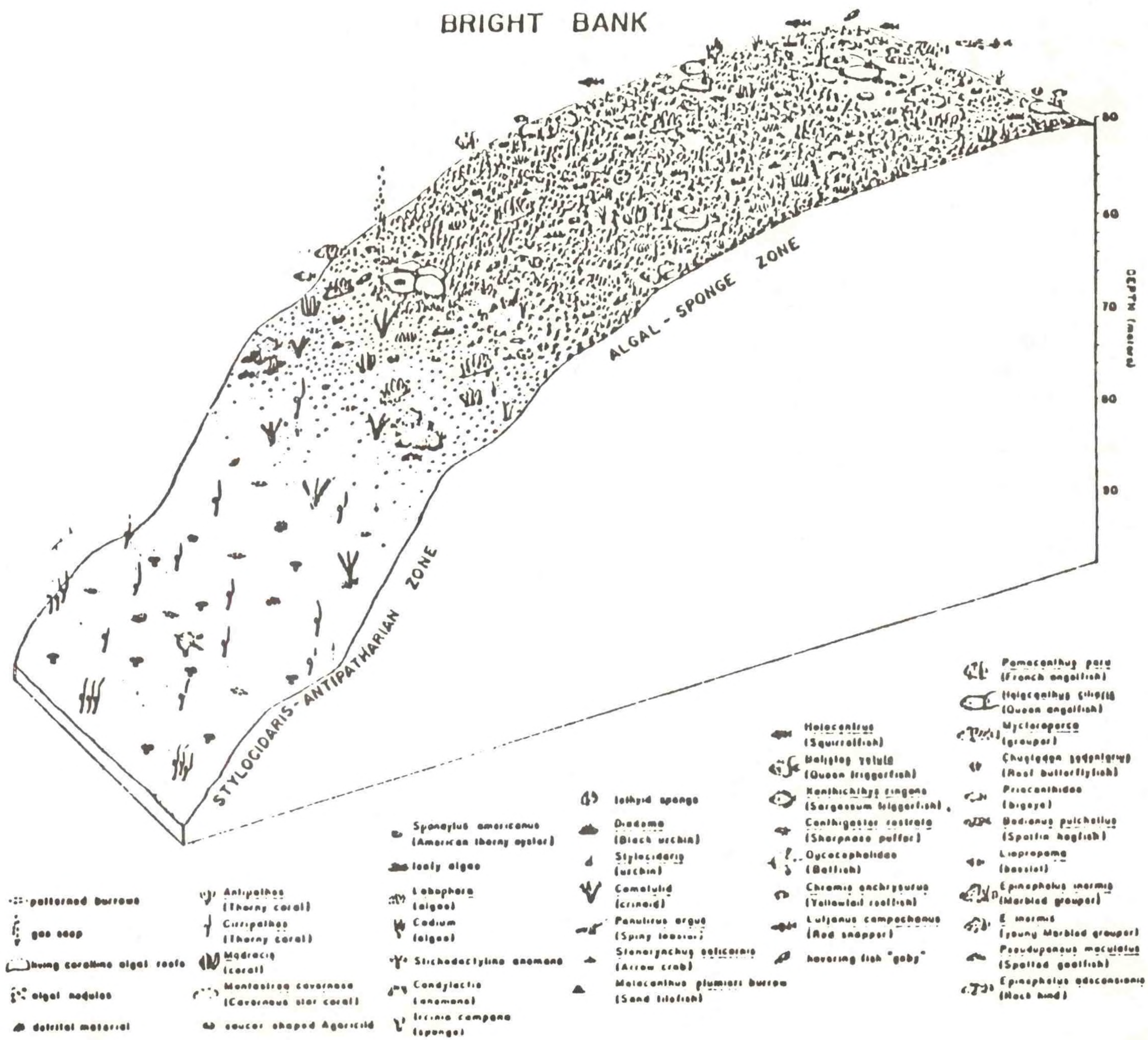

Figure 13. Based on observations made from Texas A&M research submersible DIAPHUS (after Bright, 1978.)

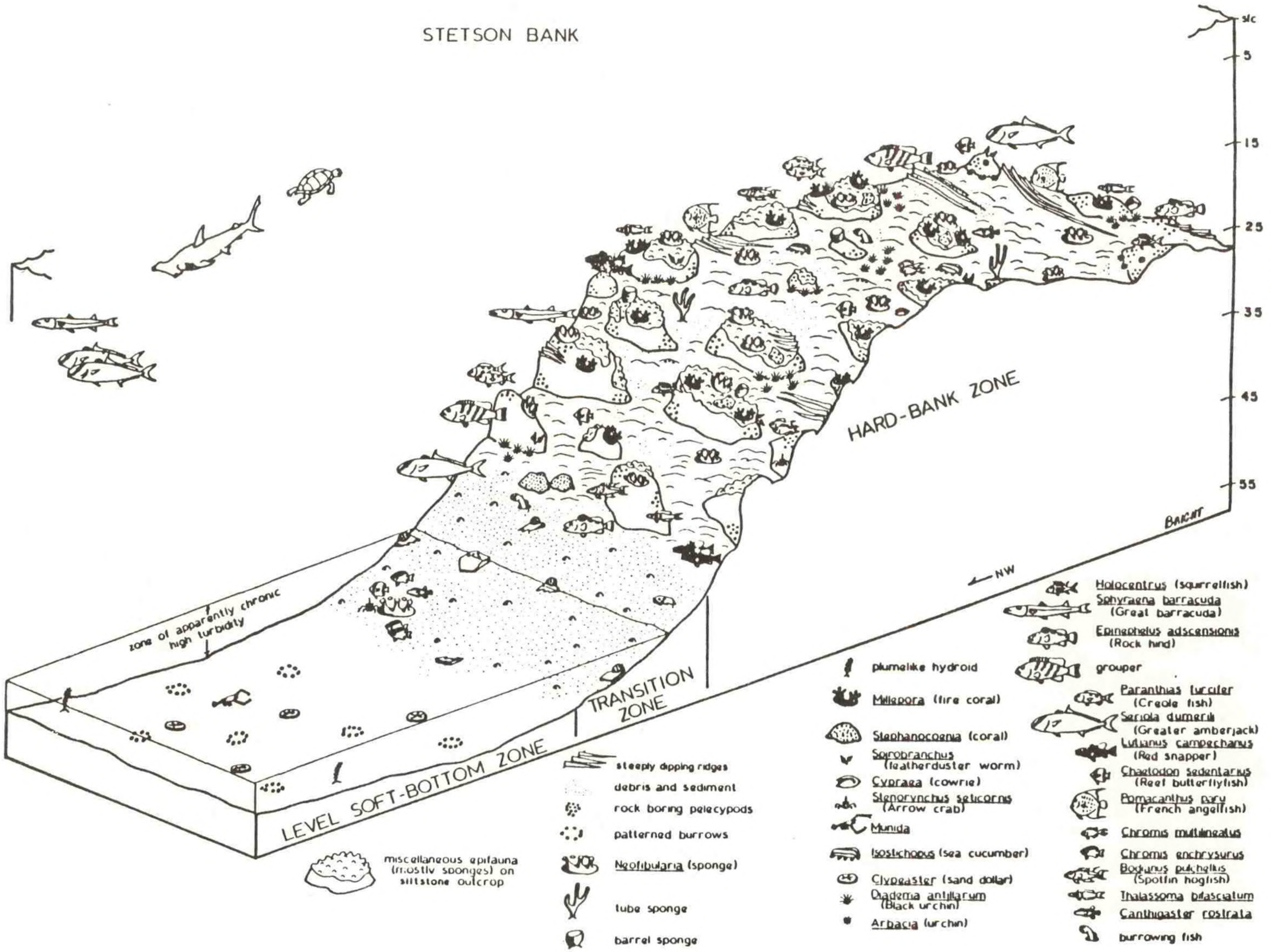

Figure 14. Based on observations made from Texas A&M research submersible DIAPHUS (after Bright, 1978.)

Figure 15. Siltstone outcrop at Stetson Bank. Note bedding and numerous holes due to rock boring pelecypods. Diademid sea urchins are extremely numerous. Epifaunal cover (mostly sponges and Millepora) varies locally from nil to 100%.

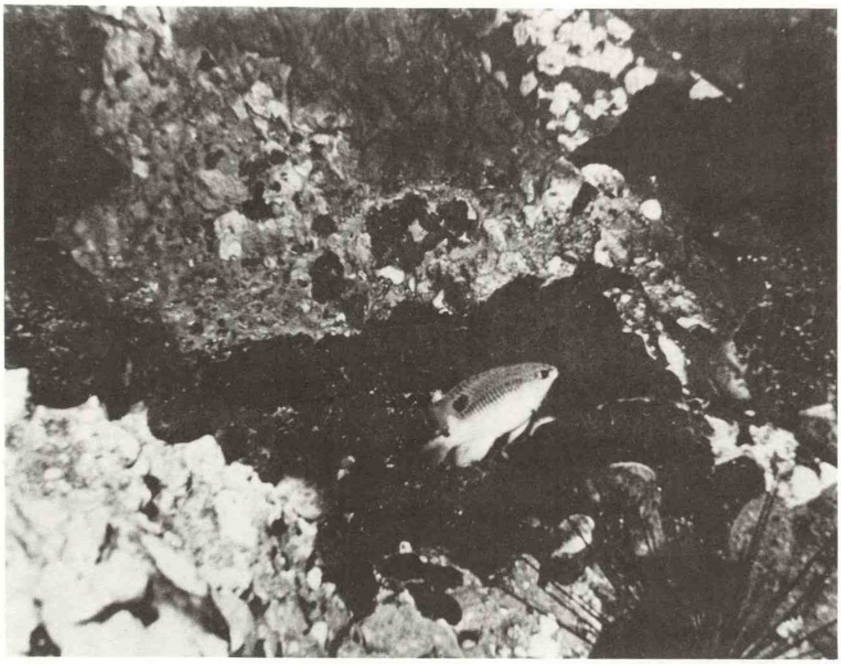

Figure 16. Epifaunal encrustations on siltstone at Stetson Bank. Millepora in top center, bare gray rock with bore holes below it with darker sponges below and to the left. The fish is Eupomacentrus (a damsel fish). Diademid urchin in lower right.

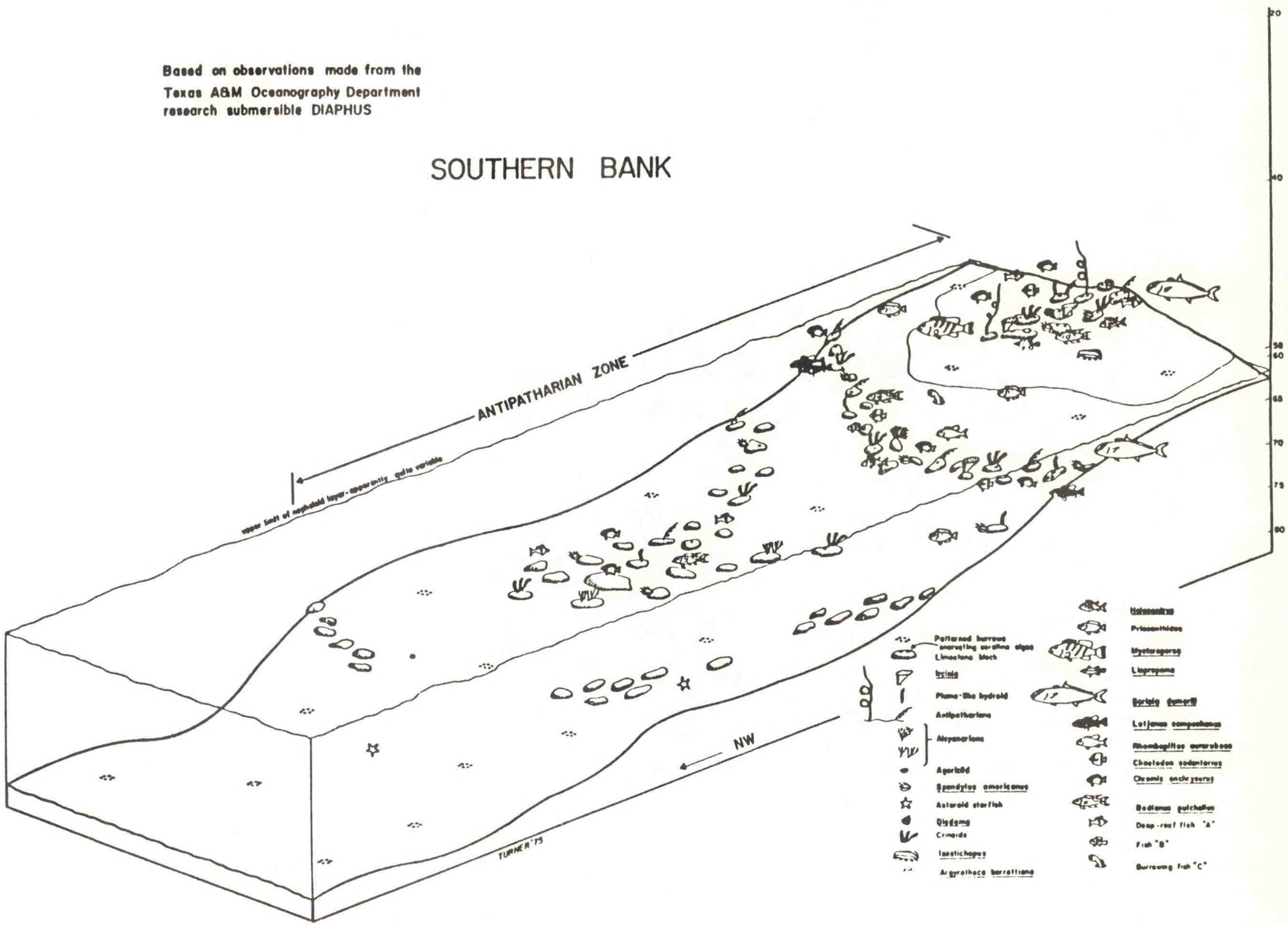

Figure 17. Southern Bank. Representative of all of the South Texas outer continental Shelf fishing banks.

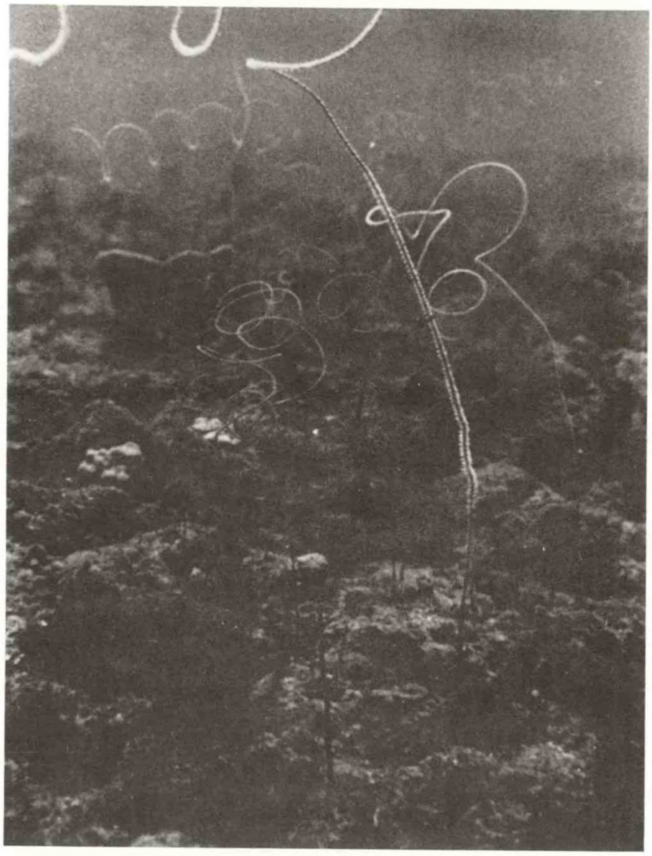

Figure 18. Top of Southern Bank showing conspicuous and abundant corkscrew-shaped antipatharian whips (Cirripathes) which are related to the precious "black coral." Comatulid crinoid in lower left. Vase-like sponge (Ircinia)in upper left. Most of the carbonate rock substratum is coverd with a thin veneer of fine sediment.

Figure 19. Saucer-sized growth of an agaricid coral, the only madreporarian coral present in conspicuous quantities on the South Texas fishing banks.

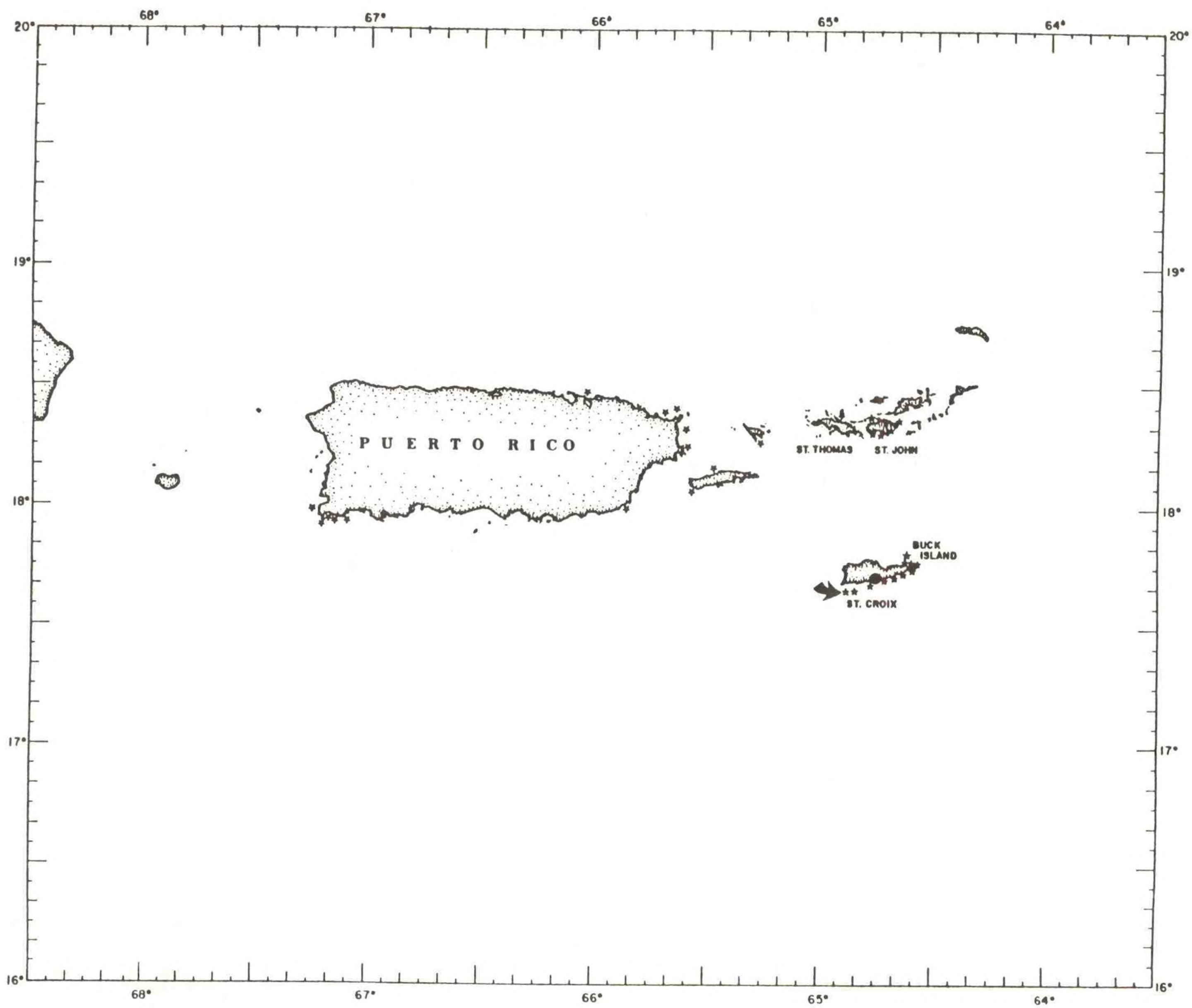

Figure 20. Corals reefs in Puerto Rico and the U.S. Virgin Islands (stars). Environmentally impacted industrial area (black dot). Very healthy shelf-edge submerged reefs (arrows).

Figure 21. Typical bank-barrier reef on the south coast of St. Croix, U.S. Virgin Islands. The bay bottom next to the beach is extensively covered with sea grasses (darker zone). The sandy central bay is strewn with small patch reefs and is protected from erosional forces of the sea and swell by the emergent linear bank barrier reef which absorbs most of the energy of the breaking waves.

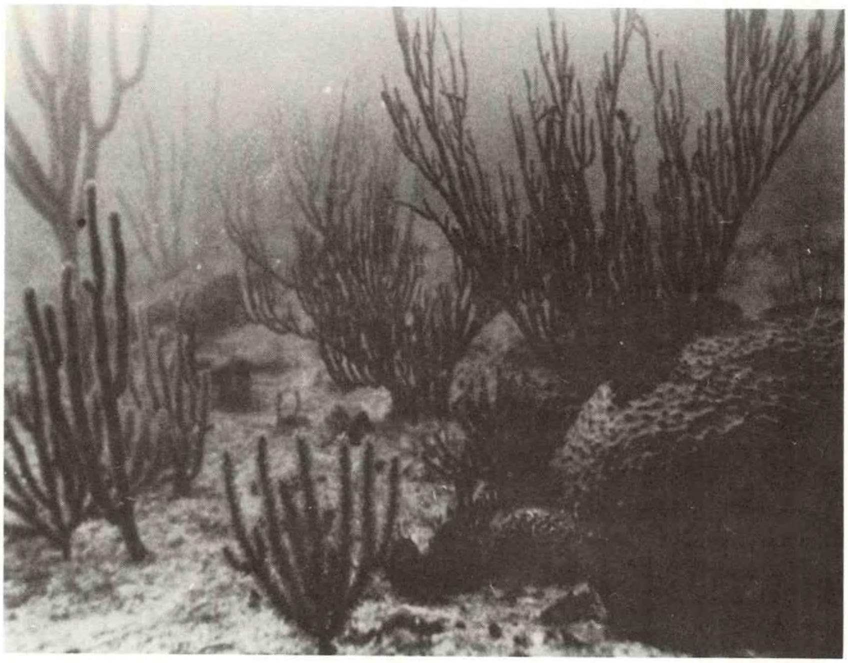

Figure 22. Typical hard-bottom seaward of the bank barrier reefs on the south coast of St. Crois. Sponges, alcyonarians and small madreporarian coral heads predominate.

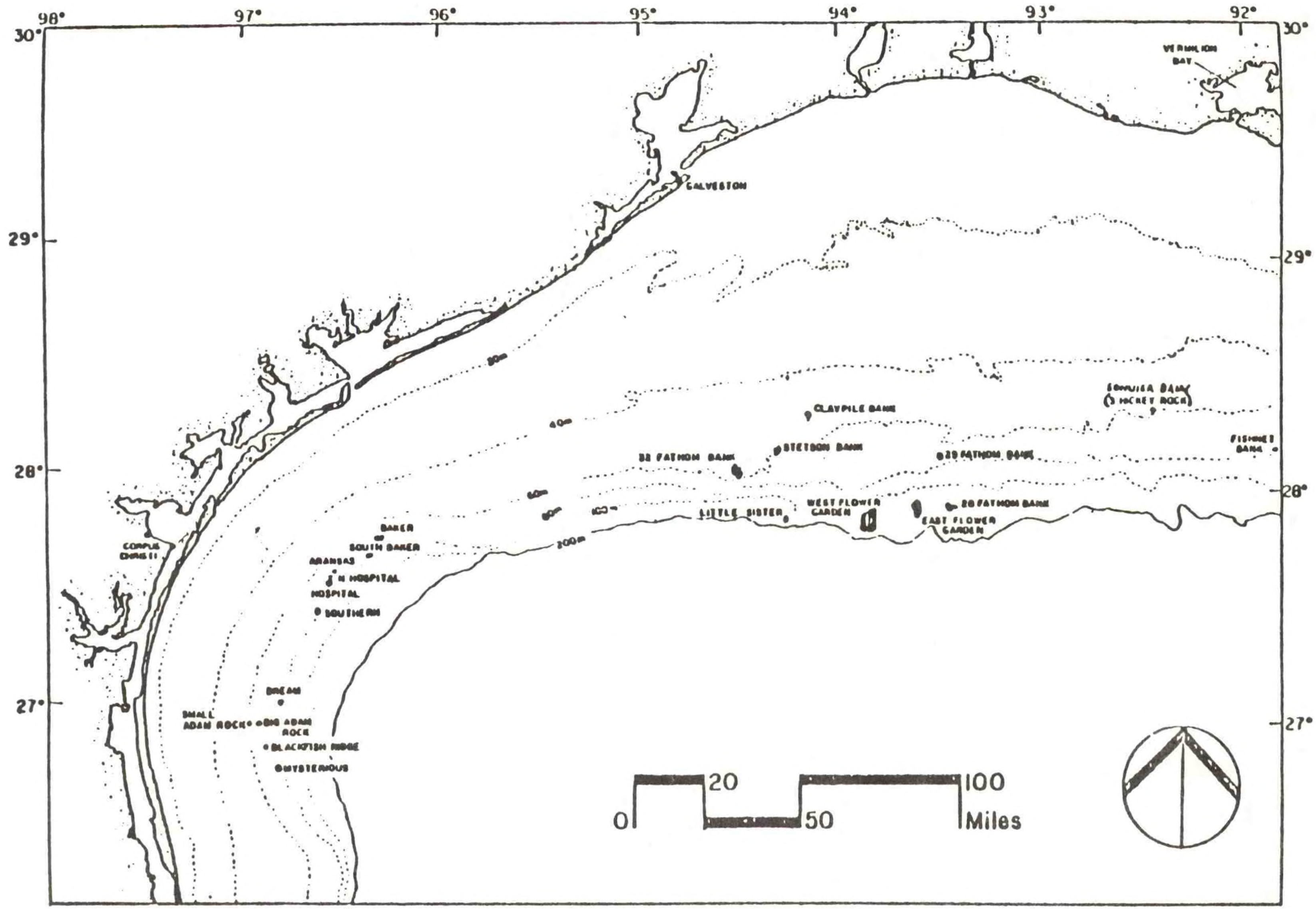

Figure 23. Major Texas-Louisiana outer continental shelf fishing banks (Texas A&M Research Foundation and Texas A&M Department of Oceanography, 1978.)

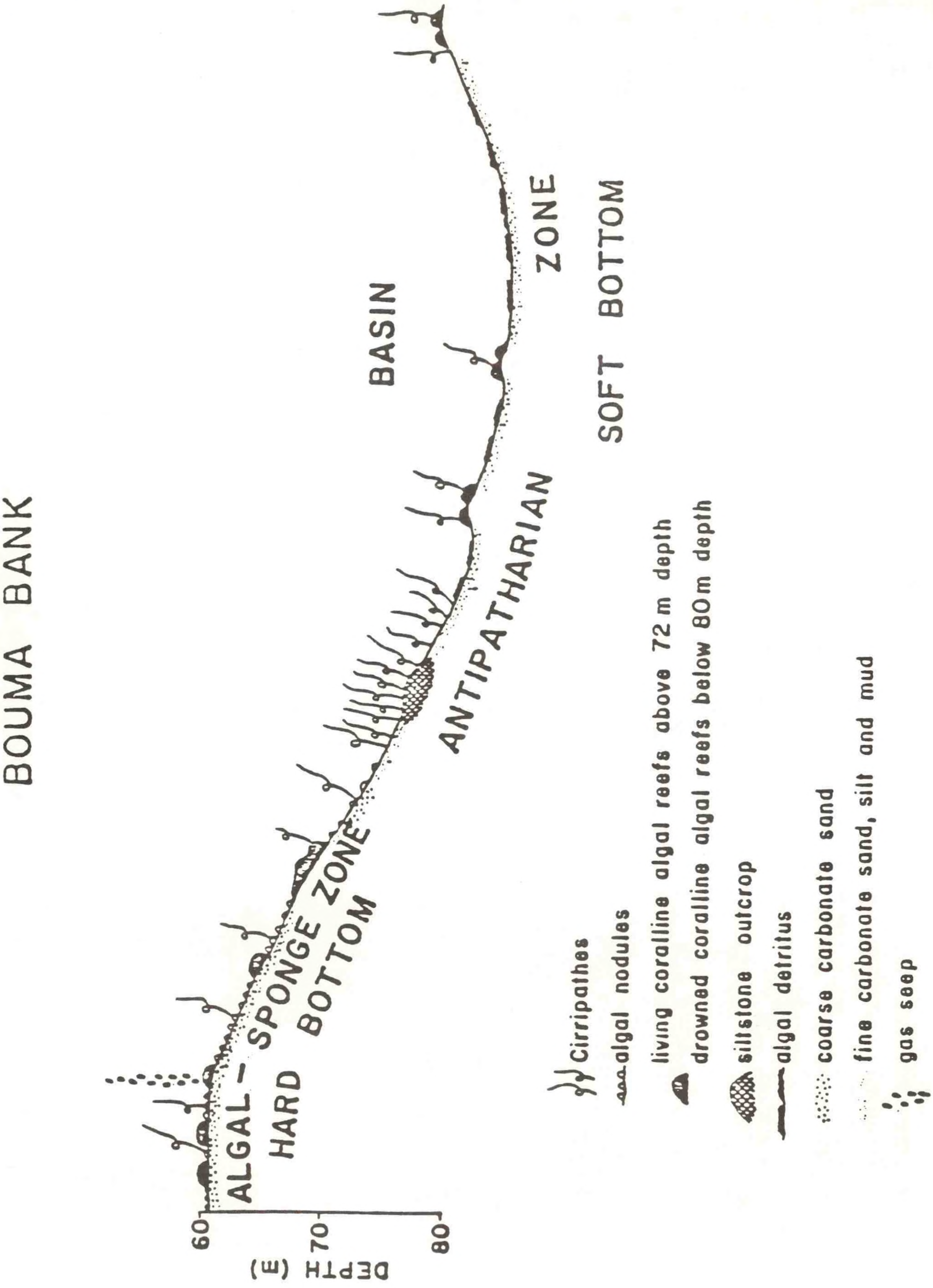
BOUMA BANK
DEPTH (m)
60
70
80
ALGAL - SPONGE ZONE
HARD BOTTOM
ANTIPATHARIAN
BASIN
SOFT BOTTOM ZONE
Cirripathes
algal nodules
living coralline algal reefs above 72 m depth
drowned coralline algal reefs below 80m depth
siltstone outcrop
algal detritus
coarse carbonate sand
fine carbonate sand, silt and mud
gas seep

Figure 24

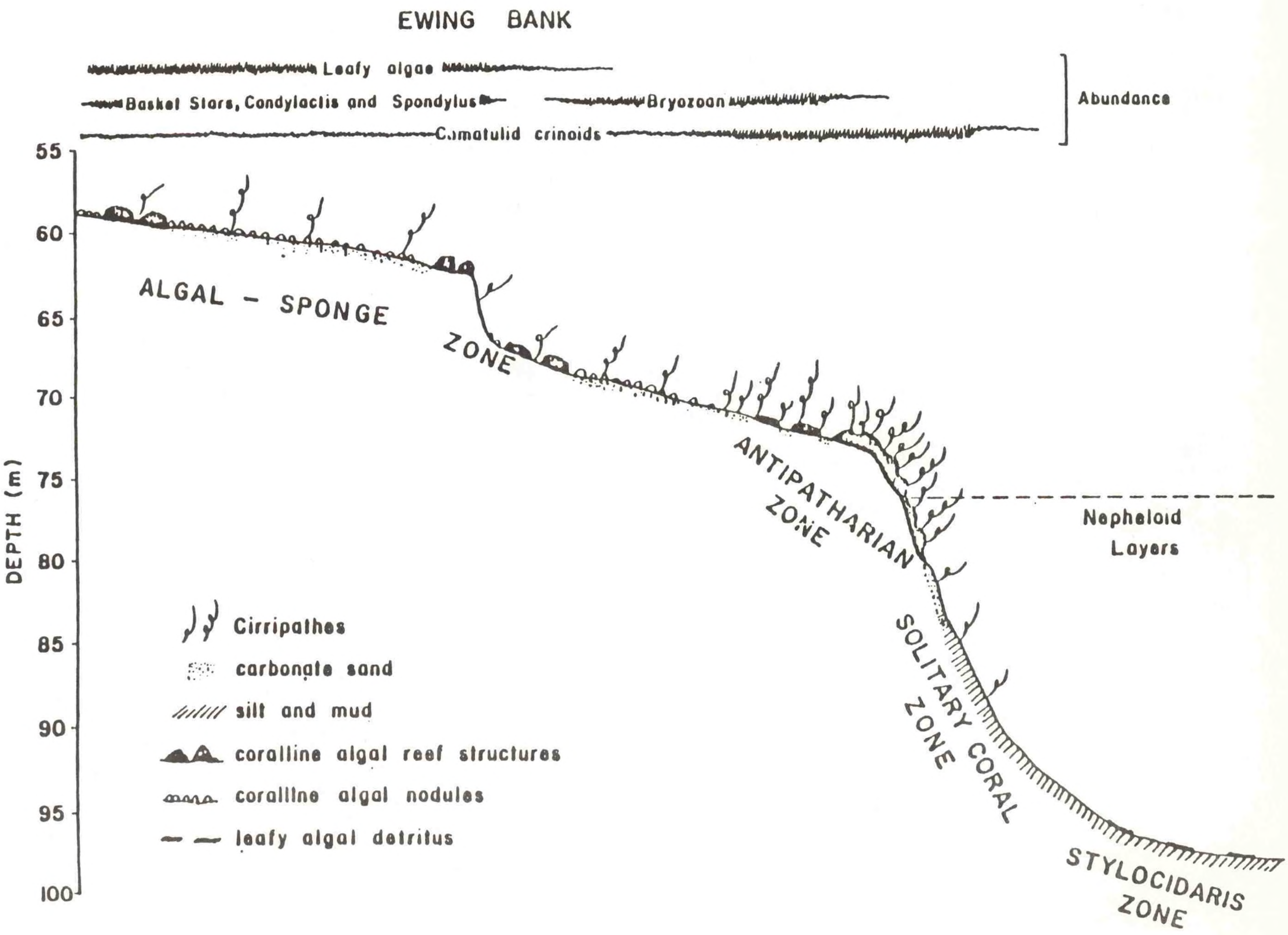
EWING BANK
Leafy algae
Basket Stars, Condylactis and Spondylus
Bryozoan
Comatulid crinoids
Abundance
DEPTH (m)
55
60
65
70
75
80
85
90
95
100
ALGAL - SPONGE ZONE
ANTIPATHARIAN ZONE
SOLITARY CORAL ZONE
STYLOCIDARIS ZONE
Nepheloid Layers
Cirripathes
carbonate sand
silt and mud
coralline algal reef structures
coralline algal nodules
leafy algal detritus

Figure 25

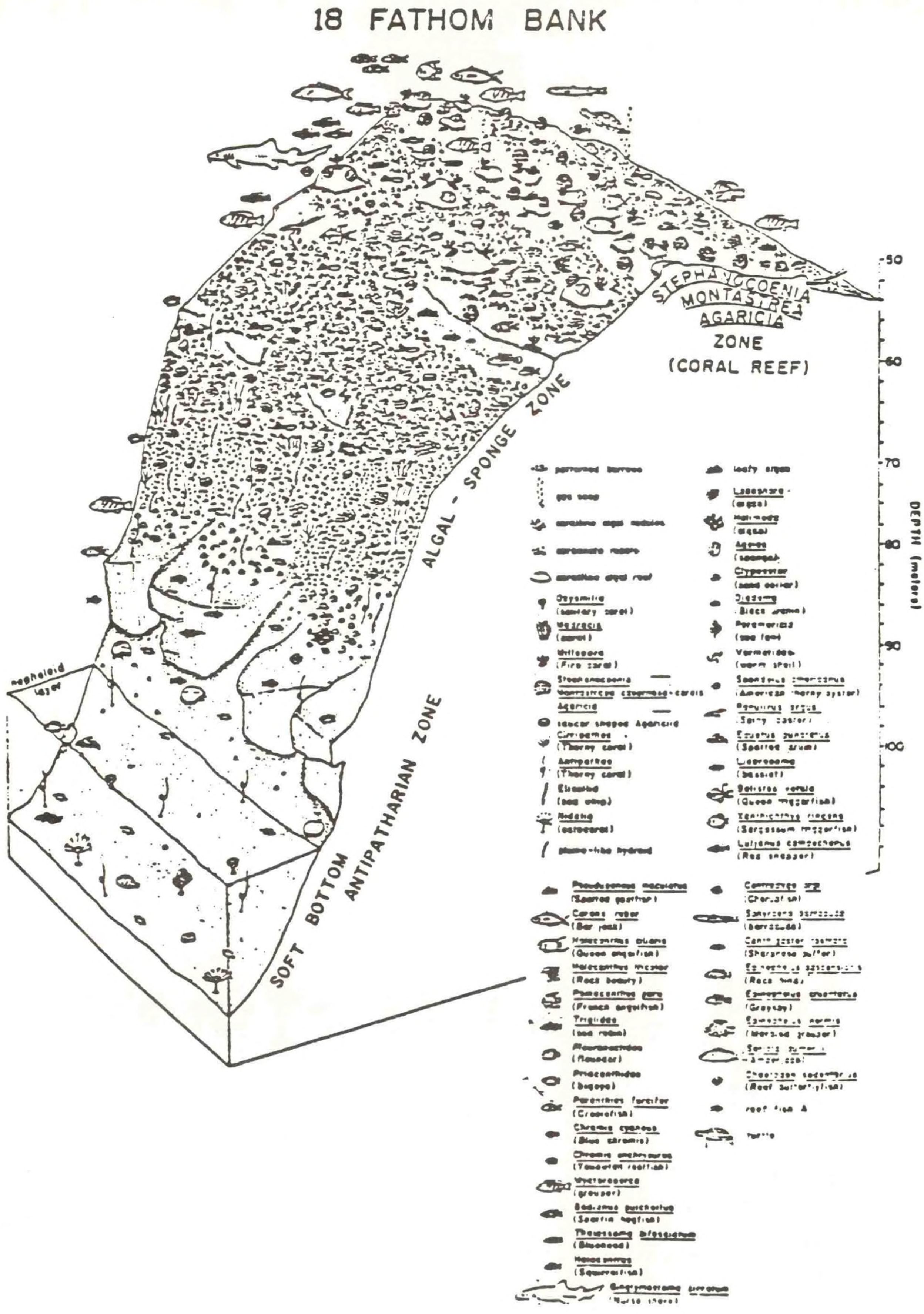

Figure 26. Based on observations made from Texas A&M research submersible DIAPHUS (after Bright, 1978.)

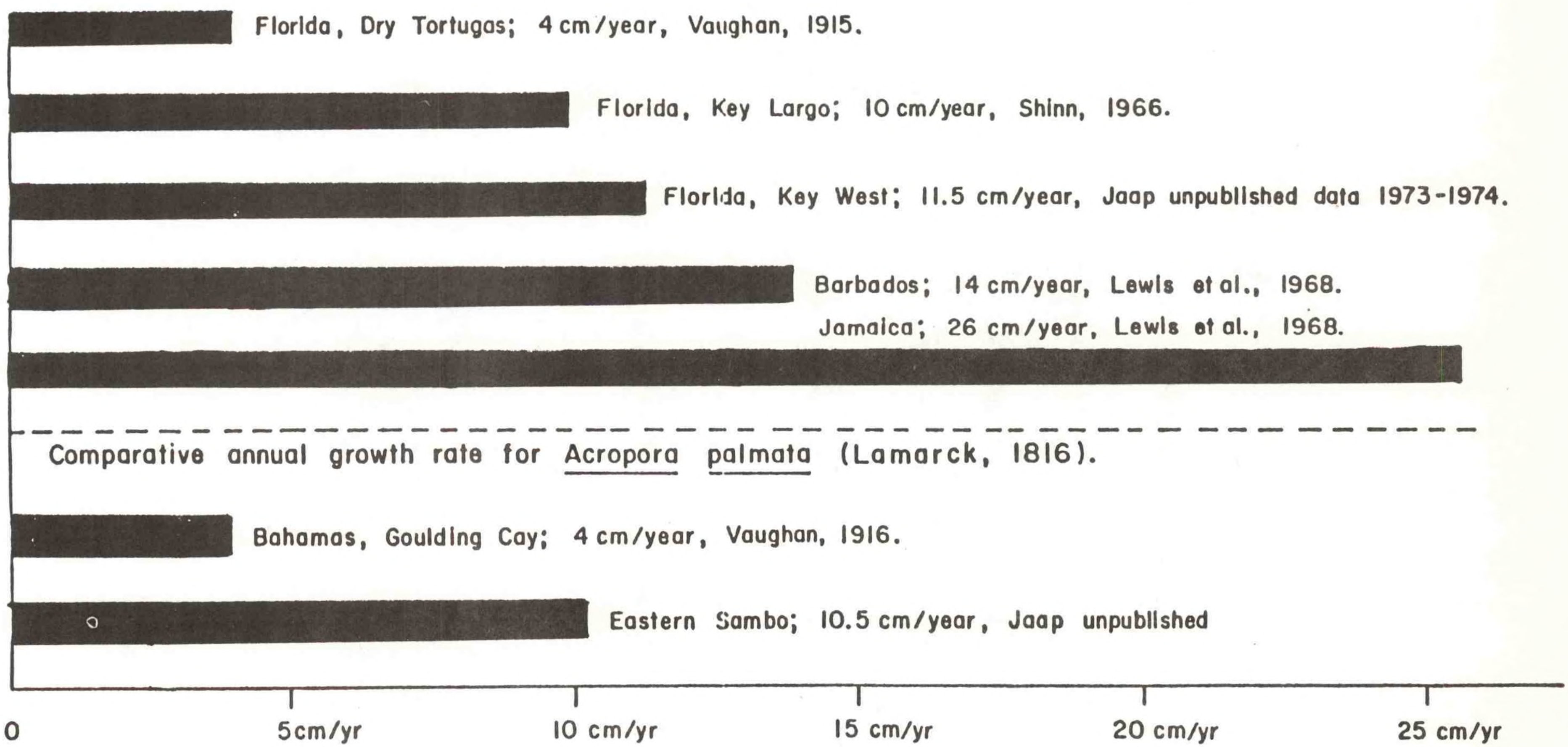

Figure 27. Some growth rates for _Acropara palmate_ and _A. cervicornis_.

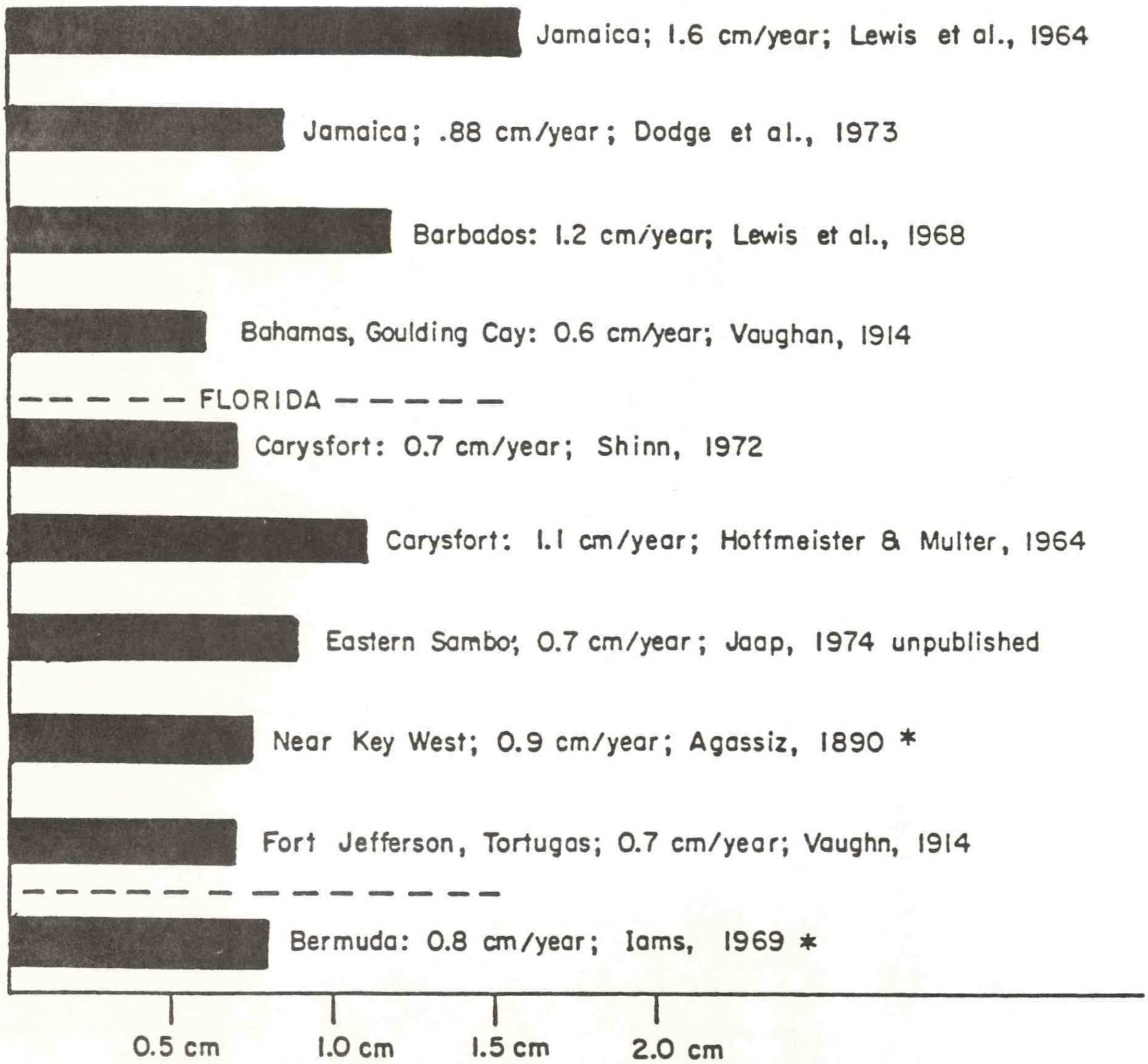

Figure 28. Some growth rates for Montastrea annularis.

Figure 29. Brain coral infected with and partially killed by Oscillatoria submembranacea in the Florida Keys.

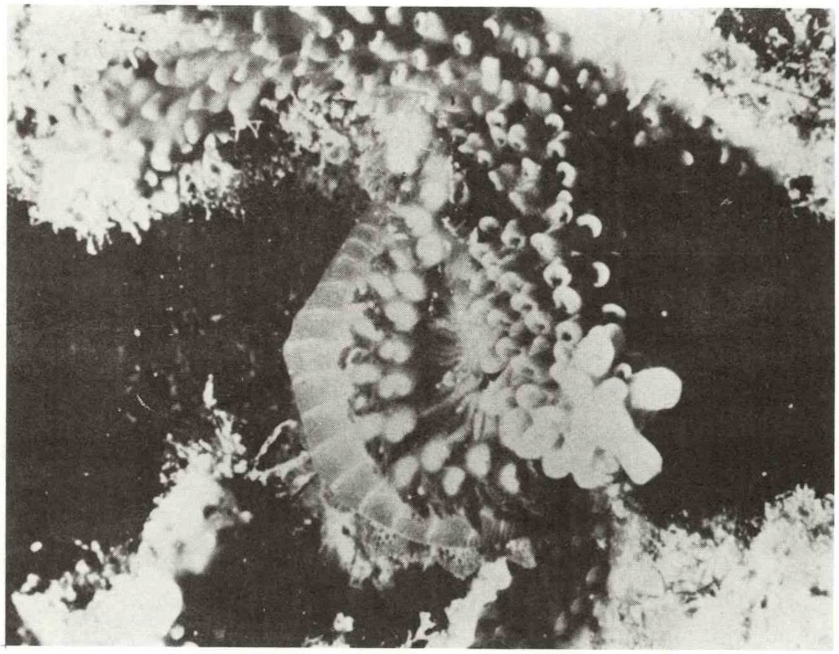

Figure 30. The fire worm, Hermodice carunculata, feeding on the coral Acropora cervicornis.

Figure 31. Upside-down but still live colony of branching Acropora palmata in now highly turbid spoil pile which used to be Long Reef in the industrial harbor on the south coast of St. Croix.

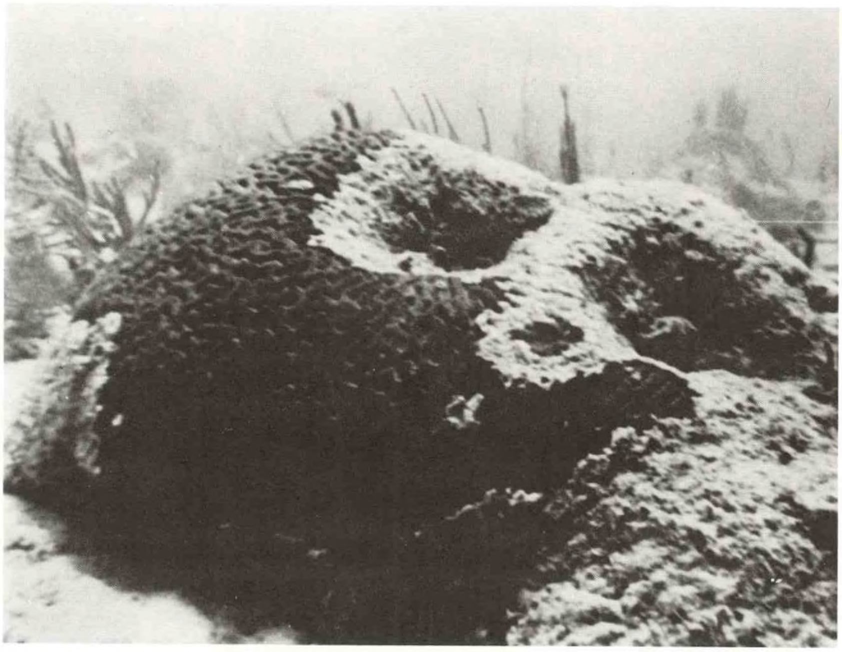

Figure 32. Brain coral head covered with and partially killed by enroaching mat of algal and sediment. Seaward part of former Long Reef referred to in Figure 26.

Figure 33. Alcyonarian deeply buried by sediment deposited as a result of Channel Construction and subsequent tanker traffic on the south coast of St. Croix.

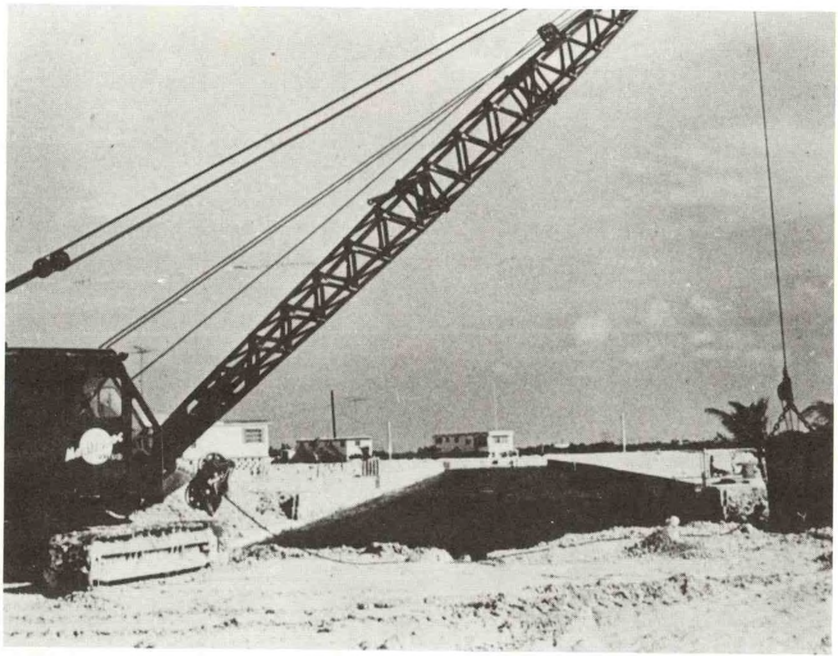

Figure 34. Typical canal construction in the Florida Keys.

Figure 35. Drill cuttings and drill mud being released through a pipe opening just below the sea surface. The larger cutting particles tend to fall straight down, collecting in a pile under or near the drill platform. Finer particles (including drill mud components) and dissolved substances tend to move laterally forming a "plume" down current of the drill platform. The plume may be a mile or more in length at the sea surface. Photo courtesy of Dr. E. A. Shinn, U.S. Geological Survey.

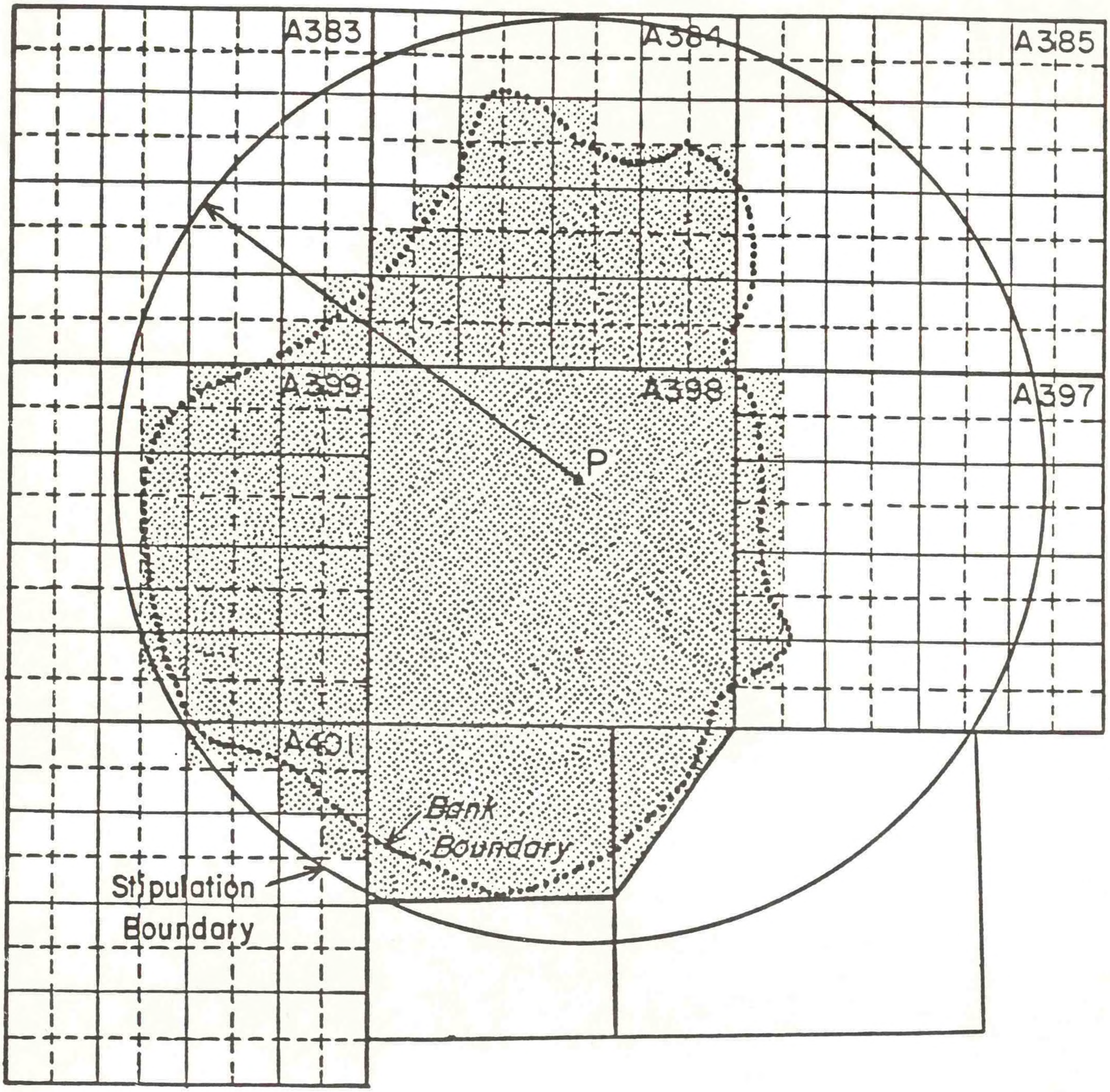

Figure 36. Summary of restrictive drilling stipulations in the West Flower Garden Bank area off Texas. Reef-building coral is located in Block A-398 around point P. Development operations, such as drilling, structures, or pipelines, are not permitted in shaded areas. Development operations involving shunting of drill effluents to the ocean bottom are permitted within the circle (radius = 20,064 feet around point P). Development operations in the white areas beyond the bank and circular boundaries are outside the stipulated area. Each numbered oil and gas lease block is a 3-mile by 3-mile square.

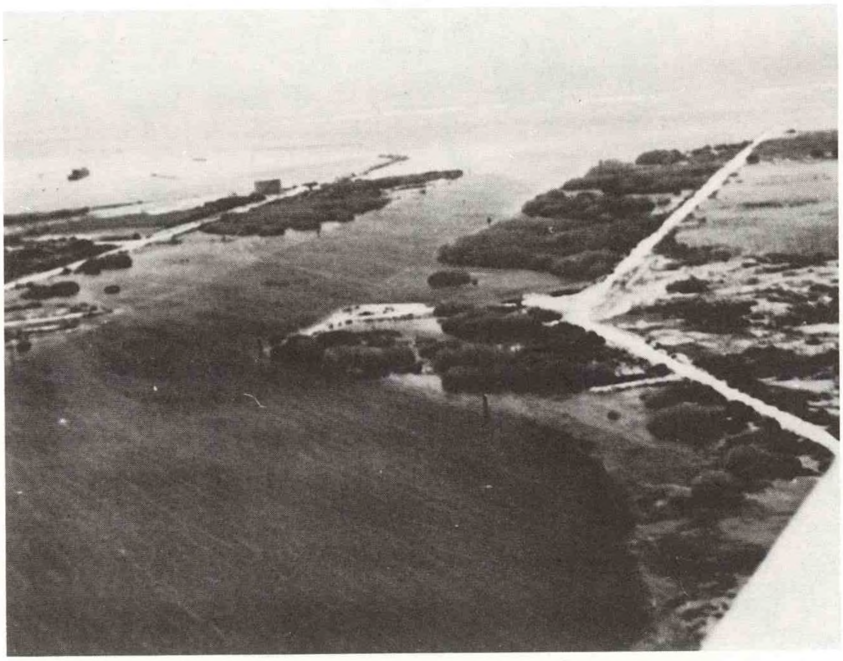

Figure 37. Part of industrial harbor on south coast of St. Croix showing killed Red Mangrove forest.

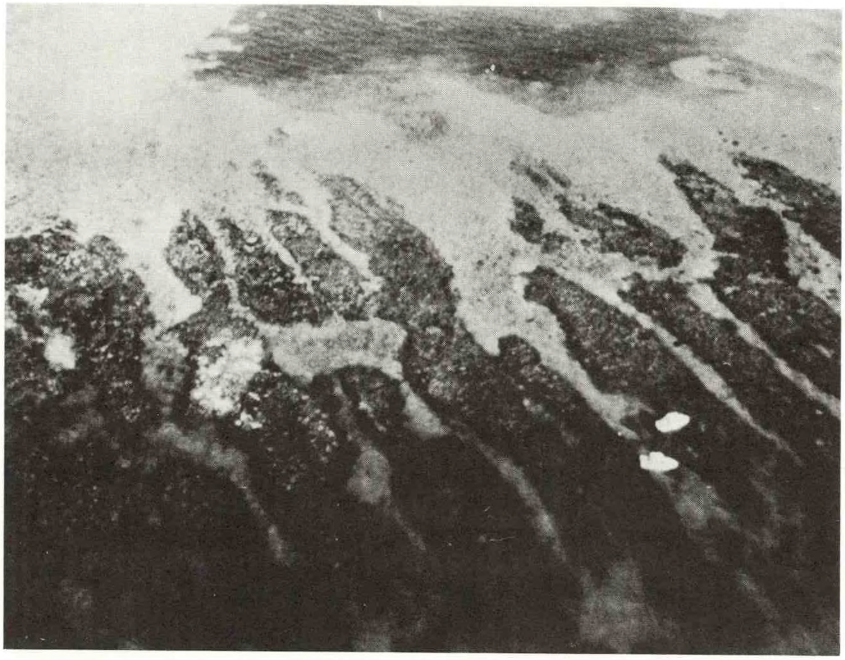

Figure 38. Shipwreck damage to spur-and-groove tract at Looe Key, Florida. Large white scar on otherwise dark reef spur to left of center shows where the vessel Lola went aground and stayed for 18 days.

Figure 39. Small boat anchor damage to coral head (three gouges) exposes tissue to infection by coral pathogens.

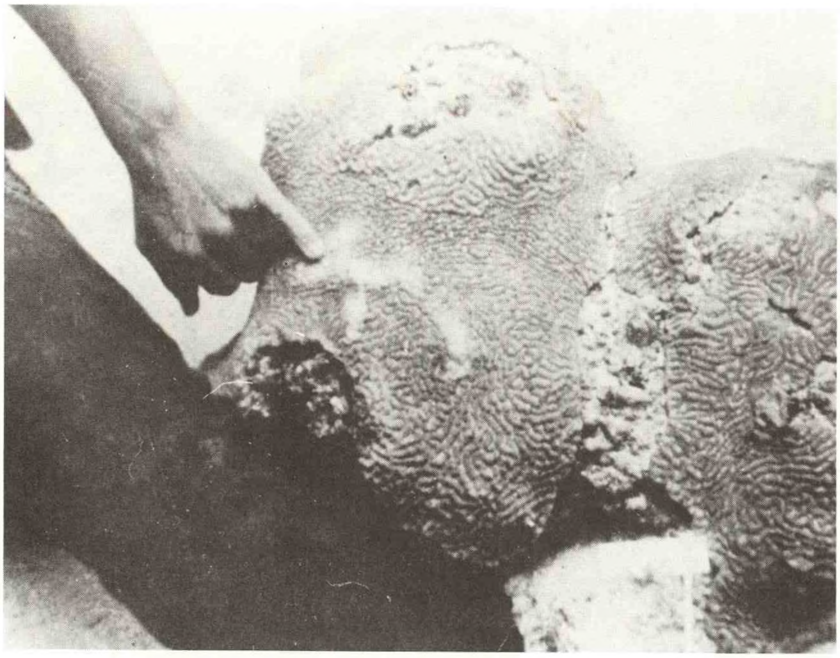

Figure 40. Discoloration of part of Meandrina meandrites head after experimental application of the fish anesthetic quinaldine.

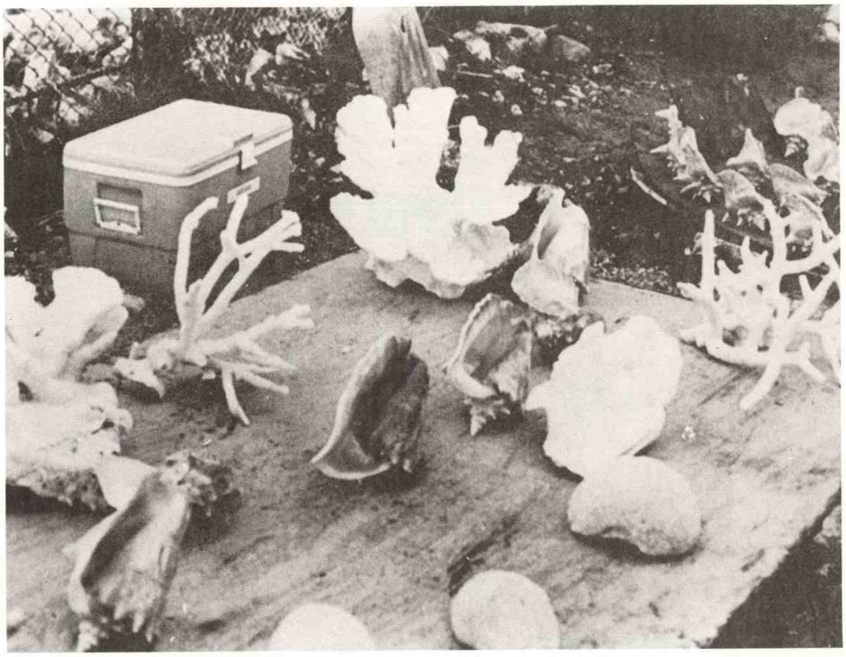

Figure 41. Florida corals for sale at local curio stand. Acropora palmata, A. cervicornis and small massive heads are shown. Shells of the Queen Conch, Strombus gigas, are also shown.

GULF OF MEXICO FISHERIES: CURRENT STATE OF KNOWLEDGE AND SUGGESTED CONTAMINANT-RELATED RESEARCH

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1. INTRODUCTION

The purposes of this paper are to (1) survey the available information on fisheries of the Gulf of Mexico, (2) give an overview of ongoing research, and (3) identify research needs so as to assess the effects of man's activities on living marine resources. Our preliminary appraisal of relevant literature indicated that there are several hundred papers in the open scientific literature dealing with Gulf fishes and fisheries, most of them on specific topics. Therefore, certain restrictions on scope of coverage would be necessary. This paper presents a selective, discursive review of the Gulf fishery resources and a discussion of the research programs that we believe offer a possible assessment of the environmental health of the area.

The Gulf of Mexico is the single most important area for fisheries production in the U.S. The total of all fisheries, including crustaceans, molluscs and other resources, represents approximately 33% by weight and 29% by dollar value of the total U.S. commercial fisheries. While we concentrate on research needs with respect to finfish, many of the comments and recommendations also apply to other important fishery organisms, such as shrimp and crabs.

In addition to being an important area for fisheries production, the Gulf is experiencing significant industrial development and population growth (see other papers from this symposium). This increased growth will undoubtedly bring an increased demand for fishery products and, along with this growth, additional pollution which may affect fisheries production in the long term.

2. THE GULF HABITAT

2.1 Zoogeography

The northern Gulf, from the tip of the Florida peninsula to the Mexican border, is classified as being included in the Carolina Zoogeographic Region (Briggs, 1970). The fauna is similar to that found in the South Atlantic from Cape Hatteras to Cape Canaveral, but the Gulf is richer in species and endemism. In many ways, however, less is known about its general ecology than that of any other coastal section of the United States. The following summary of information is taken from Briggs (1973). Chemical and physical qualities of the shelf waters are similar across the northern Gulf, except for low-salinity water at the surface near the Mississippi Delta. However, the diversity of fish fauna species of the northeastern Gulf is richer than that to the west of the Mississippi Delta because of the added presence of eurythermic tropical species. This difference may be caused by the presence of a different benthic community east of the Delta than that found in the western Gulf. It has been pointed out by Mills (1975) that the structure of the benthic community can influence the structure and associated energetics of fishery populations. The coral-sponge association in the northeastern Gulf is replaced to the west by a shrimp ground community, beginning off Mississippi. A description of the Gulf bottom communities is given by Hedgpeth (1954).

The division in fish species found in different parts of the northern Gulf appears to be based on ecological rather than physical barriers. The inshore fishes of the extreme northeastern Gulf are mostly warm-temperate components and are similar in composition to species along the Texas coast, whereas the fish fauna south of Charlotte Harbor, Florida, has a largely tropical component. While the southwest Florida Gulf offshore shelf waters contain many tropical species, a number of typical warm-temperature species (e.g., sciaenids) are conspicuously absent. An unexplained anomalous inshore pocket of tropical fishes similar to species found 500 mi to the south exists between Panama City and Destin, Florida.

The large continental shelf area that characterizes the Gulf Coast of the southern U.S. (Fig. 1) provides a fairly stable habitat (with respect to temperature and salinity) in which the majority of the commercially and recreationally important finfish species spawn. Precise spawning areas have not been identified for most species. However, the wide distribution of egg and larval stages over shelf waters implies that all of these waters are of some importance. Gulf menhaden, for example, spawn at least out to the 50-fathom curve, probably from western Florida to eastern Texas (Chapoton, 1972). Many other important fishery species, such as southern flounder, striped mullet, Atlantic croaker, red drum, and Spanish mackerel, also spawn in this area. Apparently, the larvae of many Gulf species of fishes require the relatively stable physical and chemical environment of the ocean (e.g., temperature and salinity) for initial development before their entry into the estuarine nursery area (Fig. 2).

The Gulf coast shoreline makes up the largest estuarine area in the contiguous United States (see Thayer and Ustach, this symposium). This estuarine area provides protection for the growth of many species of fish spawned in the open Gulf. Those species that are dependent on the estuary for at least a portion of their life are indicated by an asterisk in Table 1. The estuary, unlike the ocean, is an unstable habitat that is characterized by large and rapid fluctuations in temperature and salinity. It is also the area most subjected to pollutants. Unfortunately, a large proportion of the studies on fish populations of these estuarine habitats are qualitative and have not considered the habitat potentially available for use by organisms. A description of the Gulf estuarine area and its inclusive wetland habitats is presented by Thayer and Ustach (this symposium); their paper also discusses research needs for understanding these habitats, many of which pertain to productivity of fishery populations and need not be reiterated in our paper.

2.2 Fisheries

The Gulf fishes, for the purpose of this paper, can be divided into two groups: those species that are exploited as a fishery resource and those species that are not. In the exploited group, more than 50 species are caught in numbers significant enough to be included in NOAA's fishery landing reports (i.e., Current Fisheries Statistics). Recreational fishermen harvest additional species (e.g., billfishes) for which similar annual listings are not available, although approximately 60 finfish species make up the bulk of the recreational fishery in the Gulf (Thayer and Ustach, this symposium).

Within the exploited group of fishes, the following are the most important in dollar value, arranged in order of decreasing priority (arbitrarily selected as species valued at over $1 million annually to commercial fishermen): Gulf menhaden, red snapper, striped mullet, groupers, spotted sea trout, Atlantic croaker, red drum, pompano, and Spanish mackerel (Table 1). Of these species, about one-half are considered estuarine-dependent at some time in their life cycle and are primarily carnivores or omnivores as adults. Unknown, however, is the relation between the forage fish species and the estuarine habitat. All of the species, except for the spotted sea trout, spawn in the Gulf; spotted sea trout spawn in estuaries and spend most of their life cycle within this inshore habitat.

The total commerical landings of the fish at ports in the Gulf states (west coast of Florida, Alabama, Mississippi, Louisiana, and Texas) in 1975, the last year for which complete statistics are available, were 1.41 billion pounds valued at $65.1 million. This is equivalent to 35.7% of the poundage and 13.4% of the exvessel finfish value of the U.S. Considering only the food finfish (deleting the industrial and bait fish component), the 1975 catch was valued at $26.6 million, or 6.3% of the U.S. food finfish catch. In other words, the industrial fish, primarily the Gulf menhaden, more than double the value of the Gulf fisheries and are considered the most valuable fish species in the Gulf. Gulf menhaden are second only to yellow-fin tuna in annual landing value for all U.S. waters. The under-utilized species (Table 2) contribute significantly to the Gulf biomass. The adults of these stocks tend to school in the pelagic environment and are not easily caught. Many of the under-utilized species are primarily planktivorous feeders and are not estuarine dependent.

For obvious reasons, the exploited species of fish have been more intensively studied with respect to distribution and abundance, population dynamics, biology, and physiology than under-utilized or forage species. Therefore, the remainder of this paper concentrates, for the most part, on the exploited species of finfish. Information gaps, however, also exist for forage species of fish and other invertebrates, because these organisms form the major food source for higher trophic level fishery organisms. Thus, recommended research needs on mortality and growth rates, physiology, habitat utilization, etc., also should apply to other species.

3. RECENT AND ON-GOING FISHERY RESEARCH IN THE GULF

In this section, we do not attempt to describe the extensive historical data base in the Gulf, but instead give examples of types of on-going research. Additional references are in the Appendix.

3.1 University and State Research

An excellent source of larval fish distribution and abundance data for the eastern Gulf can be obtained from Houde et al. (1979), who carried out extensive ichthyoplankton surveys from Cape San Blas south in 1971-74. A major objective of this work was to provide quantitative baseline information not only on the distribution of fish larvae, but also on spawning areas and times for important fishes. Their analyses of size and abundance by species permitted estimates of larval mortality rates and adult biomass calculations for selected species. These data supply input for determining potential fishery yields of some clupeoid fishes from the eastern Gulf. Since the adult biomass calculations required knowledge on the base number of eggs, the report includes counts of clupeid and engraulid eggs sorted from samples. Their data not only provide basic information on the kinds and abundances of larvae, but also infer aspects of the ecology and life history of adult stages. A conspicuous result of their survey was that of the 20 most abundant species of ichthyoplankton, only two are considered to contribute significantly to the fishery landings in the Gulf: Opisthonema oglinum and Sardinella anchovia. These two industrial or bait species are nowhere near to being fully exploited.

An extensive assessment of the fisheries of Mississippi territorial waters has been compiled by Christmas, et al. (1978) at the Gulf Coast Research Laboratory, Ocean Springs, Mississippi. All major commerical species (except oysters) are included, and the emphasis is on estuarine and juvenile phases and some related environmental factors (i.e., temperature and salinity). Included is information on immigration, growth, size distribution and abundance, distribution, seasonal trends in abundance, prediction of abundance, length-weight relationship and condition, and age at maturity. One section in the report (by Warren, Perry, and Boyes) summarizes knowledge of species in two trawl fisheries - one for petfood and one for food fish. The following seven species make up 90% of the catch of these fisheries: Atlantic croaker (Micropogonias undulatus), spot (Leiostomus xanthurus), sand sea trout (Cynosocion arenarius), silver sea trout (C. nothus), butterfish (Peprilus burti), cutlass fish (Trichiurus lepturus), and sea catfish (Arius felis). A life history review for each of these species is given along with extensive literature citations. Another major section includes menhaden and other coastal pelagic fishes, while a third section deals with life history reviews and the distribution and abundance of striped mullet (Mugil cephalus), white mullet (M. curema), spotted sea trout (Cynoscion nebulosus), red drum (Sciaenops ocellata), and southern kingfish (Menticirrhus americanus). Although the scope of this assigned review document is specifically for Mississippi, the primary species captured from Alabama to Mexico are included, and the information has wide application in this regard.

A similar, although less comprehensive, document has been compiled for the Louisiana Department of Wildlife and Fisheries (Barrett et al., 1978). This report addresses mainly estuarine waters and is primarily a systematic account of organisms caught in a 16-ft otter trawl in seven estuaries during 2 years. No attempt was made, however, to quantify these data through gear efficiencies.

Investigators at the University of Texas Marine Science Institute, Port Aransas Marine Laboratory, have conducted both laboratory and field research on organisms in the Gulf. Extensive studies have been made by Wohlschlag and others on the ecology of fishes, and the dynamics and energetics of fish populations and on pollution effects (Wohlschlag and Cameron, 1967; Steed and Copeland, 1967; Cameron, 1969; Cech and Wohlschlag, 1973; and Wohlschlag and Wakeman, 1978). These studies have dealt, for the most part, with juvenile and adult fishes. A recent Bureau of Land Management (BLM) study, conducted by the institute, gives valuable information on the levels of hydrocarbons in various species of fish and other organisms. The institute also conducts research into finfish mariculture and has an on-going spawning and rearing program for red drum (Sciaenops ocellata) and black drum (Pogonias cromis). In the past, the institute has successfully spawned spotted sea trout (Cynoscion nebulosus) (Fable, Williams and Arnold, 1978).

3.2 Federal Government Research

The Federal government has on-going Gulf of Mexico research programs at the National Oceanic and Atmospheric Administration (NOAA), National Marine Fisheries Services (NMFS), Southeast Fisheries Center (SEFC) Laboratories at Miami and Panama City (Florida), Pascagoula and Bay St. Louis (Mississippi), Galveston (Texas), and Beaufort, (North Carolina), the NOAA Atlantic Oceanographic and Meterological Laboratories at Miami, Florida; and the Environmental Protection Agency (EPA) Gulf Breeze Environmental Research Laboratory, Gulf Breeze, Florida.

(1) The Miami Laboratory is conducting research on population dynamics, biology, and ecology of oceanic pelagic fishes and invertebrates. Included in their studies are aging, reproduction, and fecundity studies on Atlantic bluefin tuna, marlin, sailfish, swordfish and sharks, and ichthyoplankton surveys. A number of excellent papers on the identification of larval fish have been published by Richards and others (Richards and Klawe, 1972; Richards and Potthoff, 1974; Potthoff, Richards and Ueyanagi, 1979; Richards, 1979).

(2) Investigators at the Panama City Laboratory are collecting information on age, growth, reproductive and food habits of mackerel and bluefish, as well as conducting general life history studies on other Gulf species, such as reef fish. Recently completed ichthyoplankton studies under BLM contract give extensive information on larval fish distribution and abundance in the western Gulf off the Texas coast (Finucane, 1977).

(3) In Mississippi, the Pascagoula Laboratory conducts resource surveys on abundance and distribution of several fisheries in coordination with other SEFC Laboratories. The Bay St. Louis Laboratory is primarily an engineering facility for the development of remote sensing for fishery application. In addition, the laboratory provides data management for development and demonstration of computer software options and program planning analysis to provide systems engineering support.

(4) Shrimp research is continuing at the Galveston Laboratory. Primary objectives include determination of growth and mortality rates for white and brown shrimp and development of procedures to successfully produce and grow shrimp in captivity. Finfish research includes seasonal biomass estimates for northern Gulf of Mexico groundfish (e.g., species of finfish that remain close to the bottom and are available for capture by bottom trawls). Objectives of these studies include estimates of seasonal

biomass and total mortality for Atlantic croaker, spot, and sea trout; analyses of age and growth for croaker and tilefish; and analyses of environmental and ecological data to determine impact on the density of groundfish. In addition to the above research, several environmental programs are managed from the Galveston Laboratory. One on-going study is concerned with the potential effect of brine disposal from the Strategic Petroleum Reserve Program off the Texas and Louisiana coast on shrimp and red drum. Another study, which is nearing completion, is designed to determine the effects of an active gas and oil field (Buccaneer) on the composition and abundance of the biotic community in the vicinity of the oil field.

(5) The Beaufort Laboratory is involved in Gulf of Mexico studies on Gulf menhaden and other clupeoid fish, reef fish, and pollution transfer through the food chain. Menhaden studies include those directed toward obtaining age, size, catch, and effort data, and recruitment and larval survival data. Research on reef fish includes basic life history aspects (such as age, growth and mortality, food, and reproduction), and habitat and stock assessment. Initial steps have been taken to develop an information base for other clupeoid species (Reintjes, 1979). Recently, the Beaufort Laboratory has initiated a program in the Gulf (in collaboration with AOML, Miami) to determine the relationship between contaminants and food web dynamics.

One of the objectives of this joint effort is to identify and describe the relationships among trophic levels that determine the survival and growth of larvae of ecologically and economically important fishes in the northern Gulf of Mexico. Concurrently, we hope to determine the effects of differences in concentrations and chemical form of selected trace metals to marine planktonic communities, including those that support larval fish. As a result of these two studies, we will attempt to develop predictive models to estimate the biological assimilative capacity of selected areas in the Gulf of Mexico for anthropogenic additions of trace metals.

This program was initiated in response to recent legislation, the National Ocean Pollution Research and Development and Monitoring Planning Act of 1978 (PL 95-273) and the Marine Protection, Research and Sanctuaries Act of 1972 (section 202 of PL 92-532), and has been developed from on-going research at the Beaufort Laboratory.

(6) The Atlantic Oceanographic and Meteorological Laboratory at Miami is concerned with the physical, geological and chemical characteristics of the Gulf. This research will provide useful environmental information for fishery-related studies in the Gulf.

(7) The Gulf Breeze Environmental Research Laboratory is continuing its diversified research program into the effects of different natural and man-made hydrocarbons on species of Gulf fish and shellfish. These research projects include: research on the accumulation and effects of pesticides on estuarine and marine organisms; determination of the effects of drilling fluids (muds) on corals and estuarine benthic organisms through laboratory and field research, and then the relating of these data to effects in the Flower Garden reef area of Texas; and determination of the effects of various carcinogens and mutagens on marine organisms.

4. RESEARCH NEEDS AND RECOMMENDATIONS FOR STUDIES

Although there is an extensive data base on fishery species in the Gulf, for the most part field research has followed classical lines. In both estuarine and open water habitats, emphasis has been placed on the taxonomy of larval and adult stages and their relative distributions, and on life history studies of individual species (primarily those of commercial and recreational value), which include studies on length-weight condition indices, food habits, age and growth, and fecundity. Laboratory research usually has been designed to evaluate metabolism and energy requirements and the influence of salinity and temperature on these processes, as well as the effects of specific pollutants (e.g., pesticides, hydrocarbons, metals) on fishery organisms. Although relevant to our knowledge of the biology of fishery species and the effects of pollutants, the extrapolation of this laboratory information to answer environmental questions requires a more thorough knowledge of conditions in nature and the natural factors regulating the abundance of fish populations.

With few exceptions, we do not have information on these natural factors for the Gulf. Data gaps exist that must be filled before the effects of environmental contaminants on fisheries can be separated from effects of natural factors. Areas that we have identified as being most in need of additional research are: (1) early life history stages of organisms, (2) toxicity studies, (3) adult spawning areas, (4) under- or non-utilized species. We discuss each of these areas in the following sections.

4.1 Studies on the Early Life Stages

In our opinion, with respect to finfish the one area most in need of additional research in the open Gulf of Mexico is that associated with natural variables that control larval survival and, therefore, recruitment into the adult population. These natural variables include egg quality, larval vigor at yolk absorption, co-occurrence of suitable food with larvae, activity by planktonic and nektonic predators, turbulence, current direction for passive transport to nursery areas (estuary or reef), impact of ultra-violet radiation, and turbidity. These variables need to be understood for key species within functional species aggregations before the impacts of added human perturbations on the health of Gulf fish population productivity can be assessed, predicted, or prevented. Understanding the effect of these natural variables on growth and survival of prerecruits requires a combination of laboratory experiments, field experiments, and field surveys.

The extent to which natural and anthropogenic factors modify survival and production of larvae in one area of the Gulf may or may not affect the overall production of the harvestable adult population of a given species for the entire Gulf. The impact of large larval mortalities, due to pollution, for example, on recruitment to adult populations may not be significant in some cases, because compensatory mechanisms may regulate the population in the direction of a long-term average (Everhart, Eipper and Youngs, 1975). On the other hand, there are strong and convincing arguments that the period when year-class strength is determined may occur during the first year of life (Hjort, 1914; Bannister, Harding and Lockwood, 1974; Cushing, 1974; Holden, 1977).

In fisheries based on single year-class population structures (e.g., shrimp), a relationship between spawning effort (i.e., the number of adults in the spawning populations) and recruitment into the harvested population is easier to determine than for a fishery composed of several year classes, typical of most finfish species. Components of a multiple year-class population may have different rates of either natural or fishing mortality based on the vulnerability of different-sized fish. In both cases, one conclusion drawn recently (Hunter, 1976) is that factors affecting recruitment and larval fish mortality are virtually unknown. We believe that this is particularly true for the Gulf of Mexico, because of our lack of knowledge of early life stages for this area. The recent International Symposium on the Early Life History of Fish, held at the Woods Hole Biological Laboratory (2-5 April 1979), substantiates our opinion. At this symposium, 147 papers and posters were presented, but none dealt specifically with research conducted in the Gulf of Mexico. This lack of early life history data makes it impossible, in many cases, to develop proper management strategies.

We recommend that a comprehensive plan be established for the study of the early life stages of fish (through the first year of life) in the Gulf of Mexico. This plan should include both field and laboratory studies and could be modeled after studies developed by Lasker and his colleagues at the NMFS Southwest Fisheries Center and modified and used at the NMFS Southeast Fisheries Center. Initially, the plan should concentrate on nearshore species (such as sciaenids and clupeids), since they are more susceptible to pollution and represent the largest contribution to the Gulf fisheries. An outline of the factors most in need of study is given by Hunter (1976).

4.2 Environmental Contaminant Studies

Eggs and larvae of fishes are more likely to be affected by pollutants in the Gulf than adults, although adults may accumulate heavy body burdens of pollutants. This is partially because early life stages are incapable of substantial movements to avoid contaminants and partially because early life stages are often the most sensitive ones due to rapid cell division and rapid growth, which may incorporate pollutants into structural materials (de Sylva, 1969).

Contaminant research usually can be divided into laboratory effects studies and field monitoring. In most cases, these studies cannot be easily linked. We believe that it is critical to bridge the gap between laboratory and field studies. A recent ICES report (Cooperative Research Report No. 75) suggests several ways in which this could be attempted; we have selected three of these for additional discussion.

(1) Factors that might indicate "poor health" need to be developed and incorporated into ongoing biological survey work. These factors might include lesions, gill damage, or any changes in the general morphology of the organism. For example, with respect to larval fish, Theilacker (1978)

has examined the histological and morphological characteristics of jack mackerel (Trachurus symmetricus) following starvation in the laboratory, and have shown that they can be used as an indicator of starvation in the field.

(2) Lasker (1974) has successfully spawned northern anchovy (Engraulis mordax) in the laboratory and used them in the field to determine if food density was sufficient for larval survival. Hoss and Hettler (unpublished) have used laboratory- spawned spot larvae and postlarvae (Leiostomus xanthurus) to test in the field for lethal levels of a pesticide.

(3) Other techniques should be developed that will allow field monitoring. One recently developed technique that shows great promise is the otolith aging method for larval fish (Brothers, Mathews, and Lasker, 1976; Strusaker and Uchiyama, 1976). This method examines the daily growth increments found in the otoliths of fish larvae. Being able to age larvae will allow comparisons to be made between growth rates (and mortality rates) of fish from different areas and between field and laboratory conditions. It might be possible to develop a growth index that would indicate environmental quality using this method. This technique has been developed at the NMFS Beaufort Laboratory for one Gulf species, the spot (Leiostomus xanthurus).

4.3 Spawning Areas

Research to define critical spawning areas and times is needed beyond the effort that has been expended analyzing data collected from routine plankton and adult stock surveys. The ichthyoplankton distribution and abundance sampling efforts of Houde et al. (1979) and others infer much about the general spawning areas of Gulf fishes, but unless high concentrations of similarly staged eggs or very young (yolksac) larvae are collected, precise spawning habitats cannot be defined for specific species. The sexual maturity stage of adult fish sampled from exploratory fishing efforts or commercial purse seine or trawl fisheries also may indicate geographical distributions of fishes in spawning condition. However, significant numbers of running-ripe fish rarely have been reported from open Gulf waters to the extent necessary to delimit exact spawning areas other than for some reef species. Since the successful species have evolved to spawn in habitats that maximize survival, man's disruption of the processes involved in the choice and use of a potential spawning site would reduce the number of larvae produced. This interference by man may be as obvious as fishing on the spawners, or as indirect as behavioral modifications on the spawners by sublethal pollutant levels in the spawning area. Further, toxic concentrations of pollutants, such as copper, in spawning areas may destroy eggs or emerging larvae (Engel and Sunda, 1979). Sublethal concentrations may diminish food supplies or reduce larval growth rates.

To be able to prevent or reduce any of these possible effects, we believe that more effort is needed to define critical spawning areas and times, beginning with the species most important to man (perhaps Gulf menhaden, red snapper, red drum, and striped mullet, as each of these species represents a different family). We stress the phrase critical area and time because there may be many areas of secondary importance to the overall Gulf production of a given species, and these secondary, or fringe, areas could be considered more expendable in the monitoring or regulation of pollutant discharges.

If efforts are made to define spawning areas more precisely, a likely conclusion may be that most species do not have a "spawning ground" (such as is known for Clupea harengus and other species with demersal adhesive eggs). Instead, the eggs may be randomly shed and fertilized anywhere over the shelf waters by schools of adults whenever they become ripe because of the influence of temperature, photoperiod, and lunar-phase stimulating gamete maturation. If this is the case for a "target" species or group of fishes, pollutant discharge effects on spawning effort will be more difficult to control. In addition to considerations of pollution impacts on spawning, knowledge of the location of critical spawning areas and times will make early life history field studies easier; for example, estimates of natural mortality and growth of early larvae from a known spawning effort could be obtained by following a mass of recently spawned larvae and taking serial samples for ageing and size measurements. For such a study to succeed, not only will critical spawning areas and times need to be predicted, but reliable techniques for following the water mass containing the eggs and/or larvae will be required.

4.4 Under- or Nonutilized Species

Additional research on under- or nonutilized species should not be overlooked. Not only do many of these species (e.g., clupeids, engraulids) provide the food for important commercial species, but some of these species may not remain latent for man's use forever. Some of the nonutilized species (e.g., Decapterus punctatus, the round scad) seem to be universally abundant in the Gulf and eventually could be commercially valuable. Life history studies, including distribution and abundance, initiated before a non-exploited resource is harvested are necessary to provide information on biomass and age structure of the population. Some of the very abundant species that are not fished upon may even now be very useful indicators of the health of the Gulf, since the lack of fishing mortality would not complicate the biomass and distribution observations. Major ecological changes in the Gulf may be reflected by changes in the distribution and abundance of unfished species on a long-term basis.

We recognize that the above list of research needs is not complete. We also recognize that it is easier to suggest a research project than to implement that project. It is our conclusion, however, that contaminant-related research in the Gulf must be directed along the lines we have suggested to successfully evaluate "effects" on a fishery and provide the data necessary for the development of strong, rational management policies on Gulf fishery species.

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Table 1. Species landed by state, in thousands of pounds, 1975 (Only species totalling more than 100,000 pounds are shown) (Data and common names from Current Fisheries Statistics, No. 7409, NOAA/NMFS)

Common name	Scientific name	Fla. (West Coast)	Ala.	Miss.	La.	Tx.	TOTAL
Ballyhoo	Hemiramphus brasiliensis	171	-	-	-	-	171
Bluefish	Pomatomus saltatrix	436	7	75	12	-	530
Bluerunner	Caranx fusus	1,680	-	-	-	-	1,680
Bonito	Euthynnus alletteratus	121	-	-	-	-	121
Cobia	Rachycentron canadum	84	7	1	1	27	120
Cigarfish	Decapterus punctatus	696	-	-	-	-	696
Crevalle	Caranx hippos	2,825	-	22	-	-	2,847
Croaker	Micropogonias undulatus*	2,126	9,065	1,004	484	116	12,795
Dolphinfish	Coryhaena hippurus	106	-	-	-	-	106
Drum, black	Pogonias cromis*	35	20	20	276	1,172	1,523
Drum, red	Sciaenops ocellata*	759	74	72	1,362	2,120	4,387
Flounders, Unclassified	Paralichthys spp.*	219	832	105	243	493	1,892
Groupers, Except Warsaw	Epinephelus spp.	7,007	114	89	5	71	7,286
Grunts	Haemulon spp.	221	-	-	-	-	221
Herring, thread	Opisthonema oglinum	861	-	-	-	-	861
Jewfish	Epinephelus itajara	186	23	-	-	-	209
King Whiting	Menticirrhus spp.	148	218	153	144	170	833
Mackerel, king	Scomberomorus cavalla	2,622	-	-	-	-	2,622
Mackerel, Spanish	Scomberomorus maculatus	5,621	92	224	200	-	6,137
Menhaden, Gulf	Brevoortia patronus*	466	-	212,071	984,106	-	1,196,643
Moajarra	Eucinostomus spp.*	147	-	-	-	-	147
Mullet,black (lisa)	Mugil cephalus*	23,167	1,618	285	213	46	25,329
Mullet, silver	Mugil curema*	532	-	-	-	-	532
Permit	Trachinotus falcatus	207	-	-	-	-	207
Pompano	Trachinotus carolinus	1,113	9	27	17	7	1,193
Porgy	Calamus spp.	109	-	-	-	-	109
Sea catfish	Bagre marinus*	25	48	23	35	89	220
Sea trout, spotted	Cynoscion nebulosus*	2,169	104	263	1,897	1,814	6,247
Sea trout, white	Cynoscion nothus*	176	1,971	265	166	15	2,593
Sheepshead	Archosargus probatcoephalus	268	111	32	101	319	831
Snapper, mangrove	Lutjanus griseus	485	-	-	-	-	485
Snapper, mutton	Lutjanus analis	260	-	-	-	-	260

Table 1. Species landed by state, in thousands of pounds, 1975 (Cont'd)

Common name	Scientific name	Fla. (West Coast)	Ala.	Miss.	La.	Tx.	TOTAL
Snapper, red	Lutjanus campechanus	4,453	833	1,709	151	627	7,773
Snapper, vermilion	Rhomboplites aurorubens	353	-	-	-	-	353
Snapper, yellowtail	Ocyurus chrysurus	675	-	-	-	-	675
Spanish sardine	Sardinella anchovia	248	-	-	-	-	248
Spot	Leiostomus xanthrus*	136	55	5	18	-	214
Swordfish	Xiphias gladius	131	18	-	-	-	149
Tenpounder	Elops saurus	1,002	-	-	-	-	1,002
Warsaw	Epinephelus nigritus	135	-	-	-	-	135

* estuarine-dependent species

Table 2. Summary of spawning times as inferred by egg and larvae abundance of abundant pelagic, reef, and estuarine Gulf fishes (if known, locations of major spawning grounds are included)

Species	Exploited (E) or nonutilized (N)	Spawning time	Location and remarks
Elopidae			
Elops saurus (ladyfish)	E	Fall	Offshore
Clupeidae			
Etrumeus teres (round herring)	N	Late Spring - Spring	30-100 m offshore Tampa Bay
Harengula jaguana (scaled sardine)	N	Spring - Summer	<30m
Opisthonema oglinum (Atlantic thread herring)	N	Spring - Summer	<30m
Sardinella anchovia (Spanish sardine)	N	Summer (same all year)	< m entire eastern Gulf
Engraulidae (anchovies)*	N	Spring - Summer (but some all seasons)	<50 m
Gonostomatidae (light fishes)	N	All seasons	>100 m midwater offshore
Maurolicus muelleri (none)	N	Summer	>90 m
Myctophidae (lantern fishes)	N	All seasons	<100 m midwater offshore
Ariidae			
Arius felis (sea catfish)	N-E	Late Spring-early Summer	Bays and Estuaries
Bregmacerotidae			
Bregmacerous (codlet)	N	Fall peak (year round)	30-90 m
Serranidae			
Centropristis striata (black sea bass)	E	Fall-Summer-Spring	<50 m northern Gulf
Diplectrum formosum (sea bass)	N	Spring-Summer peak (year-round)	<50 m (entire area)
Epinephelus morio (red grouper)	E	Spring	
Epinephelus niveatus (Nassau grouper)	E	Spring-Summer	
Epinephelus striatus (snowy grouper)	E	Spring-Summer	
Mycteroperca microlepis (gag grouper)	E	Spring-Summer	
Mycteroperca phenax (scamp grouper)	E	Spring-Summer	

*Estuarine dependent

Table 2. Summary of spawning times as inferred by egg and larvae abundance of abundant pelagic, reef, and estuarine Gulf fishes (if known, locations of major spawning grounds are included) (Cont'd)

Species	Exploited (E) or nonutilized (N)	Spawning time	Location and remarks
Carangidae			
Caranx hippos (crevalle)	N-E	Winter-Summer (early March-early Sept)	Offshore
Chloroscombrus chrysurus (Atlantic bumper)	N	Summer	<30 m eastern Gulf
Decapterus punctatus (round scad)	N	Spring and Fall	(10-70 m entire Gulf mostly NE)
Trachinotus carolinus (pompano)	E	Spring-Summer	Offshore
Trachurus lathami (rough scad)	N	Winter-early Spring	>50 m
Lutjanidae			
Lutjanus campechanus (red snapper)	E	Summer-Fall	W. Fla. Campeche Banks
Ocyurus chrysurus (yellowtail snapper)	E	Spring-Summer (possibly year round)	
Rhomboplites aurorubens (vermilion snapper)	E	Summer	30-100 m
Pomadasyidae			
Haemulon spp. (grunts)	E	Winter-Spring	<50 m nearshore
Sparidae			
Stenotomus caprinus (longspine porgy)	E	Spring	offshore (?)
Sciaenidae			
Cynoscion nebulosus (spotted seatrout)*	E	Spring-Summer	Bays
Leiostomus xanthrus (spot)*	E	Fall-Winter-Spring	offshore >30m (not well known)
Micropogonias undulatus (Atlantic croacker)*	E	late Summer-Fall	>50 m
Mugiladae			
Mugil cephalus (striped mullet)*	E	Winter-Spring	Deeper water shelf
Trichiuridae			
Trichiurus lepturus (Atlantic cutlassfish)	E	Winter	>40 m Northern Gulf

*Estuarine dependent

Table 2. Summary of spawning times as inferred by egg and larvae abundance of abundant pelagic, reef, and estuarine Gulf fishes (if known, locations of major spawning grounds are included) (Cont'd)

Species	Exploited (E) or nonutilized (N)	Spawning time	Location and remarks
Scombridae			
Auxis sp. (mackerel)	N-E	Spring-Summer	>50 m
Euthynnus alletteratus (little tunny)	N-E	Spring-Summer	30-100 m
Scomber japonicus (Chub mackerel)	N	Winter	deep shelf and slope
Scomberomorus cavalla (king mackerel)	E	Summer	32-183 m offshore western Gulf, NE Gulf
Scomberomorus maculatus (Spanish mackerel)	E	Summer	12-34 m nearshore some on eastern Gulf, NE Gulf
Thunnus atlanticus (Blackfin tuna)	E	Spring-Summer	>100 m
Thunnus thynnus (bluefin tuna)	E	Spring	>100 m
Bothidae			
Bothus ocellatus (eyed flounder)	N	Spring-Summer (but year round)	
Bothus robinsi (flounder)	N	Winter-Spring-Summer	10-100 m eastern Gulf, southern
Etropus rimosus (gray flounder)	N	Fall	<50 m (northern)
Paralichthys spp. (flounder)*	E	Fall-Winter	offshore (not well known)
Syacium papillosum (dusky flounder)	N	Spring-Summer	10-100 m eastern Gulf, southern

*Estuarine dependent

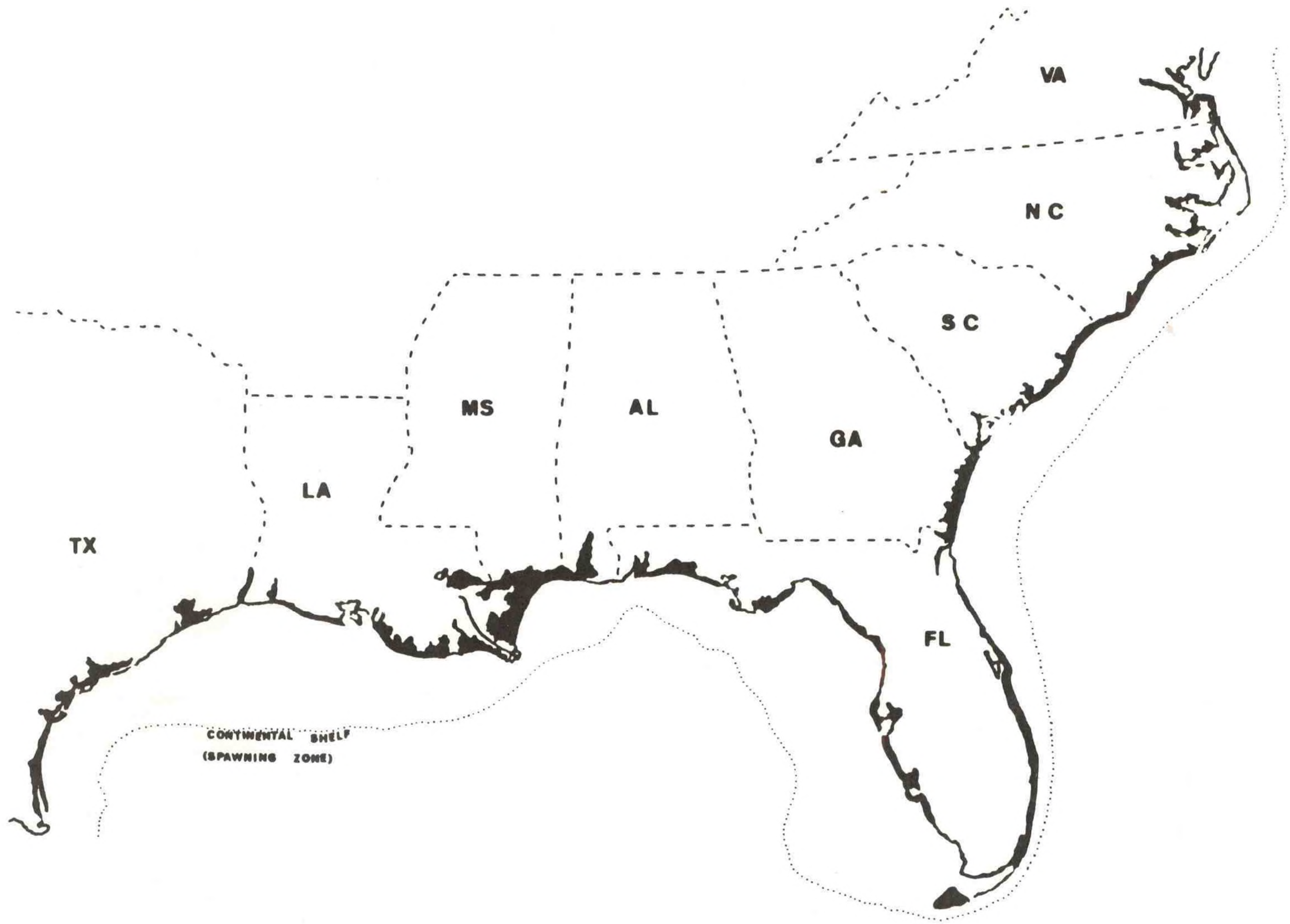

Fig. 1. Gulf coast of the Southern United States showing continental shelf where many economically and recreationally important species spawn.

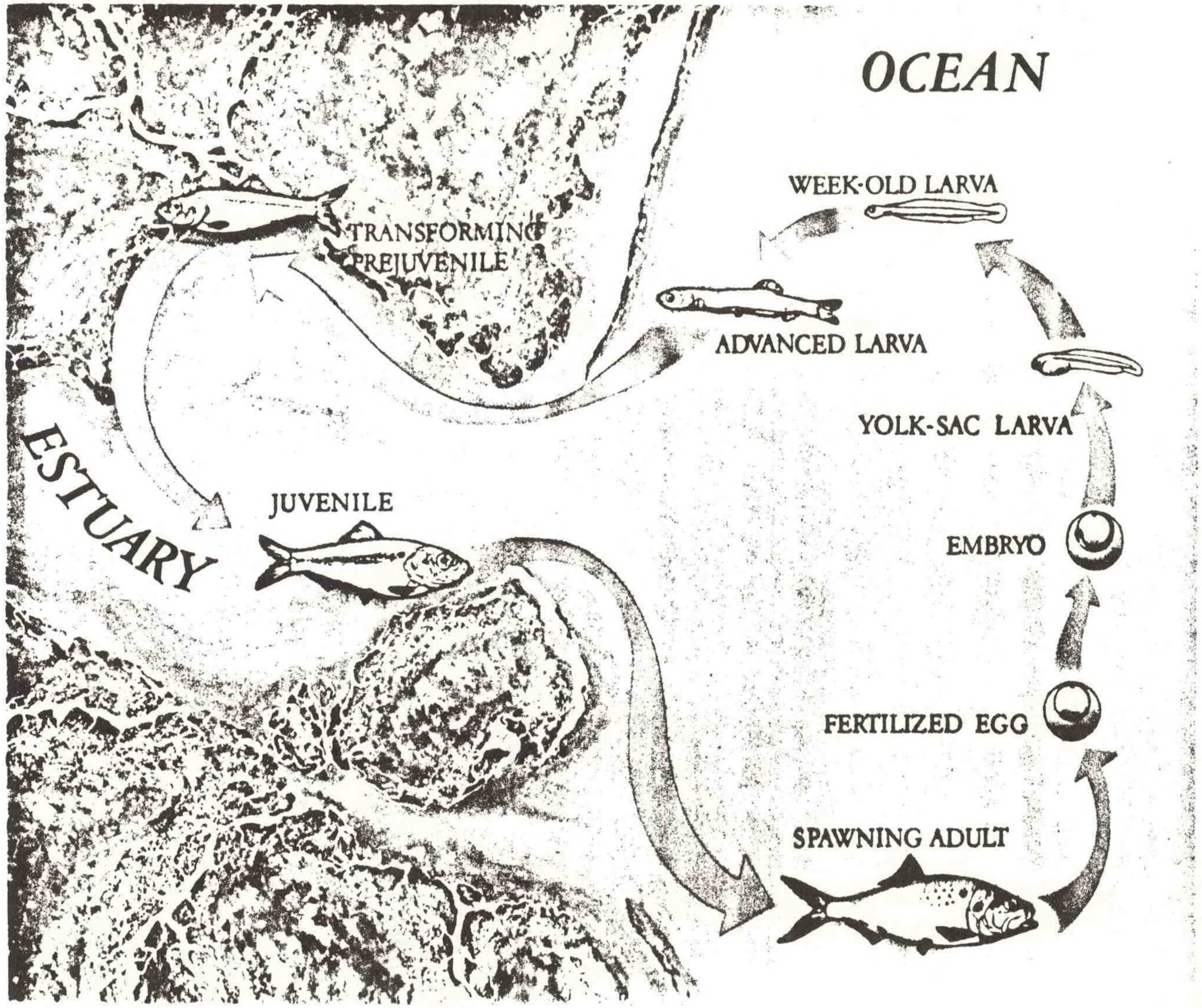

Fig. 2. Typical life cycle of an estuarine dependent species, the Gulf menhaden (Brevoortia patronus).

RADIONUCLIDES IN THE GULF OF MEXICO

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1. INTRODUCTION

The Gulf of Mexico (Fig. 1) is a partially closed basin that can be divided into two parts on the basis of its physical oceanography. The eastern Gulf of Mexico is dominated by the East Florida Loop Current. This current enters the Gulf through the Yucatan Channel over an 1800 m sill and exits through the Florida Straits across a 600 m sill. The Loop Current transports more than 25 x 10^6 m^3/s of water at velocities up to 200 cm/s (Table 1). The magnitude of this current results in the fact that the geochemistry of the eastern Gulf of Mexico resembles that of the western Caribbean (El-Sayed et al., 1972).

The western Gulf of Mexico exchanges water with the Loop Current, but has much greater residence time in the Gulf, and is influenced to a major extent by runoff from the surrounding land masses. The annual influx of river water represents 10 percent of the volume of water on the continental shelf in the western Gulf of Mexico.

The circulation patterns in the western Gulf of Mexico are not well understood, and there is little available information on residence times for water masses and particulate matter on the shelf. The chemistry of the mixing zone between the rivers and the ocean is not understood in detail, and it is difficult to make predictions about the behavior of chemical pollutants in the system because of the scarcity of such information. Moreover, the coast of the Gulf is highly industrialized and heavily populated in some areas and the impact of human activities is increasing. The study of this system's chemistry has benefitted from research on radioactive elements available as tracers for natural processes.

Radionuclides in the ocean are either natural or anthropogenic in origin. The property that distinguishes all such elements, of course, is an unstable nucleus that results in radioactive decay of the nuclide according to a characteristic half-life. This phenomenon is extremely valuable as an indicator of the rates at which chemical and physical events take place in the environment. It is also the source of life-damaging radiation, which is of concern in cases of local concentrations of large amounts of radioactive substances.

2. NATURALLY OCCURRING RADIONUCLIDES

2.1 Uranium in the Gulf of Mexico

Members of the uranium and thorium decay series have been used in a wide variety of ways to provide a time frame for chemical, physical, and biological processes in the ocean. Reviews of these methods have recently been published by Ku (1976) and Turekian and Cochran (1979). The three decay series are shown in Figure 2.

The most abundant uranium isotope is ^{238}U, which comprises 99.28% of all naturally occurring uranium and is the parent of one of the decay series shown in Figure 2. ^{235}U is less abundant (0.72%), occurs in a fixed activity ratio of 0.0437 to ^{238}U, and is the parent of another of the natural decay series. Uranium is quite soluble in oxidizing sea water and probably is present as the uranyl carbonate ion $UO_2(CO_3)_3^{-4}$. Its residence time in sea water is at least 200,000 to 400,000 years (Ku, et al., 1977). In contrast, the long-lived daughter products of the U parents, ^{230}Th and ^{231}Pa, are quite insoluble and are quickly removed to the seafloor by adsorption or precipitation processes. This chemical separation from the parent uranium isotopes creates the radioactive disequilibria that have been commonly utilized to measure rates of sediment accumulation in the ocean (Ku, 1976; Turekian and Cochran, 1979).

Between ^{238}U and ^{234}U in the decay series are two daughters with relatively short half lives, ^{234}Th and ^{234}Pa. The alpha decay that takes place during the formation of ^{234}U from its original ^{238}U parent causes an "alpha recoil" effect (Cherdyntsev, et al., 1961; Thurber, 1962; Rosholt et al., 1966) on the ^{234}U that results in its chemical fractionation from ^{238}U. Preferential leaching of ^{234}U during continental weathering causes the $^{234}U/^{238}U$ activity ratio in rivers and the ocean to be greater than 1. The ratio in sea water is nearly constant at $1.14 \pm .03$ (Ku et al., 1977). The $^{234}U/^{238}U$ activity ratio in ground water and rivers has been used to trace water mass movements through the soil in the Gulf of Mexico distributive province (Osmond and Cowart, 1976).

The uranium geochemistry of the Gulf of Mexico is influenced by several different sources and sinks for uranium. The uranium concentration of open Gulf water, both shallow and deep, was measured by Rona et al. (1956) to be about 3.39 μg/l. These values are essentially the same as those measured later by Sackett and Cook (1969) and are typical of open-ocean uranium concentrations (Ku et al., 1977). The $^{234}U/^{238}U$ activity ratios for open Gulf waters (Sackett and Cook, 1969) are $1.14 \pm .03$, the same value found for open-ocean water by Ku et al. (1977).

However, uranium concentrations in nearshore waters reflect the variable influence of river water uranium (Table 2). The uranium content and isotope ratios in river waters being added to the Gulf are shown in Table 3. Of the rivers listed, the Mississippi River adds by far the largest amount of dissolved and suspended uranium to the Gulf. It is by no means easy to determine from the available data what a reasonable estimate would be for that amount of uranium. Sackett et al. (1973) estimate the mean uranium concentration of Mississippi River water to be 0.5 μg/l after making a 0.3 μg/l correction for the uranium associated with phosphate fertilizer. Spalding and Sackett (1972) note an addition of uranium to south Texas rivers from uranium mining activities, and an overall increase in uranium in rivers entering the Gulf associated with phosphate fertilizers used in the United States. Sackett and Cook (1969) list the uranium content of a commercial fertilizer as 0.1 percent, clearly a very significant amount. Holmes and Slade (1972) have noted uranium as high as 43 μg/l in the Nueces River in the vicinity of the Texas uranium mining area. It is also possible that cultivation of land enhances uranium leaching from the soil and increases the amounts present in river water.

Considerations of the addition of uranium to rivers by human activities was made by Moore (1967), Turekian and Chan (1971), and Ku et al. (1977). In contrast to the data in Table 3, relatively uncontaminated rivers have much lower uranium concentrations; for example, the Amazon River has a uranium concentration of 0.03 μg/l (Moore, 1967; Bertine et al., 1970). Ku et al. (1977) state that the estimates of 0.3-0.6 μg/l uranium for average river water may be upper limits because of anthropogenic uranium additions.

There are several geochemical sinks for uranium in the Gulf of Mexico. These include carbonates being deposited on the sea floor and as coral reefs, anoxic sediment accumulations, and organic matter associated with shelf sediments being deposited in the Gulf.

The relationship between uranium and calcium carbonate in a variety of marine sediments is summarized in Figure 3. The uranium in Gulf sediments is unusual in several respects when compared with uranium in Pacific, Atlantic, and Indian Ocean sediments. First, the alumino-silicate portion of the sediment appears to have a rather high uranium content, about 4 ppm by the intercept on the uranium axis at 0 percent carbonate (Fig. 3). Second, some of the carbonate-rich samples, such as those from the Sigsbee Knolls, contain high concentrations of uranium not typical of the other carbonate sediments in the diagram. The work of Mo et al. (1973) has identified pteropods in the carbonate sediments as being important contributors of uranium to these sediments, with concentrations of up to 2.74 ppm U in the pteropod shells. There is an unresolved difference in the literature concerning the uranium content of foram tests. Ku (1965) reports concentrations in an Atlantic core of .0x ppm for the coccolith fraction and .025 ppm U for the foram fraction, Mo et al. (1973) report 0.27-1.19 ppm U in forams from the Gulf of Mexico, and Sackett et al. (1973) find 0.15 to 0.49 ppm U in hand-picked forams from the Gulf of Mexico.

The deposition of uranium in carbonate sediments appears to be an important part of its geochemical cycle in the Gulf. Sackett et al. (1973) offer no explanation for the high uranium content of Gulf forams. It is possible that the uranium is associated with ferromanganese coatings or organic matter analyzed along with the carbonate material.

The apparently high content of uranium in the alumino-silicate fraction of Gulf sediment has been attributed by Sackett et al. (1973) to uranium added from terrestrial sources. ^{13}C analyses on organic matter from Gulf sediment suggest a correlation between uranium enrichment and the content of terrestrially derived organic matter (Sackett et al., 1973). Uranium concentrations in river bottom sediments (Scott, 1968) and bottom and suspended sediments (Scott and Salter, in preparation) of rivers emptying into the Gulf show rather high uranium contents of appropriate levels to explain values in Gulf sediments (Table 4). However, for river suspended sediments on which both uranium and total organic carbon have been measured, no positive correlation between the parameters was found (Scott and Salter, in preparation). It is interesting to note that the uranium content in windborne Saharan dust collected at Barbados and Miami (Rydell and Prospero, 1972) is about 3.5 ppm. It seems unlikely that this uranium is related to either phosphate fertilizer or anoxic sediments.

The existence of anoxic sediments has been a candidate for a major sink for uranium in the ocean. Veeh (1967) has estimated that about 1.1 x 10^{15} μg of uranium per year are deposited in such sediments. There are several areas in the ocean where anoxic sediments are removing uranium from sea water. The most conspicuous of these near the Gulf of Mexico is the Cariaco Trench in the Southern Caribbean Sea. Dorta and Rona (1971) have shown the sediments in the Cariaco Trench to be quite rich in uranium, up to 25 ppm, and to have $^{234}U/^{238}U$ activity ratios typically higher than 1 and close to the sea water value of 1.14.

Shokes et al. (1977) have described another anoxic basin, the Orca Basin, in the northern Gulf of Mexico at 27°55'N, 91°20'W. This basin is filled with hypersaline anoxic water that has formed during dissolution of a salt structure under the sediment. The age of the basin is estimated by Addy et al. (1979) to be 7900 years. But, according to R. Weber, P. Salter and J. Johnson (personal communication), there is essentially no enrichment of uranium in the Orca Basin sediment. Transfer of material across the brine-sea water interface thus appears to be extremely slow.

Another potential sink for uranium in the Gulf exists in nearshore sediments. Aller and Cochran (1976) and Thompson et al. (1975) have shown that uranium is quite mobile in the upper parts of the sediment column in Long Island Sound. The oxidizing upper layer is depleted in uranium, possibly by reworking and oxygenation effects of benthic organisms, while the deeper reducing layers are enriched in uranium by downward diffusion from overlying water or irrigation by organisms. Trefry and Presley (1979) have cited evidence for extensive remobilization of iron and manganese in Mississippi Delta sediments. This area is one in which uranium deposition in the anoxic portions of the sediment could be potentially important, but the process has not been documented to occur in the Mississippi Delta. Iron-rich concretions forming on top of sediment in the Gulf of Mexico (Pequegnat, et al., 1972) also may represent a sink for uranium. Analyses reported by Pequegnat et al. (1972) and unpublished data of P. Salter show the concretions to contain up to 15 ppm of uranium and large amounts of ^{230}Th and ^{231}Pa.

Calculating a geochemical balance for uranium in the Gulf of Mexico is difficult for a number of reasons. The recent increase in application of phosphate fertilizer to cultivated areas makes it necessary to use a correction factor to adjust downward the uranium concentrations measured in river water. Sackett and Cook (1969) have estimated that the average pre-fertilizer uranium input to the Gulf from rivers is 3.3 x 10^7 g/yr.

An additional problem is presented by the fact that the Yucatan current annually carries 800 times as much water through the Gulf as is added by annual runoff. This results in rapid dilution of runoff contributions to marine concentration levels. In the western Gulf, however, the currents are sluggish and the residence time of the water may be around 100 years, so that the influence of runoff sources may be more conspicuous in that area.

2.2 Uranium Series Geochronology in the Gulf of Mexico: Sediment Accumulation Rates

A number of studies on Gulf of Mexico sediments have taken advantage of the fact that uranium series daughters become chemically separated from their parent uranium isotopes and form convenient "clocks" for measuring rates of sediment accumulation and other processes. ^{210}Pb has a complex geochemical system in the environment. It has a noble gas, ^{222}Rn, as a parent isotope. The Rn parent escapes from soils and water to the atmosphere where ^{210}Pb is produced after a series of short half-life decays. The ^{210}Pb is then removed by precipitation to the ocean and subsequently to the sediment. The ^{210}Pb in marine sediment also may originate from ^{226}Ra and ^{222}Rn dissolved in the water column, and the ^{226}Ra present in the sediment produces an equilibrium amount of ^{210}Pb. The sum of ^{210}Pb in the sediment from all of these sources is greater than the amount for equilibrium with the ^{226}Ra parent in the sediment, and the decay of the excess with depth in the sediment (time) yields the sediment accumulation rates. The 22.3 year half-life of ^{210}Pb makes it appropriate for use in rapidly depositing sediment.

Studies by Holmes and Martin (1978a) on the continental shelf and slope in the northwestern Gulf of Mexico have shown ^{210}Pb measurement of sedimentation rates to be a useful technique. Figure 4 is a summary of the rates reported in that paper. The ^{210}Pb in nearshore shelf sediments is low in total concentration; but in deeper water, sediments have larger total amounts of ^{210}Pb either because of shoreward transport of ^{210}Pb-rich sediment or because of the increasingly greater source of ^{210}Pb from ^{226}Ra in increasingly deeper water masses. This effect is illustrated by the distribution of surface sediment ^{210}Pb activity shown in Figure 5.

Bioturbation of nearshore sediments can create difficulties in interpreting the ^{210}Pb profiles observed in the sediment. Sediment mixing by organisms is common in the Gulf and creates ^{210}Pb profiles that flatten out toward the top of the sediment column rather than continuing to increase. Shokes (1976) has studied a suite of cores in the Mississippi Delta and has applied the modelling approach of Guinasso and Schink (1975) to these rapidly accumulating sediments to calculate the mixing rates causing the observed changes in the ^{210}Pb profiles. The ^{210}Pb accumulation rates for the Delta range from .1 $gm/cm^2/yr$ on the continental slope to up to 1.5 $g/cm^2/yr$ or higher near the river mouths. Surface sediment ^{210}Pb values also were observed to vary in this area of the Gulf, again increasing markedly, from 6 dpm/gm nearshore to 85 dpm/gm in deeper water at the shelf break. The riverine contribution of ^{210}Pb to the Gulf of Mexico is not known, but it undoubtedly influences the nearshore values; the higher ^{210}Pb values in sediments at the shelf break indicate greater pelagic contributions from deep water.

The ability to measure sediment accumulation rates on the shelf is extremely important to our understanding of nearshore geochemical processes. For example, Shokes (1976) was able to show a direct relationship between sulfate reduction and sediment accumulation rate. It seems highly probable that such processes as incorporation of uranium into the rapidly accumulating

Mississippi Delta sediments may be related to sediment accumulation rate and bioturbation rate.

Another potentially useful isotope for measuring rapid sedimentation rates is ^{228}Th. This isotope enters sea water by decay of its soluble parent ^{228}Ra. ^{228}Th precipitates or absorbs to particles and is removed quickly to the sediment, where it exists in excess with respect to equilibrium with ^{228}Ra and can be used to measure deposition rates (Koide et al., 1973). There has not yet been any application of this technique to sediments in the Gulf of Mexico. The 1.9 year half-life of ^{228}Th will restrict its use to unusual environments.

Holmes and Martin (1978b) have analyzed sediments in two cores on the continental slope in the northwestern Gulf of Mexico for ^{226}Ra, a daughter of ^{230}Th. They have found that it may be possible to use excess ^{226}Ra in these sediments to measure deposition rates in a manner similar to that used by Koide et al. (1973). The excess ^{226}Ra in the cores probably originates mostly from excess Ra being added to the Gulf by rivers. Table 5 shows $^{226}Ra/^{238}U$ ratios in water of major rivers entering the Gulf. These data show an average of 15 percent excess ^{226}Ra compared to ^{238}U. Although their work is hampered by the lack of data on the ^{230}Th intermediate parent of ^{226}Ra, the results give reasonable sedimentation rates of 0.64 and 0.71 mm/yr. These results are consistent with observations by Shokes (1976) that ^{226}Ra content decreases gradually with depth in sediments on the Mississippi Delta. The data also imply that removal of the relatively soluble ^{226}Ra to the sea floor by plankton may also be an important process in this part of the ocean, although it has not been otherwise documented in the Gulf.

Studies based on ^{230}Th and ^{231}Pa measurements in Gulf sediments have not been reported. The half-lives of these isotopes are too long (75,300 years and 32,400 years, respectively) to be useful for measuring sediment accumulation rates in the large areas of the Gulf where sedimentation rates are very high; moreover, the dominant sediment transport mechanism in the Gulf is turbidity current flows rather than particle-by-particle deposition.

The early studies reporting the development of the use of ^{230}Th and ^{231}Pa for sedimentation rates were conducted in part on sediments from the nearby Caribbean Sea (Rosholt et al., 1961; Sackett, 1960). The method is based on the assumption the ^{230}Th and ^{231}Pa behave identically in the ocean; because they are produced in a predictable way by uranium parents in sea water and both subsequently are removed to the sediments, the ratio in the sediments should therefore be predictable. The $^{230}Th/^{231}Pa$ activity ratio (theoretically 10.8 at the sediment surface) should increase with depth according to a half-time predictable from the half-lives of the isotopes and provide a means of measuring deposition rates independent of any other form of normalization or correction. This was found to be the case in the Caribbean cores, but later work in other areas uncovered large discrepancies between the predicted surface ratios and measured ratios. Sackett (1964), Ku (1965; 1966), and Ku et al. (1972) have found $^{230}Th/^{231}Pa$ ratios in surface sediments in the Atlantic and Pacific Oceans to be much higher than 10.8, and a satisfactory explanation for the discrepancy has not been found.

A few surface sediment samples from the Gulf of Mexico were analyzed by Rona et al. (1965) for U, Th, and Pa isotopes. For Campeche Bank samples, the $^{230}Th/^{231}Pa$ ratios are close to the predicted value of 10.8, ranging from 7.6 to 12.1. Two samples from the Mississippi Delta show ratios of 9.0 and 10.1. However, the samples were prepared by leaching the sediment with acid rather than by total dissolution, and the isotope ratios are thus somewhat dubious, as pointed out by Ku (1976). It is interesting to note that unpublished data of Scott and Salter show $^{230}Th/^{231}Pa$ ratios lower than 10.8 for Mississippi River sediments.

2.3 Uranium and Thorium Series Nuclides in the Water Column

Daughters of the uranium-thorium decay series are commonly used in studies of processes taking place in estuaries or in the water column of the deep ocean. The use of uranium and thorium decay series daughters to measure processes recorded by marine sediments is dependent on a knowledge of the distribution of the nuclides in continentally derived material. This is an especially critical factor in the Gulf of Mexico, because annually it receives an enormous amount of detrital sediment compared with its total area. There is a general dearth of information regarding the isotopic composition of sediment and water being added to the Gulf of Mexico by rivers. The $^{230}Th/^{234}U$ and $^{234}U/^{238}U$ activity ratios in river sediments added to the Gulf of Mexico were shown by Scott (1968) to be, in general, slightly out of isotopic equilibrium (Table 4). The Mississippi River sediments have $^{230}Th/^{234}U$ ratios of 1.4 to 2.5 (Scott, 1968; Moore, 1967). Moore (1967) reports $^{228}Th/^{232}Th$ activity ratios of 1.40 for Mississippi River water; the measured $^{226}Ra/^{230}Th$ for Mississippi River reported in that paper is 4.9, and the ^{226}Ra concentration is 0.07 dpm/l. Scott and Salter (unpublished data) have found ^{226}Ra values of 0.08 to 0.13 dpm/l, consistent with Moore's data but lower than the 0.2 to 0.8 dpm/l reported by Mallory et al. (1969).

A completely unevaluated source of ^{226}Ra into the Gulf is desorption from sediment as river water and sediment mix with sea water. Hanor and Chan (1977) have shown that Ba is desorbed as the Mississippi River mixes with the ocean; by analogy, Ra should also be desorbed from the sediments in the mixing zone. In fact, Li et al. (1977) have observed ^{226}Ra desorption to occur in the Hudson River estuary.

Both ^{226}Ra and ^{228}Ra in sea water are produced by decay of thorium parents, which are so insoluble that they themselves are essentially absent from the water. Thus, the Ra in sea water must come directly from river water, as discussed above, or from diffusion of Ra out of the pore waters of sediment into the overlying sea water. ^{228}Ra measurements in the world ocean (Moore, 1969; Kaufman et al., 1973) show very high unsupported ^{228}Ra contents in samples taken from nearshore waters. In general, the ^{228}Ra content bears a close correlation with proximity to land. The relationship can be seen in Figure 6. The $^{228}Ra/^{226}Ra$ ratios in the Gulf are about 0.5 (Kaufman et al., 1973), which is much higher than the values of 0.1-0.4 for the open North Atlantic. The ^{228}Ra is diffusing into sea water from ^{232}Th in the sediment. Thus, the pronounced continental influence of the composition of the Gulf sediments is reflected in the radium isotope content of Gulf water. Kaufman et al. (1973) express surprise that the ^{228}Ra content of Gulf surface water is not much higher than that of Caribbean surface water. This fact may be in part related to the presence of low Th carbonate sediment on the Campeche Bank.

The use of a $^{228}Ra/^{226}Ra$ ratio is justified on the basis of the much longer half-life of ^{226}Ra (1622 years as compared with 5.75 years). Even though ^{226}Ra follows the same geographical pathways into the ocean as ^{228}Ra, the longer half-life allows more thorough mixing, so that Broecker et al. (1973) have adopted the use of a constant value of 8.5 dpm/100 kg ^{226}Ra for surface ocean waters.

The diffusion of ^{226}Ra and its daughter ^{222}Rn from sediments into overlying sea water provides the means of studying eddy diffusion and advection processes in the deep ocean. Key et al. (1979) have measured these two isotopes in the water column and in pore waters of sediments at several sites in the Gulf. They found general agreement between the radon deficit in sediments and the radon surplus in overlying sea water. Their measured surplus radon in bottom water of the Gulf and the Caribbean Sea is less than 0.5 dpm/cm. The authors believe that this relatively low value supports an earlier suggestion by Broecker (1968) that rapid sedimentation dilutes the influx of radon precursors and results in low radon content in the water column.

Reid et al. (1979) have documented what they believe to be temporal variations in the ^{228}Ra content of Gulf of Mexico surface waters. Their data show a general increase from $^{228}Ra/^{226}Ra$ ratios of 0.5 in 1968 to 0.7 in 1973. They suggest possible changes in residence times for near-surface water, or variation in the relative mixing ratio of the North Equatorial Current and the Guiana Current to form the Gulf Stream. The $^{228}Ra/^{226}Ra$ ratio is 0.3 for the North Equatorial Current, but possibly higher for the Guiana Current (based on speculations in Kaufman et al., 1973). Clearly, the radium isotopes in these current systems should be studied in order to unravel the history of surface waters of the Gulf. Temporal variations in ^{228}Ra of this magnitude would interfere with attempts to derive eddy diffusion coefficients from ^{228}Ra data.

The ^{228}Th daughter of ^{228}Ra is produced in sea water by decay of radium and is also quickly removed from solution like the other Th isotopes. Broecker et al. (1973) have measured ^{228}Th in global surface waters including those of the Gulf (Fig. 7). As shown by the distribution map, there is a tendency for the $^{228}Th/^{228}Ra$ ratio to decrease toward the coast. Broecker et al. (1973) suggest that this pattern may be caused by higher productivity in coastal waters, which would lead to more rapid particulate removal rates. An alternate possibility mentioned by the same authors is removal of ^{228}Th ions by impinging on coastal sediment deposits where immediate adsorption would take place. They derive an oceanic residence time for Th of 0.7 years. Reid et al. (1979) have analyzed a number of samples from the Gulf for ^{228}Th and ^{228}Ra. They find a mean $^{228}Th/^{228}Ra$ activity ratio of $0.13 \pm .03$ in the surface layer, close to the $0.16 \pm .05$ of Broecker et al. (1973). Reid et al. (1979) derive a Th residence time of 0.5 years in Gulf surface water. They conclude from the presence of $^{228}Th/^{228}Ra$ ratios less than one at depths of 300 m that there is little Th released during the recycling and dissolution of particulate matter in the main thermocline.

Residence times of reactive elements like Th in coastal water masses may be used as homologs for the behavior of chemically reactive pollutant elements. Consequently, a thorough understanding of the behavior of these elements is of primary importance to a study of chemical pollution. A preliminary study has been made of one ^{228}Th - ^{234}Th profile in the northern Gulf of Mexico near the Mississippi Delta (Sackett and Harris, 1972). The data show a maximum ^{234}Th depletion in surface water relative to deep water of 14 percent, much lower than values of 30-50 percent reported for the Pacific and Indian Oceans (Bhat et al., 1969). ^{228}Th showed a marked decrease across the thermocline, with values near equilibrium with ^{228}Ra in the mixed zone. With the exception of this effort, essentially no work has been done in the coastal Gulf on disequilibria among Th and Ra isotopes in the water column. The work of Li et al. (1979) on ^{228}Th and ^{228}Ra in the New York Bight has yielded residence times of shelf water, exchange rates between shelf and slope waters, and removal rates of Th from the water by particles. This information allows prediction of the behavior of both very soluble and very reactive chemical pollutants added to the coastal waters. The importance of conducting similar research in the Gulf of Mexico is obvious.

3. COSMOGENIC AND ANTHROPOGENIC RADIONUCLIDES

3.1 Carbon-14

Carbon-14 enters the environment from two sources: formation in the atmosphere by cosmogenic neutron interaction with ^{14}N and formation during atmospheric testing of nuclear weapons. The 5,750-year half-life of this isotope and its presence in organic matter, calcium carbonate, and dissolved carbonate ion species have made ^{14}C chronology extremely useful in the environmental sciences. Large numbers of samples have been analyzed to obtain ages or sediment accumulation rates. For example, Frazier (1967) has described the development of the Mississippi River deltaic deposits on the basis of extensive ^{14}C measurements.

The ^{14}C geochemistry in the Gulf of Mexico has been summarized by Mathews et al. (1973). In 1954-1955, the effect of bomb-produced ^{14}C became noticeable in atmospheric samples, and there was a steady increase in the value until 1963, at which time the activity began a decline to present values. This influx of artificially derived ^{14}C amounts to a world-wide tracer experiment from which much has been learned about the ocean.

The surface water $\Delta\ ^{14}C$ values for the Gulf are shown in Figure 8. Broecker (1961) defined $\Delta\ ^{14}C = \delta^{14}C - (2\delta^{13}C + 50)\ (1 + \delta^{14}C/1000)$ where $\delta^{14}C$ = ((sample C ratio/belemnite standard C ratio) - 1)10^3 and the carbon ratio is $^{13}C/^{12}C$. Mathews et al. (1973) interpret the low coastal values as the result of river runoff in the northern Gulf on the basis of an average $\Delta\ ^{14}C$ value of 100‰ for six river samples. The low values in the southern part of the area near Yucatan may result from upwelling of deep water. The lower $\Delta\ ^{14}C$ in the Gulf may yield valuable information about the circulation of Gulf water. Figures 9 and 10 show that there has been a significant increase of ^{14}C in the Gulf since 1962. Bomb ^{14}C had penetrated to depths of 1500 m within eight years. Deep water in the eastern Gulf shows $\Delta\ ^{14}C$ values 100‰ higher than those for equivalent depths in the western Gulf, suggesting a low exchange rate between the two areas. Based on study of these profiles, Mathews (1972) has concluded that the residence time of intermediate and deep water in the western Gulf are 120 and 270 years, respectively; both are very long compared with values in the eastern Gulf. Additional ^{14}C studies in the western Gulf and across the Yucatan and Florida Straits would be very helpful in understanding Gulf circulation patterns and residence time of water masses.

3.2 Tritium

Tritium, ^{3}H, has multiple pathways into the environment. It is formed continually as a result of cosmic ray bombardment of nitrogen in the atmosphere, it is locally injected into the environment as a result of nuclear reactor operations and nuclear fuel reprocessing, and it was added to the atmosphere in significant amounts during nuclear weapons testing. Tritium has a 12.3-year half-life and is an ideal tracer for water masses because it becomes an actual component of the water (HTO).

A study of tritium values in Gulf of Mexico water has been conducted by Kincaid (1971) and Kincaid and Sackett (1971). The work consists of four surface water samples and two depth profiles. The surface samples showed units of 9.6 T.U. (Yucatan Straits), 11.5 T.U. (Yucatan Strait), 13.9 T.U. (northern Gulf), and 15.9 T.U. (western Gulf). A profile of the Yucatan Straits shows an increase in tritium to 20.8 T.U. at 150 m, corresponding to the high salinities of the subtropical underwater, and a decrease to only 10.2 T.U. at 400 m. A profile in the western Gulf shows an increase to 27.7 T.U. at 150 m and a drop to 0.0 T.U. at 600 m. Tritium is advected through the Yucatan Straits with the subtropical underwater, as shown by its correlation with salinity. The tritium excess in the western Gulf appears to result from the input of tritium to shelf waters from runoff and rainfall. Kincaid (1971) reports the tritium content of the average Mississippi River water to be 404 T.U. On the basis of a tritium box model for the Gulf, Kincaid (1971) derives a residence time for surface water. He estimates the value to be 3.5 to 6 years for water in the upper 150 m of the western Gulf.

Interest in the history of the Orca Basin (Shokes et al., 1977) has prompted measurement of tritium in samples from the hypersaline anoxic brine in that basin. There is essentially no tritium present in the brine (Schink, Guinasso and Ostlund, personal comm.), a discovery consistent with the earlier observation that no excess uranium has been deposited from overlying sea water in the anoxic sediments below.

3.3 Cs-137 and the Plutonium Isotopes

Cesium-137 and the plutonium isotopes ^{238}Pu, $^{239-240}Pu$ have proven to be quite useful in studies of the geochemistry of the environment. They are interesting also, of course, in their own right as nuclides produced in massive amounts by weapons testing in the atmosphere and by nuclear reactors. The half-lives of these isotopes are ^{137}Cs - 30 yrs, ^{238}Pu - 86.4 yrs, ^{239}Pu - 2.44 x 10^4 yrs, and ^{240}Pu - 6580 yrs.

Studies of ^{137}Cs in the ocean have shown it to be rather soluble, and in fact, it has commonly been used in combination with ^{90}Sr as a tracer to determine the history of oceanic water masses (Volchok et al., 1971). However, a significant fraction of ^{137}Cs becomes strongly adsorbed to sediment particles, especially to the clay mineral illite, in which Cs substitutes for K in the lattice.

The analysis for ^{137}Cs can be done by directly counting the gamma radiations it produces and does not require any wet chemical procedures, so that ^{137}Cs is a relatively easy isotope to measure. Simpson et al. (1976) have determined that there is a strong positive correlation between ^{137}Cs content, Pu content, and content of organic pollutants such as PCB's in sediments. The ^{137}Cs measurements are thus extremely valuable bits of information.

In light of the significance of ^{137}Cs in the coastal environment, it is surprising that very little work has been done on this subject in the Gulf of Mexico. ^{137}Cs measurements have been made by Pflaum et al. (1978) on a few sediment samples from the Mississippi Delta. They found that in rapidly depositing sediment (> 1 $gm/cm^2/yr$), ^{137}Cs and ^{210}Pb profiles are similar over the top 50 cm of the sediment column. In more slowly depositing delta sediments (< 0.2 $gm/cm^2/yr$), ^{137}Cs activity decreases sharply from 200 to < 45 dpm/kg over the top 10 cm, while ^{210}Pb is constant over that depth interval and decreases abruptly below it. They attribute the difference in profiles to the contrast in bioturbation effects on the recently deposited (last 30 yrs) fallout ^{137}Cs and the continuously deposited natural ^{210}Pb. This study is still being continued. The value of ^{137}Cs studies in the Gulf of Mexico certainly merits more work in the future on this subject.

Plutonium studies in the Gulf of Mexico are also few in number. The plutonium in the marine environment consists of a nuclear fallout fraction from weapons testing and from atmospheric burn-up of ^{238}Pu power supplies, and a fraction made up of wastes from reactors and chemical reprocessing plants. Plutonium is quite insoluble in the natural environment and is strongly sorbed to the particulate phases present in soils, rivers, and the ocean.

Scott and Salter (1978, 1979, and unpublished data) have measured ^{238}Pu and $^{239-240}Pu$ in sediments of rivers draining into the Gulf. The distribution of plutonium in river suspended sediments is shown in Figures 11 and 12. Mississippi River suspended sediment contains about 15 dpm/kg of $^{239-240}Pu$ and contributes 4.4×10^{12} dpm of Pu to the Gulf annually. This amounts to 0.03% of the total fallout Pu in the Mississippi River drainage basin. High $^{238}Pu/^{239-240}Pu$ values were observed in the Great Miami River (Ohio) suspended and bottom sediments. These values are consistent with data collected by Bartelt et al. (1974) and are the result of additions by the Mound Laboratory in Miamisburg, Ohio.

Preliminary data have been gathered on Pu in marine sediments in the Gulf. Cores from the Mississippi Delta analyzed so far show a steady decrease of Pu with depth, rather than reflecting the known time scale fluctuations in Pu fallout distribution with time. The details of the signal appear to be obliterated by the residence time on land and the delivery to the ocean by erosion and river transport. The greatest accumulation of Pu occurs in the Mississippi Delta and nearshore area and decreases markedly away from the shelf. Its distribution in the Gulf is controlled largely by physical transport of particulate matter. The behavior of Pu may be taken as an indicator for the behavior of other highly reactive pollutants in the Gulf system.

Published measurements of other man-made isotopes in the Gulf of Mexico are very scarce. Slowey et al. (1965) analyzed Gulf waters and suspended sediment for short half-lived fallout nuclides (Figure 13). Their efforts resulted in the discovery of ^{54}Mn, ^{95}Zr - ^{95}Nb, ^{106}Ru, ^{144}Ce and ^{125}Sb. The values for percent soluble metal in sea water are much higher in this paper (30-50%) than is commonly reported (Volchok et al., 1971). ^{54}Mn and ^{144}Ce were removed from surface water more rapidly than ^{95}Zr - ^{95}Nb or ^{106}Ru, based on samples taken in successive years. No attempt was made to use the data to derive residence time or particle settling rates.

4. RECOMMENDATIONS FOR FUTURE RESEARCH

This paper describes work that is largely preliminary, incomplete, or in some cases, entirely missing. Studies published to date have amply demonstrated the value of radionuclide measurements in the marine environment; the continuation of such work in the Gulf of Mexico is fundamental to our understanding of the system.

Additional studies of the nearshore environment are badly needed. A great deal can be learned from an investigation of uranium-thorium series nuclides and fallout nuclides in the nearshore marine environment of the Gulf. In particular, research should focus on transport into the coastal area, the chemical remobilization within the area, rates of accumulation of the elements in different types of nearshore environments, and fluxes out of the nearshore environment into the open Gulf. Special attention should be paid to the river water - sea water mixing zone, which for the Gulf of Mexico is most conspicuously represented by the Mississippi River Delta area. The research should be conducted in collaboration with work on organic compounds, heavy metals, and stable isotopes, which will provide a strong matrix of information of mutual benefit to all of the areas of research involved.

It has been pointed by Simpson et al. (1976), Turekian (1977) and others that many radionuclides may serve as models in the environment for the behavior of other elements such as heavy metals or organic pollutants. Thus, the plutonium isotopes and ^{210}Pb may be representative of reactive elements in the marine system, while ^{228}Ra and ^{226}Ra may represent more soluble substances. Full advantage should be taken of such analogies, especially in the complex mixing zone of estuaries. An evaluation of the river contribution of key radioisotopes to the ocean is a necessary part of such research.

There are a number of cases in which further studies of radioisotopes in the Gulf of Mexico can be of importance to the understanding of the physical oceaography of the Gulf. Carbon-14, tritium, ^{228}Ra, and ^{226}Ra studies may enlighten us about the mixing rates of eastern and western Gulf water masses. Studies of radium and thorium isotopes in shelf water and suspended sediments should make possible the determination of residence times for shelf water masses and exchange rates between shelf and slope water.

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Table 1. Statistics for the Gulf of Mexico Distributive Province (From El-Sayed et al., 1972, with permission of the publisher, The American Geographical Society.)

Area of Gulf of Mexico	
Shelf (< 200 m)	60×10^{4} km^2
Open (> 200 m)	100×10^{4} km^2
TOTAL	160×10^{4} km^2
Volume of water in Gulf of Mexico	
Shelf (using 50 m as mean depth)	3×10^{16} liters
Open (using 2000 m as mean depth)	200×10^{16} liters
TOTAL	203×10^{16} liters
Annual volume of runoff*	
Cuba	4.1×10^{12} liters
Mexico	2.2×10^{14} liters
United States	
Mississippi and Atchafalaya Rivers	6.9×10^{14} liters
Other	1.5×10^{14} liters
TOTAL	1.1×10^{15} liters
Annual volume of Florida Current	8.0×10^{17} liters

*Moody (1967)

Table 2. Uranium Concentration and $^{234}U/^{238}U$ Activity ratios of Gulf of Mexico Waters
(From Sackett and Cook, 1969, with permission of the Gulf Coast Association Geological Society.)

Type	Location	Depth (m)	Uranium $X10^{-6}g/l$	U^{234}/U^{238}*	Salinity $^{o}/oo$
Open GOM	23°45'N 92°30'W	1	3.5 ± .2		36.5
		50	3.5 ± .2		34.5
		1700	3.6 ± .2		35.0
		2900	3.4 ± .2		35.0
	23°44'N 92°32'W	700		1.18 ± .03	
	28°02'N 89°44'W	1	3.6 ± .2		35.7
	28°39'N 93°32'W	1	3.5 ± .2		34.5
	21°04'N 85°40'W	1		1.17 ± .02	
		2500		1.14 ± .04	
	22°36'N 87°32'W	1		1.17 ± .02	
	23°36'N 92°10'W	3600		1.16 ± .02	35.0
	23°44'N 92°31'W	1500		1.15 ± .03	35.0
	26°09'N 93°25'W	400		1.15 ± .03	35.2
Shelf,Bay & Estuary	Galveston Channel	1	2.6 ± .1	1.14 ± .03	25.0
	Dulce Cr. (Near Corpus C.)	surf.	4.8 ± .2	1.12 ± .06	13.7
	Los Almos Cr. (Near Corpus C.)	"	17.3 ± .7	1.28 ± .03	40.8
	Baffin Bay (Shore)	"	5.6 ± .3	1.27 ± .04	27.0
	Baffin Bay (Bridge)	"	6.4 ± .2	1.28 ± .04	29.4
	Baffin Bay (Pier)	"	4.6 ± .2	1.54 ± .04	29.0
	Laguna Madre	"	3.9 ± .2	1.15 ± .04	29.9
	Aransas Pass	"	3.0 ± .2	1.20 ± .04	29.4
	Copano Bay	"	2.1 ± .1	1.23 ± .06	12.2

Table 3. Uranium in River Water in the Gulf of Mexico Distributive Province

Sample	^{238}U, µg/l	$^{234}U/^{238}U$ Activity Ratio	Reference
Apalachicola River	<.4		Mallory et al., 1969
Pearl River	<.4		Mallory et al., 1969
Mississippi River	0.03		Rona and Urry, 1952
	1.83		Rona et al., 1956
	1.0	1.31	Moore, 1967
	0.4-1.3		Mallory et al., 1969
	0.10,0.31		Bertine et al., 1970
	0.97		Spalding & Sackett, 1972
Arkansas-Cimarron River	3.0 ± .2	1.44 ± .09	Sackett & Cook, 1969
Red River	0.6-1.2		Mallory et al., 1969
Brazos River (Tx)	0.4-0.7		Mallory et al., 1969
	1.6 ± .2	1.21 ± .09	Sackett & Cook, 1969
	0.9-2.7		Spalding & Sackett, 1972
Yegua River (Tx)	0.6 ± .1	1.01 ± .10	Sackett & Cook, 1969
Grand River (Tx)	1.0 ± .1	1.31 ± .11	Sackett & Cook, 1969
San Antonio River (Tx)	1.61		Spalding & Sackett, 1972
Guadelupe River (Tx)	0.4-0.8		Mallory et al., 1969
	1.80		Spalding & Sackett, 1972
Rio Grande River	0.9-2.5		Mallory et al., 1969
	1.15-3.49		Spalding & Sackett, 1972

Table 4. Uranium and Thorium Isotopes in River Sediments (From Scott, 1968. In Earth Planet. Sci. Lett. 4:245-252, 1968, copyrighted by American Geophysical Union.)

Sample and size fraction	U (ppm)	Th (ppm)	Th/U	^{234}U* / ^{238}U	^{230}Th* / ^{232}Th	^{230}Th* / ^{234}U	^{230}Th* / ^{238}U	^{230}Th (dpm/g)	^{234}U (dpm/g)	^{230}Th ex (dpm/g)
Brazos River										
2 - 20μ	2.42 ± 0.09			0.92 ± 0.04					1.66 ± 0.07	
< 2 μ	2.56 ± 0.07	13.05 ± 0.77	5.10	0.83 ± 0.02	0.85 ± 0.05	1.72 ± 0.12	1.55 ± 0.10	2.72 ± 0.17	1.57 ± 0.04	+ 1.15
2 - 20μ (no tracer)				0.88 ± 0.03	1.00 ± 0.04					
Red River										
2 - 20μ	2.73 ± 0.08	7.70 ± 0.39	2.82	0.94 ± 0.03	0.96 ± 0.02	0.97 ± 0.06	0.92 ± 0.05	1.86 ± 0.10	1.92 ± 0.05	- 0.06
2 - 0.2μ	3.28 ± 0.17	12.42 ± 0.60	3.80	0.91 ± 0.02	0.93 ± 0.02	1.17 ± 0.09	1.06 ± 0.08	2.84 ± 0.15	2.43 ± 0.13	+ 0.41
< 0.2μ	3.05 ± 0.14	14.23 ± 0.70	4.77	0.87 ± 0.04	0.86 ± 0.04	1.50 ± 0.10	1.33 ± 0.09	2.99 ± 0.15	2.00 ± 0.09	+ 0.99
Mississippi River										
2 - 20μ	3.29 ± 0.12	7.93 ± 0.57	2.41	0.94 ± 0.03	1.19 ± 0.06	1.74 ± 0.13	1.63 ± 0.12	3.98 ± 0.26	2.29 ± 0.09	+ 1.69
2 - 0.2μ	3.84 ± 0.23	12.68 ± 0.60	3.30	0.96 ± 0.06	1.26 ± 0.05	1.43 ± 0.10	1.37 ± 0.10	3.92 ± 0.16	2.73 ± 0.16	+ 1.19
< 0.2μ	3.47 ± 0.11	15.65 ± 0.73	4.51	0.93 ± 0.03	1.20 ± 0.07	1.92 ± 0.13	1.79 ± 0.12	4.60 ± 0.28	2.39 ± 0.08	+ 2.21
Roanoke River										
2 - 20μ	4.12 ± 0.15	13.37 ± 0.74	3.25	0.98 ± 0.03	1.01 ± 0.05	1.14 ± 0.08	1.11 ± 0.07	3.34 ± 0.18	2.92 ± 0.11	+ 0.42
2 - 0.2μ	4.78 ± 0.18	14.2 ± 0.62	2.98	1.02 ± 0.03	1.07 ± 0.04	0.98 ± 0.06	1.00 ± 0.06	3.52 ± 0.15	3.57 ± 0.16	- 0.05
< 0.2μ	3.96 ± 0.18	18.75 ± 0.97	4.74	1.04 ± 0.04	0.80 ± 0.03	1.21 ± 0.08	1.26 ± 0.09	3.65 ± 0.20	3.04 ± 0.13	+ 0.61
James River										
2 - 20μ	3.94 ± 0.14	13.6 ± 0.79	3.46	1.28 ± 0.04	0.89 ± 0.04	0.80 ± 0.06	1.02 ± 0.07	2.96 ± 0.18	3.71 ± 0.13	- 0.75
< 2μ	3.95 ± 0.13	12.9 ± 0.57	3.26	1.23 ± 0.04	0.92 ± 0.04	0.80 ± 0.04	0.98 ± 0.05	2.91 ± 0.13	3.62 ± 0.11	- 0.71

* activity ratios

Table 5. Contribution of Major Rivers, Western Gulf of Mexico, Water Year, 1960-61 (Uranium and Radium Data from Mallory, Johnson, and Scott, 1969, Holmes and Martin, 1978b).

	Uranium		Radium		
River	kg	Percent	10^{-5} kg	Percent	$(^{226}Ra/^{238}U)$[1]
Mississippi	315,244	(94.5)	11,353	(89.3)	1.05
Sabine	2,232	(0.7)	175	(1.3)	2.29
Neches	1,860	(0.5)	81	(0.6)	1.27
Trinity	4,050	(1.2)	170	(1.3)	1.23
Brazos	6,441	(2.0)	848	(6.6)	3.84
Guadalupe	2,604	(0.8)	76	(0.5)	0.89
Rio Grande	997	(0.3)	12	(0.1)	0.36
TOTAL	333,428	100.0	12,715	97.7	1.14

[1]Activity Ratio

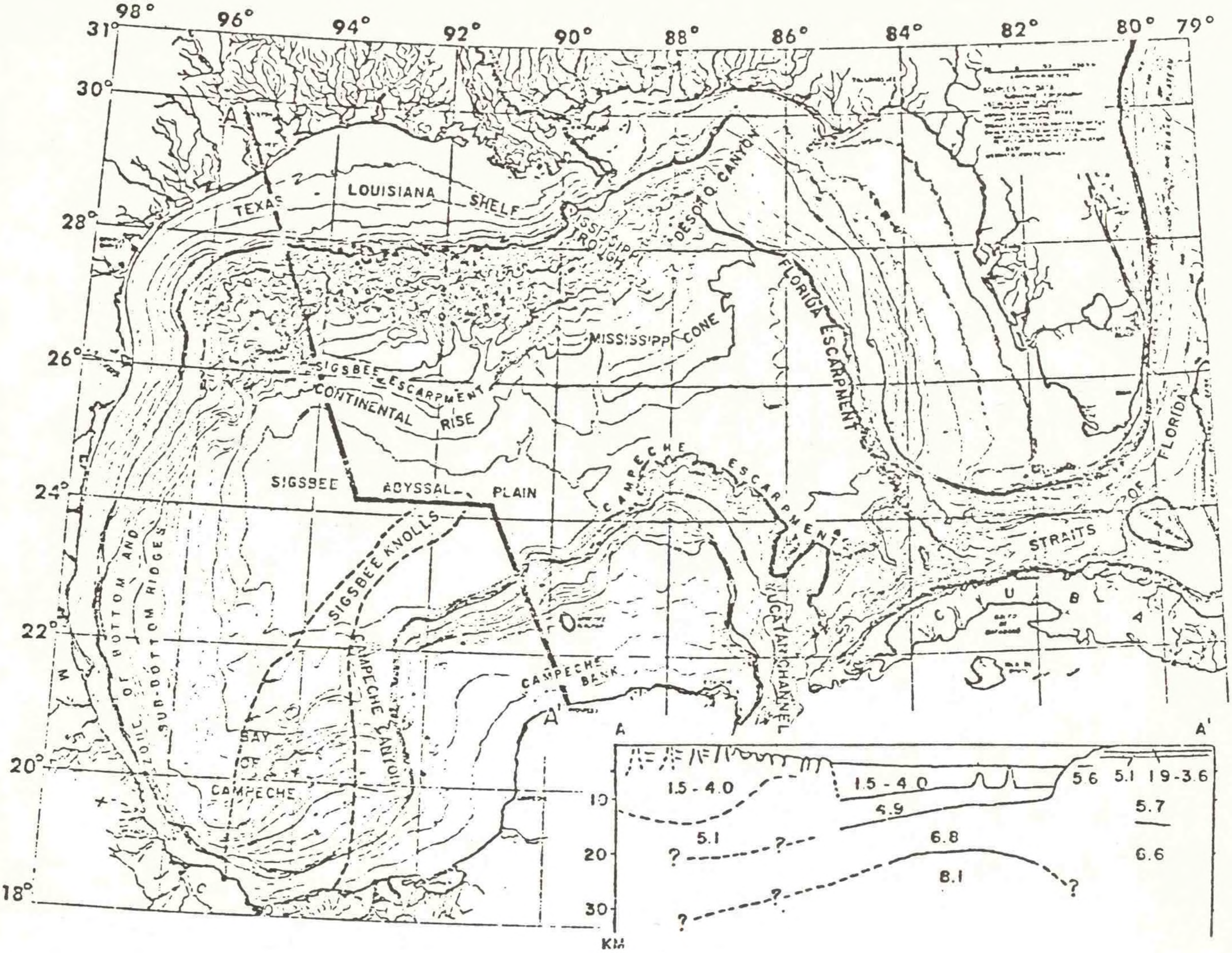

Fig. 1. Bathymetric and Physiographic Province Map of the Gulf of Mexico (From El-Sayed et al., 1972, with permission of the publisher, The American Geographical Society.)

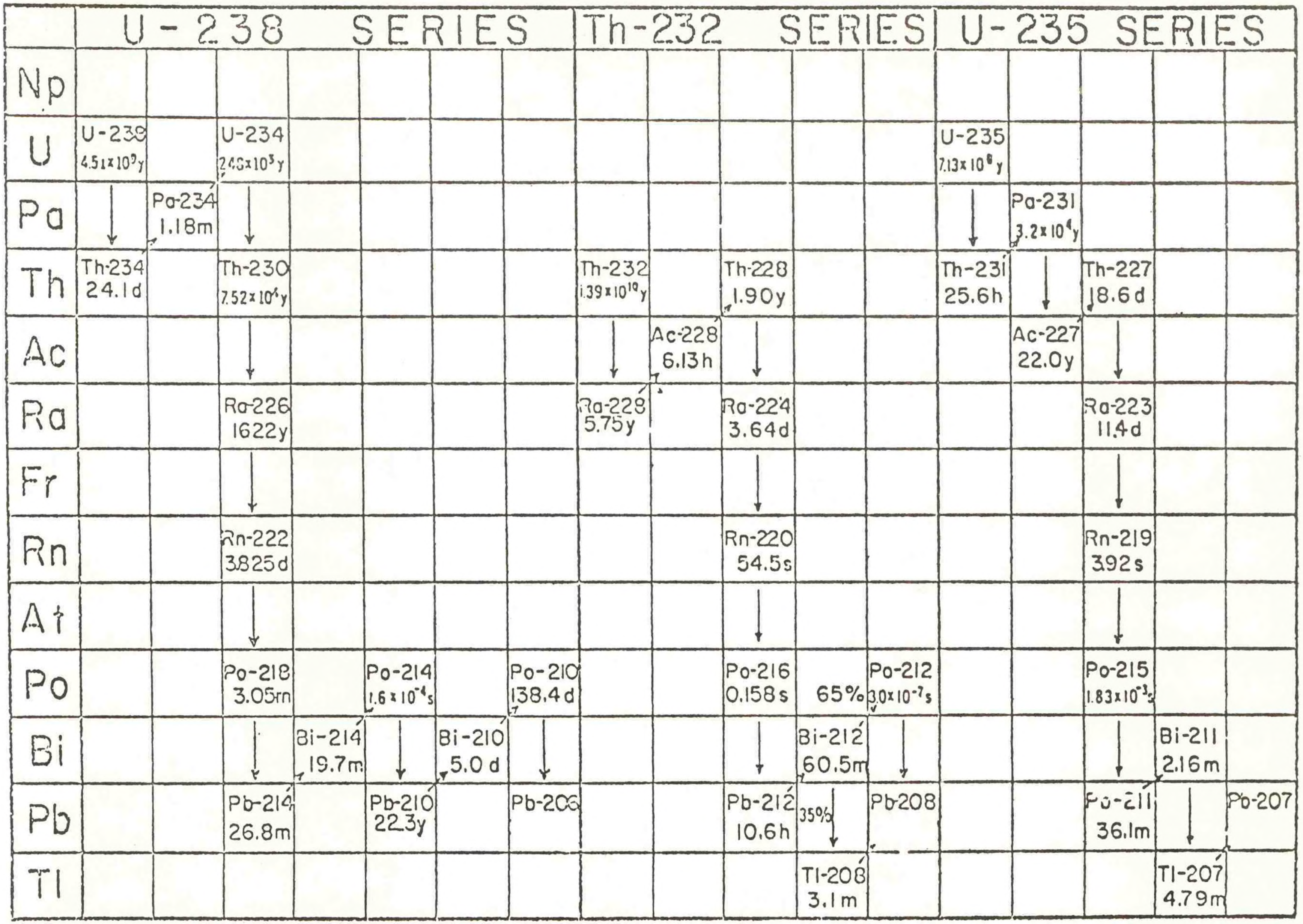

Fig. 2. Uranium and thorium decay series nuclides.

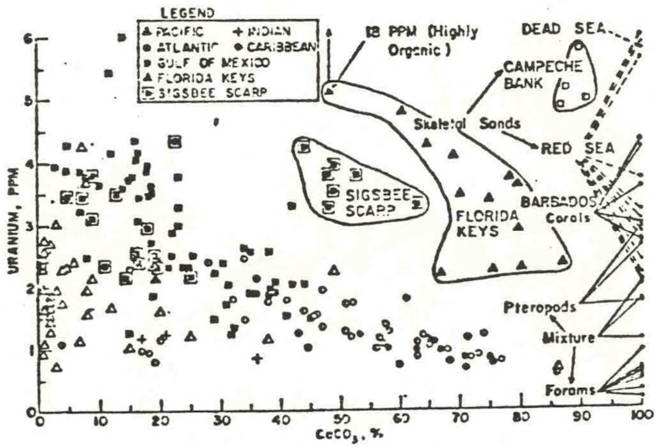

Fig. 3. Uranium Versus Calcium Carbonate in Marine Sediments.

(From Mo et al., 1973. Reprinted with permission from <u>Geochim. Cosmochim. Acta</u>, vol. 37, T. Mo, A. D. Suttle, and W. M. Sackett, Uranium concentrations in marine sediments, Copyright 1973, Pergamon Press, Ltd.)

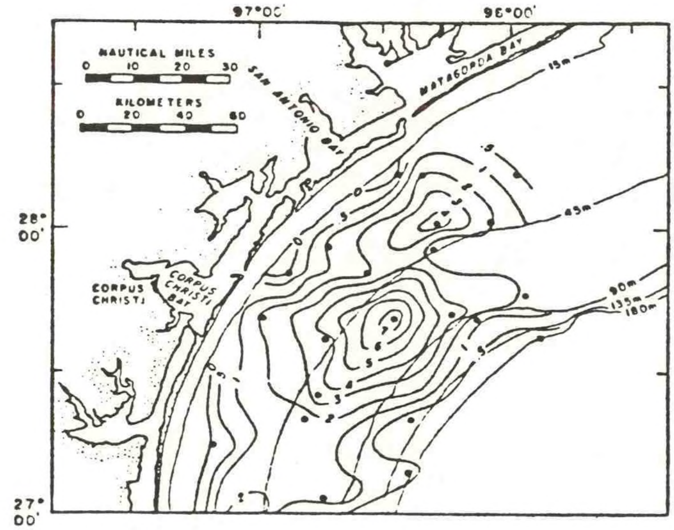

Fig. 4. Interpretive isoplath showing the relative rates of sedimentation on the central Texas shelf; Isopleths in mm y^{-1}. (Holmes and Martin, 1978b.)

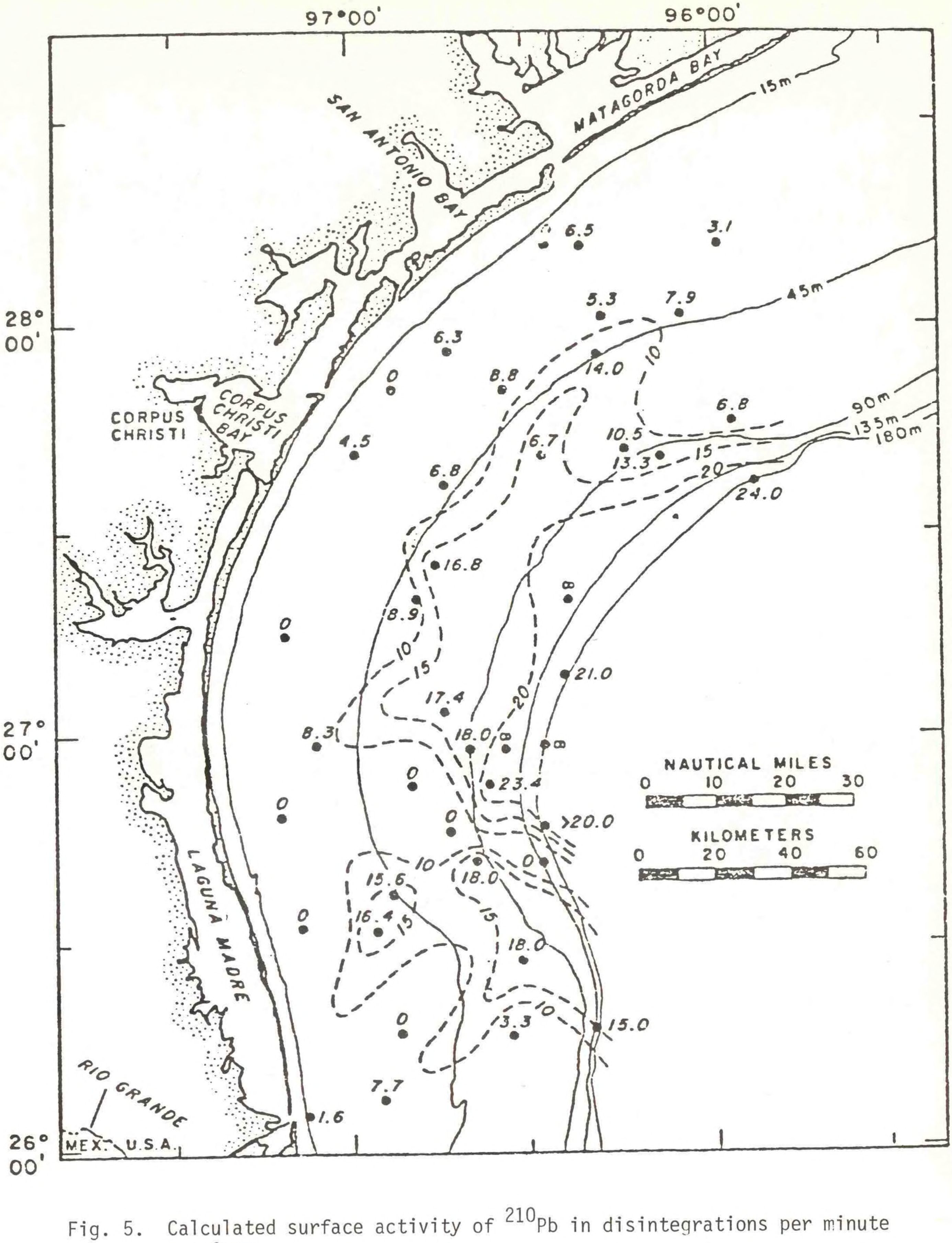

Fig. 5. Calculated surface activity of ^{210}Pb in disintegrations per minute per Gram.
(Holmes and Martin, 1977, in Environmental Studies, South Texas Outer Continental Shelf 1976: Geology, 230-246, with permission of the U.S. Geological Survey.)

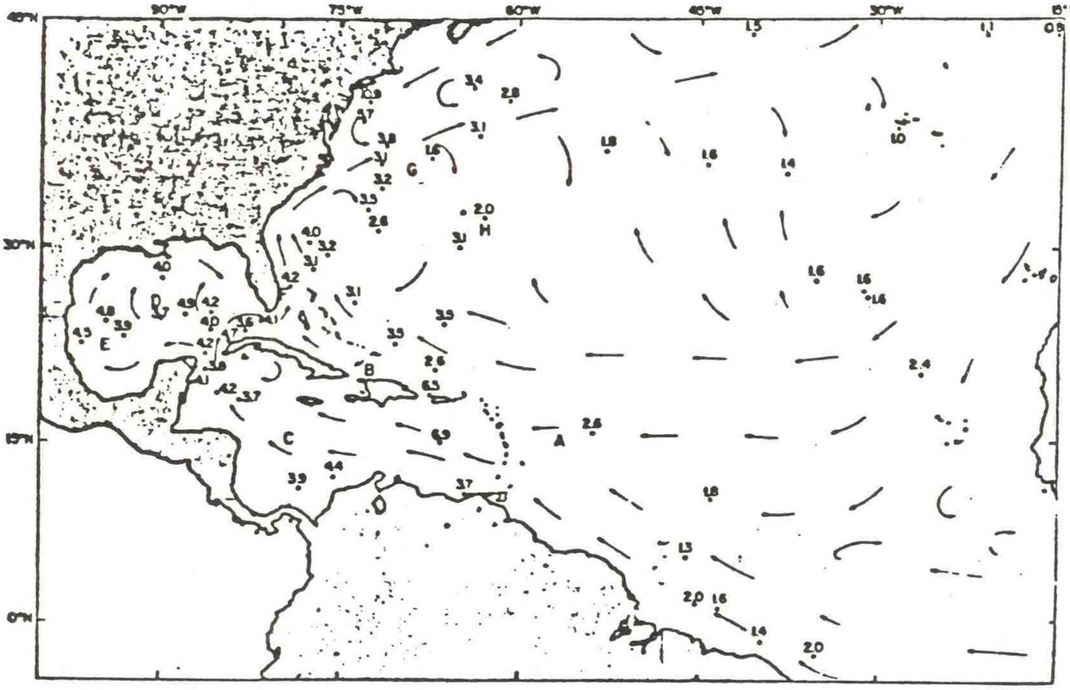

Fig. 6. The ^{228}Ra concentration in surface seawater of the Atlantic Ocean and and adjacent seas; in dpm 100 kg^{-1}. Arrows indicate flow pattern of surface currents during the winter.
(From Kaufman et al., 1973, with permission of the publisher, Springer-Verlag.)

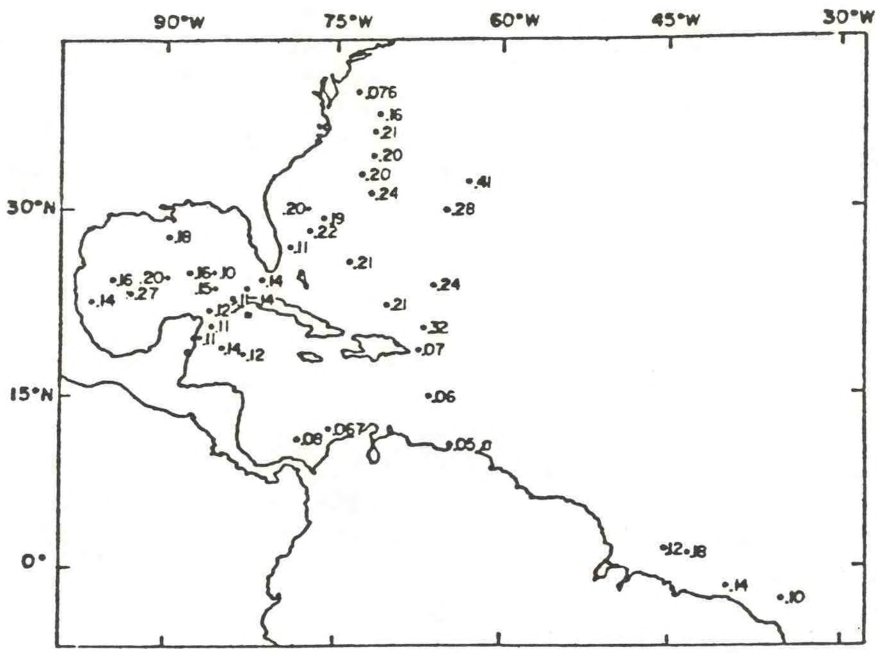

Fig. 7. The distribution of $^{228}Th/^{228}Ra$ activity ratios in the western North Atlantic, Caribbean Sea, and Gulf of Mexico.
(From Broecker et al., 1973. Reprinted from Earth Planet. Sci. Lett. 20: 3544 with permission of the publisher, Elsevier Scientific Publishing Co.)

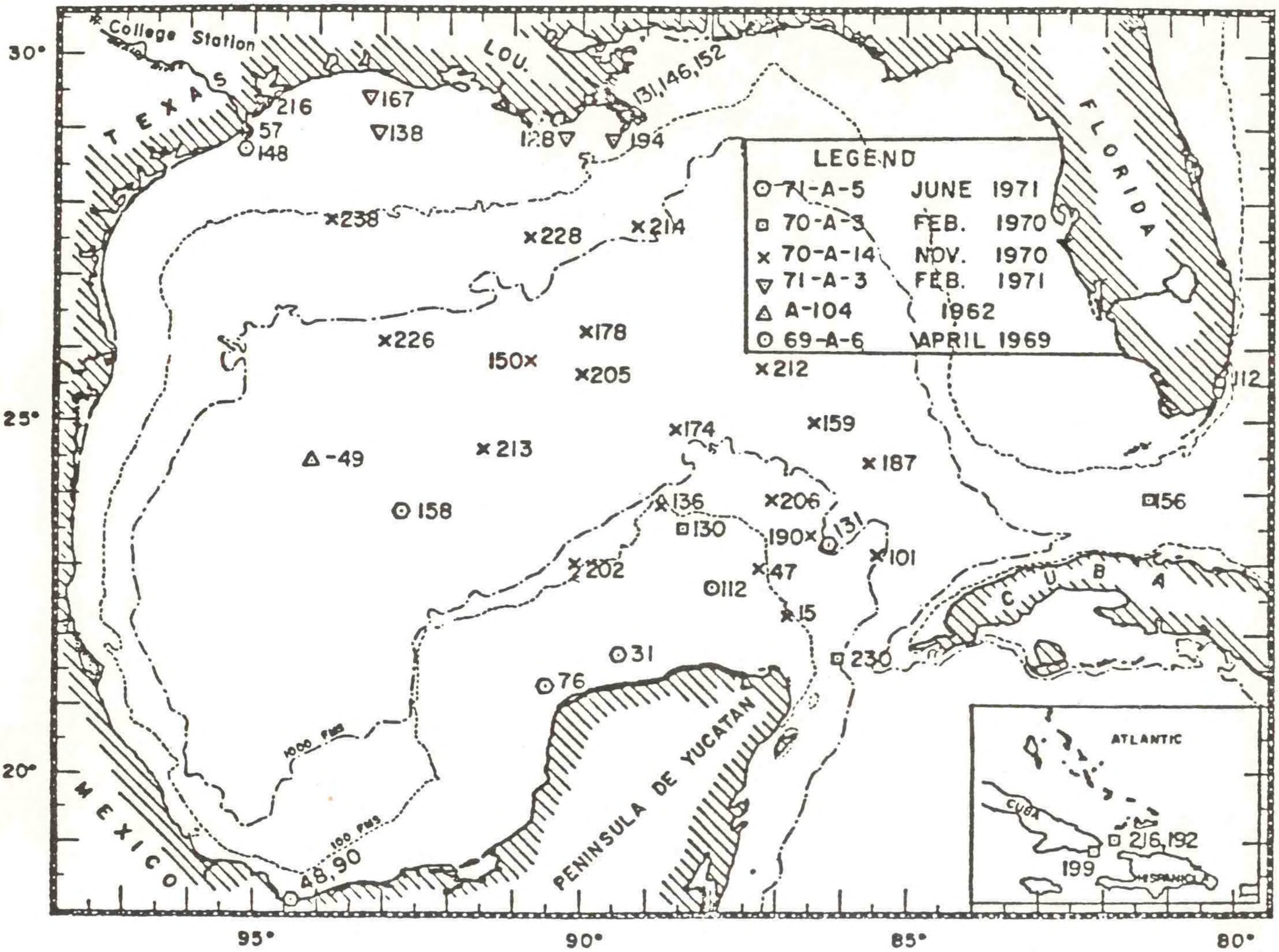

Fig. 8. Surface water Δ ^{14}C values in the Gulf of Mexico. (From Mathews, 1972, with permission of the author.)

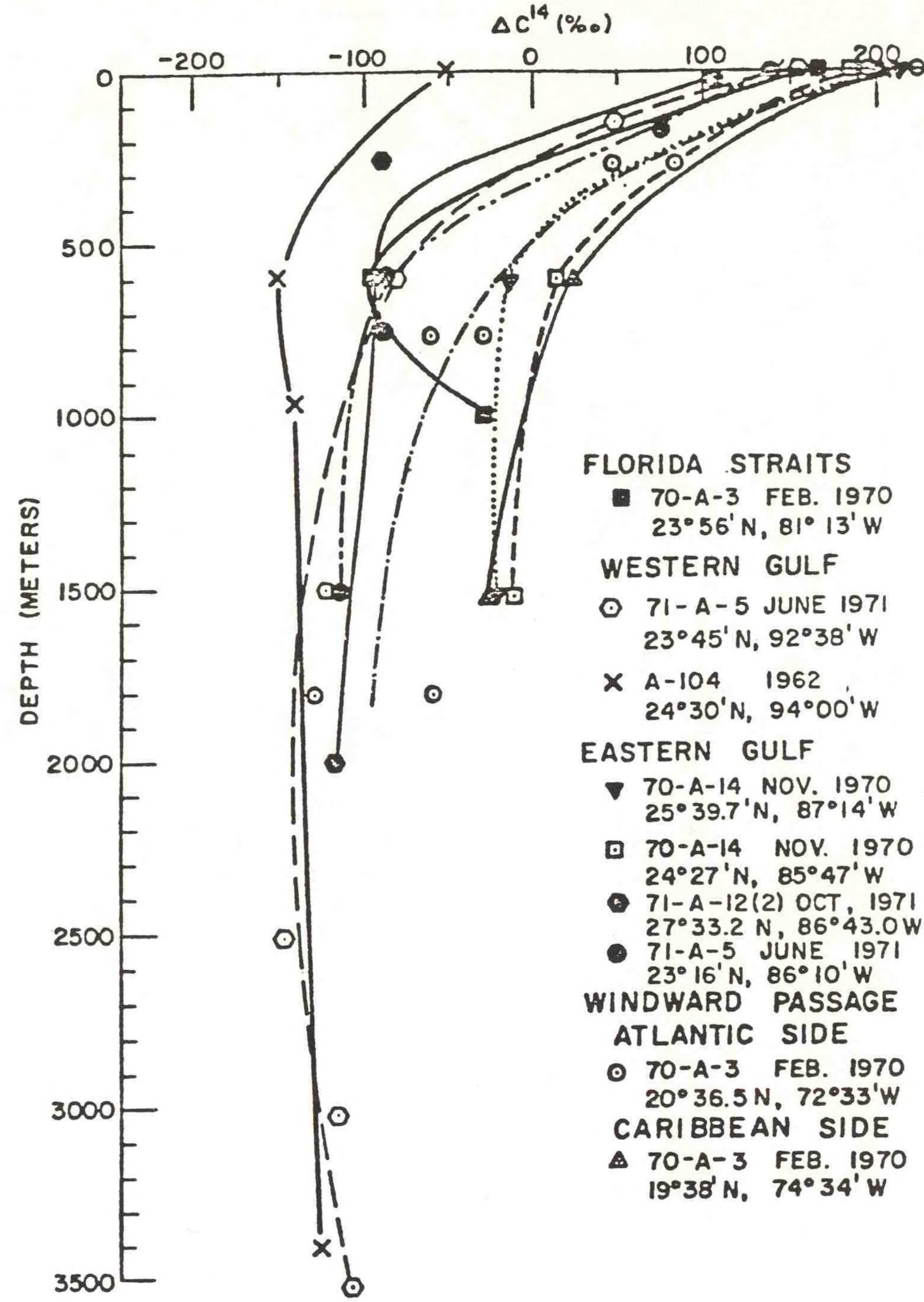

Fig. 9. Vertical profiles of $\Delta\ ^{14}C$ in the Gulf of Mexico and Caribbean Sea. (From Mathews, 1972, with permission of the author.)

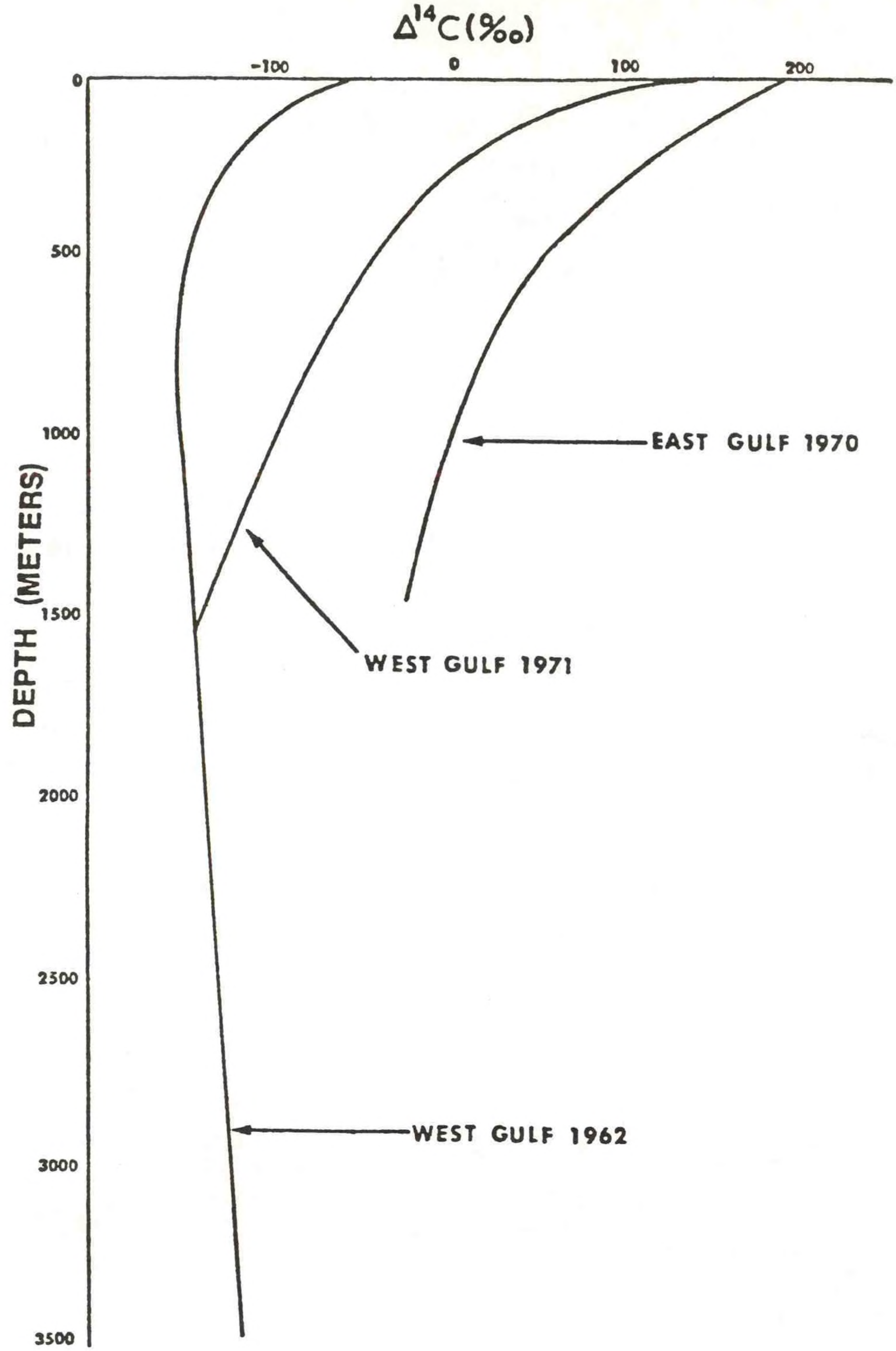

Fig. 10. Smoothed vertical profiles of $\Delta\ ^{14}C$ in the Gulf of Mexico. (From Mathews, 1972, with permission of the author.)

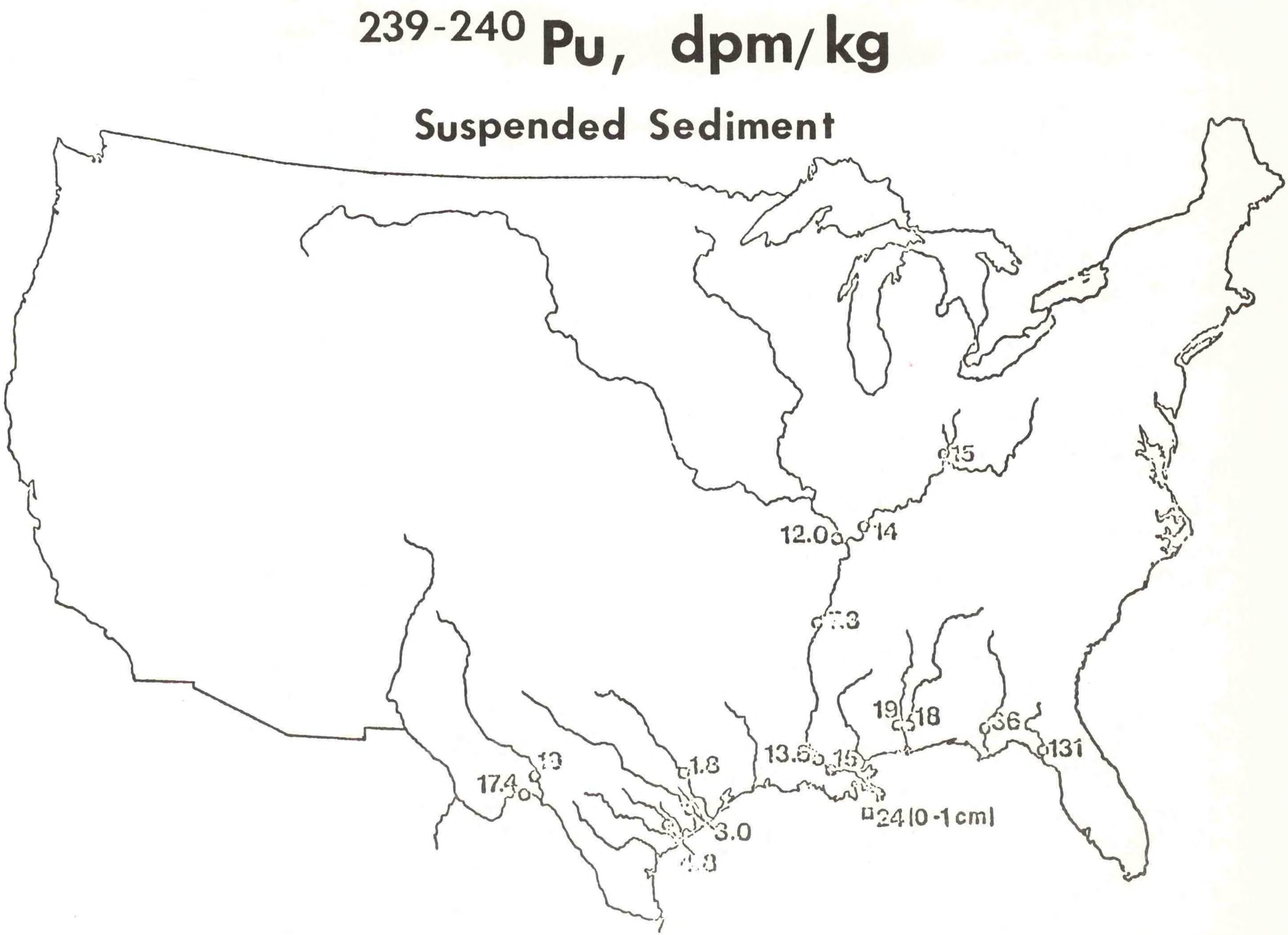

Fig. 11. Distribution of $^{239-240}Pu$ in River Suspended Sediments. (Scott and Salter, unpublished data.)

Suspended Sediment

Fig. 12. Ratio of $^{238}Pu/^{239-240}Pu$ in River Suspended Sediments. (Scott and Salter, unpublished data.)

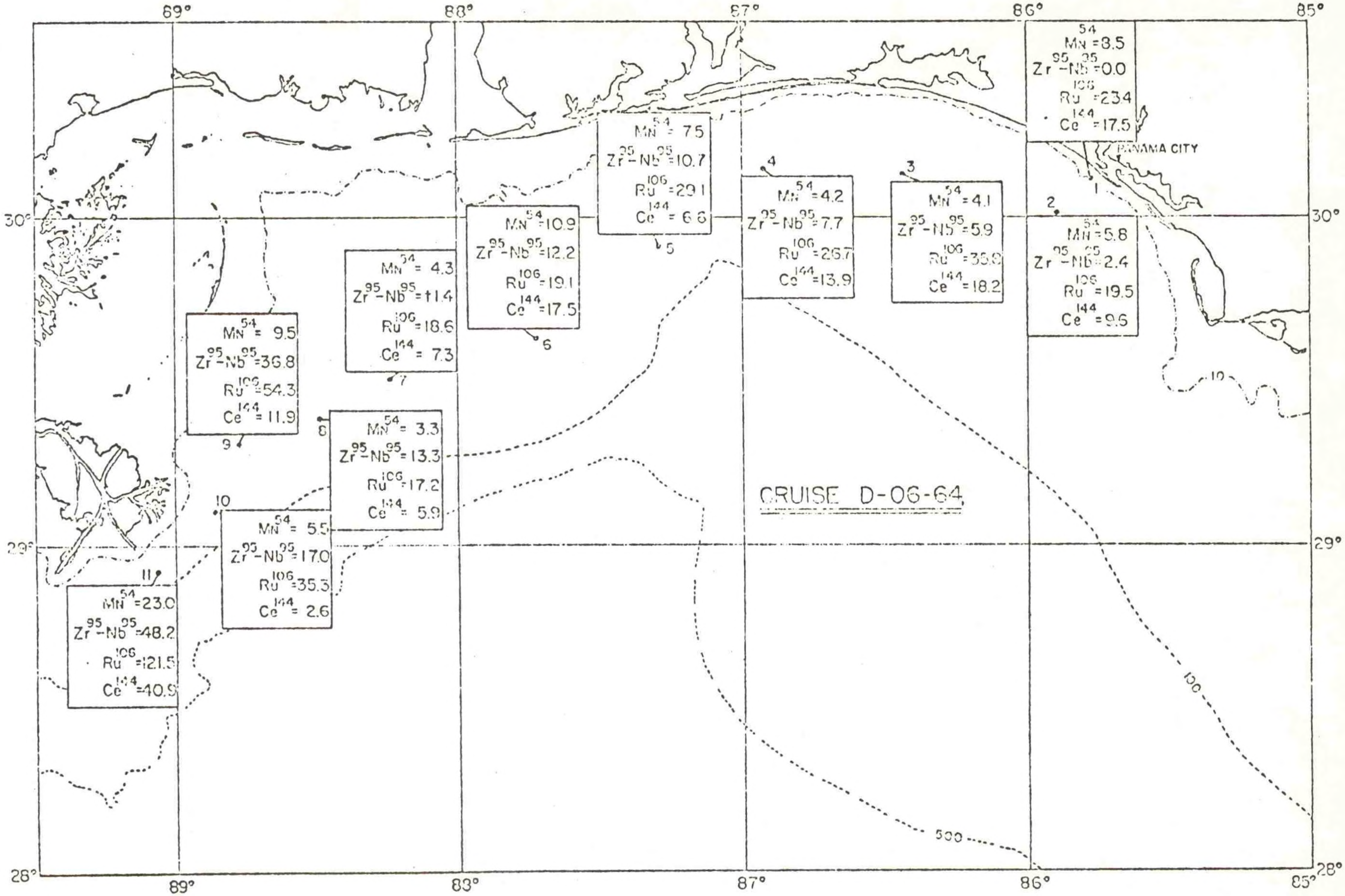

Fig. 13. ^{54}Mn, ^{95}Zr - ^{95}Nb, ^{106}Ru and ^{144}Ce Content of Particulate Fraction Collected in Surface Water in Northeast Gulf of Mexico, May, 1964.
(From Slowey et al., 1965, with permission of Narragansett Marine Laboratory.)

A REVIEW OF EXISTING KNOWLEDGE ON TRACE METALS IN THE GULF OF MEXICO

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ABSTRACT

Trace metals serve as micronutrients to marine biota and provide useful insight to the marine geochemical cycle, yet, under stressed conditions, they can be toxic pollutants. Since the Gulf of Mexico is the primary reservoir for both natural and pollutant discharges from the United States, adequate understanding of this system is needed to ensure sound environmental management.

In pursuit of this goal, the present review summarizes existing knowledge of trace metal distribution and behavior in the Gulf of Mexico. Water column dissolved and particulate metals are the expressed primary interest; however, the pertinent data base is sparse. To augment the water column focus, metal inputs by Gulf rivers and deposition in Gulf sediments are discussed. Possible approaches to fill critical information gaps are also outlined.

1. INTRODUCTION

Skepticism is the watchword in any attempt to review a body of literature on trace metal concentrations in seawater. Increased awareness of contamination during sampling and analysis, along with concern about metal species recovered during extraction, casts doubt on a significant portion of the published work. Nevertheless, the importance of seawater trace metals as micronutrients to marine biota and as precursors of mineral deposits, coupled with increased metal pollution, makes pursuit of such studies expedient. This review of trace metals in the Gulf of Mexico is designed to provide a filtered view of the present state of knowledge, thereby setting the stage for future research needs and endeavors.

Central to the expressed needs of the National Oceanic and Atmospheric Administration's Atlantic and Oceanographic Meteorology Laboratories (NOAA/AOML) are the dissolved and suspended particulate trace metals of the Gulf. To support this primary focus, complementary information on metals in riverine, planktonic, sediment and interstitial water samples is used to provide a more comprehensive account. The format for this review is, first, to discuss continental sources of metals to the Gulf, those being predominantly riverine; second, to consider dissolved and suspended particulate metal distribution throughout the varied Gulf of Mexico environments, incorporating into this a brief account of metal uptake by planktonic organisms; third, to examine the ultimate metal sink provided by the sediments and complicated by chemical diagenesis. Within this overall framework, an attempt is made to estimate metal residence times and to identify geographically important areas. When applicable, mention is made of metal speciation work attempted. Finally, critical information gaps and potential research endeavors, as required to provide sound environmental management of the Gulf of Mexico, are discussed.

A certain degree of selectivity has been invoked in this review to "filter out" old or less credible data sets. This need is particularly pressing with regard to seawater metal values, a data base which is especially sparse for the Gulf of Mexico. Many tables of data have been reviewed and reevaluated for the report; however, the need for a more reliable and comprehensive metal program became increasingly apparent during this effort.

2. RIVERINE INPUTS

Rivers are the major pathway by which the products of natural geological processes and the pollutant inputs of man are added to the oceans. Garrels and Mackenzie (1971) estimate that rivers account for 90% of the total seaward transport of dissolved and suspended solids. The Gulf of Mexico receives about 69% of the total dissolved solids (Leifeste, 1974) and 77% of the total suspended solids (Curtis et al., 1973) transported to the oceans from the continental United States. That such a significant percentage of U.S. natural weathering products and pollutants are discharged to a relatively small, semi-closed basin highlights the need to assess sources, sinks, and residence times for potentially toxic substances, including trace metals, in this reservoir. A logical starting point for this endeavor is examination of the riverine trace metal flux to the Gulf of Mexico.

Table 1 summarizes recent data for dissolved and particulate trace metals in the Mississippi River. Since the Mississippi-Atchafalaya River system transports about 86% of the total yearly flux of river particulate and dissolved solids to the Gulf from the U.S. and about two-thirds of all Gulf inputs (Fig. 1), it can be used to characterize a significant fraction of the Gulf influx. Data from Turekian and Scott (1967), the USGS (1975-1977), and Martin and Meybeck (1979) suggest that Mississippi values given in Table 1 typify those of several other Gulf Coast rivers and average world river water.

Dissolved trace metal concentrations given in Table 1 for the Mississippi River are generally lower than or equal to estimates for average river water (Table 1). The data of Trefry and Presley (1976) are weighted averages for four seasonally spaced sampling periods; however, differences observed among varying times were generally small. For example, Cr values averaged 0.52 ± 0.10 $\mu g\ \ell^{-1}$ with a range of 0.44 to 0.70 $\mu g\ \ell^{-1}$, and Cu concentrations averaged 1.9 ± 0.7 $\mu g\ \ell^{-1}$ over a range of 1.0 to 3.4 $\mu g\ \ell^{-1}$. Manganese was somewhat atypical with scatter from 1 to 40 $\mu g\ \ell^{-1}$, yet the high values were found during a low river flow, low suspended load, late summer sampling period.

The U.S.G.S. has spearheaded a large trace metal program for the Mississippi and other Gulf rivers. As their detection limits have lowered over the past several years, an increasing portion of the gathered data has become useful (Table 1). Mindful of the constraints imposed by elevated detection limits, spatial and temporal variability were examined in the 569 Mississippi River samples analyzed by the U.S.G.S. from 1972-1975. These samples were collected by the U.S.G.S. at seven locations along the lower Mississippi River from St. Francisville, Louisiana (430 km above Head of Passes), to Venice, Louisiana (18 km above Head of Passes). Chloride ion concentrations show seasonal ranges of 12 to > 50 mg ℓ^{-1} and are inversely related to water flow. Specific conductance and other major elements behave similarly. Percent frequencies of detection and average metal concentrations, however, were surprisingly uniform along this 412 km stretch of the lower Mississippi. Furthermore, there was no obvious, consistent relationship between the values found by the U.S.G.S. or the frequency of finding detectable amounts, and time of year, river flow, suspended load or other such variables. To a first approximation, it appears that major river dissolved metal loads are reasonably uniform throughout most of the annual cycle. Seasonality, however, remains a somewhat superficially addressed problem with respect to reliable Gulf Coast river dissolved metal concentrations.

Some research has been advanced on metal forms for Gulf Coast rivers as described below. Andren and Harriss (1975) used ultrafiltration techniques to show that about 65% of the total 40 ng ℓ^{-1} dissolved Mississippi River Hg was associated with a < 500 molecular size fraction. They also report that < 2% of the total dissolved Hg is in the form of methylmercury.

Metal/organic complexation studies for As have been pioneered on several small Florida Rivers (Braman and Foreback, 1973) with varying results. For example, dissolved As in the Hillsborough River was shown to be essentially all As (V) at 0.25 $\mu g\ \ell^{-1}$ whereas the Withlocoochee River (total As 0.42 $\mu g\ \ell^{-1}$) was 38% As (V), 48% dimethylarsenic acid, 14% methylarsonic acid and < 5% As (III). This work has been expanded to include Sn (Braman and Tompkins, 1979) for several central Florida rivers. Total Sn concentrations were about 9 ng ℓ^{-1} with about 45% Sn (IV), 30% methyl tin, 20% dimethyl tin and trace trimethyl tin.

Although the importance of river dissolved trace metals to the biota and to the long-term chemistry and health of the Gulf of Mexico may overshadow that of the particulate metals, clearly the suspended matter dominates total river metal transport. Trefry and Presley (1976) estimate they studied were carried with the solid phase. Studies of the Amazon and Yukon Rivers (Gibbs, 1977) and several other world-class rivers (Martin and Meybeck, 1979) reach similar conclusions.

Available Mississippi River particulate trace metal data summarized in Table 1 show that many of the particulate metal concentrations given are comparable with those for average world river suspended matter and average continental crust. Mississippi River and average river suspended matter Ag, As, Cd, Hg, Pb, and Zn concentrations, however, are several times higher than crustal abundances. Each of these six elements, except Zn, occurs at relatively low levels in nature. Mining, purification, industrial utilization, and uncontrolled discharge of these trace elements render them especially susceptible to release at well above background levels. Trefry and Shokes (1979), for example, have traced the history of Pb and Cd deposition in Mississippi Delta sediments and find evidence of significant anthropogenic inputs of these two metals.

Spatial and temporal variations in the particulate trace metal values of Trefry and Presley (1976) were relatively small during four sampling periods when the river flow and particulate load was near or above average. However, during very low flow, Fe and Al concentrations were lower by 25% because of simple dilution by organic matter. At the same time, particulate Mn, Zn, and Cu concentrations were 30-40% higher, but there was no significant difference in the Pb, Ni, Co, and Cr values. Despite this one-time deviation, the important concept is that of a relatively homogeneous flux of fine-grained (60% is < 2 μm particle size) suspended sediment.

To further delineate in a general way the modes of particulate metal transport by the Mississippi River, Trefry and Shokes (1979) carried out a series of chemical leaches on the river suspended matter. Figure 2 compares the Mississippi Data with that of Gibbs (1977) for the Amazon. The sequential leaching scheme uses 1N NH_4Cl (pH 7) to remove exchangeable (Exch.) metal ions, citrate-buffered sodium dithionite (pH 4.7) to dissolve "free" metal oxides (Ox.), sodium hypochlorite (pH 7) to release metals associated with organic matter and sulfides (org.), and, finally, an $HF-HNO_3-HClO_4$ mixture to remove lattice-held (Lat.) metals. Mississippi and Amazon River particulate metals (Fig. 2) were predominantly in the oxide and lattice phases. Data for Fe from both rivers were analogous, showing relatively equal oxide-lattice partitioning. Cobalt and Ni distributions were also similar, except the absolute values were a factor of 2 higher for the Amazon particulates. Total Mn values are reasonably close for the two rivers; however, Mississippi suspended matter Mn is present predominantly in oxide coatings. High levels of lattice Cu in Amazon particulates may be indicative of significant Cu-bearing minerals in the Amazon Basin. Partitioning of Mississippi River particulate Pb shows averages of 0.5 ppm exchangeable, 20 ppm oxide, 14 ppm organic/sulfide, and 15 ppm lattice phase.

Physico-chemical interactions at the freshwater-seawater interface may alter the time and/or location of metal deposition and metal availability to marine organisms. Desorptive processes would make metals available to organisms and delay their removal to the sediments, whereas adsorptive processes would have an opposite effect. Andren (1973) found the percent particulate Hg in the Mississippi River to vary between only 61% and 79%. This observation held over a full range of salinities and variations by a factor of 2-3 in dissolved Hg concentrations. Very little change was observed in particulate Hg concentrations across the freshwater-seawater interface and no obvious relationship was found for dissolved values (Fig. 3a). Similarly uniform particulate Al, Cd, Co, Cr, Fe, Mn, Ni, and Pb concentrations (Fig. 3 b,c) were shown by Trefry and Presley (1976). The observations argue against extensive desorption of any of these metals during mixing, but give no insight to possible removal of dissolved species. Very little additional dissolved metal concentration data are available for the Mississippi-Gulf interface. Hanor and Chan (1977), however, found Mississippi River dissolved Ba^{2+} concentrations to increase as salinity increases to several parts per thousand and then to decrease to seawater values.

The total annual flux of dissolved and particulate trace metals from adjacent rivers to the Gulf of Mexico is given in Table 2 and shows the expected predominance of transport by river particulates. This trend of riverine metal transport dominated by particulates is consistent with results for other large rivers (Gibbs, 1977; Martin and Meybeck, 1979).

3. COASTAL GULF OF MEXICO DISSOLVED AND PARTICULATE TRACE METALS

Table 3 provides a broad-brush tabulation of selected dissolved trace metal concentrations in three general areas of the Gulf of Mexico. Sites sampled in this compilation are shown in Figure 4. Unquestionably, the data base is very small, particularly in waters off the Mexican coast.

Dissolved trace metal data from three studies along the Texas-Louisiana shelf (Coastal NW GOM in Table 3) show a significant number of nondetectable concentrations. Values obtained (or bracketed) for Cd, Cr, Cu, Hg, Ni, and Pb compare reasonably with estimates for average seawater. Shokes et al. (1979) obtained relatively uniform Cr (800 ± 200 ng ℓ^{-1}), Hg (18 ± 4 ng ℓ^{-1}), and Zn (1700 ± 500 ng ℓ^{-1}) concentrations for June and August, 1978, water samples from 5 to 6 km offshore of western Louisiana. Except for Mn, surface (1 m), and near near-bottom (9 m) water, metal concentrations were relatively similar at these very nearshore sites. Bottom water Mn values, however, were as high as 100 $\mu g\ \ell^{-1}$ in contrast with < 1 to 2 $\mu g\ \ell^{-1}$ surface water concentrations. Surface sediment interstitial water also was analyzed by Shokes et al. (1979) and Mn values of 2500 to 8500 $\mu g\ \ell^{-1}$ were common. Clearly, diffusion of remobilized Mn from reducing sediments to the overlying bottom water plays a significant role in the distribution of Mn in these nearshore waters.

The role of interstitial water in influencing nearshore Mn concentrations is particularly exciting. Trefry (1977) calculated diffusive Mn fluxes from Mississippi Delta sediments of about 200 to 1000 $\mu g\ cm^{-2}\ y^{-1}$. These large fluxes were found to occur over at least 1000 km^2 of the delta wherein sedimentation rates are > 0.5 g $cm^{-2}\ y^{-1}$. In areas of lower sediment accumulation rates, much of the Mn oxide dissolved under reducing conditions reoxidizes within the sediment column. Interstitial Fe concentrations (2200 to 25,000 $\mu g\ \ell^{-1}$) reported by Shokes et al. (1979) also support large fluxes of dissolved Fe from the sediment; however, bottom water Fe values (5 to 22 $\mu g\ \ell^{-1}$), though high, are considerably lower than those found for Mn. This difference is most likely associated with the differential oxidation kinetics of the two elements. Interstitial water chemistry appears to play a far less significant role in the cases of Cr, Hg, Pb, Ni, Zn, and Cd. Nevertheless, the role of interstitital solutions in changing the chemistry of nearshore waters remains an important avenue of research.

A major dissolved trace metal effort carried out along the coastal eastern Gulf of Mexico is that reported by Corcoran (1972) for waters off the Alabama-Florida border (Fig. 4). Cadmium, Cr, Cu, Mn and Zn concentrations for 240 samples, collected quasi-synoptically over a 48-hr period, show distinct gradients of decreasing concentrations offshore (Fig. 5). The low values listed in Table 3 for the coastal eastern Gulf approximate those of normal seawater and are typically from sites located 10 to 15 km offshore. Superimposed on this trend are several tongues of higher metal-containing waters; one infiltrates the area from the west and others extend seaward from the coast (Figs. 5 and 6). Several of the trace metal trends observed correlate well with the physical characteristics of area waters as shown on the sigma-t plot in Fig. 7. Tongues of water from the west and from coastal bays, as well as isolated pockets of water with distinct hydrographic characteristics, are clearly evident in Fig. 7. Augmenting physical data with trace metal values to investigate the dynamics of nearshore water movements and biological productivity invites further inquiry.

Many of the extreme values obtained by Corcoran (1972) were from bottom water samples or in water moving seaward from coastal bays. These observations reinforce the importance of sediment-seawater interactions in coastal areas and stress the role of lateral advection of inland waters in altering metal concentrations within 10 to 15 km of the coast.

One set of additional data for the eastern coast of the Gulf (Braman and Topkins, 1979) shows average total Sn to be about 4 ng ℓ^{-1} along the

Florida coast. Species distribution shows about 40% Sn (IV), 15% methyl tin, 33% dimethyl tin, and 12% trimethyl tin. These values are about one-half those for Florida rivers, yet the degree of methylation is somewhat similar.

Particulate trace metal concentrations from the coastal western Gulf are taken from Holmes et al. (1977) and Shokes et al. (1979) and summarized in Table 4. Sporadically high values (> 200 μg g^{-1}) were obtained for Cr, Pb, and Zn in both studies, whereas somewhat less variability was found for Cu, Fe, and Mn. Holmes et al. (1977) report generally lower metal concentrations than Shokes et al. (1979), partially because of sampling area differences. (Holmes's sites were from an area of coarser grained, higher $CaCO_3$-containing sediments along the South Texas coast, whereas Shokes's site was off Louisiana (Fig. 8).) Holmes's findings also partially resulted from differences in sample digestion (Holmes used only HNO_3). Before subjecting their samples to total dissolution, Shokes et al. (1979) initially leached particulate samples with 25% acetic acid. Considerable variations in the percent of total metal leached were observed, as Cu, Pb, and Zn removal ranged from about 10 to 80% of total, with Mn release bracketed between 40 and 80% and the Fe dissolved fraction restricted to 4-20% of the total.

Offshore Louisiana suspended particulates (Shokes et al. 1979) were sampled four times at four sites over one year. Although suspended matter metal distribution is patchy, Shokes et al. (1979) have isolated a couple of general trends. Total particulate Fe and Cu concentrations decrease during winter and late spring periods, yet the leachable fraction increases significantly. This is presumed to be a function of the presence of more organic-rich particles at these times. Manganese values also peak during late spring; however, no seasonal variability was found in the percent Mn leached.

Coastal eastern Gulf of Mexico particulate trace metal concentrations from the four areas identified in Figure 8 are highly variable (2 to 3 orders of magnitude) and, therefore, median values (presented in Table 4) better represent the overall data set. Sediment metal data from these four areas (Trefry et al., 1978) somewhat similarily show one to two orders of magnitude variability, although the individual concentrations are generally much lower. For example, total particulate Cu and Fe concentrations for the southern Florida shelf site during one sampling period were 44 and 4000 μg g^{-1}, respectively, compared with 1.3 and 1790 μg g^{-1} sediment values. Total suspended loads ranged from 10 to 120 μg ℓ^{-1}, and it is difficult to make any direct comparisons between suspended matter and sediments.

At the western extremities of this eastern Gulf area where total particulate levels are about 400-2200 μg ℓ^{-1}, comparisons are somewhat easier, as shown below:

	Suspended Matter	Sediments	Miss. Delta Particulates
Cu (ppm)	30	7	46
Fe (%)	3.4	2.3	4.6
(Cu/Fe) x 10^{-4}	8.8	3.0	10

Here, suspended matter Cu/Fe ratios are more typical of their Mississippi River source material than the sediments actually deposited at this site some 80-100 km from the Delta.

The above discussions point out several of the problems associated with particulate trace metal analysis. First, of course, is the difficulty of obtaining consistent trace metal data when suspended loads are low. Secondly, collecting a representative sample for a given area is difficult when the instantaneous sample provided by a Niskin bottle is used, versus the more integrated composite of a sediment trap.

Average metal concentrations in Mississippi Delta particulates (Table 4) vary only slightly relative to those for the Mississippi River (Table 2). Most of these Delta samples were taken from surface waters within 5 km of the river mouth, and although suspended matter levels had dropped from 200 mg ℓ^{-1} to 20 mg ℓ^{-1}, the river character was, as could be expected, still dominant. High concentrations of particulate Cd and Pb reflect the significant anthropogenic inputs previously discussed. Copper behavior was somewhat an exception to the above trends as Delta values averaged 25% higher than those for the river. These are believed to be directly related to biological factors. For example, one particulate sample contained a large copepod larva and had a Cu concentration of 170 $\mu g\ g^{-1}$. Furthermore, a higher percent organic carbon was found in the Delta samples (5% versus < 2%) and a significant correlation existed between organic carbon and particulate Cu concentrations.

Marine plankton provide an important means for scavenging trace metals. Data for zooplankton from the northwest Gulf of Mexico (Sims, 1975; Horowitz and Presley, 1977; Presley and Boothe, 1977), given below, show reasonable uniformity and orders of magnitude metal concentration factors for plankton relative to seawater.

(Concentrations in $\mu g\ g^{-1}$ Dry Weight)	Cd	Cr	Cu	Ni	Pb	Zn
Horowitz and Presley (1977)	2.9	4.3	20	7	20	120
Presley and Boothe (1977)	3.5	4.4	13	7	11	113
Sims (1975)	1.5	-	9	4	14	58

Sims (1975), however, calculates a very small contribution by plankton to sediment metal concentrations in the northwest Gulf. A potential for greater contribution of plankton metals to the slowly accumulating, carbonate-rich sediments of the West Florida Shelf and the Yucatan Shelf, however, certainly exists and has been pointed out by Trefry et al. (1978).

4. CENTRAL GULF OF MEXICO DISSOLVED AND PARTICULATE TRACE METALS

Deep water Gulf of Mexico dissolved metal concentrations (Table 3) are few in number with the Cu, Mn, and Zn values of Slowey and Hood (1971) still the most extensive data set available. Summarized below, Slowey and Hood (1971) present total, particulate, and extractable (peroxydisulfuric acid oxidiation followed by diethyldilhiocarbamate extraction) values for 42 open Gulf samples.

(Concentrations in ng ℓ^{-1})	Cu	Mn	Zn
Total	1300	310	3500
Particulate	400	30	400
(Total - Particulate)	900	280	3100
Extractable	900	260	2600

These averages approximate average seawater estimates and show the overwhelming importance of the dissolved load in open ocean samples. Highest concentrations in the Slowey and Hood (1971) study were predominantly at surface and intermediate depths. Figure 9 demonstrates a more dramatic example of such distribution at a western Gulf site. The dissolved fraction retains its predominance in most cases for this western site. However, another fraction, that which was nondialyzable through 4.8 nm pores, plays a significant role in the intermediate maxima for Cu and Zn. This suggests a strong organic association for these two metals and Slowey and Hood suggest the source to be from decomposing organisms. Martin et al. (1976) have clearly demonstrated the importance of biological activity to observed Cd profiles in the waters off California where they found strong nutrient-Cd correlations throughout the water column.

Depth variations for total Cu and Mn from Slowey and Hood's data reinforce the picture of higher metal levels in the surface and mixed layers of the ocean. Uniform, low values for Cu, Mn, and Zn typify deep Gulf waters (Slowey and Hood, 1971).

Depth	Cu (ng ℓ^{-1})	Mn
10 m	760	480
100-500 m	610	390
> 500-1500 m	740	230
> 1500 m	420	210

Any attempt to develop an areal pattern for dissolved trace metals is difficult. Much of the available surface water dissolved Cu data is plotted on Figure 10 with no obvious trends. In fact, Slowey and Hood (1971) emphasize the similarity between Cu levels in coastal (730 ng ℓ^{-1}) and deep water (900 ng ℓ^{-1}) Gulf environments. Similar agreement is shown for Zn (2500 vs 2600 ng ℓ^{-1}). Coastal water dissolved Mn values (1500 ng ℓ^{-1}), however, are almost six times higher than deep Gulf averages. This difference most likely results from continental and interstitial Mn fluxes to nearshore waters.

Data from Davis (1968), Custodi (1971), and Alexander (1964), given in Table 3, further demonstrate the low levels that can be expected in open Gulf samples. Bolter et al. (1964) found that Cs concentrations at 10 and 3000 m for one site in the central Gulf (Fig. 4) average 350 ng ℓ^{-1} and note that these levels are significantly higher than the 280 ng ℓ^{-1} average ocean values. They further suggest that source-sink relationships for the Gulf may be somewhat different than in the large ocean basis. Analysis for Ag, Co, Ni, and Sb at the same central Gulf site (Schutz and Turekian, 1965) are listed below and show Gulf of Mexico values (except for Ni) to be significantly higher than estimated average seawater concentrations (Brewer, 1975) or than values reported for other ocean basins by Schutz and Turekian (1965).

(Concentrations in ng ℓ^{-1})				
Depth (m)	Ag	Co	Ni	Sb
10	180	1200	2000	580
3000	140	500	1600	340
Avg. seawater (Brewer, 1975)	40	50	1700	200

Beyond the continental shelves, suspended particulate chemistry has been limited to the major elements, including Fe and Al. Betzer and Pilson (1971) show that particulate Fe concentrations in the bottom 1000 m of the eastern Gulf (340 ng ℓ^{-1}) are significantly higher than those in the shallower water above (102 ng ℓ^{-1}). This feature was not observed in the western Gulf where bottom water particulate Fe (156 ng ℓ^{-1}) is only slightly higher than shallower water values (117 ng ℓ^{-1}). These data are then used to support the existence of a near-bottom nepheloid layer in the eastern Gulf.

Feely (1974, 1975) traced the permanent, but highly variable, near-bottom nepheloid layer of the Gulf of Mexico, analyzing particulates for Fe, Al, and other major elements. At the stations identified in Fig. 8, total suspended matter concentrations averaged 24 $\mu g\ \ell^{-1}$ above the nepheloid layer and 54 $\mu g\ \ell^{-1}$ in the layer. Particulate Al concentrations, however, averaged 3 times higher in the nepheloid layer (1.52 $\mu g\ \ell^{-1}$ or 2.1% Al) than above it (0.51 $\mu g\ \ell^{-1}$ or 2.8% Al). Particulate Fe values, however, were similar in (0.34 $\mu g\ \ell^{-1}$) and out (0.38 $\mu g\ \ell^{-1}$) of the nepheloid layer, even though Fe concentrations for the particulates were significantly higher above the nepheloid layer (1.7%) than in it (0.7%).

Although no trace metal data is available, Feely's data for total suspended matter and particulate Fe at three sites in the Gulf help to identify suspended sediment transport pathways and allow estimation of possible particulate trace metal levels. Station 1 data (Fig. 11) show a midwater lens of particles with corresponding increases in Al, Fe, and Si. Such layers, presumably generated by bottom scouring along the slope, may transport significant amounts of sediment and trace metals to the deep Gulf. In the abyssal plain region of the Gulf, total particulate levels stay below 20 $\mu g\ \ell^{-1}$ throughout the water column (Fig. 12). At these levels, particulate trace metals would, for most metals, make up a negligible portion of the total metal content.

5. SEDIMENT TRACE METALS

Sediments serve as the "ultimate sink" for the oceans' trace metals and provide a useful tool for the identification of important areas of past and present metal deposition. Holmes has overseen massive sampling and analytical efforts for sediment trace metals along the continental shelf and slope (Holmes, 1973) and the central Gulf of Mexico (Holmes, 1976). Figure 13 shows representative sediment metal distribution for the shelf and slope using Cr as an example. Very low Cr concentrations typify the Florida shelf, with highest values along the outer shelf and slope of the northwest Gulf, west of the Mississippi Delta. This trend is consistent with that observed for other trace metals and reflects the metal-poor nature of the carbonate-rich Florida shelf and the metal-rich, fine-grained clay sediments west of the Mississippi Delta (Table 5). Since the primary metal source to the Gulf is Mississippi River suspended matter and since shelf transport of this material is largely to the west, the observed trends in Figure 13 are as expected. One site on the outer Florida shelf (in the area of 25-26°N and 84°W) was found to have notably high sediment Cd levels, possibly the result of biological uptake in this nutrient-rich outer shelf water where depths are shallow enough to restrict Cd regeneration within the water column. Analogous to the Florida shelf, the Campeche shelf carbonates are similarly low in trace metals (Angino et al., 1972).

Table 5 shows that Mississippi Delta sediments have 20-50% lower Mn, Cu, Co, Ni, and Zn concentrations and metal/Al ratios than Mississippi River particulates. These differences are observed despite uniform Fe, Al, Cr, and V concentrations and similar grain-size distribution. Chemical fractionation of the delta sediments shows that a reduction in oxide-phase metal concentrations accounts for these depletions. Trefry (1977) shows that reducing conditions in delta sediments promote loss of oxide-phase Mn and Fe through reduction-diffusion. Calculated fluxes of dissolved Mn and Fe from the surface centimeters of sediment to the overlying seawater range from 200 to > 1000 $\mu g\ cm^{-2}y^{-1}$. Measured losses of Cu, Ni, Co, and Zn from delta sediments may also be related to a reduction-diffusion mechanism. The magnitude of the Mn loss from about 1000 km^2 of Mississippi Delta sediments is estimated to be $3.6 \times 10^{10}\ g\ y^{-1}$, about six times greater than the total dissolved Mn load of the Mississippi River system.

In outer shelf and slope areas, Holmes (1976) and Trefry (1977) find Mn-rich layers in surficial sediment layers as remobilized Mn is reoxidized within the sediment column. Deep Gulf of Mexico sediments from the strictly pelagic deposits of the Sigsbee Knolls have Cu, Co, and Ni concentrations (ratioed to Al) that are about 50% above Mississippi River particulate and abyssal Gulf sediment values and Mn concentrations that are 2 to 3 times above river values. Little change in average Fe, Zn, Pb, Cr, and V concentrations occurs between Mississippi Delta and knoll sediments. Accompanying the change in concentration from nearshore to abyssal sediments for some metals is an increase in percent clay (< 2 μm) from 50-80% and a decrease in sedimentation rate from 1 $g\ cm^{-2}y^{-1}$ (Miss. Delta) to 0.01-0.1 $g\ cm^{-2}y^{-1}$ (outer shelf and slope) to < 0.002 $g\ cm^{-2}y^{-1}$ (Sigsbee Knolls). Trefry (1977) has shown that chemical deposition from seawater of some of the metals studied (Cu, Mn, Ni) is fast enough to increase expected levels in knoll sediments, but not in abyssal plain sediments. Furthermore, chemical deposition rates for some elements, including Pb and Zn, are too slow to significantly enrich any Gulf sediments.

6. SUMMARY AND CONCLUSIONS

To say we understand the distribution and behavior of trace metals in the Gulf of Mexico is, at best, an overstatement. Nevertheless, considerable interest in such knowledge has existed for many years. Although trace metal studies of Mississippi River water and particulates and Gulf sediments have progressed well, we do not have a good grasp on water column metal relationships.

In summary, we recognize the importance of Mississippi-Atchafalaya River particulates as a metal source to the Gulf. Furthermore, alumino-silicate lattices and oxide coatings on particles provide the major phases for this metal transport. River-dissolved metal concentrations are low, most likely controlled by the high suspended load and pH of most Gulf rivers. Interactions at the freshwater-seawater interface do not serve to add dissolved trace metals to the Gulf, and further study is needed to see if significant removal occurs for selected metals.

Dissolved metals in the waters of the continental shelf are variable but low, frequently below modest detection limits. Strong evidence for the enrichment of bottom water dissolved Mn by diffusion of reduced Mn^{2+} from sediment interstitial water is given in at least two studies near the Mississippi Delta where high sedimentation rates induce reducing conditions. Nearshore trace metal concentrations from a study off the Alabama-Florida border appear to follow water mass movement as a quasi-synoptic study shows dissolved trace metal contours following lines of constant sigma-t.

In coastal waters, unlike the open Gulf, particulate trace metals frequently comprise a significant percentage of the total water column metals. However, values are extremely variable and do not always follow a logical trend, since they are sometimes elevated by contamination and sometimes biased by inclusion of metal-concentrating organisms. When significant trends are observed, they may be most helpful in tracing particulate origins, especially those from the Mississippi River and the Mn-rich outer slope.

Beyond the continental shelf, trace metal data is sparse. Slowey and Hood (1971) show higher dissolved metal levels at surface or intermediate depths, suggesting release of metals from decomposing organisms as the midwater source. Bottom water values were considerably lower than those of the mixed layer. Deep water suspended loads, as sampled with Niskin bottles, are low at 10-20 $\mu g\ \ell^{-1}$. Hence, particulates play an insignificant role in total trace metal levels in these instances.

Sediment metal studies for the Gulf of Mexico show the carbonate-rich Florida shelf to be almost devoid of sedimentary metals in great contrast to the Mississippi Delta and outer shelf areas to the west of the Delta.

These differences are strictly a function of source material, and Trefry and Presley (1976) estimate that > 90% of the massive sediment load of the Mississippi River is deposited in an area < 1% of the Gulf. Suspended sediment, which escapes nearshore burial and is transported to the deep Gulf, is generally not enriched in metals to the extent found in classic pelagic red clays. This distinction is influenced by greater deep Gulf sedimentation rates (mostly > 10 cm/1000 y) and a significant $CaCO_3$ contribution (20-50%) to abyssal Gulf sediments. Evidence of significant enrichment of Cu, Co, Mn, and Ni in Sigsbee Knoll sediments is most likely a function of lower sedimentation rates on these isolated topographical highs.

To put some of the reviewed material into perspective, the next step is to fashion a picture of source/sink relationships for the Gulf and attempt to put this into a general timeframe.

Although riverine inputs have been considered in some detail, one must remember that the 1×10^{15} ℓ y^{-1} river water additions to the Gulf of Mexico are completely overshadowed by the 785×10^{15} ℓ y^{-1} volume transported by the Loop Current. Although 2300 years are required to fill the Gulf with river water, only 3 years are needed to fill it with Caribbean Sea water. We know roughly that Mississippi River dissolved metal concentrations are 2 to 10 times higher than Gulf levels, yet we know considerably less about Caribbean Sea metal distribution. Slowey and Hood (1971) use their data to suggest that inflow through Yucatan Straits may provide a much greater source of metal than that from the Mississippi. For example, if the Mississippi carried 1000 ng ℓ^{-1} of a given metal (where Gulf values were 100 ng ℓ^{-1}) and incoming Yucatan water were at only 110 ng ℓ^{-1}, then the annual Yucatan influx of this metal (above ambient Gulf levels) would be eight times higher than Mississippi inputs. Even though a major portion of the Yucatan flow quickly moves through the Gulf, its magnitude gives it the potential to significantly influence (by enrichment or dilution) Gulf metal distribution.

Although we are aware of the enormous potential of the Loop Current to influence Gulf chemistry, it still behooves us to calculate residence times for several metals for which river and Gulf data are available. When we use the relationship for residence time (τ):

$$\tau = \frac{A}{\frac{dA}{dt}}$$

where A = total amount of metal in the Gulf of Mexico (g)

$\frac{dA}{dt}$ = annual input of metal to the Gulf from rivers (g/y^{-1})

and the values from Table 3, Fe, Mn, Ni, and Zn have residence times of about only 200-300 years and Cd, Cr, Cu, and Hg have times of about 500-1500 years. Compared with world ocean estimates (Brewer, 1975) most of the above (except Fe) are one to two orders of magnitude lower. Much of this difference is caused by the short time period required to fill the Gulf with river water relative to world ocean filling. Nevertheless, these calculated short time periods may provide important insight to active removal processes in this restricted basin. Feely et al., (1971), for example, calculate particle residence times for the deep Gulf of Mexico to be on the order of 3 years when particulate Al distribution is used. A similar residence time can be calculated by dividing the total particulate load of the Gulf (with 30 μg particles ℓ^{-1}) by 5% of the annual river input.

Somewhat akin to the above discussion are the conclusions of Trefry and Shokes (1979) regarding pollutant metal inputs from the Mississippi River. They note that pollutant Pb fluxes from the Mississippi River to the Gulf of Mexico are about 6,000 metric tons per year, or about 30 times higher than estimated for the Southern California coastal zone (Bruland et al., 1974). Similarily, anthropogenic Cd inputs from the Mississippi (about 300 tons y^{-1}) are about 35 times greater than those reported for Southern California. The massive sediment load of the Mississippi (about 300 million tons y^{-1}), however, dilutes these significantly higher fluxes to concentration levels comparable with those observed off Southern California. Such dilution may completely obscure pollution inputs of some of the other metals. For example, no significant alteration in Mississippi Delta sediment Cr flux (22,000 tons y^{-1}) would be observed by adding the 350 tons of pollutant Cr found for the California Coast, or even 3 or 4 times that amount. In this manner then, the Mississippi provides a viable outlet for carrying enormous loads of industrial and municipal metal wastes without significantly increasing natural (background) metal levels.

7. FUTURE RESEARCH NEEDS

As initially alluded to, the important facets of the trace metal chemistry of the oceans are the involvement of metals in biological processes and the geochemical cycling and possible enrichment of some metals in sedimentary deposits. Although several inferences have been made on these processes from available data, we outline below some of the major areas that should be addressed and some that may require less emphasis.

First, reliable total dissolved metal profiles are needed for each of the major Gulf areas. These need to be obtained using every precaution in sampling equipment and shipboard handling, including an ocean-going clean lab. Analyses must be carried out with every attention to detail and under clean-lab conditions. Otherwise, further effort will continue to render questionable results. The major thrust of such efforts should be to (1) trace the vertical distribution of metals in areas of varying productivity and potential anthropogenic inputs;, (2) quantify the release of interstitial metals to nearshore bottom waters, particularly in areas and at times when circulation is restricted;, (3) determine metal levels in incoming Caribbean Sea water, eddies that break off from the Loop Current, and outgoing Florida Straits water;, and (4) further evaluate trace metal/water mass relationships in nearshore (especially the Mississippi Delta) and Yucatan Straits areas. Nutrient, organic matter, productivity, and hydrographic data would necessarily complement the trace metal data.

NOAA/AOML already has initiated a dissolved trace metal effort in their ROME (Role of Organics in the Marine Environment) project. Choosing sites off the Mississippi River, in upwelling areas off Yucatan and the west coast of Florida, and in the Loop Current, NOAA researchers plan to correlate the role of trace metals, humic substances, and nutrients with phytoplankton productivity. A program of this magnitude should greatly enhance the present state of knowledge.

Metal speciation has been, and continues to be, the Holy Grail of marine trace metal chemists. Such studies in the Gulf of Mexico have been limited to quantifying As, Hg, Sb, and Sn species on a very limited scale in coastal or bay waters. These studies and other less species specific work (dialysis and chemical extraction techniques) have clearly demonstrated the importance of the organic ligand to the above metals as well as Cu and Zn. Certainly, species information is important to the understanding of marine chemical reactions and potential metal toxicities; however, we still are faced in many cases with unreliable total metal concentrations. Thus, the attainment of good total metal data with supporting parameters should be the first objective for the Gulf of Mexico, to which species may be added at a later time.

With respect to particulate trace metals, use of sediment traps in nearshore areas would greatly enhance our ability to quickly assess anthropogenic inputs. Bruland (personal communication) has shown that sediment-trapped samples (of about 1 to 2 months) provide a much more realistic view of incoming metal fluxes than spot Niskin samples. A sediment trap program also would be useful in examining the geochemistry of offshore transported shelf sediment. Study of deep water suspended matter trace metals in the Gulf probably should be deemphasized initially, since particulates provide a negligible portion of the total metal load. The most important consideration to all future trace metal investigations is stringent quality control, for, with good data, the distribution and behavior of dissolved trace metals in the ocean will certainly become more than a confused patchwork.

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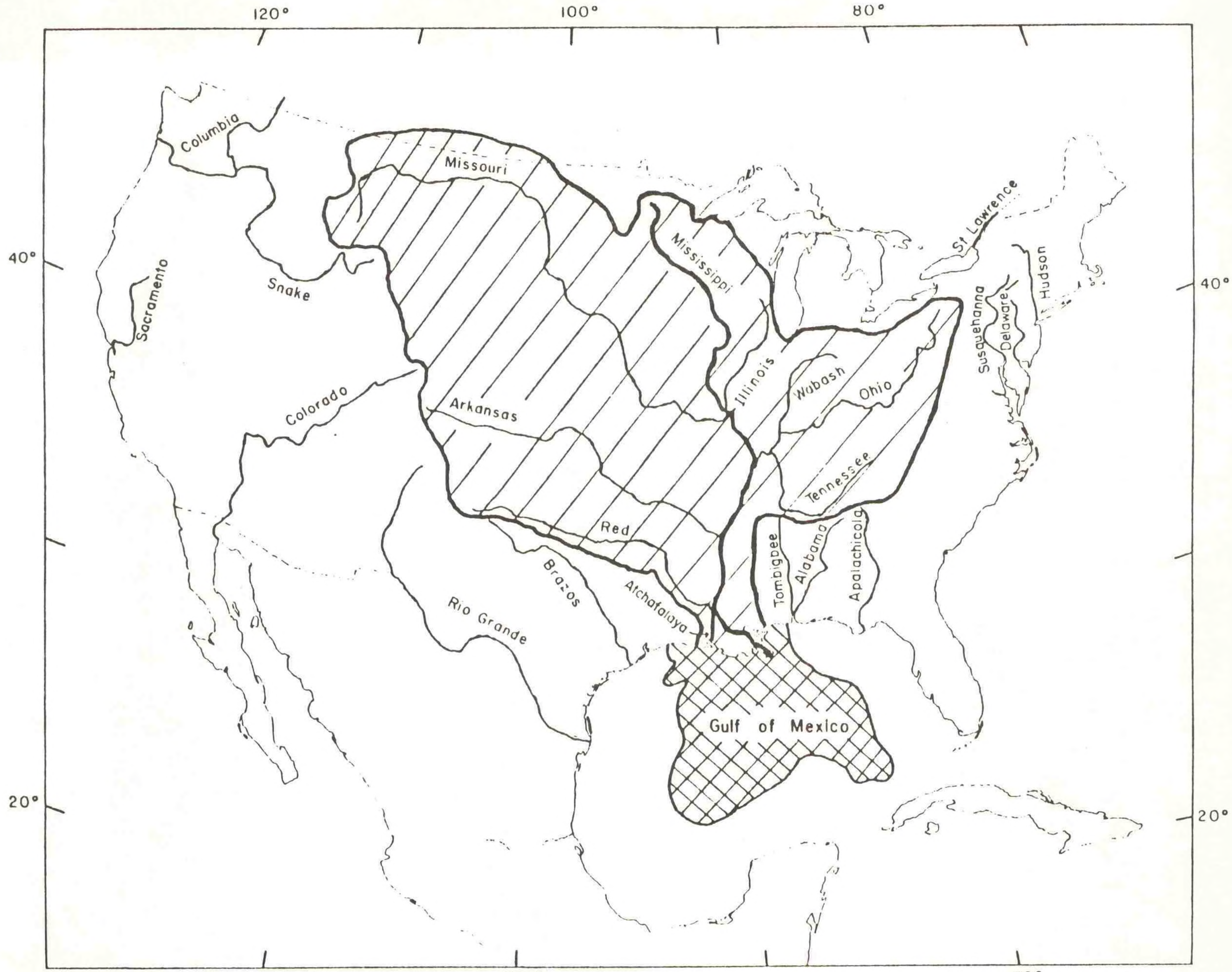

Fig. 1. The Mississippi River drainage basin and Mississippi Distributive province of the Gulf of Mexico.

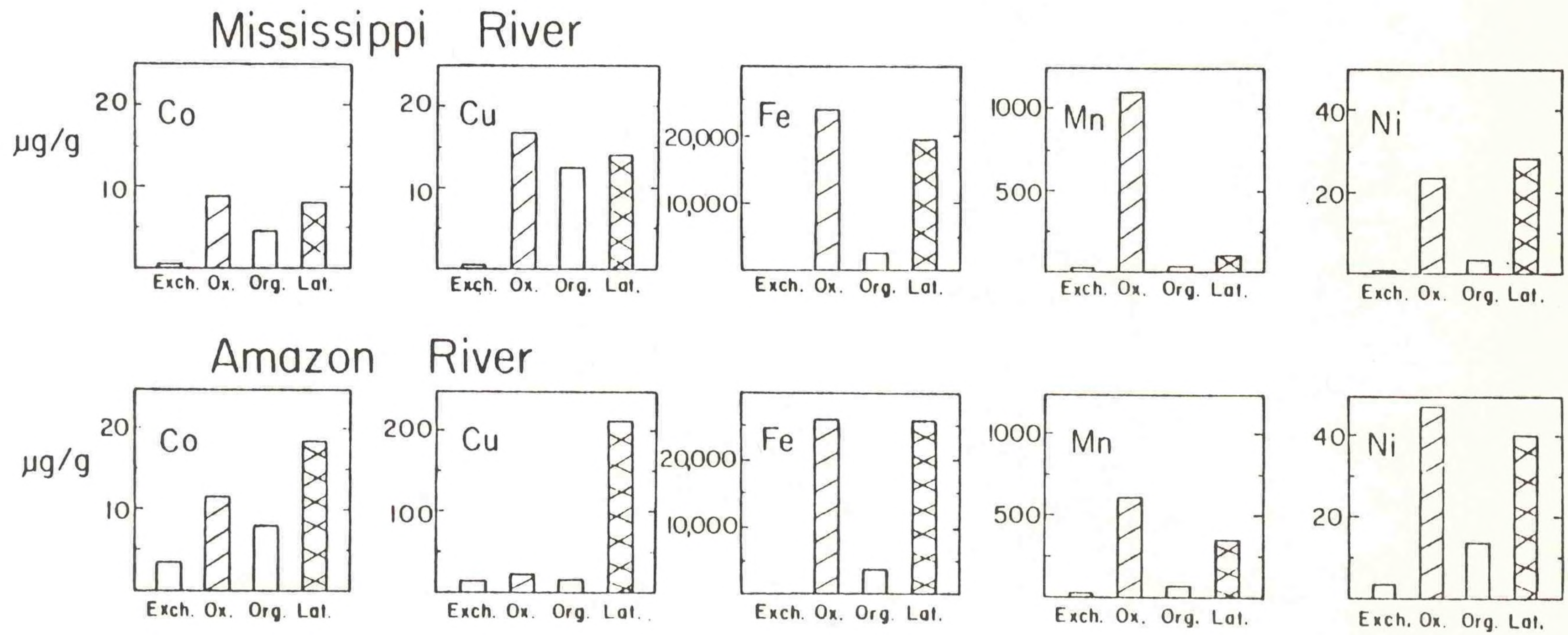

Fig. 2. Trace metal partitioning in Mississippi (Trefry and Shokes, 1979) and Amazon River (Gibbs, 1977) suspended matter.
(From Gibbs, 1977, Bull. Geol. Soc. Amer. 88:829-843, with permission of the publisher, The Geological Society of America.)

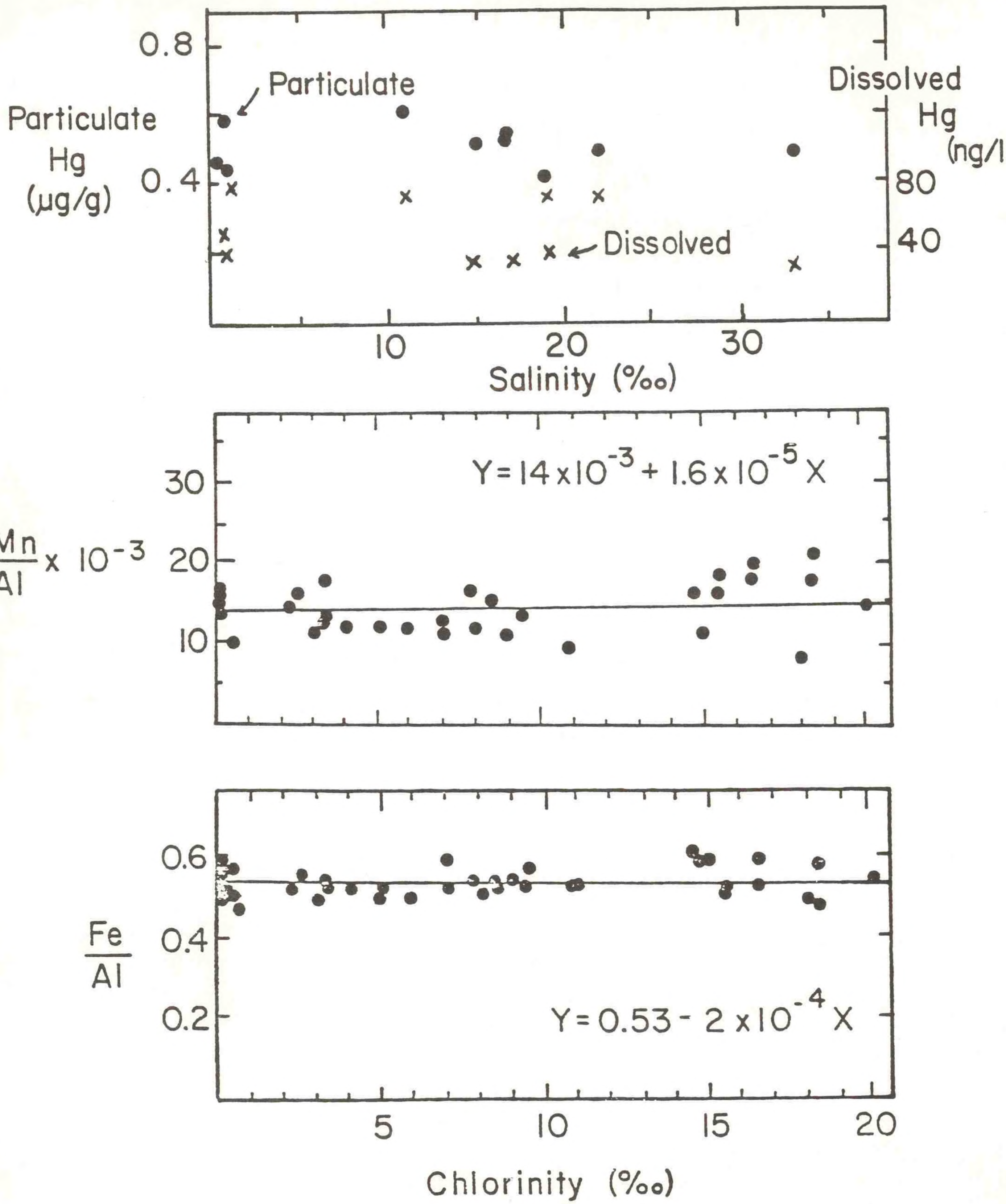

Fig. 3. Particulate trace metal distribution across the Mississippi River-Gulf of Mexico interface. (Hg from Andren, 1973; Mn and Fe from Trefry and Presley, 1976.)

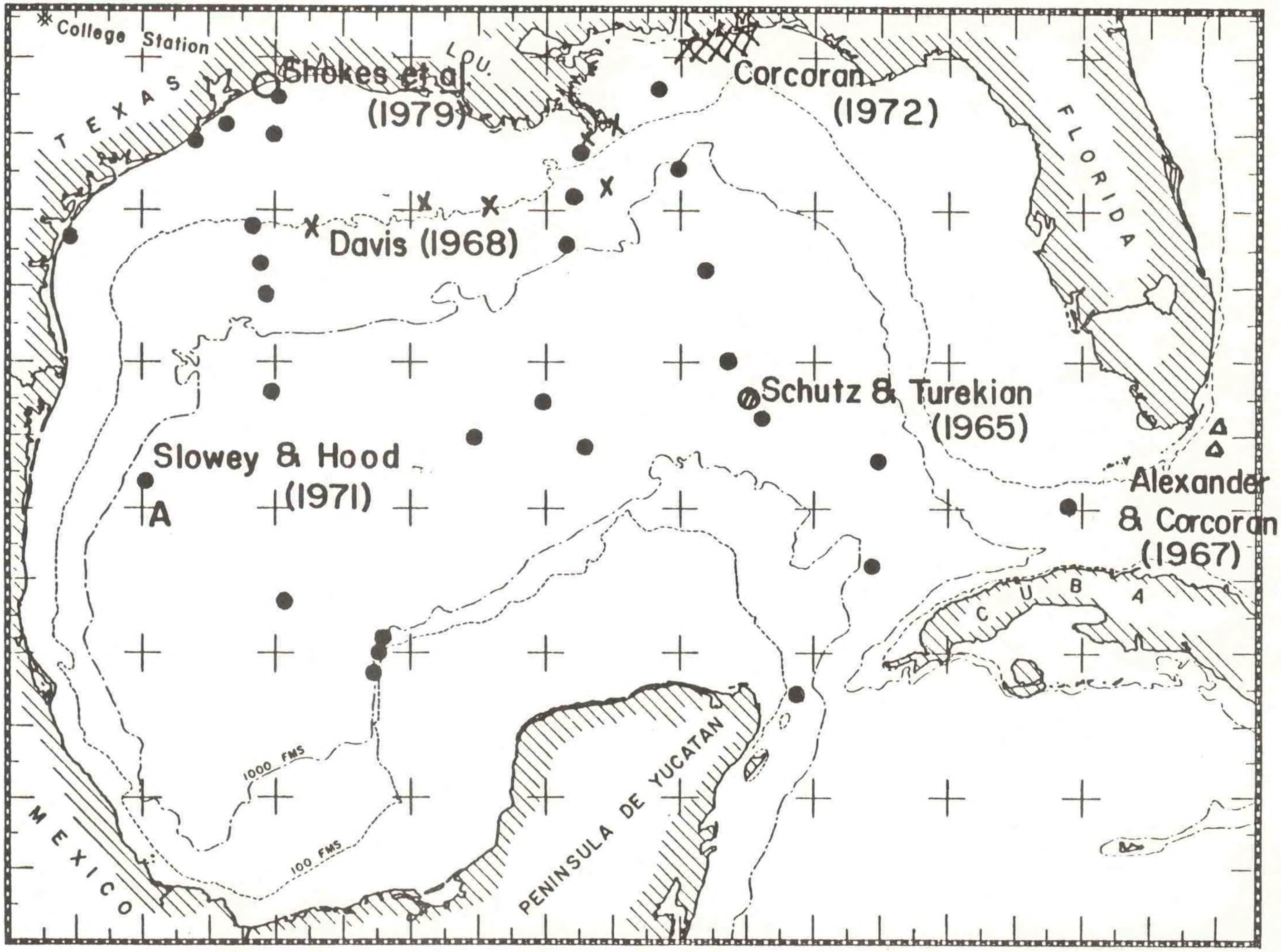

Fig. 4. Dissolved trace metal sampling sites.

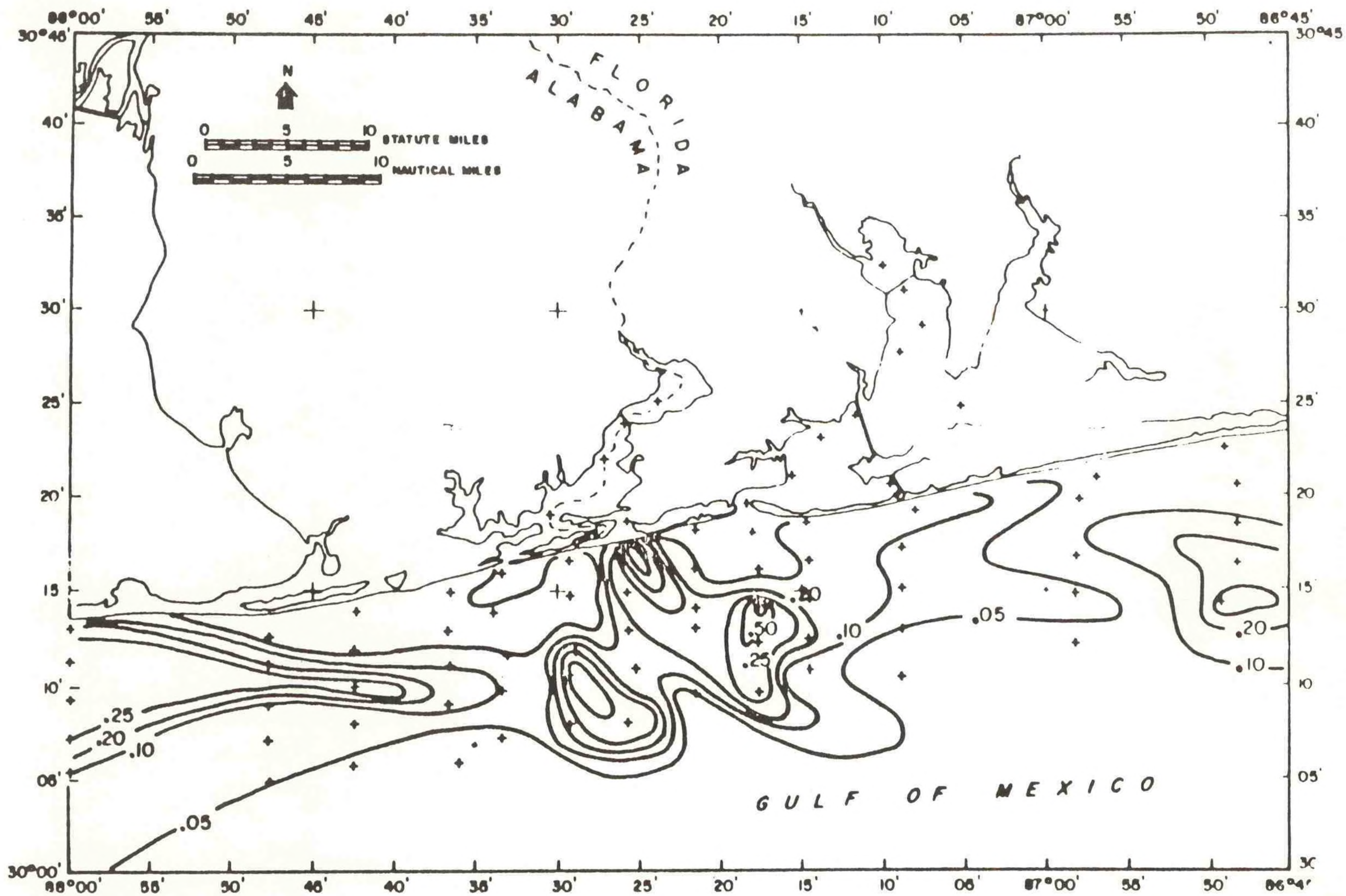

Fig. 5. Surface water dissolved Cd concentrations along the eastern coastal Gulf of Mexico. (Corcoran, 1972, with permission of the author.)

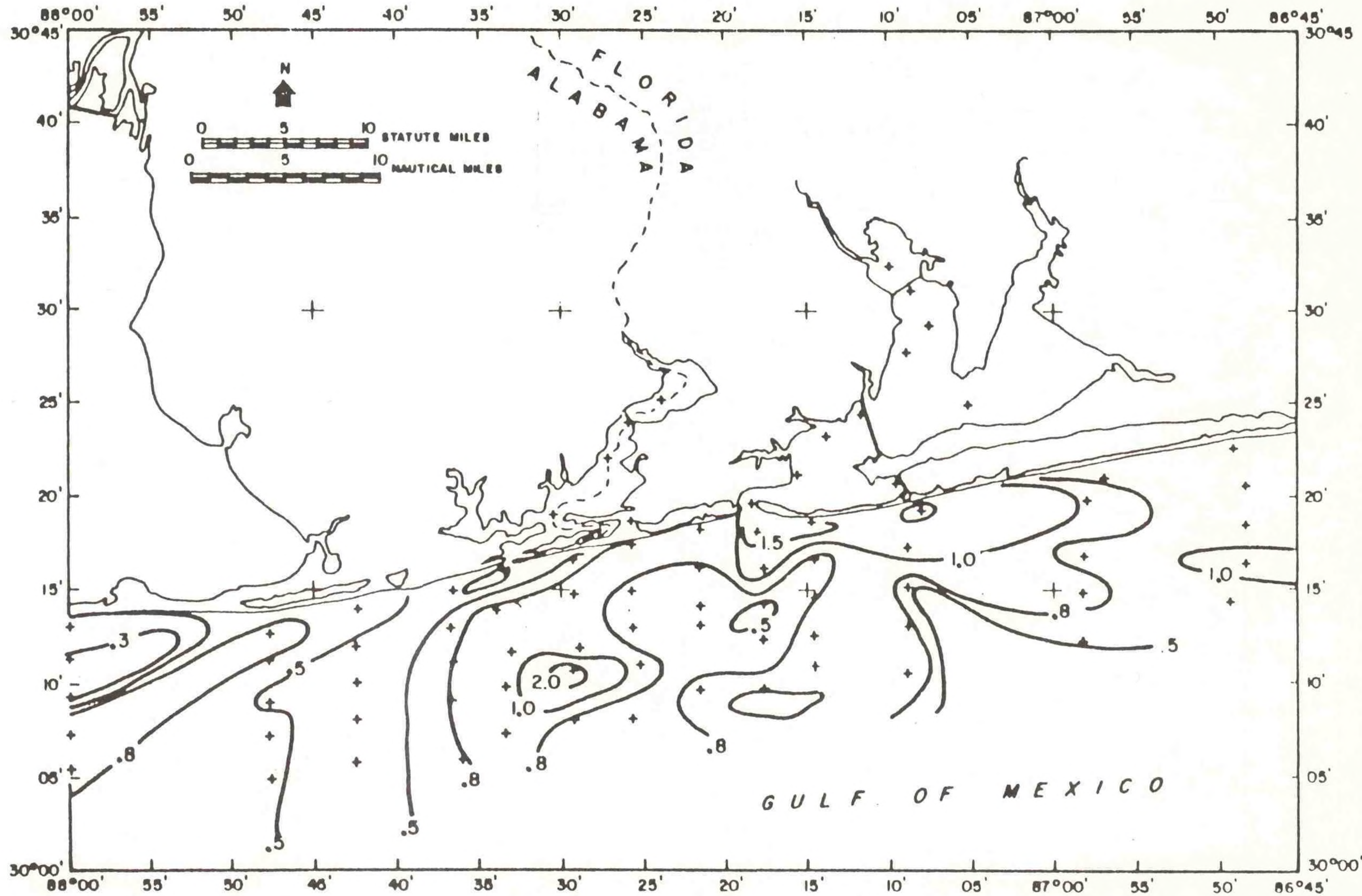

Fig. 6. Surface water dissolved Cr concentations along the eastern coastal Gulf of Mexico. (Corcoran, 1972, with permission of the author.)

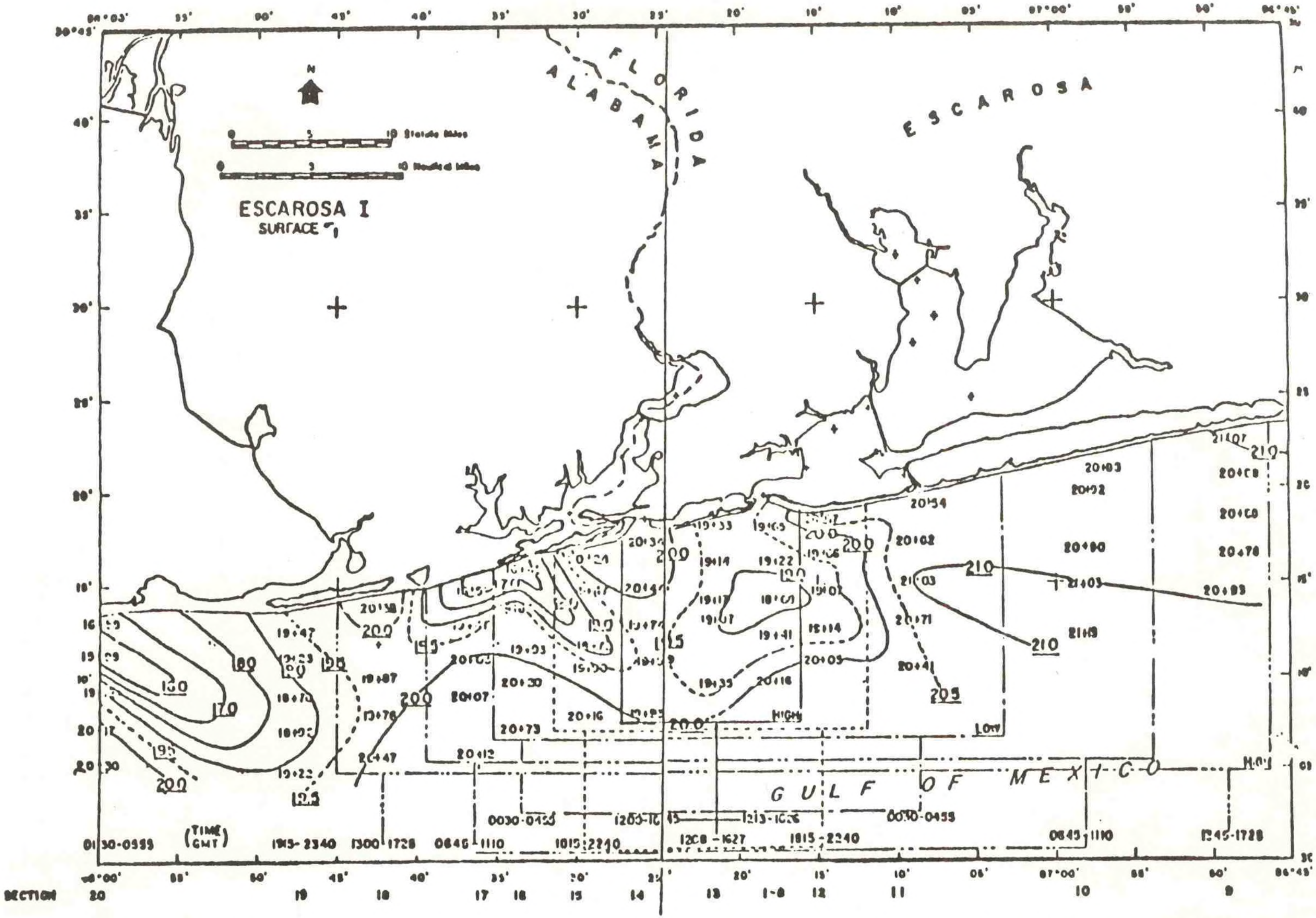

Fig. 7. Surface water sigma-t distribution at trace metal sampling sites examined in Figs. 5 and 6. (Corcoran, 1972, with permission of the author.)

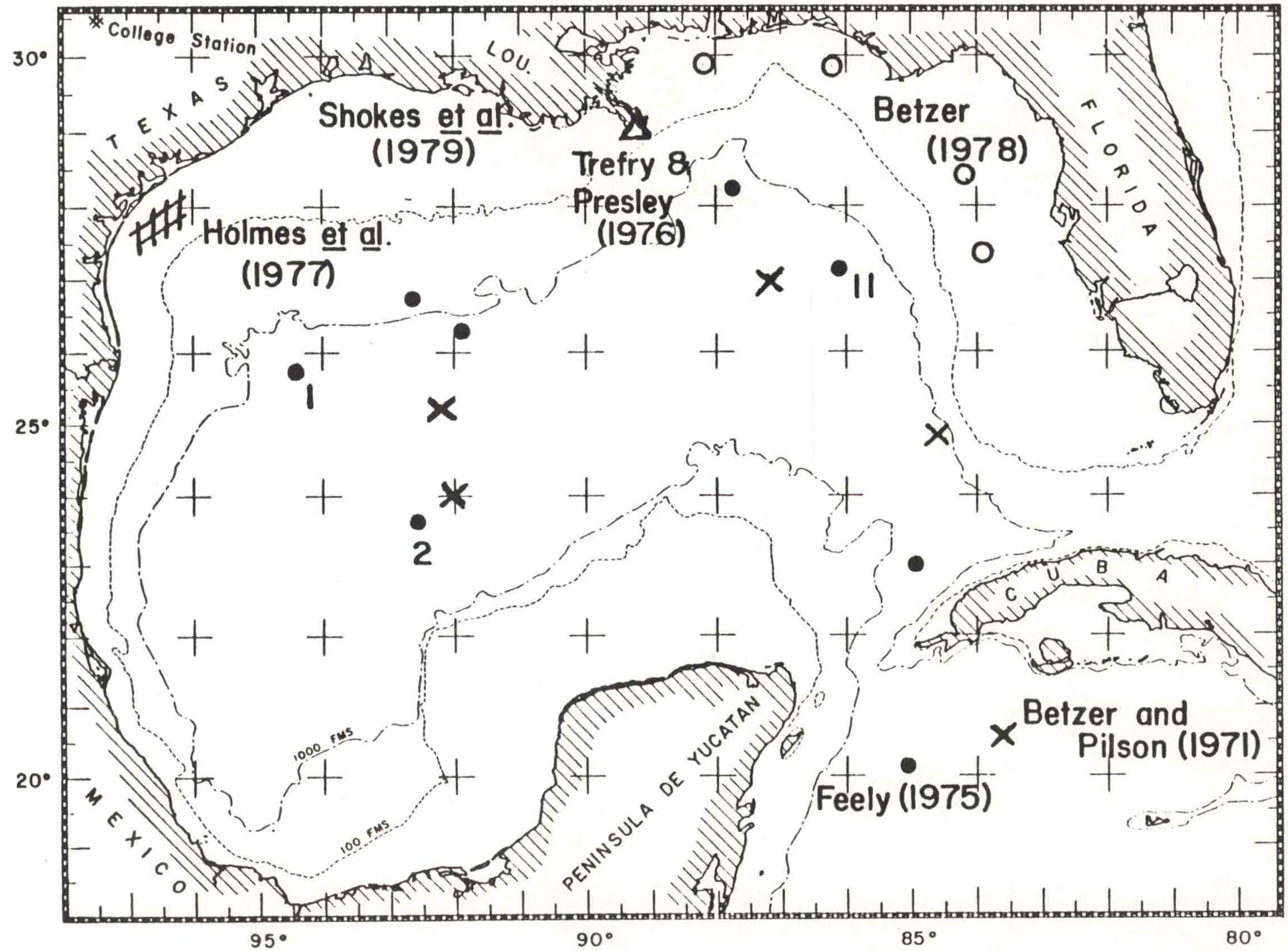

Fig. 8. Particulate trace metal sampling sites.

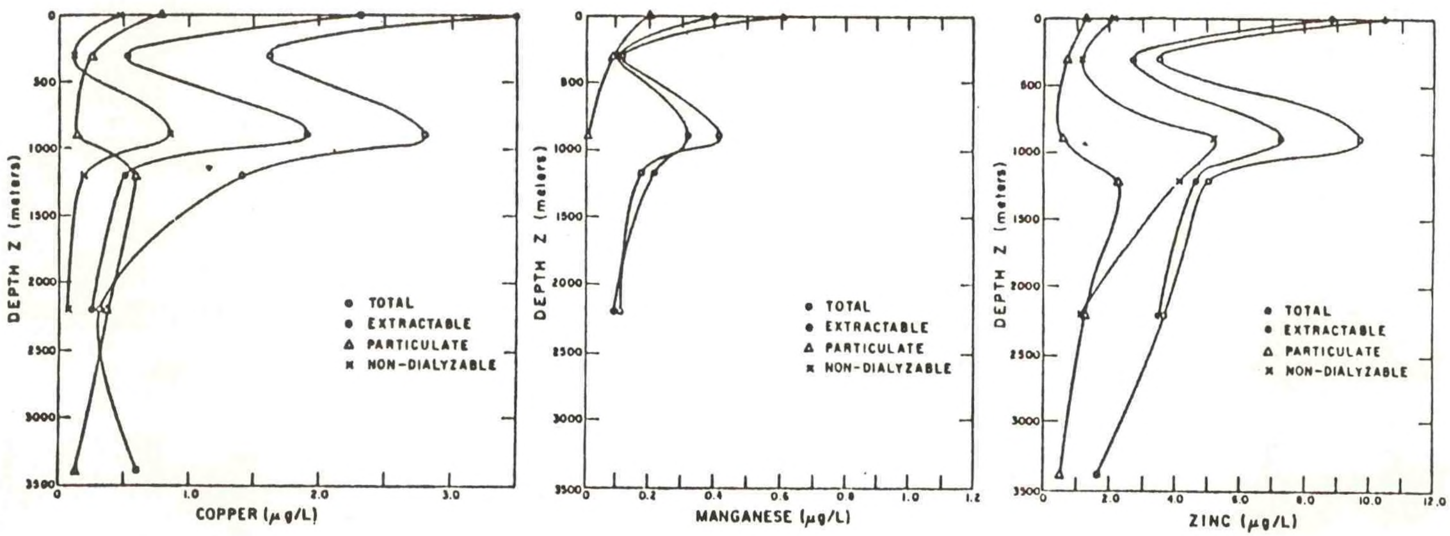

Fig. 9. Vertical profiles of Cu, Mn and Zn at western Gulf of Mexico site A. (From Slowey and Hood, 1971. Reprinted with permission from Geochim. Cosmochim. Acta, 35, J. F. Slowey and D. W. Hood, "Copper, manganese, and zinc concentrations in the Gulf of Mexico waters." Copyright 1971, Pergamon Press, Ltd.)

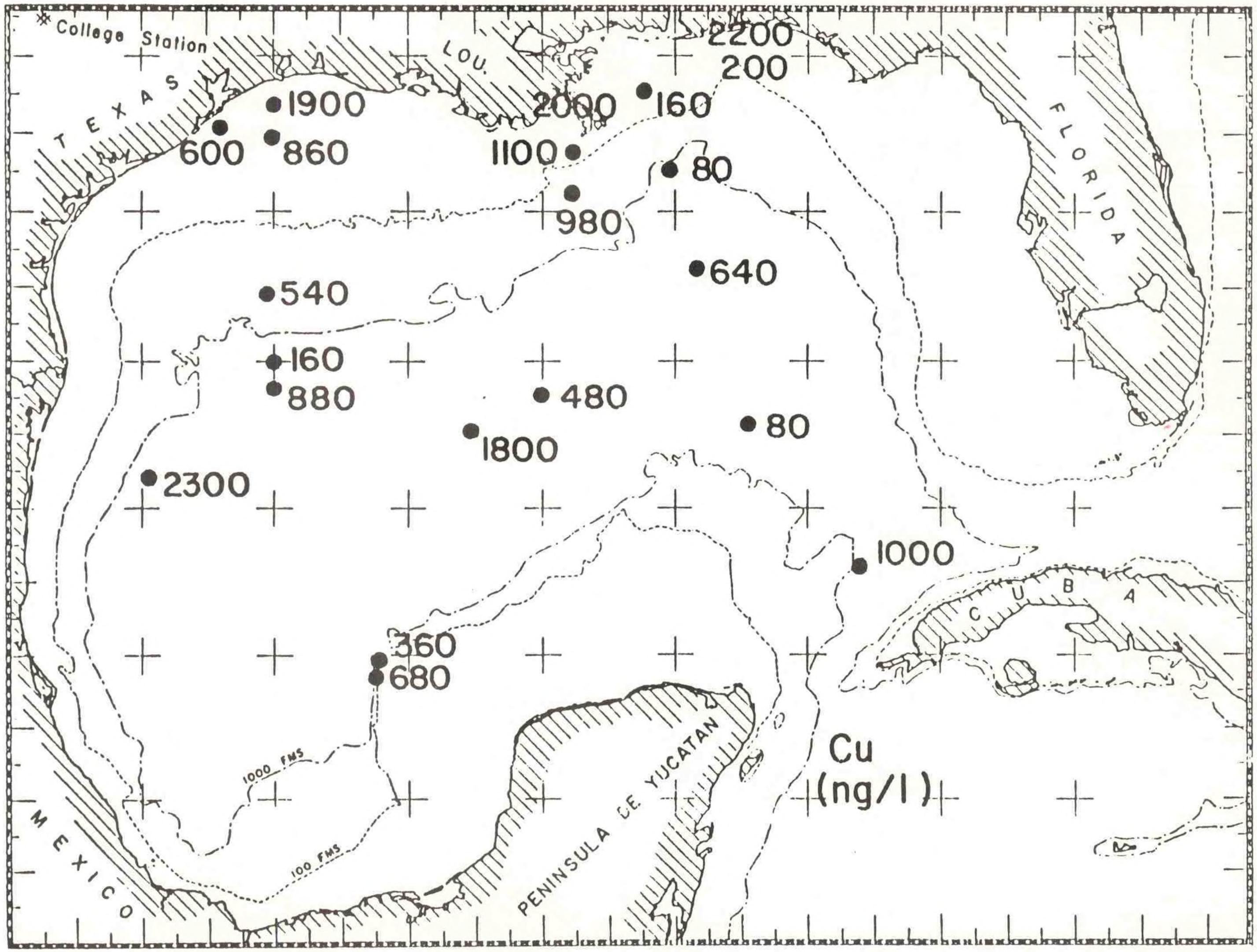

Fig. 10. Surface water dissolved Cu concentations. (Data from investigators identified on Fig. 4.)

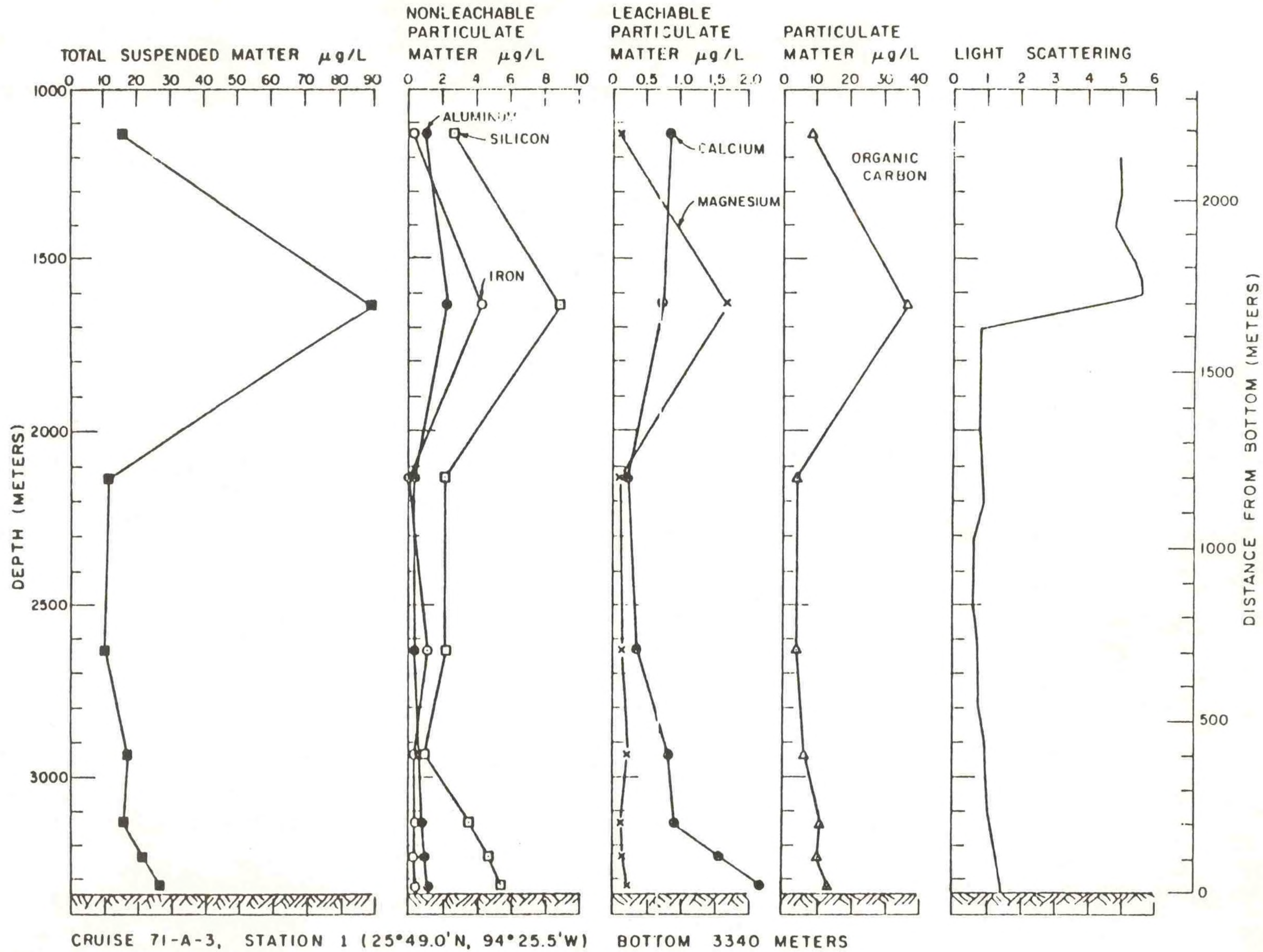

Fig. 11. Suspended mater Fe, Al and selected parameters for western Gulf of Mexico Station 1. (See Fig. 8 for location; profiles from Feely, 1975.)

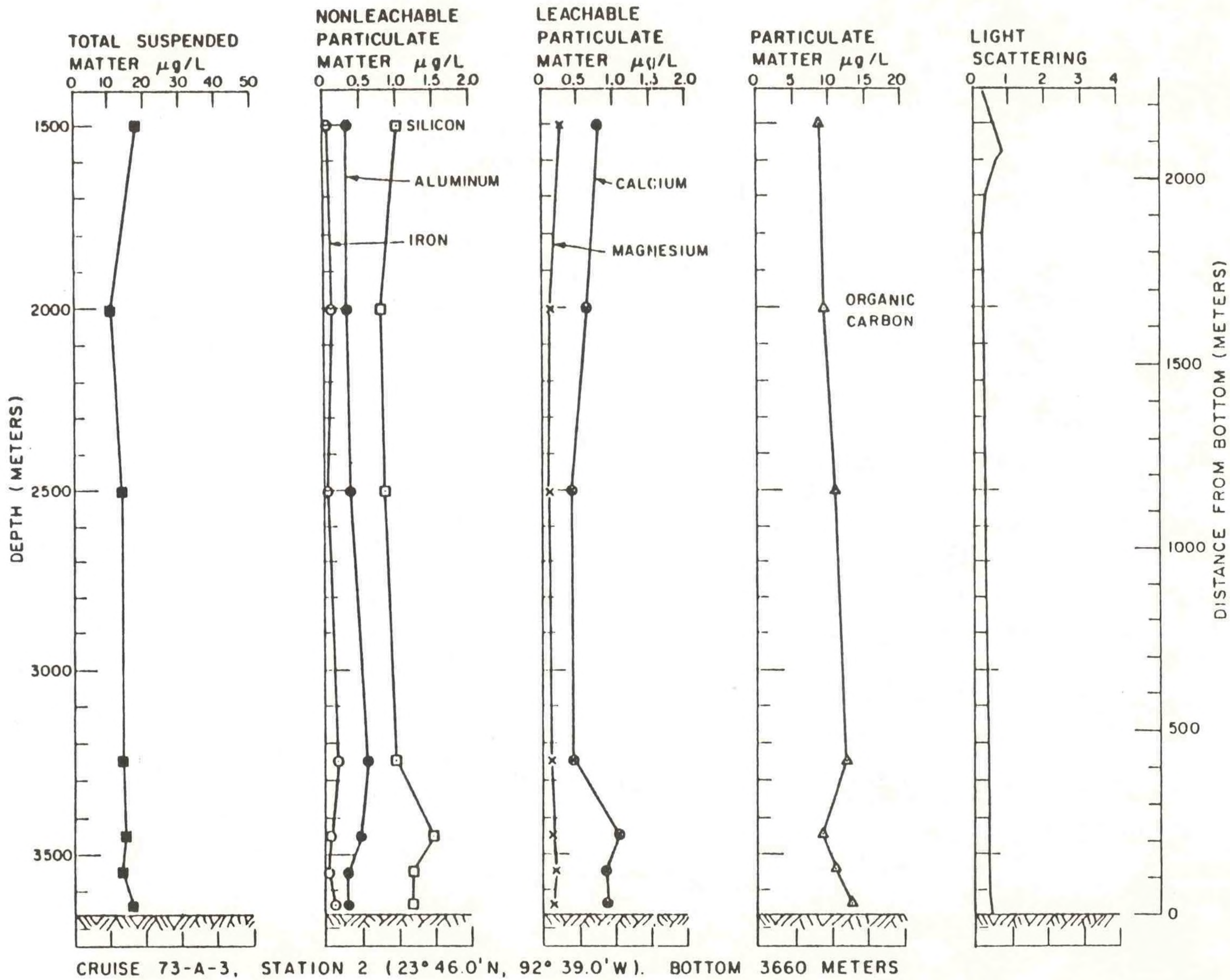

Fig. 12. Suspended mater Fe, Al and selected parameters for abyssal Gulf of Mexico Station 2. (See Fig. 8 for location; profiles from Feely, 1975.)

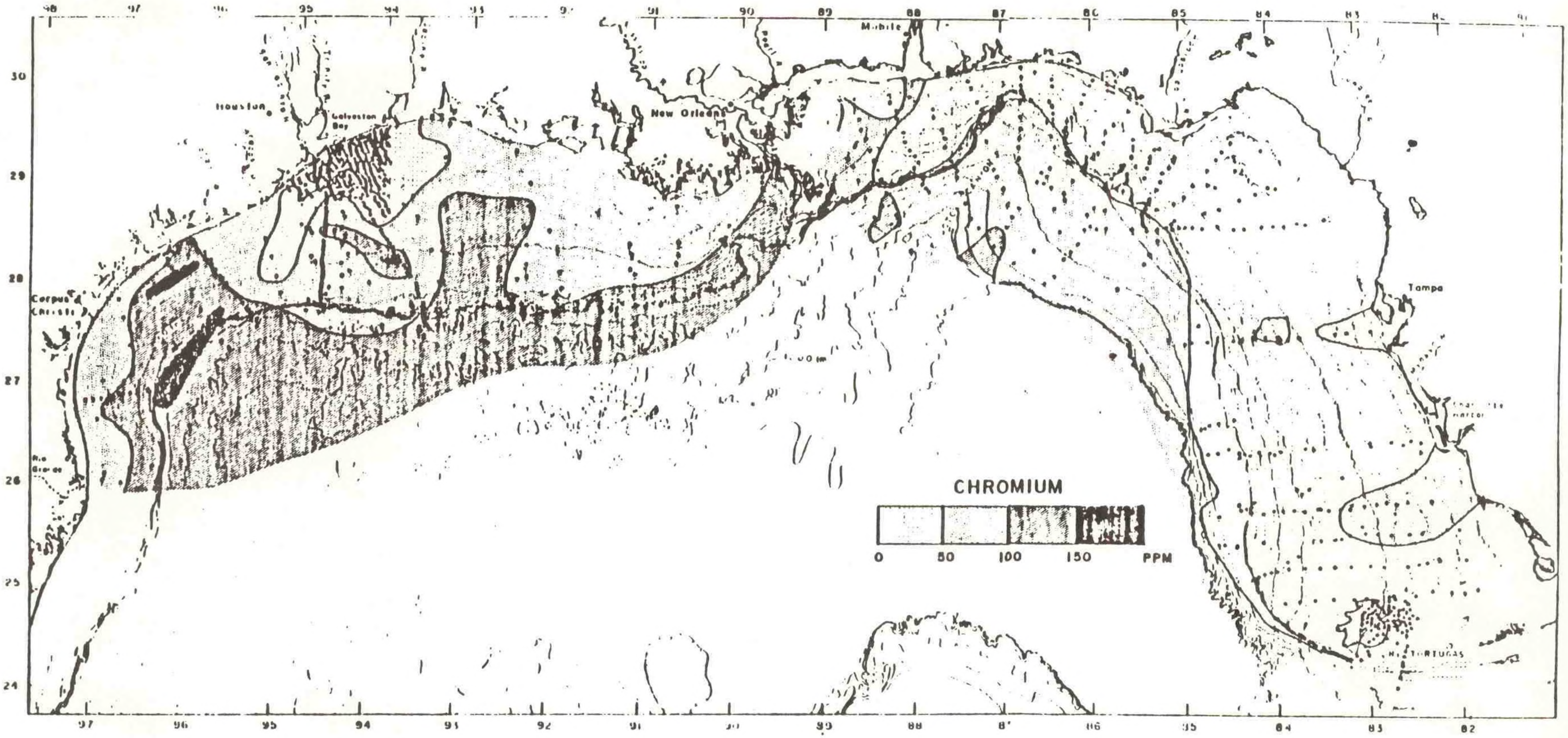

Fig. 13. Sediment Cr concentrations for the continental shelf and slope of the northern Gulf of Mexico. (From Holmes, 1973.)

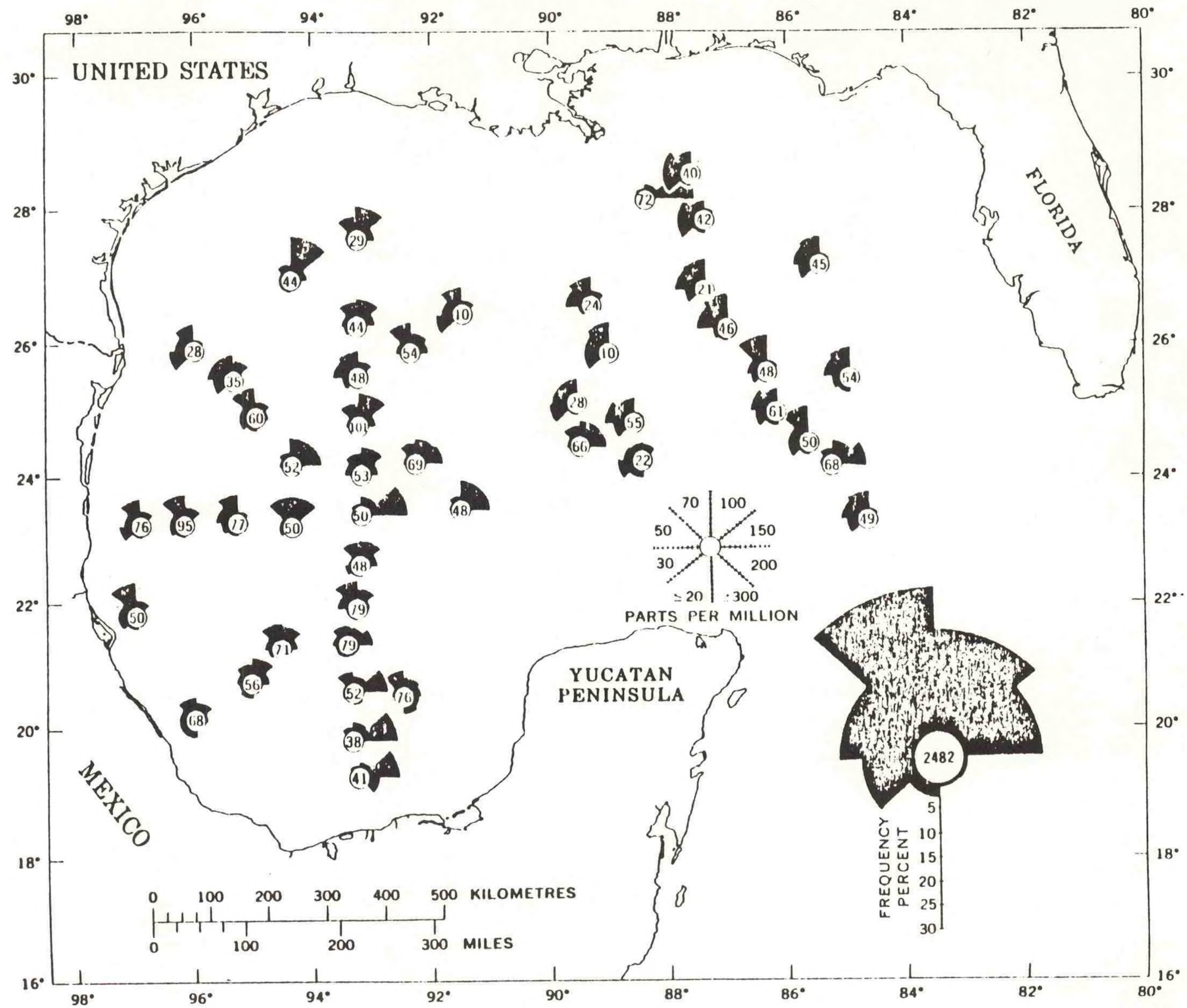

Fig. 14. Sediment Cr concentrations for the central Gulf of Mexico. (From Holmes, 1976.)

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