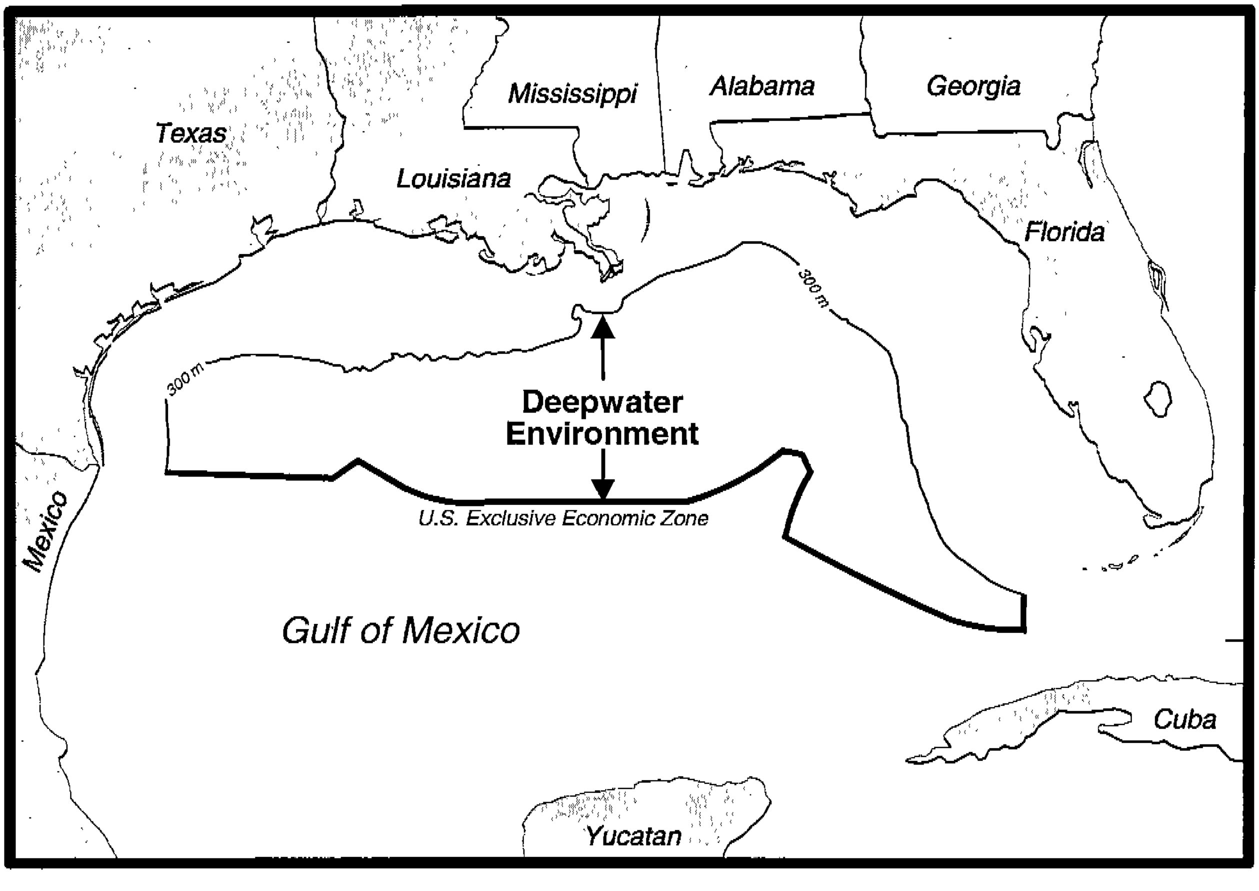
OCS Study
MMS 2000-049

# Deepwater Gulf of Mexico Environmental and Socioeconomic Data Search and Literature Synthesis

## Volume I: Narrative Report



U.S. Department of the Interior
Minerals Management Service
Gulf of Mexico OCS Region

OCS Study
MMS 2000-049

# Deepwater Gulf of Mexico Environmental and Socioeconomic Data Search and Literature Synthesis

## Volume I: Narrative Report

Author

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Prepared under MMS contract
1435-01-98-CT-30916
by
Continental Shelf Associates, Inc.
759 Parkway Street
Jupiter, Florida 33477-9596

Published by

**U.S. Department of the Interior**
**Minerals Management Service**
**Gulf of Mexico OCS Region**

**New Orleans**
**July 2000**

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## Suggested Citation

Continental Shelf Associates, Inc. 2000. Deepwater Gulf of Mexico Environmental and Socioeconomic Data Search and Literature Synthesis. Volume I: Narrative Report. U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study MMS 2000-049. 340 pp.

## Acknowledgments

This synthesis report was prepared by Continental Shelf Associates, Inc. (CSA) with the assistance of technical experts (primarily from Texas A&M University) serving as independent consultants. The CSA Program Manager was David A. Gettleson and the report editor was Neal W. Phillips. The Annotated Bibliography was compiled by David B. Snyder with the assistance of Kristen L. Metzger and Marilyn Morris, librarians at Harbor Branch Oceanographic Institution Inc. Melody B. Powell was the technical editor. Suzanne R. Short prepared the final graphics and Deborah V. Raffel was responsible for word processing. Clerical support was provided by Deborah M. Cannon, Karen I. Stokesbury, and Caroline M. Simpson.

CSA especially wants to acknowledge the chapter authors for their excellent contributions to this report:

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# Acronyms and Abbreviations

| | |
|---|---|
| ADCP | acoustic Doppler current profiler |
| AXBT | air-dropped expendable bathythermograph |
| bbl | barrel |
| BGN | Board of Geographic Names |
| BOPD | barrels of oil per day |
| BT | bathythermograph |
| CASE | Consortium for Analysis Studies of Eddies |
| CTD | conductivity, temperature, depth |
| CZCS | coastal zone color scanner |
| DCM | deep chlorophyll maximum |
| DOC | dissolved organic carbon |
| DOM | dissolved organic matter |
| DSDP | Deep Sea Drilling Program |
| EEZ | Exclusive Economic Zone |
| EJIP | Eddy Joint Industry Program |
| EPA | Environmental Protection Agency |
| FAD | fish attracting device |
| FPSO | floating production system with storage and offloading |
| GMFMC | Gulf of Mexico Fishery Management Council |
| GOM | Gulf of Mexico |
| IAS | Intra-Americas Sea |
| IES | inverted echo sounder |
| IKMT | Isaacs-Kidd Midwater Trawl |
| LATEX | Texas-Louisiana Shelf Circulation and Transport Processes Study |
| LC | Loop Current |
| LCE | Loop Current eddy |
| LNG | liquefied natural gas |
| LOOP | Louisiana Offshore Oil Port |
| MBOPD | thousand barrels of oil per day |
| MMBOE | million barrels oil equivalent |
| MMS | Minerals Management Service |
| MMSCFPD | million standard cubic feet per day |
| MOCNESS | Multiple Opening/Closing Net Environmental Sensing System |
| MODUs | mobile offshore drilling units |
| NECOP | nutrient enriched coastal ocean productivity |
| NGOMCS | Northern Gulf of Mexico Continental Slope |
| NMFS | National Marine Fisheries Service |
| NOAA | National Oceanic and Atmospheric Administration |
| NOS | National Ocean Service |
| NPZ | nutrients-phytoplankton-zooplankton |
| OCS | outer continental shelf |
| OPEC | Organization of Petroleum Exporting Countries |
| PAH | polynuclear aromatic hydrocarbon |

# Acronyms and Abbreviations

## (continued)

| | |
|---|---|
| POC | particulate organic carbon |
| POM | Princeton Ocean Model |
| ROV | remotely operated vehicle |
| RQ | respiratory quotient |
| SAIC | Science Applications International Corporation |
| SSHA | sea surface height anomaly |
| SST | sea surface temperature |
| TABS | Texas Automated Buoy System |
| TLP | tension leg platform |
| TLWP | tension leg work platform |
| TSM | total suspended matter |
| UNAM | Universidad Nacional Autonomia de Mexico |
| USFWS | U.S. Fish and Wildlife Service |
| VLH | volatile liquid hydrocarbons |
| VOC | volatile organic compounds |
| VPR | video plankton recorder |
| WDV | wet displacement volume |
| XBT | expendable bathythermograph |
| XCP | expendable current profiler |
| XCTD | expendable current-temperature-depth |

# Chapter 1: Introduction

## Background

Recent years have seen a great increase in oil and gas industry interest in the deepwater Gulf of Mexico. Contributing factors have included significant hydrocarbon discoveries, passage of the Deepwater Royalty Relief Act, the availability of infrastructure, and the emergence of innovative technologies to find, develop, and produce oil and gas in the deepwater environment (Cranswick and Regg 1997). This deepwater development poses a number of environmental, socioeconomic, and technological issues. Some are new, and others are similar to those associated with oil and gas activities on the shelf. However, as Carney (1998) noted, "deepwater oil and gas development is a reality at the same time that deepwater environmental research is at a low."

The Minerals Management Service (MMS) is the primary Federal agency responsible for ensuring that oil and gas related activities on the Outer Continental Shelf (OCS) are conducted in a safe and clean manner. The MMS has a strong environmental mandate and conducts an Environmental Studies Program to obtain information for regulatory and leasing decisions (MMS 1999). As part of that program, an MMS-sponsored "Workshop on Environmental Issues Surrounding Deepwater Oil and Gas Development" was held in 1997. Workshop participants identified synthesis of existing environmental and socioeconomic data as an important priority (Carney 1998).

This synthesis report addresses the need for a comprehensive search and integration of environmental and socioeconomic data for the deepwater Gulf of Mexico. As such, it is one of several ongoing and planned MMS studies pertinent to deepwater oil and gas activities. These include two other "desktop" studies—a reanalysis and synthesis of deepwater physical oceanographic data and a literature review of environmental risks of chemical products used in deepwater operations—as well as new field studies of the continental slope benthos, synthetic drilling fluids, and benthic effects at selected continental slope sites.

## Objectives

The general purpose of this program was to gather environmental and socioeconomic information related to the deepwater environment, in order to

- describe the ecosystem;
- understand the environmental processes that drive the system; and
- understand processes potentially sensitive to anthropogenic activities, particularly oil and gas operations.

For the purposes of this program, the deepwater environment is defined geographically as extending from a depth of 305 m (1,000 ft) to the border of the U.S. Exclusive Economic Zone (**Figure 1.1**). This includes the deepwater portion of all three Gulf of Mexico OCS planning areas (Western, Central, and Eastern).

Specific objectives were to develop (1) a synthesis report that summarizes available information by topic and synthesizes it in a framework to describe the deepwater Gulf ecosystem, dominant environmental processes, biologically sensitive pathways, and socioeconomic activities in the area; and (2) a computer-searchable database (annotated bibliography) incorporating existing literature, relevant data, and ongoing research pertaining to geological, physical, chemical, and biological processes of the study area, social and economic data and literature, and deepwater technology.

## Methods

The synthesis effort was organized by discipline, with specialists in each discipline serving as chapter authors. Computer searches were conducted using the DIALOG information retrieval system to identify published literature, unpublished reports, data sets, and ongoing or planned studies. Chapter authors helped to select databases and keywords for the searches. Preliminary bibliographies were circulated to the authors, each of whom was familiar with the literature in their respective area of expertise. Additional references were provided by the chapter authors to complete the bibliographic listing. Subsequently, annotations were downloaded using DIALOG and imported into Pro-Cite, a bibliographic computer program. Further details on the annotated bibliography are provided in Volume II.

After the completion of the computer searches, a synthesis planning meeting was held during April 1999. Chapter authors presented preliminary overviews of their respective topic areas, and discussed approaches for producing the synthesis report.

## Report Organization

The report is divided into chapters for the following topic areas:

- 2-Deepwater Technology
- 3-Geology
- 4-Physical Oceanography
- 5-Chemical Oceanography
- 6-Water Column Biology
- 7-Non-Seep Benthos
- 8-Seep Communities
- 9-Protected Species
- 10-Fishes and Fisheries
- 11-Socioeconomics

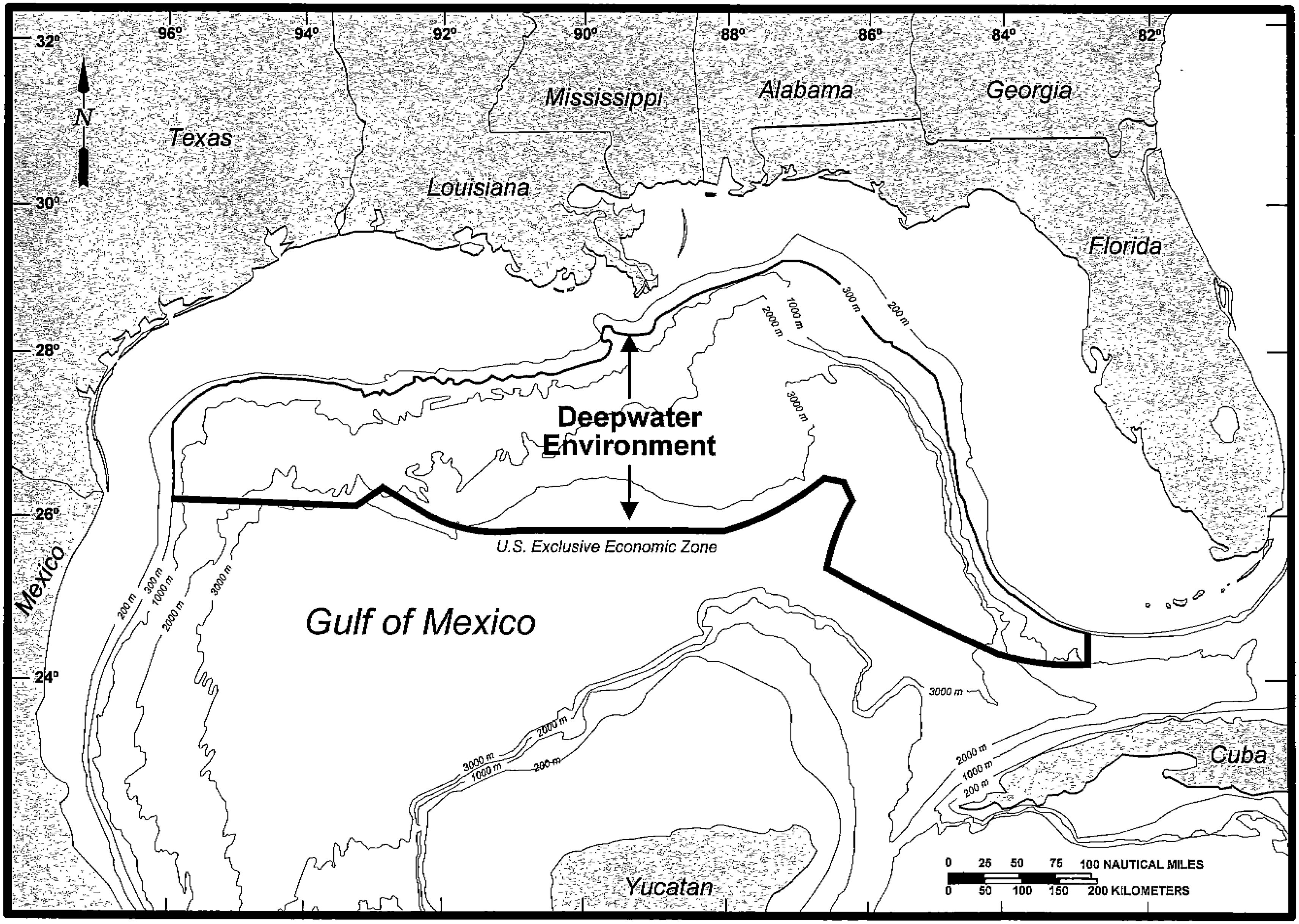

Figure 1.1. Deepwater study area.

A final Synthesis Chapter draws together information from preceding chapters to identify significant findings, key issues associated with oil and gas related activities in the deepwater environment, and critical information needs.

A table of contents is provided at the beginning of each chapter to orient the reader. References cited in each chapter are listed at the end of that chapter. The Annotated Bibliography, provided as a separate Volume II, includes both references cited in the report and other relevant citations.

## Literature Cited

Carney, R.S. 1998. Workshop on environmental issues surrounding deepwater oil and gas development: Final report. OCS Study MMS 98-0022. U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. 163 pp.

Cranswick, D. and J. Regg. 1997. Deepwater in the Gulf of Mexico: America's new frontier. OCS Study MMS 97-0004. U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. 43 pp.

Minerals Management Service. 1999. Environmental Studies Program website. http://www.mms.gov/eppd/studies/index.htm.

# Chapter 2: Deepwater Technology

*E.G. Ward*

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## Introduction

In many respects, offshore oil and gas production has its roots in the Gulf of Mexico. Oil and gas production in the Gulf of Mexico started in 1947 in about 5 m water depth. Much of the technology and experience developed for the Gulf established standards and practices for subsequent offshore oil and gas developments throughout the world.

### Shallow Water Production from Fixed Platforms

The first offshore platform was installed in the Gulf in 1947 in about 5 m of water. There has been a steady march toward ever-increasing depths since that time. In the 1960's, depths had just exceeded 100 m. In 1978, the Cognac platform was installed in 300 m. The Bullwinkle platform was installed in 413 m of water in 1989, and is the deepest fixed platform. During this 40-year span, some 7,000 platforms have been installed and have served the industry and public well in providing a reliable and economical means of developing and producing oil and gas. About 4,000 platforms are currently in place and producing.

Exploratory drilling precedes the installation of a production platform. Mobile Offshore Drilling Units (MODUs) are used to drill exploratory wells. Following a discovery of hydrocarbons, one or more delineation wells may be drilled to confirm the commercial significance of the discovery. A production platform is installed once a discovery is judged to be commercially viable.

The function of these platforms is to provide a workspace that can be used to support the development drilling of production wells and production equipment. A drilling rig on the platform is used to drill and complete the production wells. The well system and drilling operations are functionally similar to that used onshore. A number of wells are drilled from each platform. Flow rates for wells completed in reservoirs typical of shallow water locations have typically been in the range of up to 2,500 barrels of oil per day (BOPD).

The production equipment separates the produced oil, gas, and water, and the oil and gas are transported to shore through separate pipelines laid on the seafloor. Onboard pumps and compressors provide the necessary energy to transport the oil and gas to shore. The produced water is passed through an oil-water separator and discharged into the ocean.

These bottom-founded platforms are fixed to the seafloor by a foundation consisting of pilings driven deep into the ocean floor. The decks upon which the equipment is placed are located at an elevation high enough above sea level to avoid being inundated by severe waves. The strength of the platform and its pile foundation are designed to resist the lateral forces and overturning moments caused by severe hurricane waves, currents, and winds. These platforms tend to be quite stiff and the response to loads is mostly static.

## Deepwater Production to Date

As reservoirs have been discovered and produced in shallower waters, the search for new hydrocarbon reserves has turned to ever-increasing depths. For the purposes of this report, we will adopt a depth of 305 m (~1,000 ft) as the delineation between "deep" and "shallow" water. Lease sales in the 1980's began to focus on deepwater acreage, and exploration drilling soon followed. Discoveries were made, but development activities lagged a bit due to the downturn in oil prices in the mid-1980's and the time to develop and implement the technology needed to produce oil and gas in water depths of several thousand feet.

Deepwater discoveries and production have increased very rapidly during the 1990's as shown in the following **Figure 2.1**. Production statistics are shown for 1994–1998 (Congdon and Fagot 1999). The production rate shown for 1999 is an extrapolation, but agrees with an earlier estimate (Morrison 1997). The estimated 1999 production represents a five-fold increase in 5 years.

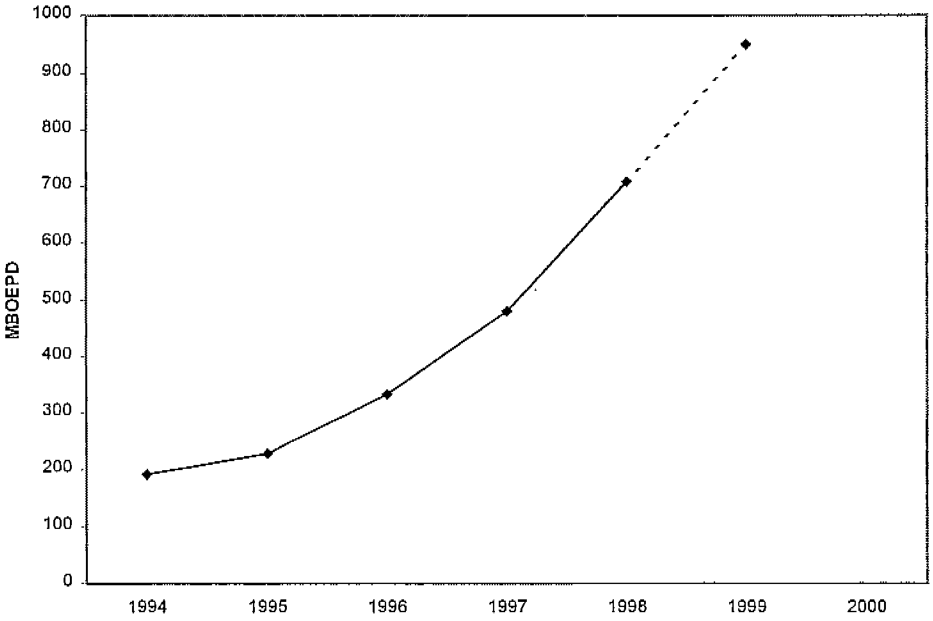

Figure 2.1. Deepwater production in the Gulf of Mexico (thousands of barrels oil equivalent per day, MBOEPD).

## Deepwater Development Activities to Date

Deepwater oil and gas development has evolved and built upon the technology and operational experience that have been successfully employed in shallower waters in the Gulf of Mexico. Production systems have now been installed in water depths approaching 1,500 m. Lessons learned include the following:

- Large, productive reservoirs exist in the Gulf. A well at Ursa recently produced over 50,000 BOPD (Smith 1999). Such daily production rates in the Gulf were unheard of a few years ago and are due to the characteristics of deepwater reservoirs and large advances in well technology. The largest estimated reserves are 1,000 million barrels oil equivalent (MMBOE) for a prospect named Crazy Horse in about 1,800 m depth (DeLuca 1999b).
- The industry has proved that it can develop reserves in a safe, environmentally sound, and an economic manner in depths approaching 1,800 m.

In the following section, we will discuss the technology involved in these developments and its implementation.

### Deepwater Production Systems

A number of different systems have been developed for deepwater production. These include bottom-founded structures (fixed platforms and compliant towers), floating systems (tension leg platforms [TLPs], spars, semisubmersibles), and subsea systems. These systems are shown in **Figure 2.2** (Cranswick and Regg 1997). The systems installed on specific projects and the water depths are listed in **Table 2.1** (Cranswick and Regg 1997; Offshore Magazine, various articles 1997–1999).

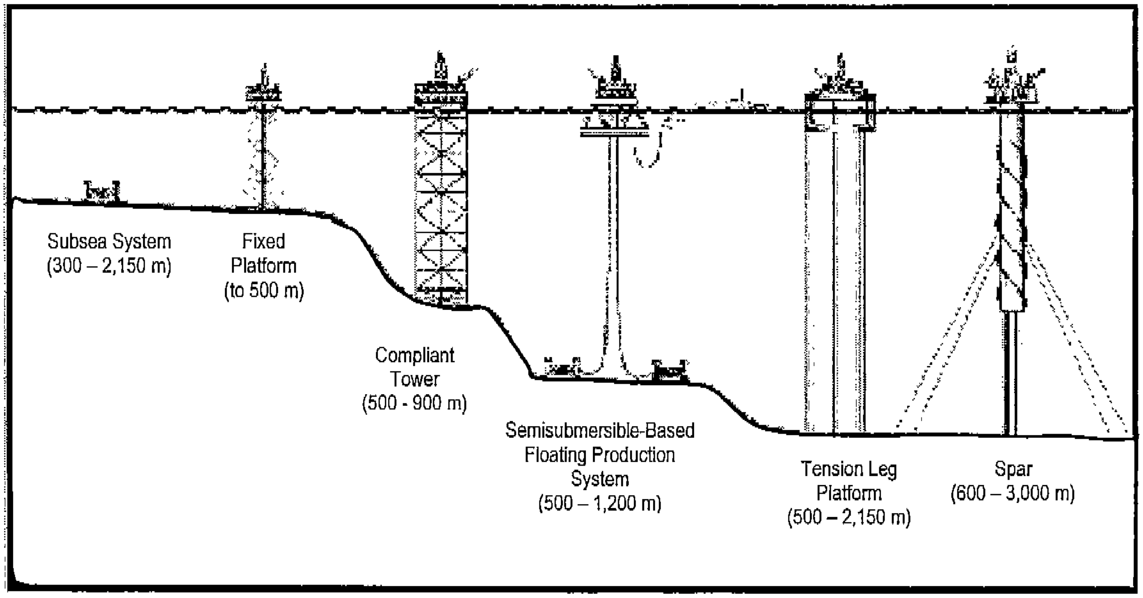

Figure 2.2. Deepwater production systems in the Gulf of Mexico.

Table 2.1. Production systems for current deepwater projects in the Gulf of Mexico

| Project | Water Depth (m) | Production System Type | First Production |
|---|---|---|---|
| Baldpate | 611 | Compliant Tower | 1998 |
| Petronius | 536 | Compliant Tower | 2000 |
| Amberjack | 315 | Fixed platform | 1991 |
| Bullwinkle | 414 | Fixed platform | 1989 |
| Cognac | 313 | Fixed platform | 1979 |
| Pompano I | 394 | Fixed platform | 1994 |
| Lena | 311 | Guyed Tower | 1983 |
| Cooper | 670 | Semisubmersible | 1995 |
| Genesis | 794 | Spar | 1999 |
| Hoover | 1,468 | Spar (w/Diana) | 2000 |
| King | 1,005 | Subsea | 2000 |
| Oyster | 367 | Subsea | 1997 |
| Shasta | 318 | Subsea | 1995 |
| Tahoe | 459 | Subsea | 1994 |
| Tahoe II | 459 | Subsea | 1996 |
| VK 862 | 319 | Subsea | 1995 |
| Zinc | 452 | Subsea | 1993 |
| Popeye | 612 | Subsea (shelf) | 1996 |
| Macaroni | 1,101 | Subsea (Auger) | 1999 |
| Angus | 612 | Subsea (Bullwinkle) | 1999 |
| Rocky | 546 | Subsea (Bullwinkle) | 1997 |
| Troika | 832 | Subsea (Bullwinkle) | 1998 |
| Diana | 1,346 | Subsea (Hoover) | 2000 |
| Europa | 1,189 | Subsea (Mars) | 2000 |
| Pompano II | 570 | Subsea (Pompano I) | 1995 |
| Mensa | 1,644 | Subsea (shelf) | 1997 |
| Auger | 875 | TLP | 1994 |
| Brutus | 880 | TLP | 2001 |
| Jolliet | 526 | TLP | 1989 |
| Marlin | 990 | TLP | 1999 |
| Mars | 899 | TLP | 1996 |
| Ram-Powell | 995 | TLP | 1997 |
| Ursa | 1,230 | TLP | 1999 |
| Allegheny | 974 | TLP (Seastar) | 1999 |
| Morpeth | 498 | TLP (Seastar) | 1998 |

Fixed platforms have been installed in depths to 413 m. While it is technically feasible to extend the fixed platform concept to the 500 to 750 m water depth range, the large capital costs for these platforms result in projects that are not economically feasible. The compliant tower, another bottom-founded structure that has some similarities to a fixed platform, has also been developed and implemented. Compliant towers can be a cost effective alternative in water depths in the range of 500 to 750 m. However, the number of applications appears to be limited by the limited acreage in the Gulf in this water depth range. Because of these water depth limitations, the major emphases have been on various floating production systems and subsea production systems. Floating production systems and subsea systems have ushered in the development of deepwater production in the Gulf. Floating production systems in the Gulf include TLPs, spars, and semisubmersibles. These systems provided the flexibility of being cost effective over the range of water depths being developed in the 1990's, and can be extended to even deeper water. We will next review the deepwater technology that has been developed and implemented to date.

## Floating Production Systems

### General Attributes of Floating Systems

Floating production systems generally have a number of functionally similar components or elements. Major components include the hull, deck, topside equipment, well system, mooring system, and transportation system for the produced oil and gas. These are described below to provide a context for understanding, comparing, and contrasting the specific systems.

*Hull and Deck.* The hull provides the necessary buoyancy to support deck, topsides, mooring system, and well risers. The deck (actually several stacked or multilevel decks) sits atop the hull and supports the topsides, drilling equipment (if any), and personnel quarters.

*Topsides.* The topsides includes production facilities and equipment to separate produced oil, gas, and water; water treatment facilities to clean the produced water so that it can be discharged overboard; and control and safety systems to monitor, control, and meter production. The topsides also include power generation equipment and the pumping and compression equipment needed to send the production to shore. The topsides may also include drilling equipment. For floating production systems without drilling equipment, wells are pre-drilled by MODUs, and MODUs are required to return for well maintenance and recompletions. Such wells are completed as subsea wells that are tied back to the floating production system by flowlines and risers.

*Well Systems.* There are two types of well systems used on floating production systems—surface wells and subsea wells. Surface well systems have a dry wellhead and tree that is located on the deck of the floating system. A vertical rigid production riser connects the surface wellhead and tree to the well at the seafloor. Relative movement between the riser and the floating production system is accommodated by a riser tensioning system that provides a constant top tension through either mechanical means or buoyancy. Surface well systems on floating production systems are a direct extension of the well systems used on platforms, with the main difference being the complexity and dynamic response of the riser. Surface well systems are limited to floating systems with little vertical motion and thus little relative motion between the floater and the bottom-fixed riser. Advantages of surface well systems include the relative ease of drilling, maintaining, and servicing wells from a drilling or workover rig on the floating production system, simpler well monitoring and control equipment, and the ability to receive the produced oil and gas directly onboard for immediate processing without the produced fluids having to flow unprocessed through a flowline.

Subsea wells have a wet wellhead and tree that is located on the seafloor. The wells are offset from the floating production system typically by at least several miles. A subsea well is connected back to the floating production system by seafloor flowlines and a compliant flexible production riser. The relative motion between the fixed subsea well and the floating production system can be accommodated by the flexibility that is provided by the riser length and shape (e.g., catenary or lazy wave) and/or the riser material. No riser tensioning system is used. The inherent flexibility of such riser systems allows subsea wells to be used on floating production systems with significant vertical motion. Subsea wells have to be drilled, maintained, and serviced by a MODU. This decouples the drilling and well servicing equipment and operations from the floating production system. This can result in simpler floating production system and less impact of simultaneous drilling and production operations. Also, the wells can be spread out and distributed to penetrate the reservoir where needed resulting in simpler, shorter, more direct wells which are cheaper to drill. (Compare this to having to drill deviated wells from a common surface location that have to include significant horizontal segments to reach different parts of the reservoir.)

A major challenge is ensuring continuous flow of unprocessed oil and gas from subsea wells through the flowlines on the seafloor. These flowlines lie on the seafloor and are thus subjected to the cold temperatures at the ocean bottom. The produced oil and gas are cooled as they flow through the flowlines. Paraffin and asphaltene compounds in produced oil and hydrates in produced gas, which are normally in solution at reservoir temperatures and pressures, can be deposited as they cool and eventually plug the flowlines. Once they are plugged, it can be very difficult and costly to clean out the flowlines and reestablish production. Several techniques are used to assure flow. Flow assurance measures include the injection of chemicals at the well head to inhibit the formation of paraffin, asphaltene, or hydrate plugs; insulated flowlines to maintain a higher temperature; and periodic cleaning by pumping mechanical devices through the flowlines. These flow assurance measures add significant capital and operational costs to the subsea wells, often negating savings due to other advantages. Other disadvantages include more complex well monitoring and control equipment, and the need for an umbilical to provide power, control, and chemicals to the subsea wells.

*Mooring Systems.* Mooring systems connect the floating production system to piled foundation systems or anchors on the seafloor. The mooring system provides the lateral restoring forces to resist the horizontal wave, wind, and current forces trying to offset the floating production system. The significant offset motions are due to wind, current, and wave drift, and generally have periods of several minutes. Mooring systems are generally designed to restrict the lateral offset of the floating production system to about 10% of the water depth, e.g. about 30 m in 300 m of water. Both top-tensioned risers and catenary risers can be designed to accommodate such motions. The mooring system can be a tendon system, a catenary mooring system, or a taut mooring system.

A tendon system utilizes a number of vertical tendon members. Several tendons are attached to each corner of the system and are affixed to pile foundations at the seafloor. The tendons are made of heavy pipe. The tendons are installed in a manner that leaves them under a very large pre-tension. As the production system is offset, a restoring force is developed due to the horizontal component of the tendon tensions. (The effect is like an inverted pendulum.) The seafloor footprint generated by this mooring system is small—no larger than the structure itself. However, the vertical load on the structure due to the pretension and the weight of the tendons is quite large and increases the buoyancy requirements for the floating system.

A catenary mooring system uses a number of legs made up of steel wires and chain segments. Several legs are attached to each corner of the system in a symmetrical pattern. Each leg is made up of a segment wire line, which is attached to the floating production system, and a heavy chain segment lies along the bottom and attached to an anchor of pile at its end. The length of each leg is on the order of 1.5 or more times the water depth, and drapes down from the floating system in a catenary shape to a point near the chain touch down point, and then lies on the seafloor and stretches to the end attached to the anchor or the pile. As the production system is offset, a portion of the chain is pulled off of the bottom and its hanging weight increases the tension in the upstream legs and thus provides a restoring force. This is a relatively simple mooring system that has been used for decades on semisubmersible MODUs. Disadvantages include the weight of the mooring system and the congestion on the seafloor caused by the large horizontal footprint of the mooring system.

### Tension Leg Platforms

TLPs are the dominant deepwater floating production system in the Gulf to date. Six TLPs have been installed in depths ranging from 525 to 1,230 m (Chianis and Poll 1997). The hulls have four columns (up to 26 m diameter) that are connected by pontoons (**Figure 2.3**). The first TLP in the Gulf, Jolliet, was a small TLP with no onboard drilling capability and a modest production facility. Auger (Bourgeois 1995) and subsequent TLPs have been much larger and include drilling and extensive production facilities. The decks are large (up to 90 m square) and can support extensive topside facilities (Zimmer et al. 1999). The large size of the decks provides flexibility, and the facilities on some TLPs have been expanded or modified to increase the production capacity (Judd and Wallace 1996). The largest capacity facility is on Ursa and is rated at 150 thousand barrels of oil per day (MBOPD) and 400 million standard cubic feet of gas per day (MMSCFPD) (Jefferis et al. 1999; Smith et al. 1999).

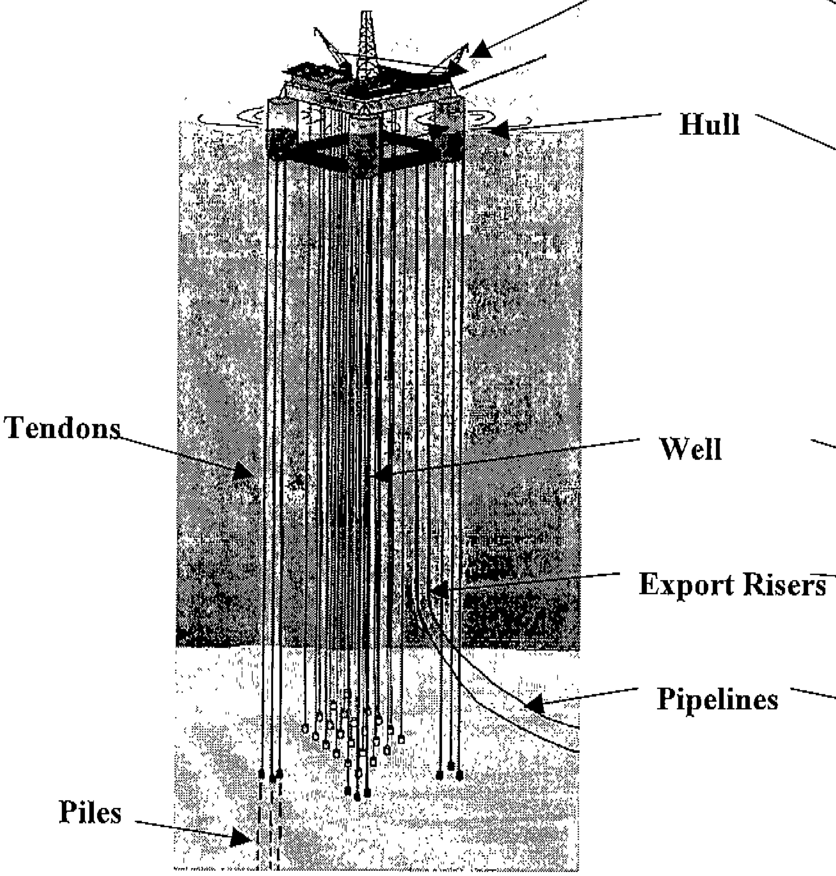

Figure 2.3. Schematic showing major components of a TLP.

Figure 2.4. Schematic showing major components of a spar.

The mooring system is made up of three or four tendons attached to each corner. The tendons are made of large, high strength, thick-walled pipe that is about 1 m in diameter and 25 mm thick. These are connected to foundation elements that are affixed to the seafloor by long piles driven into the seabed. These TLPs have little vertical motion due to the low natural frequencies of vertical motions resulting from the high tendon tensions. The high tension is produced by excess buoyancy designed into the hull. The small vertical motions facilitate the use of surface well systems with top-tensioned risers.

TLPs in the Gulf to date have utilized a surface well system. All TLPs except for Jolliet are equipped with an onboard drilling rig for drilling and servicing production wells. Subsea wells located at some kilometers away have been tied back to TLPs (DeLuca 1999a).

Two mini-TLPs of the Seastar design been installed in depths of 500 and 975 m (Kibbee 1996; Kibbee et al. 1999; Furlow 1999a). These smaller systems are designed to produce smaller fields than would be economically feasible with larger and more costly TLPs. These mini-TLPs receive production from a few nearby subsea wells that were drilled by MODUs. These mini-TLPs support full, but small, production processing facilities.

The hull on these mini-TLPs is a shallow draft column. The mooring system has tendons that are attached to a cruciform structure at the bottom of the hull. These mini-TLPs have the attractive motion characteristics of the larger TLPs, which facilitates the use of catenary risers for both the production risers from the wells and the export risers.

### Spars

Two spars have been recently installed in the Gulf of Mexico (Meyer et al. 1998; Krieger et al. 1999), and a third is being installed in late 1999–early 2,000 (Furlow 1999c). Depths range from 590 to 1,468 m. The spar hulls are a large diameter, deep-draft column (**Figure 2.4**), with diameters ranging up to about 40 m and lengths of 215 m. The deep draft naturally provides small vertical motion so that surface well systems can be used. Deck sizes range up to about 90 m square. The Hoover-Diana spar has the largest topside facilities and can process 100 MBOPD and 325 MMSCFPD.

Surface well systems are used on the larger spars, Genesis and Hoover-Diana, which also have onboard drilling capability. The hulls have a central opening or moon pool through which the production risers pass. Subsea wells can also be tied back to the spars (Meyer et al. 1998).

The mooring systems are a multi-leg catenary system. Each of the legs is made up of wire rope and chain segments, which are affixed to the seafloor with driven piles or suction caissons. The length of each mooring leg is typically about 1.5 times the water depth.

### Semisubmersible-Based Floating Production Systems

One semisubmersible-based floating production system is currently active in the Gulf. Another was installed, but removed when the project was abandoned due to poor reservoir performance. Semisubmersibles have a long and successful history as successful drilling rigs for exploratory drilling, and new rigs have been recently built that can drill in depths over 3,000 m (DeLuca 1999d). Semisubmersible-based floating production systems were thought to be an attractive option for deepwater a few years ago. Particularly, the conversion of an existing semisubmersible drilling rig to a floating production system was seen to have the advantages of building on proven technology and saving time and money. However, the demand for drilling rigs increased with the need to explore all the newly leased acreage, and the availability of used, capable rigs that could be purchased and converted at a reasonable costs diminished drastically. Further, semisubmersibles have larger vertical motions in storms. This is not a problem during exploratory drilling since the drilling riser can be disconnected and the well can be temporarily abandoned for a storm. However, production and export catenary risers must remain attached during storms, and the large vertical motions create significant technical and costly design challenges (Hays 1996). Thus, other production systems have been favored to date.

## Subsea Production Systems

A Subsea Production System is simply one or more subsea wells and related equipment that produce oil and/or gas to a host facility. Subsea well systems have been discussed previously in the Well Systems section since any Floating Production System can host one or more subsea wells. Other equipment in a Subsea Production System can include a subsea manifold, a template, jumpers, flowlines and production risers, umbilical, and pipelines (Kirkland et al. 1996). The complexity and amount of equipment is determined proportional to the number of wells in the system. Wells may be individually tied back to a host, or several wells may be connected to a manifold by short jumper lines, with the manifold being connected by a flowline to the host.

Technology is not presently available for subsea processing of oil and gas produced from subsea wells. Thus, the oil and gas must flow unprocessed through the flowlines to the manifold and the host. As discussed previously, waxes in oils and hydrates in gas can cause flow restrictions or complete plugging of flowlines and pipelines. Wax and hydrate inhibitors are pumped from the host through umbilical lines and injected into the flowlines at the wells or manifold. The umbilical lines also provide power and control functions from the host to the wells and manifold.

There are many variations in the way the components can be configured for specific project needs (Beckmann et al. 1996; Prichard et al. 1996; Mason and Upchurch 1996; McLaughlin and Alford 1996). **Figure 2.5** shows a schematic for a subsea system with three wells and a manifold that is connected to a fixed platform host. **Figure 2.6** shows an artist's rendition of the components of a two well system with a manifold. The equipment is large: wellheads and trees can be 5 m high, and a manifold can be 10 m high. Sometimes the equipment and wellheads for a subsea system are integrated into a single template structure placed on the seafloor. The deepest subsea system in the Gulf is Mensa in 1,644 m of water (McLaughlin 1998).

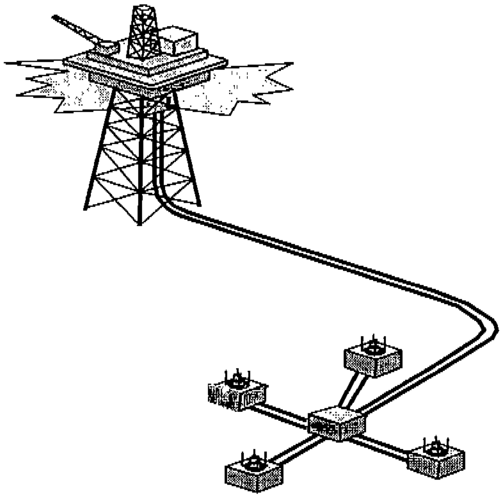

Figure 2.5. Subsea production system configuration.

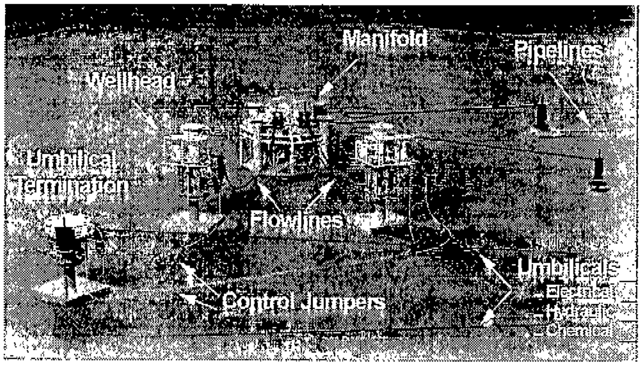

Figure 2.6. Subsea production system components.

## Transportation Systems

Processed oil and gas are transported from the floating production systems to shore in separate pipelines. The pipeline transportation system for deepwater production is functionally very similar to that which had been developed and used for production from shallow water platforms for decades. The pipelines either go directly to shore and connect to other pipelines there, or go to a shallow water platform that is connected to the existing pipeline infrastructure that goes to shore. The oil and gas is processed sufficiently to be of sales quality as it leaves the floating production system and is commingled in the existing pipeline infrastructure. Pumps and compressors add energy to the oil and gas, respectively, to ensure that it will flow to its destination or to the next pumping or compression station. Chemicals to inhibit corrosion and to improve the flow properties may be added as the production leaves the platform. The capability to pump "pigs" through the pipelines to mechanically scrape and clean the pipe interior is provided.

However, the sizes and lengths of deepwater pipelines and the seafloor terrain upon which they rest have created technical and economic challenges. In deepwater, the sizes of the equipment and pipelines tend to be larger to handle the high production rates from deepwater production systems, and thicker walled pipe is necessary to resist the higher water pressures and operating pressures. Thus, the pipelines have become very heavy, and different installation methods, such as J-lay and significant changes to the S-lay system originally developed for shallow water, had to be developed. These heavy and thick-walled pipes can buckle easily during installation as the pipe is laid on the seafloor, and the laying process has to be carefully controlled. The thick-walled pipe also has required the development of new welding techniques. The seafloor terrain in deepwater is much rougher than relatively smooth, uniform, and gradually sloping seafloor characteristic of the shelf. Hills, valleys, and ridges along with areas with relatively soft, unstable bottoms and other areas with hard bottoms characterize the topography. The features can cause instabilities and movement in installed pipelines. Pipeline routes must be selected to avoid such areas, and the pipelaying process must be carefully controlled to ensure that the pipeline avoids the features. Deepwater pipelines have been successfully installed to water depths of about 1,800 m in the Gulf.

Deepwater pipelines are very expensive, and have been estimated to cost more than $1 million per mile (DeLuca 1999d). Thus, pipeline costs can be a significant factor in the overall cost of a deepwater development, particularly when the development is a long way from the existing infrastructure of pipelines.

## Future Deepwater Development Activities

### Future Deepwater Production

Referring back to **Figure 2.1**, deepwater production during 2000 should easily exceed 1 million barrels per day (MMBOEPD). If the linear trend continues, production could increase six times the 1994 value, a six-fold increase in just 6 years.

Lease acquisitions, exploration drilling, and discoveries all suggest a continuing strong increase in deepwater production from ever-increasing water depths (Ray 1998). The Minerals Management Service (MMS) has estimated that total Gulf oil production in 2002 could reach about 2,000 MBOPD and that roughly 70% would of the total oil and gas production would be from deepwater. Deepwater leasing has been strong since 1994 and set record highs in 1997. Deepwater drilling has been active in 1999 and there have been 12 new deepwater discoveries in the Gulf as of September (DeLuca 1999b). Further, there are 26 new deepwater drilling rigs expected to be delivered by the end of 2000, and 10 of these will begin in the Gulf (DeLuca 1999c).

Estimates of the potential volumes of recoverable deepwater reserves range from 8 to 15 billion barrels of oil (Morrison 1997). The MMS's most recent (1995) forecast of Gulf of Mexico deepwater oil and gas potential was about 13 billion BOE (Bacigalupi et al. 1995). As noted at a recent MMS Information Transfer Meeting (Oyne, December 1999), 370 deepwater wells have been drilled since 1995, with a number of significant discoveries. The MMS announced the initiation of a new study to revise the estimated potential in light of recent activities and experience, and it is expected that the estimated potential will increase substantially. (Note that the estimated potential includes no reserves from the relatively untested MMS Eastern Planning Area in the northeastern Gulf).

The above indicates that the deepwater Gulf of Mexico will continue to be an important oil and gas area. The ever-increasing water depths and the increasing distance from infrastructure will continue to provide both technical and economic challenges. We next examine some of the expected impacts on deepwater production systems.

### Floating Production Structures

#### Spars

Spars have been studied for applications to deeper depths, and compared to TLPs (Huang et al. 1999). Although the number of applications and experience is limited as of this date, spars appear to be quite flexible and show a low cost sensitivity to increases in water depth. Spars are significantly more cost effective than large TLPs at depths beyond 2,000 m, and thus are presently the favored concept for a production system with surface wells for deeper water projects. The applications of a taut mooring system using lightweight synthetic (for example, polyester) rope and/or the use of a truss spar may further reduce the cost and increase the effectiveness of spars.

### Tension Leg Platforms (TLPs)

Large TLPs can be extended beyond the present deepest depth of 1,230 m. It is theoretically possible to extend them to 3,000 m with the present tendon systems, but spars are likely more cost effective in depths beyond 2,000 m (Huang et al. 1999). To maintain the small vertical motions that are a major TLP advantage, the tendon area and weight must increase as depth increases to maintain a high vertical stiffness. The tendon wall thickness must also increase to resist collapse in deeper water. Increases in the weight of the conventional tendon system require a larger TLP hull to provide the additional buoyancy, and the hull and tendon weights (and the TLP costs) increase rapidly beyond 2,000 m. Several ideas for having lighter tendons (stepped diameter steel tendons, composite tendons) for deepwater TLPs are being studied (*Offshore Engineer* 1999; Chianis and Poll 1997) and have the potential to significantly increase the depth at which TLPs are cost effective choices.

The median discovery volume is about 100 MMBOE for the deepwater Gulf (Ray 1998). Smaller reservoirs in about 1,000 m depth cannot be economically developed with large TLPs, and the economics get worse with increasing depths. Several mini-TLP concepts are being pursued to provide cost effective TLPs for these smaller reservoir volumes. The Seastar concept has already been deployed in depths to 1,000 m, and the concept is being studied for projects in depths to 1,850 m (Matten et al. 1999; Furlow 1999a). Mini-TLPs with three columns have been studied (Huang et al. 1999).

### Floating Production Systems with Storage and Offloading (FPSO)

As the push to deeper water leases continues, new discoveries will be made that are farther and farther from the existing pipeline infrastructure. With deepwater pipelines costing $1 million per mile (DeLuca 1999d), transportation costs for the produced oil and gas can have a significant negative impact on project economics and may prevent certain discoveries from being developed. Oil can be produced to an FPSO, stored, and then offloaded onto a shuttle and shipped to shore. This transportation option can save the cost of expensive deepwater oil pipelines. Thus, the FPSO can be an attractive deepwater production system option for the Gulf (D'Souza 1999a,b).

FPSOs are often a ship-shaped vessel, but other large volume hulls that can accommodate large storage tanks, e.g., a spar, could be used. Tankers are most commonly used because of their large tanks, and tanker-based FPSOs can be either a conversion of a trading tanker or purpose built. A large turret is built into the tanker, and the ship can rotate relative to the tanker. The mooring system is attached to this geostationary turret. The tanker is free to rotate around the turret, and weathervanes with the prevailing wind, waves, and currents. The tanker-based FPSO cannot accommodate a drilling rig. A MODU is used to drill subsea wells that are tied back to the FPSO through flowlines with compliant risers, which are attached to the geostationary turret. The turret includes provisions for containing the flow from the risers to the tanker. Associated gas produced with the oil must be separated and either transported to shore by a gas pipeline, or reinjected. The export riser for a gas pipeline would be also attached to the turret. **Figure 2.7** shows a schematic of a tanker-based FPSO.

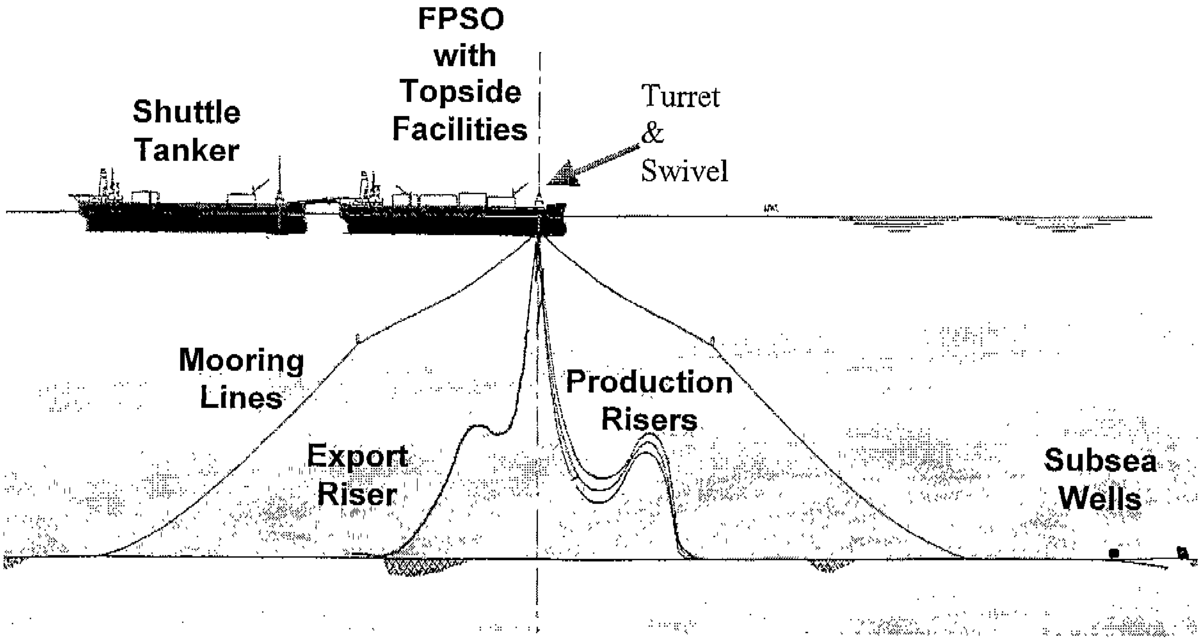

Figure 2.7. Schematic of tanker-based FPSO offloading to a shuttle tanker.

Today there are 66 FPSOs in service or under construction (McNeely et al. 1999). None have been permitted in the Gulf to date. The MMS is conducting a study to prepare an Environmental Impact Statement for the use of tanker-based FPSOs in the Gulf (George et al. 1999). The MMS is also sponsoring a comparative risk analysis that will compare the risks of an FPSO operating in the Gulf against the risks of other deepwater production systems currently operating in the Gulf (Gilbert and Ward 2000). Both studies should be completed in late 2000, and will be used by the MMS in their decisions to permit FPSOs in the Gulf (Furlow 1999d).

## Subsea Production Systems

Subsea production systems will continue to be pursued as a means of lowering the development costs for remote deepwater oil and gas fields through reducing or completely eliminating the need for a floating production system and increasing the recovery from subsea oil wells. The focus will be on subsea pressure boosting and flow assurance.

Subsea pumps add energy so that produced fluids from subsea wells can flow to a distant transportation infrastructure point, such as a shallow water platform or a floating production system for processing and/or further pressure boosting. They also reduce the backpressure on wells so that more oil can be produced from the reservoir as it is being depleted and its pressure drops. Various solutions and systems are being developed. Subsea multiphase pumps can pump a mixture of oil, gas, and produced water (Chiesa et al. 1998). The produced fluids can also be separated using subsea separators prior to the pipeline (Radicioni et al. 1998). Gas can be separated from the produced liquids (oil and water), and the oil can be subsequently separated from the water. The oil can be pumped into a pipeline using a single-phase pump, and the water can be reinjected into the formation by another pump (Bringedal et al. 1999). These various pieces of separators and pumps can be used as building blocks or components, and configured and integrated into systems that fit the particular reservoir and development requirements (Pourier and Alary 1998). Other system components include system and well controls, motors, and equipment to convert and control power, monitor well performance, and inject chemicals for flow assurance. The integrated systems become complex. Components and equipment has been prototyped and tested, and there have been limited pilot trials and actual applications of integrated systems.

Control functions, power, and any chemicals are provided through an umbilical that is connected to a host production system or transportation interface point. Umbilicals are complex and costly, and their cost and installation difficulty increases with depth.

System maintenance is done using Remotely Operated Vehicles (ROVs) deployed from surface vessels. MODUs are used to undertake well workovers and recompletions.

Flow assurance will continue to be an important consideration in the expanded use of subsea well and production systems. In addition to the continuing development of inhibitors, other techniques are being actively developed to prevent wax and hydrate formation in flowlines. Flowline heating (Bass and Langner 1998), pipe-in-pipe (Hoose et al. 1996), and insulated pipelines (Chin et al. 1999) are being developed and deployed as a means to prevent heat loss leading to wax and/or hydrate formation. Trenching pipelines into the seafloor is also being considered as an option for insulating deepwater pipelines (Lokay 1999).

Further experience and developments will increase both the economic and technical confidence and use of subsea wells and development systems in present water depths. Currently offsets (distance from subsea wells to surface host system) of 20 to 25 miles are considered to be "at the leading edge" (Furlow 1999b). Offsets will increase with experience and confidence. Additional development will also be needed as water depths increase.

### Transportation Systems

Oil and gas pipeline and flowline costs will continue to increase with increasing depth and distance from infrastructure. Additional developments will focus on the design, construction, and installation to reduce the costs of extrapolating current technology (Coutarel 1998; Heerema 1998; Bonnell et al. 1999; DeLuca 1999b).

As discussed above, FPSOs provide an alternative to oil pipelines. However, there is often a considerable amount of associated gas with oil production in the Gulf (Furlow 1999e). The present options for handling gas include reinjection in the reservoir and transporting to shore via a deepwater pipeline (Curole et al. 1997). As the opportunities for reinjecting gas are limited, most deepwater developments will include an expensive deepwater pipeline. An alternative is to process the gas onboard the FPSO and convert it to product that can be transported via a ship in a similar fashion as the use of shuttle tankers to transport oil. Several processes to convert gas to different liquid products are being investigated (Verghese 1998; Agee 1999; Grimmer 1999; Rodvelt et al. 1999). Though the fundamental idea is attractive and sound, the technical and economic challenges of successfully deploying these processes on an FPSO are formidable. In addition, liquefied natural gas (LNG) is being considered, but the gas volumes from a deepwater development system needed to justify the costs of the special cryogenic transportation vessels are quite large.

## Future Technology Challenges

Experience to date has indicated the oil industry can, with evolving technology, successfully develop deepwater production in the Gulf of Mexico in depths approaching 1,800 m in a safe, environmentally responsible, and economic manner. New technology will be needed to continue this success and overcome the technical and economic challenges of producing oil and gas in depths to 3,000 m. High rate, high ultimate recovery wells, reduced project cycle time, and reductions in capital costs are important to the economic success of deepwater developments, and will become even more critical as depths approach 3,000 m.

Many technical challenges have been discussed in the previous section. There are other technical challenges and needs that were not mentioned. Some of the more significant topics include drilling wells in areas prone to shallow water flows (Jefferis et al. 1999), deepwater risers and moorings (Kavanagh and O'Sullivan 1999; Ward et al. 1999), and geotechnical properties of the deep ocean bottom (Dutt et al. 1997). Research and development activities are underway, and future needs will continue to be addressed through projects conducted and/or sponsored by individual companies, through joint industry funded projects, and through broad industry sponsored programs such as DeepStar (Verret and Hays 1999) and the Offshore Technology Research Center (1988-1999a,b). Technology assessment and research and development in support of deepwater development and regulations are also being sponsored by the MMS through their Technology Assessment and Research Program.

The worldwide interest in developing deepwater oil and gas has also led other research activities overseas. These activities provide another source of ideas and technology for meeting deepwater challenges in the Gulf of Mexico.

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# Chapter 3: Geology

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## Basin History

The Gulf of Mexico is an Atlantic-type passive continental margin (Martin 1978). During the Late Triassic, rifting occurred between the North American plate and the African/South American and Eurasian plates. As the North American plate drifted away from the Africa/ South American and Eurasian plates, the Gulf of Mexico basin was born in the stretched zone. Seawater flowed intermittently into the basin, depositing over 3 km of salt during the Late Middle Jurassic (Martin and Bouma 1978). During the Late Jurassic, carbonate deposition was dominant. During the Middle Cretaceous, slow subsidence of the carbonate shelves with little clastic input resulted in a reef system being built (Stuart City/Lower Cretaceous reef trend) that extended from southern Texas eastward to southern Louisiana to the shelf edge of Florida and to the eastern Campeche Escarpment. In the Late Cretaceous-Paleocene, due to a Laramide orogeny in the interior continent, detrital sediments started to flux into the northern and western Gulf of Mexico (Coleman et al. 1986). The Gulf of Mexico was inactive during the late Eocene; in the Oligocene, the southern Rockies underwent intensive volcanism; in the early Miocene, the normal faulting molded the relief we see today; during middle Miocene and Pliocene, the western U.S. underwent a series of broad uplifts (Winker 1982). During the Cenozoic, the total thickness of sediments was estimated to be over 15 km in the northwestern Gulf of Mexico (Martin and Bouma 1978). In the southern and eastern part of the Gulf of Mexico, carbonate deposition remained active since the Late Jurassic-Early Cretaceous, with only small amounts of detrital sediments being deposited in the Quaternary (Coleman et al. 1986).

## Study History

In the 19th century, geological work was conducted along the borders of the Gulf of Mexico. Early investigations were by individual scientists and later by geological survey institutions. Our basic understanding of the geology of the Gulf of Mexico was mainly attributed to the efforts of the petroleum industry. Before the 1920's, survey methods were limited to surface observations used to find oil and gas seeps, and torsion balance refraction seismograph to locate the shallow salt structures. In the 1930's, the invention of the reflection seismograph not only doubled the oil and gas discovery but also enabled us to examine the geology of the Gulf to greater depths and detail. The thousands of oil wells drilled helped reveal detailed stratigraphy of the areas in and around the basin. The first offshore exploration in the Gulf of Mexico started in 1938, and the first offshore seismic survey was conducted in 1944 (Salvador 1991). Since then, the study of Gulf of Mexico geology has varied from large-scale sediment studies in the northern Gulf of Mexico (e.g., Fisk et al. 1954; Fisk 1956; Moore and Scruton 1957; Shepard 1959; Scruton 1960), to salt tectonics and seismic stratigraphy (e.g., Ewing and John 1966; Lehner 1969; Bouma et al. 1978; Doyle et al. 1979; Bouma 1981), to sedimentology and mineralogy (e.g., Roberts et al. 1986) and the cause and results of erosion and turbidite deposition (e.g. Martin and Bouma 1982; Roberts et al. 1986), to sequence stratigraphy.

## Seafloor Morphology

**Figure 3.1** illustrates the physiography of the Northern Gulf of Mexico.

The Early Cretaceous carbonate areas that comprise the Florida Terrace and the Campeche Terrace, with dips less than 2° and 4°, respectively, are relatively flat. On the seaward side, these terraces are bound by the Florida Escarpment and the Campeche Escarpment. The two escarpments represent a depth difference of up to 2,300 m, cover a 40 km wide area, and display the steepest slope gradients (up to 40°) of the region. The West Florida upper continental slope, in water depths of about 500 m, contains a terrace that was composed of Miocene sediments (Coleman et al. 1986). A series of gullies and small canyons that crease the upper and middle slope are associated with mass movement processes that range from creep to massive slides to gravity-induced folds tens of kilometers long (Doyle and Holmes 1985). The northern part of the Campeche Escarpment also contains a series of gullies and small canyons, spaced about 5 km apart, that cut through the slope. At 27.3°N and 25.7°N, two 4,000 $km^2$ sized, dual-folded zones lie parallel to the Florida Escarpment. The Vernon Basin is located between these two fold zones.

At the northern end of the Florida Escarpment is the NNE-SSW aligned De Soto Canyon, which separates the carbonate-dominated Florida platform from the terrigenous-dominated environment to the west. West of the De Soto Canyon many NNW-SSE directioned canyons formed during the late Wisconsin sea-level lowstand. These canyons include Dorsey and Sounder Canyons. Except for a canyon due west of the De Soto Canyon, that cuts through the shelf break, all other canyons seem to originate at a water depth of 400 m or deeper and extend more than 60 km basinward. To the west

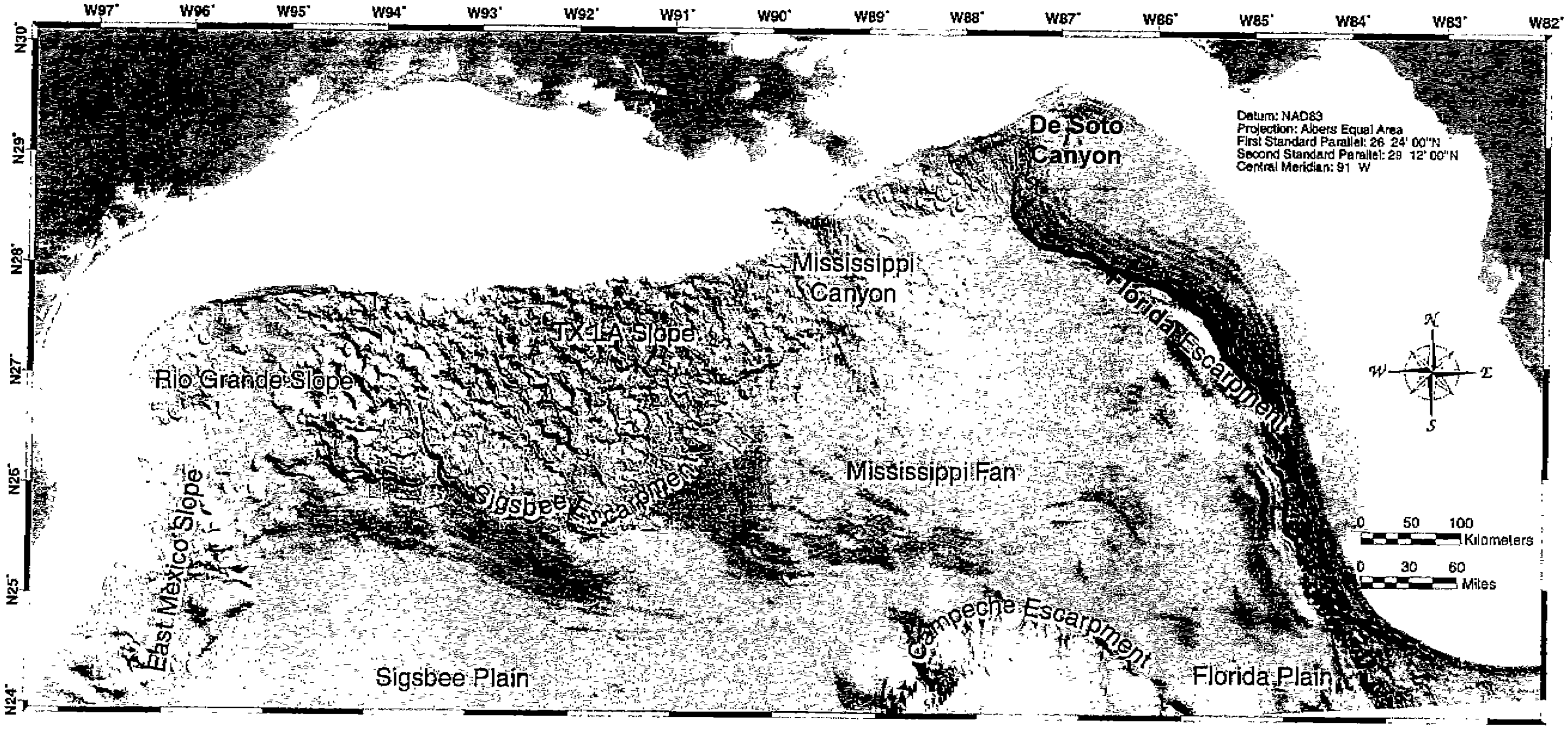

Figure 3.1. Bathymetric map of the northern Gulf of Mexico deepwater area. Water depths range from about 150 m in the north to about 3,700 m in the Sigsbee Plain. This bathymetry is a shaded relief based on multibeam and digitized seismic data. The simulated sun has an azimuth of 45° and an angle of 45°.

of these canyons are a series of pancake-shaped, 5 to 15 km wide salt domes, which become more scattered and smaller in size in a basinward direction. The first sub-salt well drilled in the Gulf of Mexico was by Exxon on one of the pancake domes called Mickey.

The largest submarine canyon in the Gulf of Mexico is the U-shaped Mississippi Canyon, which is a late Pleistocene erosional feature that cuts through the shelf break (Coleman et al. 1986). The canyon has a width of about 30 km. Approximately 120 km from the canyon mouth the Pleistocene Mississippi Fan appears. The canyon/fan complex extends for more than 500 km past the shelf edge onto the Sigsbee Abyssal Plain. The Mississippi Fan occupies an area of about 145,000 km$^2$.

The Mississippi fan is a large deep-sea fan consisting of a broad arcuate accumulation of predominantly Pliocene and Pleistocene sediments. The Mississippi Fan is flanked on the east by the West Florida carbonate platform and on the north and west by the Texas Louisiana Continental Slope. The deeper parts of the fan merge with the Florida Plain to the southeast and with the Sigsbee Plain to the southwest. Significant contributions to the fan have come from sources other than the Mississippi Embossment, particularly from the Campeche Escarpment, the Florida Escarpment, and the De Soto Canyon (Feeley et al. 1985). Feeley et al. (1985) suggest that eight seismic sequences comprise the Plio/Pleistocene section of the Mississippi Fan and these sequences are bounded by basin wide unconformities. They state that the basic transport/deposition mechanisms are mass transport (slump, debris flow), turbidity current flow (channelized and unchannelized), and pelagic deposition. They suggest that mass transport appeared to be the dominant process for deposition and may account for up to 30% of the total amount of sediment deposited on the Fan. Channelized lobe development (channel and overbank deposits) apparently occurred late in the evolution of the majority of sediment sequences observed and that it may be associated with a rise in sea level.

The Texas-Louisiana Slope is located west of the Mississippi Canyon. It occupies an area of about 120,000 km$^2$ and contains the widest slope (up to 230 km) and the most rugged morphology in the northern Gulf of Mexico. There are over 105 domes and basins that have been named and approved by the U.S. Board of Geographic Names (BGN) (Bouma and Bryant 1994). Although the average continental slope gradient is less than 1°, a local slope gradient can exceed 40°. The domes and basins in the area range from 5 to 30 km in diameter. The domes are prominent on the upper slope, they increase in size to become salt massifs that surround basins on the middle slope, and lie under basins on the lower slope (Simmons 1992). The basinward termination of the slope is the Sigsbee Escarpment, which is a surficial expression of the basinward salt front (Moore et al. 1978). This salt front displays an extruded tongue feature with an elevation of about 600 m above the continental rise, and comprises gradients ranging from 10° to 20°. Several canyons break the semi-continuous Sigsbee Escarpment: Green Canyon, Farnella Canyon, Cortez Canyon, Bryant Canyon, Keathley Canyon, and Alaminos Canyon. There are fan deposits between the Green and Farnella Canyons that merge with the Mississippi Fan. Some channels are visible on top of these coalesced fans that radiate outwards in a basinward direction. Southward of Bryant Canyon lays the

Bryant Fan, which is about 25,000 $km^2$ in size. This fan reaches to the Cortez Canyon in the east, Keathley Canyon in the west, and extends about 170 km south from the canyon mouth. The lack of fan deposits in the mouth of Keathley Canyon suggests that this canyon is structurally controlled (Lee 1990). Due east of Green Canyon is Green Knoll, a salt diapir with over 400 m of relief. Using a submersible, a brine pool and active seeps were found on the east side near the crest of the knoll, although no salt exposure was observed. The oversaturated brine waters coming out from the seeps on the knoll have braided drainage patterns (Roberts et al. 1991). Besides the Green Knoll, brine seeps were also observed in Orca Basin (Shokes et al. 1977), in the East Flower Garden Bank area (Brooks et al. 1979), and in the drill hole at Site 66 (Manheim and Bischoff 1969).

In the northwest portion of the Gulf of Mexico, the Rio Grande Slope separates the Texas-Louisiana Slope from the East Mexico Slope. Similar to offshore Mississippi and Alabama, the Rio Grande Slope displays more than 15 pancake-shaped domes. In the area are a series of canyons that cut through the shelf break. The canyons are broad and tend to be located between domes or banks. Between Price Spur and Calhoun Dome, there are many tightly spaced canyons that form a 22 km wide valley with a 7 km wide bank. There are only a few small canyons, hundreds of meters wide that cut through the Rio Grande Slope. A number of the canyons observed may be an artifact due to the lack of detailed multibeam data in the western Gulf. At the seaward end of the western continental slope, the Perdido and Alaminos Canyons appear. The submarine fans that downdip from these two canyons merge basinward and are much smaller in size than the Bryant Fan (about 5,000 $km^2$).

To the south of the Rio Grande Slope is the East Mexico Slope. The northern portion of the East Mexican Slope is mainly controlled by diapiric activity. The southern side of the East Mexico Slope represents the northern end of the Mexican Ridges (Bryant 1986). At the basinward limit of the Texas-Louisiana, Rio Grande, and East Mexico Slopes, is the Western Gulf Rise, which is about 40 km wide. In between the Western Gulf Rise, the Mississippi Fan, and the Campeche Escarpment is the Sigsbee Plain, which has a water depth of about 3,700 m. In between the Campeche Escarpment and the Florida Escarpment is the Florida Plain, with a water depth of about 3,400 m. Except for the Sigsbee Knolls, which are up to 250 m above the Sigsbee Plain, these two abyssal plains have an average slope gradient of less than 0.5° and are the flattest mapped regions in the deepest part of the Gulf of Mexico.

## Structures

### Salt

Of all the geological events taking place within the northwestern Gulf of Mexico the action of salt, halokinesis, is the most striking and influential in the modification of the structure of the continental slope. **Figure 3.2** displays the location of salt on the northwestern Gulf of Mexico Continental Margin.

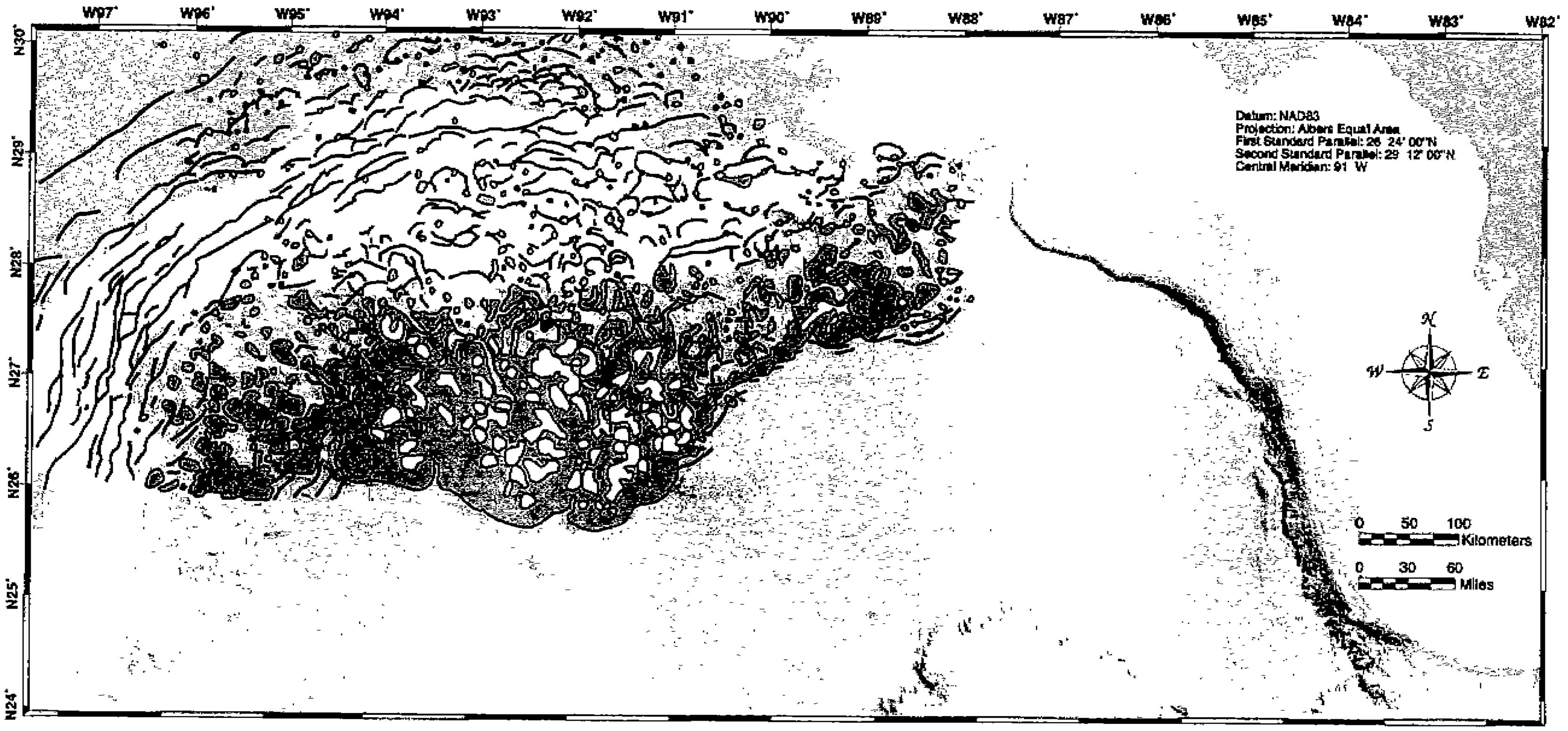

Figure 3.2. Salt and fault distributions in the northern Gulf of Mexico (Adapted from: Diegel et al. 1995). This map only shows structure distributions north of 26°N and west of 88°W. The light-shaded background is the bathymetry map as shown in Figure 3.1.

Bradshaw and Watkins (1995) have depicted salt migration pathways in the northwestern Gulf of Mexico as a complex interplay of basement architecture with subsequent depositional loading. They suggest that "the original deposition of Middle Jurassic Louann Salt was systematically offset right lateral along–strike across a series of northwest-southwest orientated transfer faults." They suggest that two major phases of postrift salt migration are evidenced in the shallow Neogene allochthonous salt sheets across the Sigsbee slope region, and are remnants of a deeper Paleogene salt canopy. They state that "A Paleogene canopy was emplaced when salt migrated vertically out of the original middle Jurassic salt basins due to early gravity spreading and differential sediment loading down dip of Lower Cretaceous and Paleocene shelf margins." The geographical distribution of this canopy was essentially controlled by earlier segmentation of Middle Jurassic salt basins across transfer faults, occurring most landward to the southwest and systematically farther seaward across each transfer fault. Generation of the Perdido foldbelt was synchronous with emplacement of the Paleogene salt canopy due to minor lateral migration of mother salt over deep basinal strata. Bradshaw and Watkins (1995) state that rapid remobilization of Paleogene allochthonous salt occurred in the Neogene when shelf margins began to prograde into the offshore Texas area. They suggest that variations in thickness of the sediment across the margin created lateral pressure gradients within the underlying salt. The pressure caused the salt to move from areas of higher pressure to areas of lower pressure, or seaward and upward. They suggest that in some cases salt migrated seaward for long distances and that the "remobilization of salt along the Neogene shelf margins was not synchronous." They state "that shelf margin loads encountered first one basin then another because of irregular location of salt basins and the irregular advance of the shelfedge." They figured that the " loading and spreading combined to displace salt over 100 km onto the Sigsbee slope and the seaward migration of salt created extensive salt withdrawal basins."

Salt deposited in the Gulf of Mexico during late Triassic and Jurassic contains a group of minerals that include sodium and potassium chlorides (Nelson 1991). In the Gulf of Mexico, 90% to 98% of the salt is composed of halite (NaCl), which has a density of 2.16 $g{\cdot}cc^{-1}$ (Halbouty 1979; Kupfer 1989). The most common impure salt is anhydrite, which has a density of 2.96 $g{\cdot}cc^{-1}$. With 95% of halite and 5% of anhydrite, the bulk density of the salt would be about 2.2 $g{\cdot}cc^{-1}$ (Nelson 1991). On top of the salt diapirs, the meteoric waters may resolve the halite and keep the less soluble anhydrite (Murray 1966; Posey and Kyle 1988), which forms cap rock (Murray 1966; Posey and Kyle 1988). As time progresses and when hydrocarbons are present, the anhydrite lying in between the salt diapir and cap rock will accumulate and may convert to calcite and hydrogen sulfide (Feely and Kulp 1957; Kyle et al. 1987).

In the northern portion of the Gulf of Mexico basin, salt was deposited in interior basins and in coastal and offshore basins (Martin 1978, 1980a). The interior basins include onshore Texas, north Louisiana, Arkansas, Mississippi, Alabama, the Florida panhandle, and the northeast Gulf of Mexico. The coast and offshore basins include onshore south Louisiana and southeast Texas, and Louisiana and Texas shelf and slope (Humphris 1979; Martin 1978, 1980). In the south of the Gulf of Mexico, the salt basin includes the

Campeche Escarpment, the Bay of Campeche, and onshore southern Mexico. **Figure 3.3** illustrates the location of major salt basins in the Gulf of Mexico (Simmons 1992).

Salt and salt structures in the Gulf of Mexico usually have many shapes. Simmons (1992) described various salt structures in the Gulf of Mexico as follows. A salt pillow is a circular or elliptical shaped salt structure with conformable contact with overlying sediments. A salt stock or salt dome is a cylindrical and usually mushroom-shaped salt that pierces through the overlying sediments. Salt massifs are moderate-sized salt structures with irregular shape and large overhangs (Martin 1984). A salt wedge is a large landward-dipping structure that usually thickens with depth (Ray 1988). A salt tongue is an asymmetrical lobe that usually spreads downdip. A salt sill is a subhorizontal intrusion at shallow depths (Nelson and Fairchild 1989). Salt canopies, a common structure on the upper and middle continental slope off Texas and Louisiana, are two coalescing salt structures (Jackson and Talbot 1989). A salt diapir is salt that has penetrated the overlying sediments. Other terms used to describe salt include salt halokinesis—which is salt movement under gravitational movement; autochthonous salt is salt that is still attached to its source; allochthonous salt is salt that has being separated from the mother salt. In the Gulf of Mexico, the majority of salt is allochthonous salt that has gone through many stages of mobilization and emplaced at a shallower depth than the original salt deposit.

Jackson and Talbot (1986) classified the driving forces of salt into buoyancy, differential loading, gravity spreading, thermal convection, and halotectonics. The low density of salt makes it more buoyant compared with their surrounding sediments and often rises as diapiric structures. In the offshore Texas and Louisiana, assuming a salt average density of 2.2 $g{\cdot}cc^{-1}$, the depth to achieve a sediment density that is greater than the salt density is about 1,500 m, while to support a salt diapir to rise from the source layer to the seafloor requires 3,600 m thick of sediment (Nelson 1991). The size of the source and the purity of the salt will also influence the density inversion depth (Trusheim 1960). Unlike the theory of buoyancy, differential loading does not require a deeper depth (Jackson and Galloway 1984). The differential loading can be due to slope gradient like in a prograded shelf where there is difference in sediment loading and water column. A differential loading can also occur if there is lateral facies change (Simmons 1992). Gravity spreading is gravity-induced lateral spreading (Ramberg 1981). Gravity spreading occurred at or above the neutral buoyancy level and is believed to be the cause of extensive salt tongues observed in the Gulf of Mexico (Ramberg 1981; Jackson and Talbot 1986; Nelson and Fairchild 1989). Halotectonics is the influence caused by tectonics and the relief caused by the growth fault extension and basinward compression may have the relief that can initiate salt buoyancy and differential loading. **Figure 3.4** illustrates the nature of the salt nappe as it appears on the lower continental slope. The seismic characteristics of intraslope supralobal basins are also illustrated. **Figure 3.5** shows the termination of the salt nappe at the Sigsbee Escarpment.

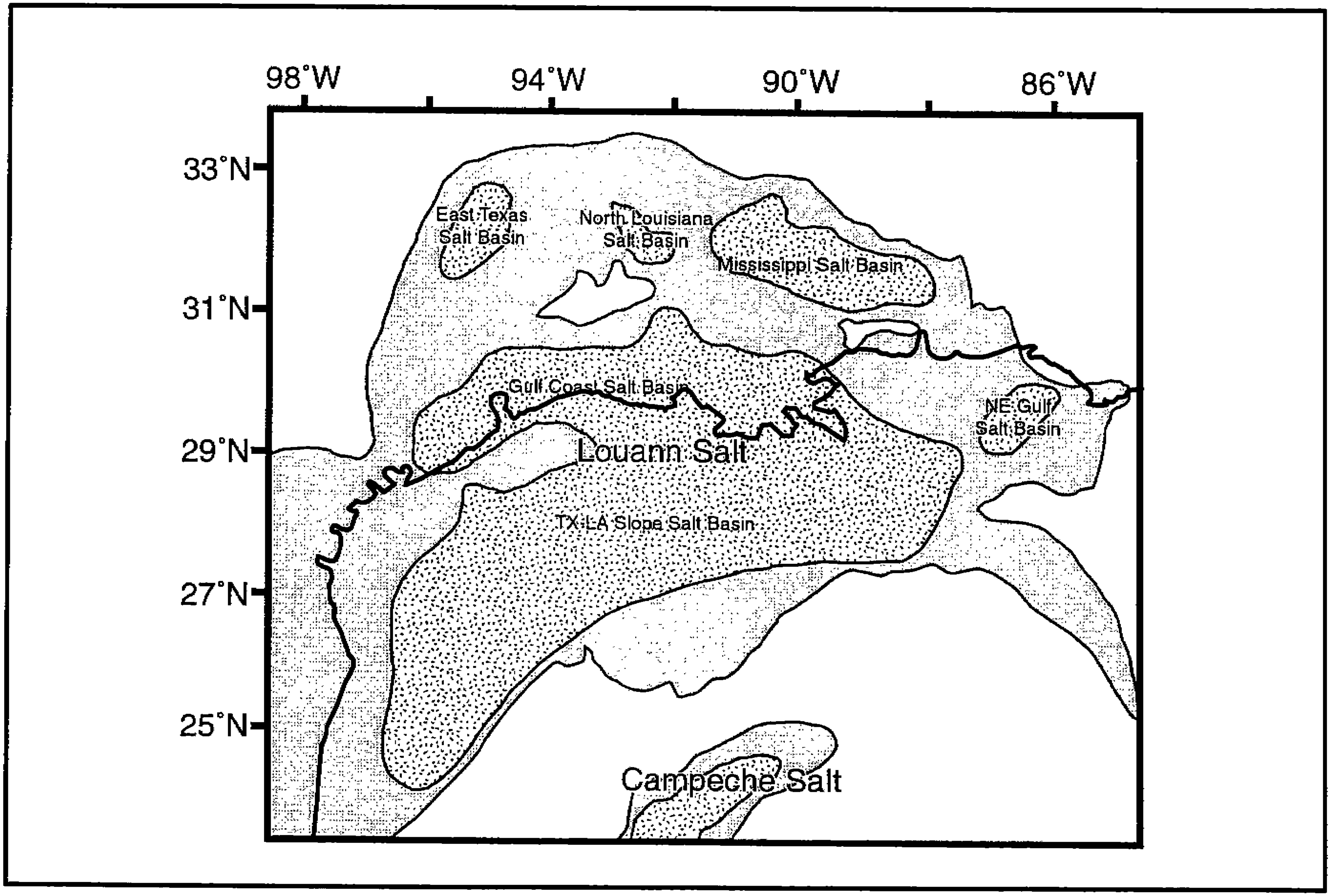

Figure 3.3. Major salt basins in the northern Gulf of Mexico (Adapted from: Simmons 1992). Gray color represents the extent of the salt. Stippled areas represent major salt basins, which contain original Middle Jurassic salt greater than 1,000 m thick.

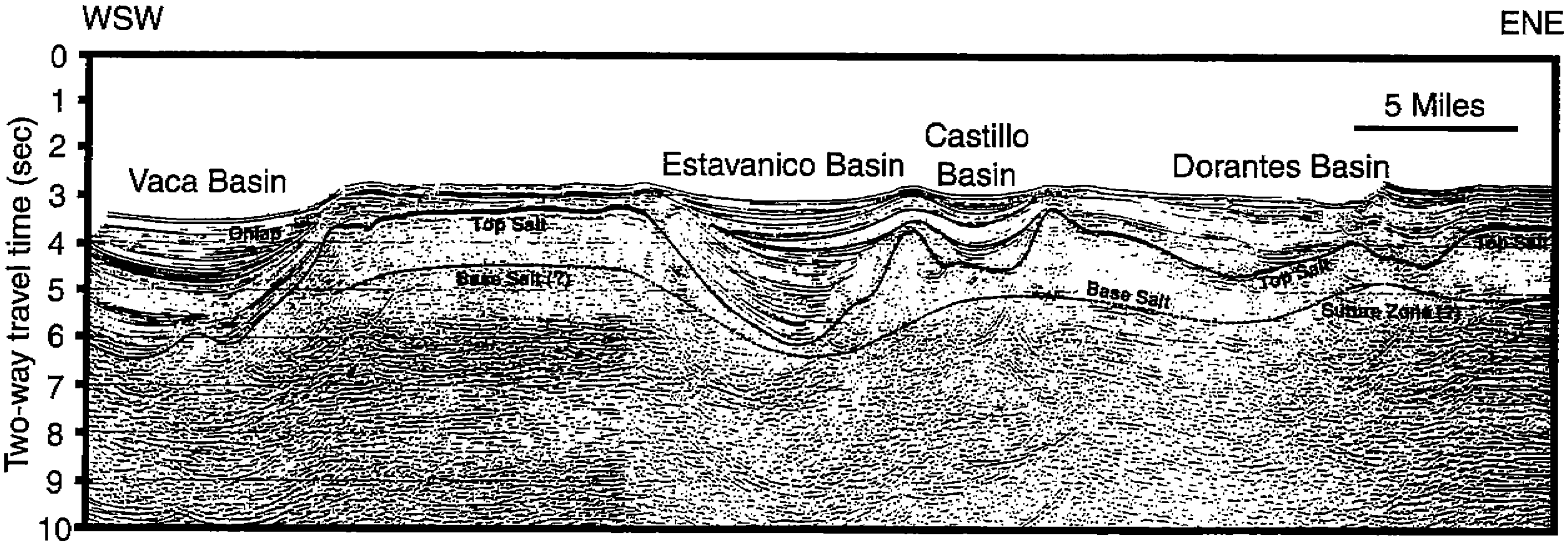

Figure 3.4. Seismic line across the lower continental slope (Adapted from: Simmons 1992). Note that salt is underlying these supralobal basins (for example, Vaca Basin, Estavanico Basin, Castillo Basin, and Dorantes Basin).

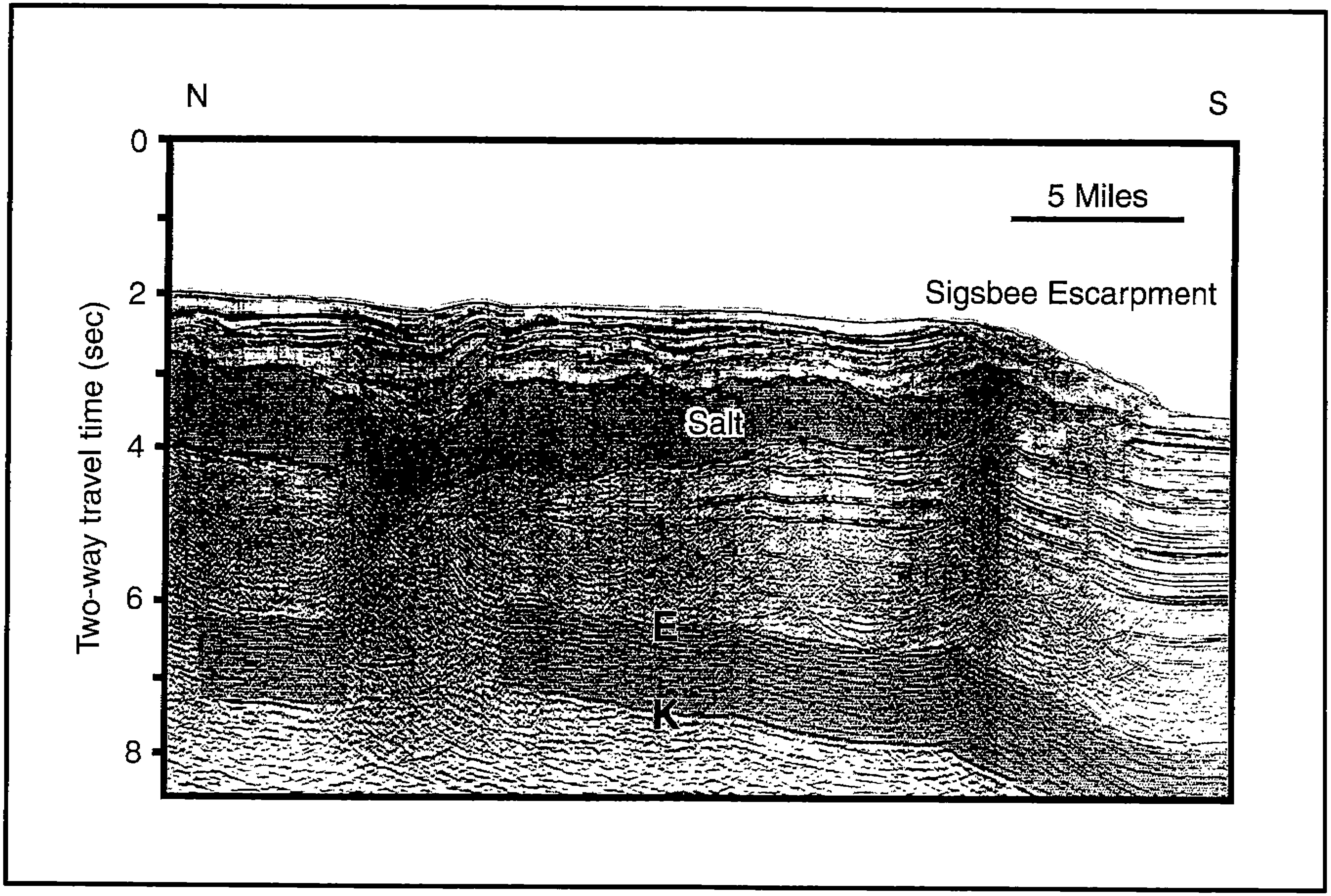

Figure 3.5. Seismic line across the Sigsbee Escarpment (Adapted from: Diegel et al. 1995). The leading salt nappe is expressed as the Sigsbee Escarpment on the seafloor. The "E" and "K" represent the Eocene and Cretaceous reflectors, respectively.

The general belief about salt evolution in the northwestern Gulf of Mexico is that salt has flowed upward from its mother source and spread laterally basinward. Buried salt can be remobilized and can pierce through its overburden and spread basinward many times. In terms of chronological evolution of salt in the northwestern Gulf of Mexico, West (1989) stated that salt moved seaward from the effects of sediment loading and formed a salt swell in the seaward portions of the depocenter during the middle Miocene. The salt swell became diapiric and pierced through the overburden and caused seafloor relief during the upper Miocene. Growth faults and salt swells blocked sedimentation and allowed the salt to be pushed further seaward during the upper Miocene-Pliocene times. Continued sediment deposition helped the salt's upward and outward movement (early Pleistocene). Salt prograded seaward due to further rapid sediment loading (late Pleistocene).

## Faulting within the Continental Slope

In a continental slope environment, we usually expect extension in the upper slope, compression in the lower slope, and translation in the middle slope. In the Gulf of Mexico, even with a regional slope gradient of less than 1°, the extension combined with rapid subsidence, differential compaction, and gravitational sliding caused normal faulting in the shelf edge and upper continental slope. These normal faulting usually are listric-shaped and many are down-to-the-basin faults that die out on top of a decollement layer, which usually is salt or shale (Nelson 1991). As the progradation of the depocenter proceeds the growth faults may invert to counter-regional growth faults with mounded-shaped structure on the downdip side (Seni and Jackson 1989).

In the lower continental slope, the compression is manifested by folding and thrusting. Examples of these folding and thrusting are the shallow-depth deep-rooted Mississippi Fan Fold Belt and Perdido Fold Belt (Blickwede and Queffelec 1988; Weimer and Buffler 1989). Some of these fault planes have a span of 30 m at the seafloor and provided conduits for gas and fluids (Roberts et al. 1986).

In the translation zone of the middle continental slope of the northwestern Gulf of Mexico, the structure is a mixture of extension, compression, and translation. In the intraslope basins, normal faulting has been observed on the top of salt diapirs, in the upper wall along the basin rims, and on the basin floors. In these extension areas, the cause is a combination of salt diapiric activity, steep slope gradients, and salt withdrawal. In the salt diapir case, faults are usually high-angled with a radial pattern, and die down and away from the diapir. **Figure 3.2** illustrates the distribution of major faults in the northwestern Gulf of Mexico.

## Sedimentation in the Northern Gulf of Mexico

The sedimentation patterns in the Gulf of Mexico are mainly influenced by geomorphology, salt halokinesis, faulting, sea level changes, and sediment input.

The last major sea level lowstand, the Wisconsinan, occurred about 18,000 yr ago, and during that time sea level dropped about 60 to 120 m (Bloom 1983). During the early Holocene (14,000 to 11,000 yr BP), sea level rose rapidly. The rapid melting of the ice sheet created large discharges that carried large amounts of sediments that were deposited on the outer shelf and upper slope in a short time. The rapid deposition and burial produced overpressured sediments on steep slopes that caused instability and mass movements and sediment gravity flows (Prior and Coleman 1978; Prior and Coleman 1980; van den Bold et al. 1987). The Mississippi River during the last lowstand in sea level, late Wisconsinan, carried more than 13 times its current sediment load ($80 \times 10^{11}$ $kg \cdot yr^{-1}$ compared with $6 \times 10^{11}$ $kg \cdot yr^{-1}$; Perlmutter 1985). When sea level was low, sediments migrated seaward, which caused rapid build-out in front of the prograding delta lobes (Coleman et al. 1986). During the Holocene sea level rise, with little terrigenous sediment input deposited sediments a much slower rate ($<10$ $cm \cdot kyr^{-1}$) (van den Bold et al. 1987).

During sea-level highstand, the majority of the coarse-grained sediments are trapped within the shelf province and hemipelagic sediment settling became dominant in the deep water (Bryant et al. 1995). Sea-level highstand deposits tend to be parallel laminated but are highly bioturbated and comparatively thin compared to sea-level lowstand deposits. From 60 piston cores taken in the Gulf of Mexico, Davies (1972) observed the upper 20 to 50 cm layer of *Globigerina* ooze overlying argillaceous lutite and sand/silt interbeds that range from 1 mm to 150 cm in thickness. From radiocarbon dating, Davies concluded the sharp base of the ooze is the 11,000 yr ago Pleistocene-Holocene boundary (Ewing et al. 1958). The upper clay-sized ooze layer displays parallel lamination and bedding, and is attributed to the pelagic settling. In the Mississippi Fan, single laminae may represent seasonal fluctuations, whereas the single bed may represent long-term (100 yr) fluctuation of climate (Huang and Goodell 1970).

Except for the carbonate platforms offshore Florida and Campeche, the detrital sediments in the deepwater Gulf of Mexico are mainly transported subaerially by river systems during sea-level lowstands (Beard et al. 1982). During lowstands, the canyons cut into the outer shelf and upper slope and became conduits that carried coarser-grained sediments to the deep water. The transporting mechanisms are gravity-induced mass movements (Middleton and Hampton 1976). Depending on the interaction of the grains with the density flow, they may be turbulence-supported turbidity currents or matrix-strength-supported debris flows. Movement can also result from less deformed whole body movement along a surface or slides, or from slump deposits.

Turbidity currents are considered the most important transportation mechanism that carried sand and silt beds thicker than 5 cm in the Gulf of Mexico. Turbidite beds display erosional bases, graded bedding, and Bouma sequence C-D-E. The bioturbation only occurs in the uppermost part. The bioturbation is not affected by the size of the sediment, but rather a factor of the sedimentation rate. In the Bouma sequence, C is current ripple lamination; D is parallel lamination; E is a structureless unit. In the Gulf of Mexico, a complete Bouma sequence is rare. A (graded bed) and B (parallel lamination) are usually missing. The absence of A and B in the sediment of the Gulf of Mexico is due to the predominance of fine sand, silt, and clay sediment (Davies 1972).

The influence of bottom currents on the distribution of sediments has been controversial in the deepwater environment. Roberts et al. (1982) suggested that certain bedform erosions in the Gulf were the results of oceanic currents. Martin and Bouma (1982) suggested slumping was the cause of bed truncations, and van den Bold et al. (1987) believed bottom currents were insignificant in a water depth deeper than 200 m in the Gulf of Mexico. Recent Texas A&M University Deep Tow surveys in the Gulf of Mexico on the lower continental slope confirmed that there were deepwater processes which produced 20 m-spaced, 5 m wide mega-furrows that were sub-parallel to the bathymetric contour lines southward of the Sigsbee Escarpment. These mega-bedforms indicate swift bottom currents in water depths of over 3,000 m.

## Sediment Sources and Drainage Patterns

Due to the mixing and unidentifiable origin of clay minerals after sediment transport (Hagerty 1970), Davies (1972) used heavy minerals to trace the origin and source of the sediments in the Gulf of Mexico and categorized five mineral assemblages in the surficial sediments. The major sources of sediments from the north are the Rio Grande, Colorado, Brazos, and Mississippi Rivers. By running a watershed model based on the bathymetry, Liu and Bryant (1999) also delineated similar drainage paths in the Gulf of Mexico. **Figure 3.6** illustrates the sediment provinces and drainage patterns of the northern Gulf of Mexico. Four drainage systems were identified: western, central, northeastern, and southeastern continental slope areas. All drainage patterns align well to today's major river systems in the northern Gulf: sediment sources from the west (Rio Grande system), the northwest (Brazos and Colorado Rivers systems), and the north (Mississippi River system). The carbonate-dominated platforms in the eastern and southern Gulf of Mexico show fewer drainage paths and suggest less contribution from the southern rim. These drainage systems merge basinward and can be up to 500 km long. The western system includes E-W oriented patterns on the East Mexico Slope and sinuous NW-SE oriented patterns on the Perdido Slope. In the East Mexico Slope area, the paths coincide with gully/canyon structures. On the Perdido Slope, the Perdido and Alaminos Canyons are the major tributaries at the base of the slope. The drainage paths tend to move around salt domes on the upper slope of the Perdido Canyon. On the upper slope of the Alaminos Canyon, the paths tend to go through the intraslope intralobal basins.

In the area located offshore Texas and Louisiana, sinuous drainage patterns are mainly in the N-S directions. The path that crosses Keathley Canyon is straight and follows a major fault that formed the canyon (Lee 1990). The drainage paths to the east of Keathley Canyon are highly irregular and are located between salt domes on the upper slope, and through the intraslope supralobal canyons of the lower continental slope. In Farnella Canyon, the drainage path cuts through the slope and the canyon, while in other canyons, such as Bryant, and Green Canyons, the drainage paths originate at the mouth of the canyons.

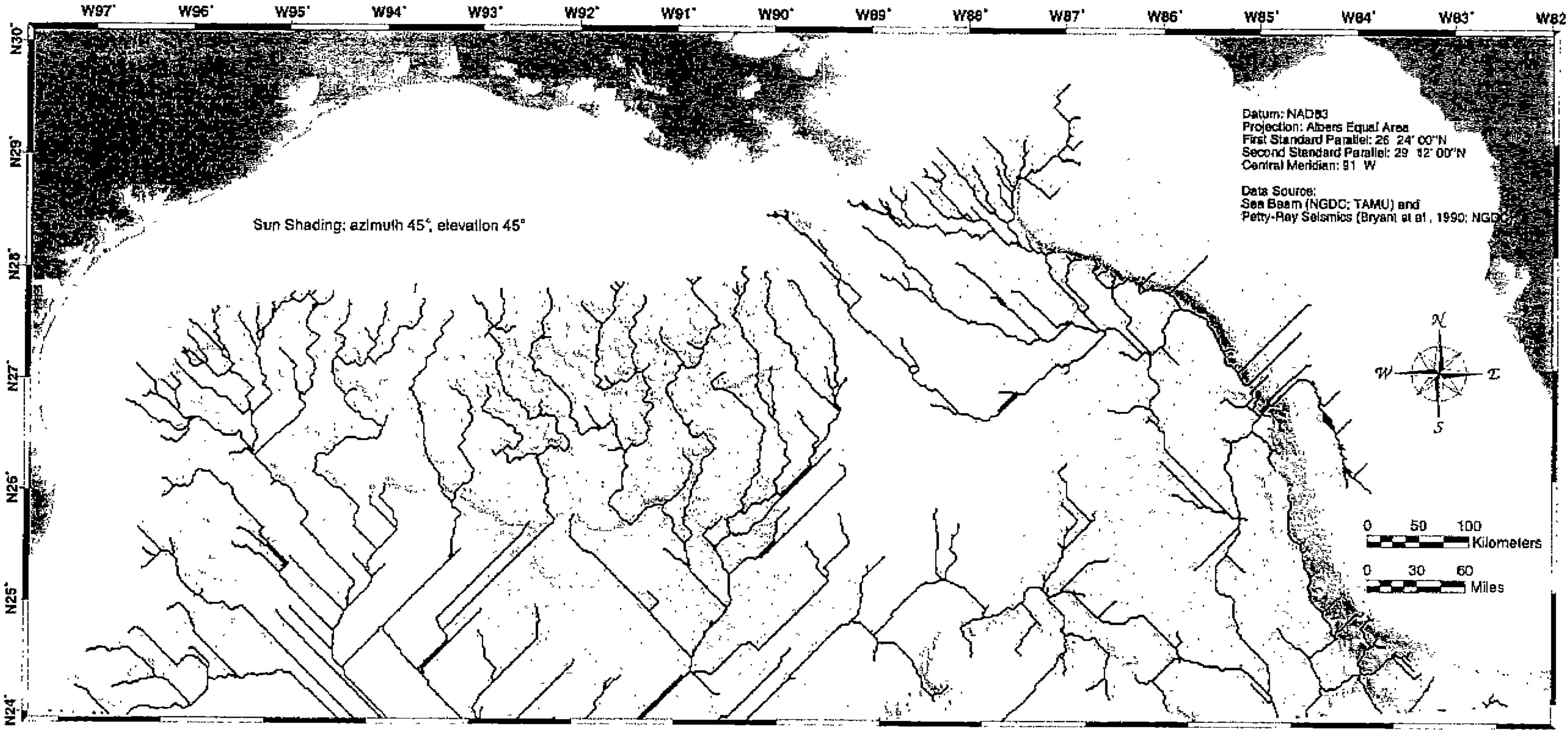

Figure 3.6. Bathymetry derived drainage patterns in the northern Gulf of Mexico deepwater environment. The black line is the drainage. The drainage meanders and passes in between salt domes on the upper slope. The drainage is straighter and traverses basins on the lower continental slope. The light-shaded background is the bathymetry map as shown in Figure 3.1.

In the northeastern area, many drainage paths align in a NW-SE direction on the Louisiana-Mississippi Slope and few paths align in an E-W direction on the West Florida Slope. In the Mississippi Canyon area, the drainage path goes down the canyon and swerves to the east at a water depth of about 2,800 m. To the east of the Mississippi Canyon, drainage paths tend to go around salt domes and the base of the Florida Escarpment, and merge at a water depth of about 3,100 m. This merged drainage path then goes between the Mississippi Fan and a series of topographic highs west of the Florida Escarpment.

In the southeastern part of the Gulf, either due to the carbonate platforms or to the less detailed topographical data available, the drainage paths are less sinuous. Generally, they come down from the Florida Escarpment, the Campeche Escarpment, and the Mississippi Fan. The paths go around the escarpments, fan, and then move south. There are also a few paths that come down the Pourtales Escarpment, as well as the Tortugas Terrace.

## Depocenters

During the Cenozoic, the maximum deposition occurred in depocenters that migrated eastward and represented the fastest prograding shelf edge that are generally parallel to present day's coastline (Murray 1952). In the lower Tertiary, the depocenter was in the Rio Grande Embayment. In the middle Tertiary, the depocenter was in the Mississippi Embayment (Shinn 1971; Woodbury et al. 1973). In the Eocene, the depocenter was in the south Texas (Woodbury et al. 1973). In the Miocene, the depocenter was in the south Louisiana (Woodbury et al. 1973) and in the Pliocene, in the Vermilion to West Delta central shelf areas (Woodbury et al. 1973). In the Pleistocene, the depocenter was in the High Island Area to the South Timbalier outer-shelf and upper-slope areas (Shinn 1971). The present shelf edge at a water depth of 200 m is a Pleistocene depositional feature (Moore and Curray 1963; Lehner 1969; Woodbury et al. 1973). **Figure 3.7** illustrates the location of the depocenters and shelf edge location through time.

In the major depocenters of the northern Gulf, subsidence can be up to 17,000 m (Hardin 1962). But in general the supply of sediment has been greater than the subsidence rate, and despite the transgression and regression that has occurred in the Cenozoic, the shelf edge still prograded basinward by as much as 402 km with an average of 5 to 6 $\text{km}\cdot\text{my}^{-1}$ (Hardin 1962; Woodbury et al. 1973; Coleman et al. 1986). The shelf edge prograded rapidly from late Miocene to middle Pliocene for about 80 km (Woodbury et al. 1973). During late Pliocene and Pleistocene, the depocenter shifted over 320 km southward while the shelf edge prograded 80 km southward (Woodbury et al. 1973).

The average Holocene sediment thickness on the continental slope in the northwestern Gulf of Mexico is 70 cm, which gives an average sedimentation rate of 4.6 $\text{cm}\cdot 1{,}000\ \text{yr}^{-1}$. Roberts et al. (1986) and Beard (1973) documented a much higher rate at 20 to 30 $\text{cm}\cdot 1{,}000\ \text{yr}^{-1}$, on the slope and in the deep Gulf.

In the Quaternary, there were about 300 m thick of sediments were deposited on the shelf (Lehner 1969). In the same period, as much as 3,600 m of sediments were deposited offshore Texas and Louisiana, especially in the salt withdrawal intraslope basins

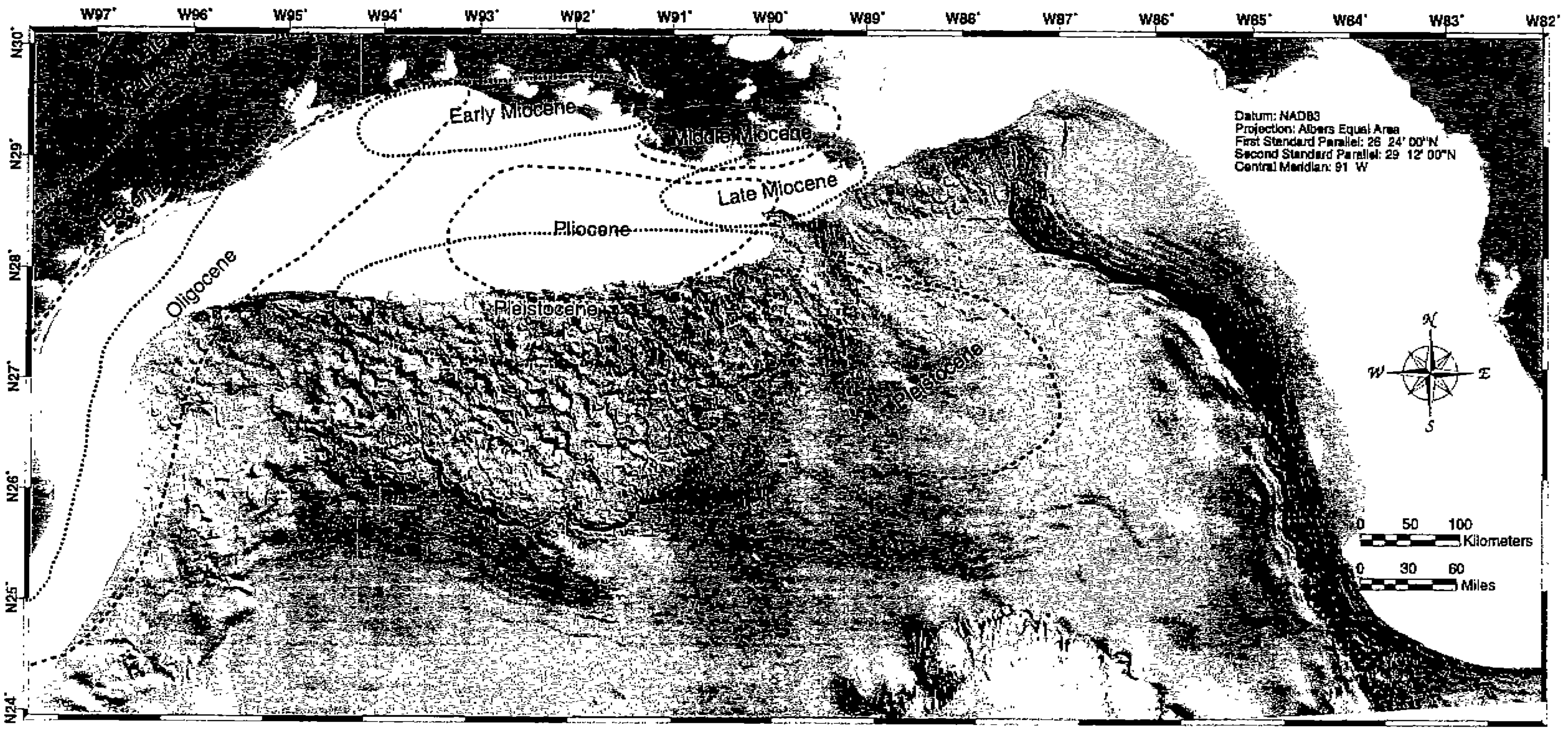

Figure 3.7. The location of depocenters through Cenozoic in the northern Gulf of Mexico (Adapted from: Woodbury et al. 1973). The light-shaded background is the bathymetry map as shown in Figure 3.1.

(Coleman et al. 1986), and up to 3,000 m thick of sediments were deposited in the vicinity of Mississippi Fan. Out of 983 million tons/year of sediments to the Gulf, 775 million tons are detrital (Moody 1967). The sands and silts cover over 35% of the Gulf of Mexico (Davies 1972).

## Continental Slope Basins

The Gulf of Mexico is unique in the construction and evolution of its northwestern continental margin and in particular the continental slope off Texas and Louisiana (**Figure 3.1**). The processes that determined the physiography of the continental slope are almost completely dominated by the halokinesis of allochthonous salt. Bathymetric maps constructed by Texas A&M University (Bryant et al. 1990) and maps produced from multibeam bathymetric data collected by the National Oceanic and Atmospheric Administration (NOAA) and the National Ocean Service (NOS), reveal the presence of over 90 intraslope basins with relief in excess of 150 m. Intraslope-interlobal and intraslope-supralobal basins occupy the upper/middle and lower continental slope respectively.

Gealy (1955) originally interpreted the origin of the hummocky topography of the northwestern Gulf of Mexico as the result of gravity slumping. Later, extensive seismic surveying and drilling revealed the role that salt plays in controlling the geomorphic and geological features of the area (Moore and Curray 1963; Lehner 1969; Garrison and Martin 1973; Buffler et al. 1978; Humphris 1978; Watkins et al. 1978; Martin 1980b; Buffler 1983; Winker and Edwards 1983; Shaub et al. 1984; Bouma et al. 1986; Worrall and Snelson 1989).

The continental slope off Texas and Louisiana, the major petroleum province in the Gulf of Mexico, is 180 to 240 km wide and covers the area from the continental shelf break to the continental rise south of the Sigsbee Escarpment (**Figure 3.1**). Water depths in the area range from approximately 200 to 3,400 m. The regional slope angle of the continental slope from 100 to 3,000 m water depth is about 1°. Surprisingly, the maximum submarine slope angles are reached on the flanks of the intraslope basins and not on the Sigsbee Escarpment. The slope basins are the major sediment depocenters of the slope and most hydrocarbon deposits will be found in the basins and in sub-salt areas. The average relief of intraslope basins is 309 m, while the average east-west dimension is 12.2 km. The slope angles of submarine flanks of the intraslope basins can obtain angles in excess of 40°, too steep in most cases for any present day engineered structures. The average angle of the continental slope off Texas and Louisiana is between 8° to 9°. The slope of the Sigsbee Escarpment averages 15° to 20° but can reach up to 30° locally.

Of the multitude of intraslope basins on the continental slope, Gyre, Orca and Pigmy Basins are the most popular researched areas. Orca and Pigmy Basins have been drilled during Deep Sea Drilling Program (DSDP) Leg 96 (Bouma et al. 1986). The popularity of Orca Basin, an interlobal basin, is its unique brine pool that occupies the western and northern portion of the basin. The brine pool is the result of salt leaching to seawater from the shallow subbottom exposure of salt near the top of diapirs. The anoxic environment created by the trapped brine preserves biogenic material and is conducive to the formation of black shales. Orca Basin was formed between coalescing diapirs, while Pigmy and Gyre Basins were developed by the coalescing of salt canopies.

## Salt Induced Physiography of the Upper and Middle Continental Slope

Detailed bathymetry proves to be extremely valuable in displaying characteristics of salt structural styles based on multichannel seismic interpretation. In general, bathymetric highs correspond to shallow salt structures buried less than 1 second (two way travel time) below the seafloor. Bathymetric lows correspond to thicker sediment-filled intraslope basins (Bryant et al. 1990). The bathymetry of the upper/middle slope consists of relatively flat ridges and basin floors separated by intraslope escarpments. The intraslope escarpments have relief up to 500 m across, slopes between 6° and 12°, and in some instances in excess of 40°. Ridges correspond to laterally spreading, flat-topped salt tongues overlain by thin sediments (100 to 500 msec).

**Figure 3.8** shows multichannel seismic lines, across the Pigmy Basin area that traverses a salt tongue spreading over the basin. The salt tongue has an asymmetrical lens shape and clearly resolved base. Its internal seismic character is reflection-free except for multiple energy reflecting between the top of salt and the seafloor. The leading edges of salt occur along the base of the escarpments, typically within 200 msec of the seafloor. Stratigraphic reflections diverge around these leading edges, presumably at the depth of lateral intrusion. The deformation front represents the veneer of sediment undercut and uplifted in the vicinity of the advancing salt front. The implied depths of intrusion (100 to 200 m) are in agreement with estimates by Nelson and Fairchild (1989) based on the thicknesses of onlapped deformation fronts from buried examples in the Mississippi Canyon area. Little, if any, onlap onto the deformation fronts is observed in this vicinity, suggesting salt tongues are actively intruding the shallow subsurface. **Figure 3.8** shows the very thick section of sediment within Pigmy Basin.

Basically, the upper/middle Louisiana Continental Slope consists of very large salt domes and salt ridges separated by trough and valley-like basins. The salt structures responsible for the large domes and ridges include deeply rooted massifs, and laterally spreading salt tongues. Each style of salt emplacement has distinctive bathymetric characteristics. Deeply-rooted massifs are common on the upper and middle slope. The ridges are commonly elongated in a NW-SE direction, a prominent trend across the northern Gulf of Mexico, which appears to correspond with a deep crustal fabric. The upper surfaces of the ridges are generally uneven or domed at various points along the ridges. The adjacent interdomal basins tend to have a fairly rounded cross-sectional shape. The sediment fill within the basins dips away along the ridge flanks, reflecting both doming within the ridges and salt withdrawal from below. The resulting seafloor physiography is very complex and is well illustrated by a map of the Pigmy Basin area in **Figure 3.9**.

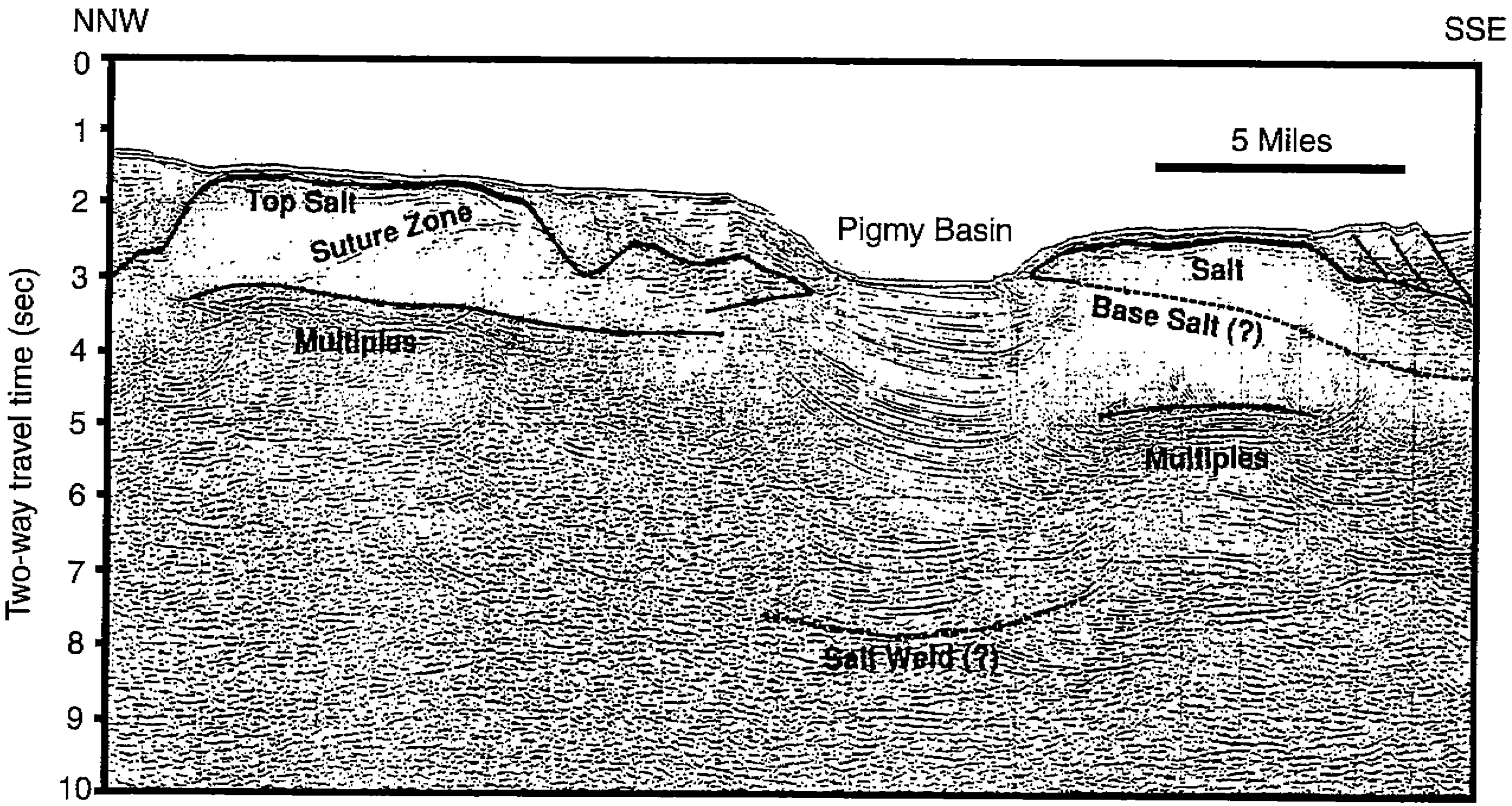

Figure 3.8. Seismic line across the Pigmy Basin (Adapted from: Simmons 1992). Line location is shown in Figure 3.9. Note the coalescing of salt fronts form the basin wall. Beneath the basin floor, the salt had evacuated.

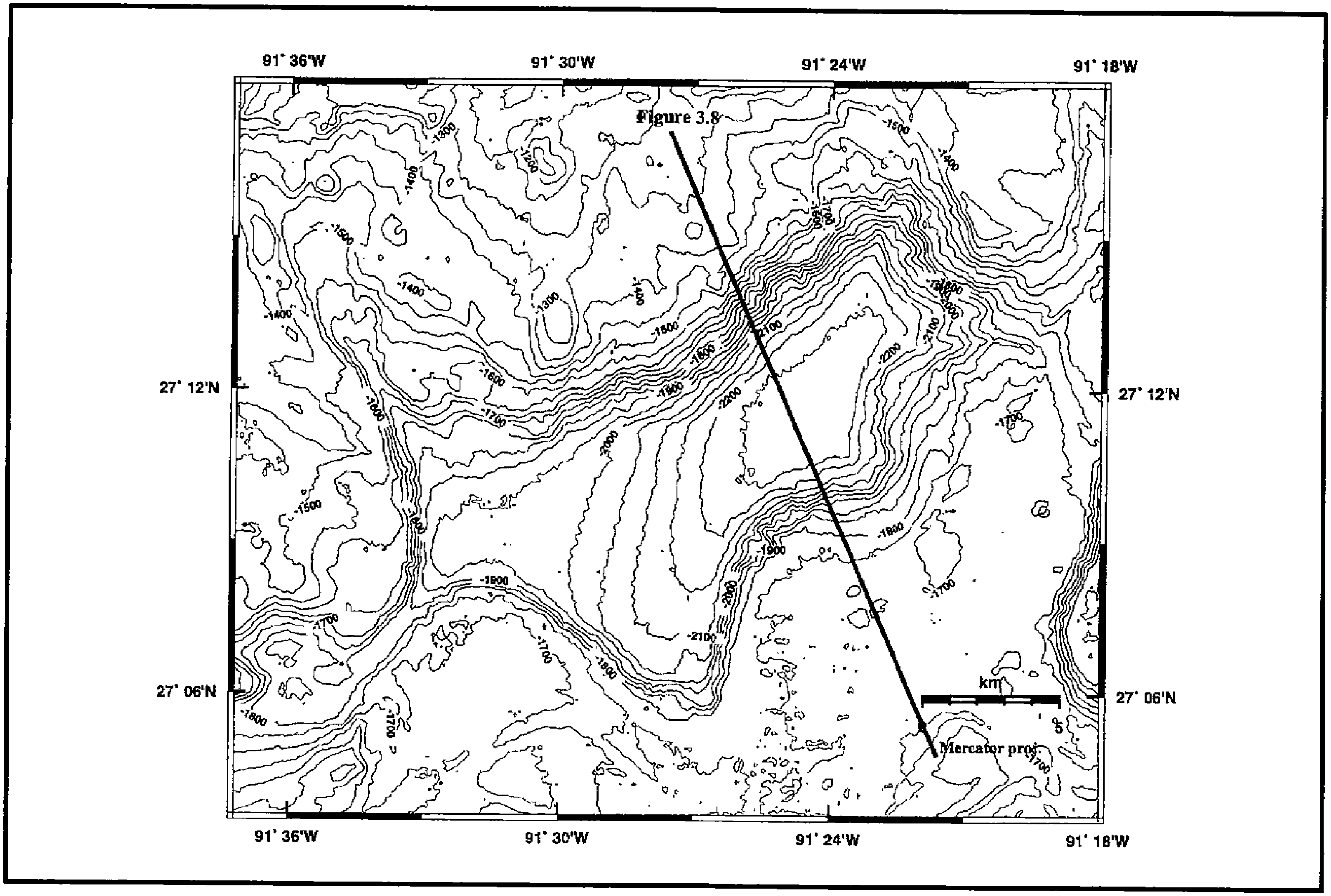

Figure 3.9. Bathymetric contour map of the Pigmy Basin. The contour interval is 50 m. The location of the seismic line from Figure 3.8 is shown in black line.

There are tens of intraslope-interlobal basins within the area covered by **Figure 3.10**. The basins are very irregular in shape and have steep sidewalls and generally flat basin floors. **Figure 3.9** is a bathymetric map of Pigmy Basin. The flanks of Pigmy Basin outline the limit of coalescing salt structures, as show in the seismic profile in **Figure 3.8**. A good portion of the basin area consists of fairly high angled sidewalls; the stability characteristics of the basin walls are totally unknown. The flat nature of the basin floor would indicate the possibility that density flows played a role in their development. Certainly, the majority of sediments within the basin are the products of turbidity current activity during the Cenozoic. Very little is being deposited within the basin at the present time. The sediments that make up the flanks of the basin are high water content smectite-rich clays that may be very gassy as was the sediments recovered on DSDP Leg 96, Hole 619 from the Pigmy Basin floor. Installation of seabed engineering structures within the basin would necessitate the determination of the role that creep and general slope stability and instability would play in the generation of density flows resulting from slope failure.

## Salt Induced Physiography of the Lower Continental Slope

As stated before, regional salt sheets cover much of the lower Louisiana and portions of the Texas Continental Slope. A salt nappe complex apparently accounts for much of the salt across the lower slope. The Sigsbee Escarpment represents the composite leading edge of the complex (**Figure 3.5**). Thickness of the salt nappes locally exceeds 6 km (Worrall and Snelson 1989) (**Figure 3.4**). Across other areas of the lower slope the salt sheets are canopies made up of convergent salt tongues. In both cases the shallow salt, and likewise the bathymetry, is generally flat and relatively smooth across the top. **Figure 3.10** is a physiographic map of the lower continental slope off Louisiana known as the Vaca Basin area, that shows the nature of the lower slope.

Salt canopies can be located and are characterized by narrow, steep-faced valleys along internal suture zones between constituent salt tongues. Bathymetric relief across the lower continental slope occurs mainly within isolated, generally elliptical supralobal basins. These basins are predominantly filled by Plio-Pleistocene sediments subsiding into the underlying salt sheets. They are generally asymmetrical, and the deepest points within the basins generally correspond to points of maximum sediment fill. The seismic profile in **Figure 3.11** cuts across Vaca Basin and other lower slope basins and illustrates the nature of intraslope-supralobal basinal structure.

The supralobal basins generally display continuous, high-amplitude reflections alternating with low-amplitude facies. Similar observations have been described by Armentrout (1987), Weimer (1989), and Lee (1990), and have been attributed to a Plio-Pleistocene glacio-eustatic cyclicity. The high-amplitude reflections tend to drape the area, and are thought to represent condensed intervals of pelagic and hemipelagic sediments within transgressive and highstand systems tracts. The low-amplitude facies onlap the condensed intervals and expand towards the focus of basin subsidence

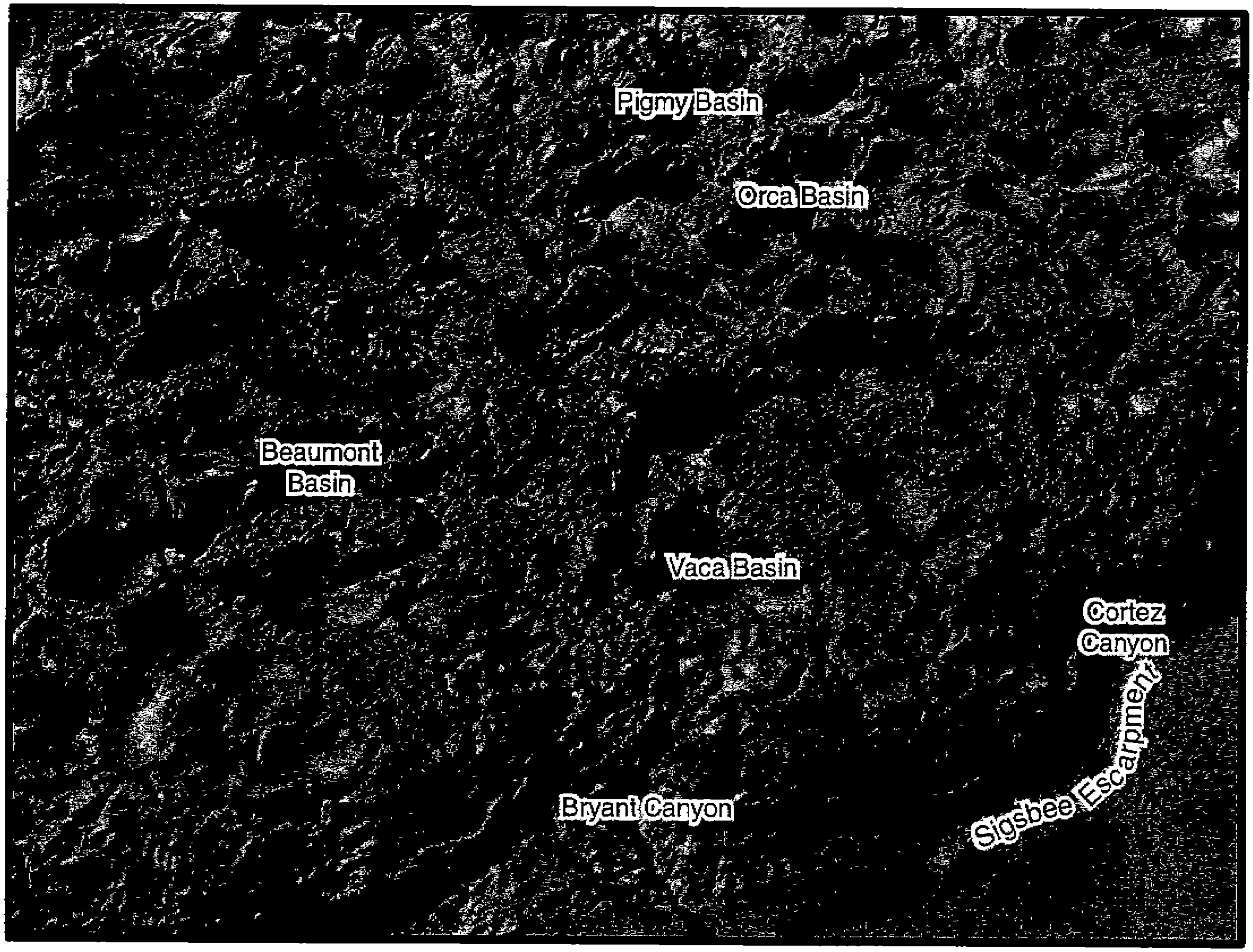

Figure 3.10. Perspective view of the seafloor relief of the middle and lower continental slope, northern Gulf of Mexico. On the middle slope, the relief is typified by asymmetric and rugged basins, for example, Pigmy Basin. On the lower slope, the relief is typified by symmetric and smoothed basins, for example, Vaca Basin. The vertical exaggeration is 10X.

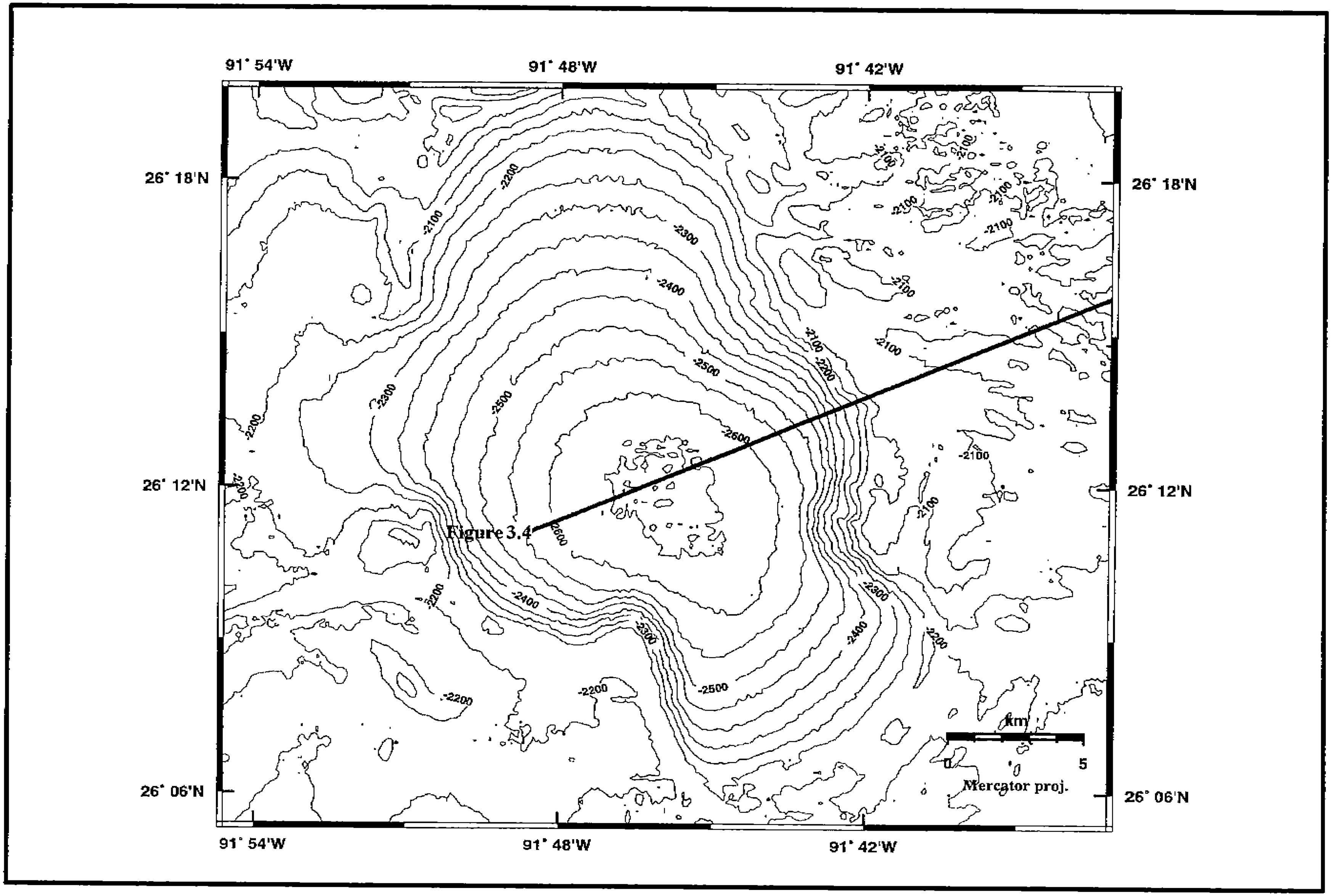

Figure 3.11. Bathymetric contour map of the Vaca Basin. The contour interval is 50 m. The location of the seismic line from Figure 3.4 is shown in black line.

suggesting differential sedimentation within the lower slope depressions by sediment-gravity or density flows during lowstands of the eustatic cycles.

Basin subsidence is accomplished by evacuation of underlying salt. Subsidence histories are commonly episodic. This is particularly evident in Vaca Basin where initial basin subsidence appears to be relatively slow and accompanied by the accumulation of relatively concordant strata. These older strata flank the basin margins at high angles, indicating large amounts of post-depositional subsidence. An onlap surface overlying a series of high-amplitude reflections seems to mark a point where basin subsidence decelerates. The onlapping strata flank the basin margins at lower angles, principally filling a deep, pre-existing depression. A possible scenario is that subsidence of the Vaca Basin was initially controlled by differential loading caused by lateral variations in sediment thickness, but while the sediments were still relatively buoyant compared to the salt. Sediment densities increase with depth due to compaction, whereas salt densities are essentially constant with depth. Sediment thickness increased until a critical thickness was reached where average sediment densities exceeded that of salt. At this point, subsidence proceeds rapidly until salt is completely evacuated and the sediment fill bottoms out against the base of salt. Rapid basin subsidence should cease, but the depression formed by the rapid subsidence will continue filling up with sediments, onlapping the basin margins. In order for subsidence to continue, the average density of the infilling sediments must be larger than that of the salt. The density of high porosity smectite-rich clays typical of the Gulf of Mexico region have relatively low densities and are generally underconsolidated, making it difficult to achieve the necessary average densities to exceed that of salt except at very deep burial depths. It is difficult to envision such clays initiating the necessary forces of subsidence in the thin sediment fills of high relief basins such as Vaca Basin. In contrast, sand-rich sediments can reach average densities exceeding that of salt at fairly shallow depths. Thus, it is suggested that the intraslope-supralobal basins may contain large amounts of sand at depth within their fill; an interesting and perhaps an important aspect related to the petroleum reservoir characteristics of intraslope-supralobal basins. The physiography of the lower slope is comparatively smooth, such as across the Vaca Basin area. Bathymetric relief exists mainly as rounded depressions corresponding to supralobal or suprasalt sedimentary basins subsiding into a regionally extensive salt sheet locally 3 to 4 km in thickness. The supralobal basins have average slopes generally between 6° and 8°, but locally up to 30°. **Figure 3.10** is a bathymetric map of Vaca Basin showing the very bowl shaped appearance of the basin and the smooth round basin walls. The basin appears, as would a ball pressed into soft mud.

## Geohazards

The engineering and geological constraints on the continental slope off Texas and Louisiana related to hydrocarbon recovery will require both novel geological and geophysical surveys and engineering methods to economically overcome. Significant seafloor engineering problems in deep waters include slope instabilities, both short-term (slump) and long-term (creep), pipeline spanning problems, mass transport from unknown causes, and unusual stiffness and strength conditions (Hooper and Dunlap 1989). The geohazards (engineering and geologic constraints) present in and on the central and western continental slope are many in number and are mainly due to the activity of salt and rapid sedimentation.

The main geohazards on the slope and resulting effects are as follows:

- Faults – sediment tectonics, halokinesis
- Slope Stability – slope steepening, slumps, creep, debris flow
- Gassy Sediments – sediment strength reduction, hydrates, sediment liquefaction
- Fluid and Gas Expulsion Features
- Diapiric Structures – salt, mud, hydrates
- Seafloor Depressions – blowouts, pockmarks, seeps
- Seafloor Features – sediment waves, differential channel fill, brine-low channels, sea-bed furrows
- Shallow Waterflow
- Deep Water High-Velocity Currents – mega-furrows, sea-bed erosion

The near-surface geology and topography (the area of most concern in relationship to submarine slope stability) of the continental slope off Texas and Louisiana are a function of the interplay between episodes of rapid shelf edge progradation and contemporaneous modification of the depositional sequence by diapirism and mass movement processes. Many slope sediments have been uplifted, folded, fractured, and faulted by diapiric action. Oversteepening on the basin flanks and resulting mass movements have resulted in the appearance of highly overconsolidated sediments underlying extremely weak pelagic sediments. The construction of the Mississippi Canyon is in part a function of sidewall slumping and pelagic drape of low shear strength sediments. In contrast, slope oversteepening and subsequent mass movement have resulted in high pore pressures in rapidly deposited debris flows on the upper slope and on basin floors, resulting in unexpected decreased shear strengths. Biogenic and thermogenic gas induces the accumulation of hydrates and underconsolidated gassy sediments, which are common on the upper slope. On the middle and lower slope, gassy sediments are not common except in the basins that do not have a salt base such as Beaumont Basin. The salt nappe restricts the upward movement of gas from below.

Holocene and Pleistocene sediment cores recovered from the continental slope off Texas and Louisiana from conventional piston coring and from DSDP activities reveal the presence of unconsolidated gassy clays, silty clays, sands, and clayey sands, many containing gas hydrates.

The intraslope intralobal basins located on the upper slope range in water depths from 1,500 to 2,200 m. The bathymetry of the Central and Western areas is shown in **Figure 3.2**. The bathymetry of the upper to middle continental slope area consists of relatively flat ridges and basin floors separated by intraslope escarpments. The intraslope basin escarpments have relief up to 700 m and slopes between 5° to 30° and in specific locations up to 50°. Ridges that rim the basins correspond to late laterally spreading flat-topped salt tongues overlain by a thin sediment cover (Bryant et al. 1995). The deeper portions of intraslope intralobal basins are salt free and exhibit a dissected topography consisting of a multitude of small submarine canyons along the walls. Cores taken on the wall of some basins indicate that as much as 3 m of sediment has been removed by slumping. The intraslope-supralobal basin on the lower continental slope where the physiography is comparatively smooth (**Figure 3.1**) shows that the relief exists mainly as a rounded depression. The formation of basins on the lower slope is where subsidence is accomplished by evacuation of underlying salt (salt withdrawal).

The submarine canyons along the Sigsbee Escarpment, Alaminos, Keathley, Bryant, Cortez, Farnella and Green Canyon are the result of the coalescing of salt canopies, the migration of the salt over the abyssal plain and the erosion of the escarpment during periods of low sea stand (Bryant et al. 1992). The bathymetry of the canyons is illustrated in **Figure 3.1**. In addition to the canyons that form along the escarpment, numerous small submarine canyons and gullies line the escarpment along with large slumps. Seaward of the canyons submarine fans of various sizes extends out onto the continental rise. A significant portion of the canyon walls and the escarpment contains slopes of 5° to 10° and slopes in excess of 15° are not rare. Large slope failures are present in the Green Canyon area.

The major faults on the continental slope are associated with massive accumulation of sediments and are called growth faults. These growth faults form contemporaneously and continuously with sediment deposition. The growth faults are found mostly on the upper continental slope and on the continental shelf where sediment accumulation is the thickest (see **Figure 3.2**). The most common types of fault on the middle and lower continental slope are "groups of geometrically classified fault families and fault welds that are kinematically and genetically linked to each other and to associated salt bodies and welds. Linked fault systems can contain extensional, contractional, and strike-slip components. Extensional fault families are formed by basinward translation, subsidence into salt, or folding. Those fault families that accommodate basinward translation are balanced by salt extrusion or contractional fault families" (Rowan et al. 1999). Rowan et al. related five associations of linked fault systems that are directly related to five types of salt systems: autochthonous salt (salt in place), stepped counterregional, roho, salt-stock canopy, and salt nappe. Faulting resulting from the formation of salt diapirs from autochthonous salt is the most common type fault on the upper slope while faulting from salt-stock canopy and salt nappe are most common on the middle and lower continental slope. Extensive faulting can be found on the rim of most intraslope intralobal and supralobal basin on the middle and lower continental slope. The faults are extensional faults caused by the upward movement of salt resulting from pressures created by sediment accumulation within basins. This type of faulting results in the occurrence of a large number of small faults in the area of the seafloor under going extension. In some areas of the slope the upward migration of salt results in the seafloor being totally fractured (faulted) and continuously displaced.

Portions of some of the submarine canyons, like Bryant Canyon, are being filled with salt due to the loading of the salt by sediments on the margins of the canyon. The salt migrates upward, filling the canyon that was created by turbidity current flow active during times of low-sea stand. The migration of salt into the canyon may occur at the rate of centimeters per year.

On the middle and lower continental slope, salt may be very close to the seafloor in certain areas and, on features such as the salt plug called "Green Knoll," salt is exposed at the seafloor and is being dissolved by seawater, resulting in the collapse of the cap of the knoll. In Orca Basin, an intraslope intralobal basin, salt is exposed at the bottom of the northern portion of the basin and a famous brine pool has formed within the basin. Where salt is close to the seafloor, for the emplacement of structures that require foundation piles, new engineering methods will be necessary to accommodate such structures on salt.

Water currents can be a problem to structures on the continental slope, but they may be a major problem to structures such as platforms, bottom assemblies and pipelines at the base of the Sigsbee Escarpment starting in water depths as shallow as 1,200 m and as deep as 3,300 m. Recent studies have revealed the presence of large mega-furrows at the base of the Sigsbee Escarpment. These large bedforms, 20 to 30 m wide and as deep as 10 m, occur along the base of the Sigsbee Escarpment and extend to a distance of 20 km south of the escarpment. They are the result of high velocity bottom currents occurring along the base of the escarpment (see **Chapter 4**). The mega-furrows have been found extending from 90° to 92.5° W Longitudes, and probably extend westward beyond that location and possibly as far west as Alaminos Canyon.

Shallow waterflow, also known as geopressured sands, is the uncontrolled flow of sand and water that can create significant sediment pile up at the wellhead. It is the results of compaction disequilibrium or differential compaction and usually occurs at 360 to 530 m below the seafloor. It is more likely to occur on the upper and middle slope and less likely to occur above the salt nappe, the tabular salt blocking the escape of overpressures from below.

**Table 3.1** summarizes the properties related to geohazards of upper, middle, and lower continental slopes intraslope basins and lower slope canyons and the Sigsbee Escarpment.

Table 3.1. Engineering constraints and possible geohazards of intraslope basins and canyons

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**Upper to Middle Slope Intraslope Interlobal Basins**

- Steep sidewalls average 10° to 20°, maximum 50°
- Small submarine canyons and gullies dissect basin escarpments
- Basin wall sediments may be unstable and undergoing modification by creep and slump processes
- Low shear strength debris flow sediments on basin floor
- Basin floor subject to debris flows from side wall slumping
- Stiff sediments on highly faulted ridges between basins
- Hydrates, gas sweeps, carbonate bioherms and chemosynthetic organisms may be present
- Basins may contain low shear strength gassy anoxic sediments
- Isolated basins subject to formation of brine pools
- Basin sediments underconsolidated at shallow subbottom depths

**Lower Slope Intraslope-Supralobal Basins**

- Elevated faulted ridges between basins
- Elevated ridge along basin rim
- Basins are bowl shaped with low angle basin floor
- Soft surficial sediments within basin
- Structures on basin floor subject to debris flow
- Basin sediments underconsolidated at shallow subbottom depths

**Lower Slope Canyons and Escarpments**

- Side walls average 10° to 15°, maximum 30°
- Small submarine canyons and gullies dissect escarpment and smaller canyon escarpments
- Canyons and escarpment structurally active from effects of halokinesis
- Very rugged topography
- Slump deposits and slope failure common
- Small submarine fans on canyon floor formed from debris flows and turbidity currents
- In very deep water
- Sediments underconsolidated at shallow subbottom depths
- High velocity bottom currents and mega-furrows present at base of Sigsbee Escarpment

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# Chapter 4: Physical Oceanography

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## Introduction

Although there have been many hydrographic measurements made in the Gulf of Mexico, few surveys of the entire Gulf have been over short enough durations so that the data could be combined to obtain nearly synoptic descriptions. Examples of such surveys are those of *Hidalgo* 62-H-3, *Geronimo* cruises in the 1960's, and *Kane* 1969. The resulting patterns are similar and illustrated by **Figure 4.1** (after Nowlin 1972) based on the *Hidalgo* 1962 cruise. Contours represent the streamlines of the surface geostrophic surface currents relative to a 1,000-m reference surface. These currents reflect the medium to large-scale distributions of temperature and salinity, and thus density. This pattern also is characteristic of time-averaged outputs from numerical models of the circulation of the Gulf (e.g., see Hurlbert and Thompson 1980, 1982). Thus, this pattern more nearly reflects the time-averaged, or background, circulation and not necessarily the instantaneous currents at any specific time.

The flow lines entering the Gulf through the Yucatan Channel, turning clockwise, and then exiting the Gulf into the Straits of Florida represent the Loop Current. That current is a part of the western boundary current system of the North Atlantic, and it is the principal current and source of energy for the circulation in the Gulf of Mexico. The Loop Current may be confined to the southeastern Gulf of Mexico or it may extend well into the northeastern or north central Gulf, with intrusions of Loop Current water even to the shelf edge of Louisiana or of the Florida panhandle (see e.g., Huh et al. 1981; Paluszkiewicz et al. 1983).

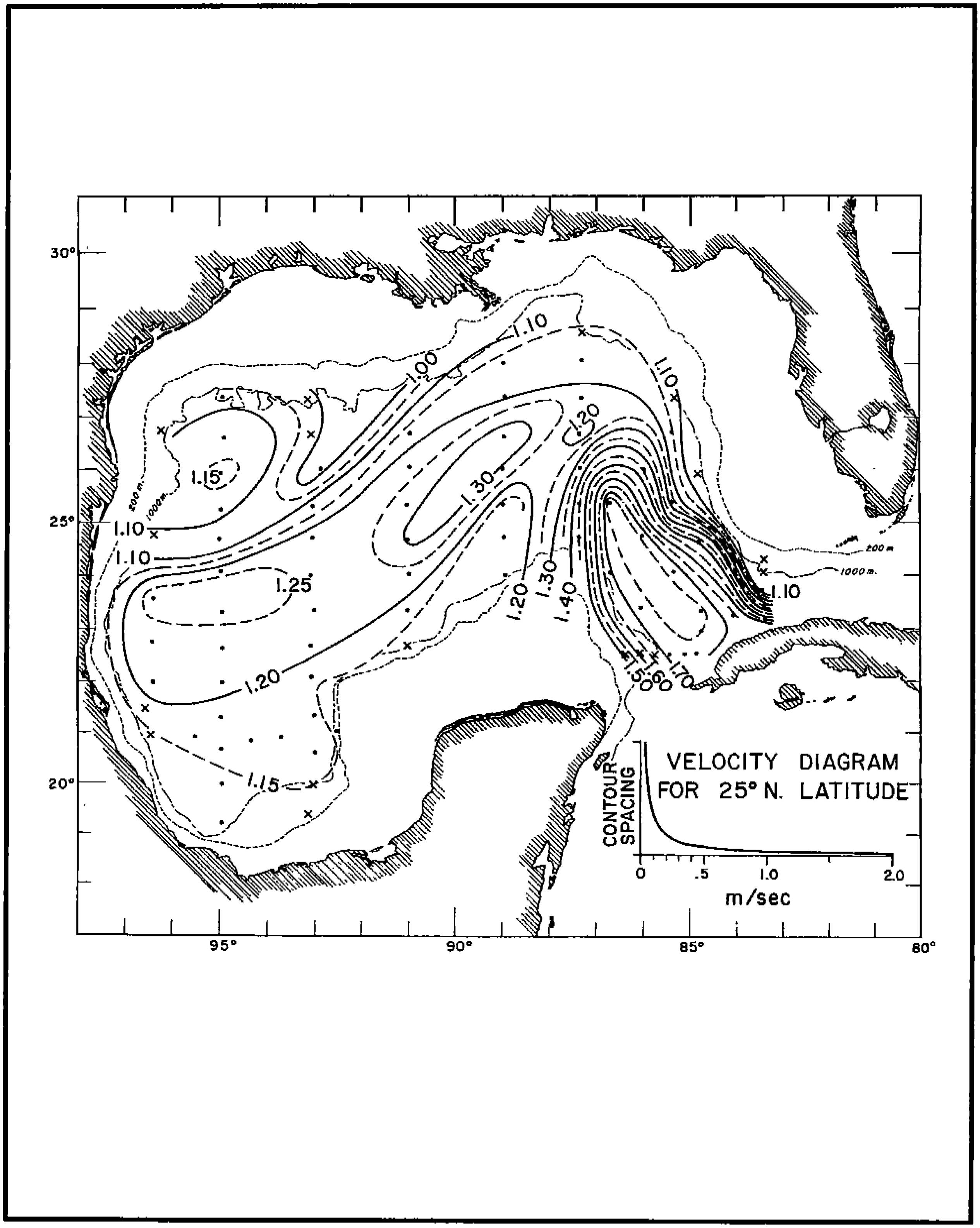


Figure 4.1. Geopotential anomaly (dynamic m) of the sea surface relative to the 1,000-db surface, constructed from *Hidalgo* 62-H-3 data collected February-March 1962. Stations shallower than 1,000 db, and for which extrapolation was used by Nowlin (1972) to estimate the geopotential anomaly, are indicated by x's.

Closed rings of clockwise rotating (anticyclonic) water called Loop Current eddies (LCEs) separate aperiodically from the Loop Current. Studies on the frequency of Loop Current intrusions into the eastern Gulf and of the frequency of LCE separation (Sturges 1992, 1994; Sturges et al. 1993; Vukovich 1988, 1995) clearly show these to be chaotic processes.

Currents associated with the Loop Current and its eddies extend at least to depths of 800 m, the sill depth of the Straits of Florida; geostrophic shear is observed to extend to the sill depth of Yucatan Channel (2,000 m). These features may have surface speeds of 150 to 200 $cm \cdot s^{-1}$ or more; speeds of 10 $cm \cdot s^{-1}$ are not uncommon at 500 m (Cooper et al. 1990). Anticyclonic eddies separate from the Loop Current with frequencies peaked at 8 to 9 months and at 13 to 14 months (Sturges 1994). Lifetimes of these Loop Current eddies can be one year or more (Elliot 1982). Therefore, their effects can persist at one location for long periods—weeks or even months (see e.g., Nowlin et al. 1998a,b)—if the eddies remain stationary over such periods.

The Gulf may also be forced remotely by the advection of potential vorticity. Connections in mesoscale variability between the tropical Atlantic, Caribbean Sea, and Gulf of Mexico were studied using simulation from three ocean models by Murphy et al. (1999). They found that (primarily anticyclonic) eddies formed in the Caribbean, in part due to the advection of potential vorticity from the Atlantic, pass through the Caribbean along a well defined corridor and may enter the Gulf via the Yucatan Channel. There is some evidence that such Caribbean eddies may influence Loop Current eddy shedding or other mesoscale variability in the Gulf.

In addition to currents associated with the Loop Currents and with mesoscale eddies and their formation and decay, two significant long-period circulation features are believed to be generated locally by the wind in the Gulf. There is an anticyclonic (clockwise rotating) feature oriented about ENE-WSW with its western extent near 24°N off Mexico and a cyclonic gyre centered near 20.8°N, 94.5°W ± 1° in the Bay of Campeche.

Atmospheric forcing also results in a variety of episodic or short-period ocean phenomena. These include surface wind waves, near-inertial oscillations, diurnal cycling, and energetic current surges. The forcing events include frontal passages, extratropical cyclogenesis, tropical storms, and hurricanes.

The astronomical tides do not result in currents within the Gulf of much concern in open water. Transports of water through the Straits of Florida and Yucatan Channel associated with some of the principal tidal components are sizable, but not of direct concern to the deepwater area of interest.

In summary, there are at least five classes of energetic currents in the deepwater portion of the Gulf of Mexico of potential concern to those involved with offshore oil and gas production and transportation. These classes are:

(1) currents resulting from energetic, episodic atmospheric events, including cold air outbreaks, extratropical cyclones, and tropical cyclones such as hurricanes;

(2) surface-intensified currents arising from the major surface circulation features (the Loop Current, the anticyclonic LCEs derived therefrom, and both cyclonic and anticyclonic eddies spun up in the Gulf);
(3) currents extending from about 1,000 m through the deeper water column with little depth variation (e.g., those believed to be associated with topographic Rossby waves), sometimes with bottom intensification;
(4) high-speed, subsurface-intensified currents or jets; and
(5) currents responsible for large, linear furrows discovered along the base of the continental slope in some locations of the northwestern Gulf.

Data available for study of the hydrography and principal significant currents include meteorological stations; shipboard estimations of weather, sea state, and ship drift; wave measurements; oceanographic station data (STD/CTD/bottle measurements); bathythermograph (BT), expendable bathythermograph (XBT), expendable current-temperature-depth (XCTD), and air-dropped expendable bathythermograph (AXBT) measurements; surface velocity estimates and temperature estimates from satellite-reporting surface drifters; time series of currents, temperature, and salinity at fixed locations using single-point current meters and acoustic Doppler current profilers (ADCPs); current measurements in the upper several hundred meters using shipboard ADCPs; expendable current profilers (XCP); tide gauges; inverted echo sounders (IES); pumped seawater systems collecting and analyzing samples from underway vessels; and satellite-derived measurements of sea surface temperature (SST), sea surface height anomaly (SSHA), and sea surface color. For some of these observations, compilations of variability for the Gulf of Mexico have been prepared. Examples include the monthly fields of surface and upper layer subsurface temperatures compiled from BTs and XBTs by Robinson (1973); the representations of steric sea level height around the Gulf by Whitaker (1971); compilations of temperature, salinity, oxygen, and phosphate measurements in the Gulf by Churgin and Halminski (1974); or wind fields over the Gulf by Rhodes et al. (1985, 1989).

## Classical Hydrography

Although surface waters of the Gulf of Mexico are greatly modified by heat and freshwater exchanges through the surface, river discharges, and wind mixing, no subsurface water masses of consequence are thought to be formed locally. Instead, water masses originate mainly in the Atlantic Ocean and are modified as they spread through the Caribbean Sea into the Gulf. These water masses enter the Gulf through the Yucatan Channel from the Yucatan Basin.

Sill depths of both the Caribbean and Gulf control which water masses eventually enter the Gulf. Using property distributions, McLellan and Nowlin (1963) estimated the sill depth in Yucatan Channel to be between 1,650 and 1,900 m. Bryant and Bryant (1990) show a Yucatan sill depth greater than 1,750 m but less than 2,000 m. Thus, global ocean water masses in depths greater than these cannot penetrate into the Gulf.

In the Caribbean, extrema in properties may be used to label four water masses in the upper 1,000 m: Subtropical Underwater, 18°C Sargasso Sea Water, Tropical Atlantic Central Water, and Antarctic Intermediate Water. The source regions for these waters are discussed in Morrison and Nowlin (1982). Small amounts of upper North Atlantic Deep Water may enter the Caribbean between 1,100 and 1,600 m through the Anegada-Jungfern Passage and between Hispaniola and Jamaica. However, they are mixed with Caribbean Mid-Water (Metcalf 1976) before entering the Gulf. The characteristic water properties, depths, and isopycnal surfaces for the property extrema of these water masses are given in **Table 4.1**.

Morrison and Nowlin (1977) described the water masses found in the Loop Current of the eastern Gulf, and Morrison et al. (1983) described the water masses and properties found offshore in the western Gulf. The characteristic water properties, depths, isopycnal surfaces, and range of values in the extrema cores are given in **Table 4.1**. These are briefly described below, together with a description of surface water and deep basin water.

Surface salinities in the Gulf generally are between 36.0 and 36.5. In waters bounded by the Loop Current, surface or near-surface pockets of low salinity (<36.0) water have been observed and are thought to be derived from low salinity Caribbean surface waters (Schroeder et al. 1974; Morrison and Nowlin 1977). Low-salinity surface waters also have been observed intruding over the shelf edges (e.g., <33 off Texas-Louisiana and <35 off Louisiana-Mississippi-Alabama). These are derived mainly from the Atchafalaya-Mississippi River system (Parr 1935; Schroeder et al. 1974).

The Subtropical Underwater is identified in the Caribbean Sea and in the Loop Current of the eastern Gulf of Mexico by a subsurface salinity maximum at 150 to 250 m centered about 25.40 $kg \cdot m^{-3}$ in sigma-$\theta$. In the Loop Current, maximum salinity values in this core are 36.7 to 36.8. Most of the water in the western Gulf of Mexico has a less pronounced upper salinity maximum—typically from 36.4 to 36.5, with even higher values seen from stations taken in recently-detached anticyclonic Loop Current rings that moved into the region. As the waters of the Loop Current enter the Gulf, those along its western boundary are vertically mixed by the interaction of the current with bathymetry, resulting in a flattening of the pronounced subsurface salinity maximum associated with the Subtropical Underwater source of those waters (Nowlin 1972). Moreover, after separation, Loop Current eddies eventually spin down in the Gulf. That process entails mixing, which likewise reduces the salinity at the maximum and may spread the lesser maximum over a larger range of depths—0 to 250 m according to Morrison et al. (1983).

Table 4.1. Water masses of the Caribbean Sea and Gulf of Mexico

| | Eastern Caribbean[1] | | | Eastern Gulf of Mexico[2] | | | | Western Gulf of Mexico[3] | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Water Mass | Depth m | $\sigma$ kg·m$^{-3}$ | Feature | Depth m | $\sigma$ kg·m$^{-3}$ | Feature | Range | Depth m | $\sigma$ kg·m$^{-3}$ | Feature | Range |
| SUW-LC | 150-250 | 25.40 | $S_{max}$ | 150-250 | 25.40 | $S_{max}$ | 36.7-36.8 | | | | |
| SUW | | | | 150-250 | 25.40 | $S_{max}$ | 36.4-36.5 | 0-250 | 25.40 | $S_{max}$ | 36.4-36.5 |
| 18°C W | 200-400 | 26.50 | $O_{2\,max}$ | 200-400 | 26.50 | $O_{2\,max}$ | 3.6-3.8 mL·L$^{-1}$ | | | | |
| TACW | 400-700 | 27.15 | $O_{2\,min}$ | 400-700 | 27.15 | $O_{2\,min}$ | 2.85-3.25 mL·L$^{-1}$ | 250-400 | 27.15 | $O_{2\,min}$ | 2.5-2.9 mL·L$^{-1}$ |
| AAIW | 600-800 | 27.30 | $NO_{3\,max}$ | na | na | $NO_{3\,max}$ | na | 500-700 | 27.30 | $NO_{3\,max}$ | 29-35 µg-at·L$^{-1}$ |
| AAIW | 700-900 | 27.40 | $PO_{4\,max}$ | 700-900 | 27.40 | $PO_{4\,max}$ | 1.8-2.5 µg-at·L$^{-1}$ | 600-800 | 27.40 | $PO_{4\,max}$ | 1.7-2.5 µg-at·L$^{-1}$ |
| AAIW | 600-900 | 27.40 | $S_{min}$ | 800-1000 | 27.50 | $S_{min}$ | 34.86-34.89 | 700-800 | 27.50 | $S_{min}$ | 34.88-34.89 |
| AAIW | 800-1000 | 27.50 | $SiO_{3\,max}$ | | 27.50 | $SiO_{3\,max}$ | * | | 27.50 | $SiO_{3\,max}$ | * |
| UNADW | 1100-1600 | 27.70 | $S_{max}$ | | | | | | | | |
| | at sill | 27.75 | $SiO_{3\,min}$ | | | | | | | | |
| | at sill | 27.75 | $PO_{4\,min}$ | | | | | | | | |
| | at sill | 27.75 | $NO_{3\,min}$ | | | | | | | | |
| MIX** | | | | 900-1200 | 27.70 | $SiO_{3\,max}$ | 23-25 µg-at·L$^{-1}$ | 1000-1100 | 27.70 | $SiO_{3\,max}$ | 24-28 µg-at·L$^{-1}$ |

1 - Morrison and Nowlin 1982

2 - Nowlin and McLellan 1967; Morrison and Nowlin 1977

3 - Nowlin and McLellan 1967; Morrison et al. 1983

na = data not available for the study

SUW-LC = Subtropical Underwater within the Loop Current and Caribbean Sea
SUW = Subtropical Underwater in the Gulf but outside the Loop Current
18°C W = 18°C Sargasso Sea Water
TACW = Tropical Atlantic Central Water
AAIW = Antarctic Intermediate Water
UNADW = Upper North Atlantic Deep Water
**MIX = Mixture of low silicate UNADW and very high silicate Caribbean Mid-Water
*high $SiO_3$ in AAIW and MIX waters results in broad $SiO_3$ maximum approximately from 27.50 to 27.70

In the Caribbean Sea and Loop Current, the water mass below Subtropical Underwater is 18°C Sargasso Sea Water. It is found at depths from 200 to 400 m and is identified by an oxygen maximum centered about 26.5 $kg{\cdot}m^{-3}$ in sigma-$\theta$. Oxygen values greater than 4.2 $mL{\cdot}L^{-1}$ are found in the Caribbean near entrances of this water from the greater North Atlantic. Within the Loop Current, oxygen maxima are only between 3.6-3.8 $mL{\cdot}L^{-1}$. Remnants of this water can be identified by weak relative oxygen maxima with values slightly greater than 3 $mL{\cdot}L^{-1}$ near sigma-$\theta$ of 26.5 $kg{\cdot}m^{-3}$ in some western Gulf stations, but oxygen is not a useful tracer there.

Tropical Atlantic Central Water is identified by relative minima in vertical profiles of dissolved oxygen. In the Caribbean Sea and Loop Current, it is found from 400 to 700 m and identified by oxygen values below 3 $mL{\cdot}L^{-1}$ centered about 27.15 $kg{\cdot}m^{-3}$ in sigma-$\theta$. This water is clearly seen with similar characteristics at western Gulf stations although at depths closer to 400 m.

Beneath the Tropical Atlantic Central Water and extending over a vertical range of 700 to 1,200 m are remnants of the Antarctic Intermediate Water. This water is identified in the Caribbean and Loop Current by a nitrate maximum, a phosphate maximum, and a salinity minimum found at increasing depths. This water is clearly seen in the western Gulf with similar extrema, but at shallower depths ranging from 500 to 1,100 m.

The silicate maximum associated with Antarctic Intermediate Water also is found generally beneath the salinity minimum in the Caribbean. By the time this water mass reaches the Gulf of Mexico, this silicate maximum has been masked by the presence of very high silicate waters below it. In both the eastern and western Gulf, silicates are high (~23 to 25 $\mu g\text{-}at{\cdot}L^{-1}$) throughout the 27.50 to 27.70 sigma-$\theta$ range. Those at the 27.50 level can be associated with Antarctic Intermediate Water. Those at deeper levels to 27.70 result from a mixture in the Caribbean Sea of low silicate upper North Atlantic Deep Water and the very high silicate Caribbean Mid-Water beneath it (Morrison et al. 1983). These high concentrations are attributed to very slow renewal of the Caribbean Sea deep waters and re-solution of silicate from sediments (Richards 1958; Metcalf 1976; Morrison et al. 1983).

Waters of the deep basin of the Gulf from below the sill depth to the bottom exhibit no discernible horizontal variations and only small vertical gradients in potential temperature and salinity (McLellan and Nowlin 1963; Nowlin and McLellan 1967). Using a number of data sets from different cruises, similar results were found for dissolved oxygen by Nowlin et al. (1969; they also concluded that the dissolved oxygen data of McLellan and Nowlin [1963] were faulty). Observations below the sill depth had a mean potential temperature of about 4.02°C, a mean salinity of 34.972, and a mean dissolved oxygen of 5.0 $mL{\cdot}L^{-1}$ (McLellan and Nowlin 1963; Nowlin et al. 1969). The lack of gradients suggests either that basin water has a common source or the residence time is great enough to erode away any horizontal gradients by exchange processes (Nowlin 1972). The potential temperature versus salinity relationships from stations on the Gulf and Caribbean sides of the Yucatan sill depth are very similar, which is consistent with possible present-day displacement of deep Gulf waters by Caribbean Sea waters (Nowlin 1972).

Shown in **Figure 4.2** are composite plots of temperature vs. salinity, temperature vs. depth, and salinity vs. depth for the winter cruise 62-H-3 that covered the entire Gulf. Seen in these plots is the large range of near-surface values, especially because sampling extended over the shelves. Also seen are rather large ranges of depths at which specific values of temperature or salinity are found in the main pycnocline and the very narrow ranges at depth. This observed near-uniformity of both salinity and temperature (and thus density) on depth surfaces implies that the major geostrophic currents in the deep Gulf of Mexico are expected to be nearly barotropic. Later in this review, that is demonstrated to be the case. However, there must be some horizontal density gradients, especially near continental slopes, because deep currents appear intensified near the boundaries.

**Figure 4.3** better illustrates upper layer waters with two different distributions. Caribbean type water with a high maximum salinity marking the core of the Subtropical Underwater (SUW) is found within the region enclosed by the Loop Current and LCEs, illustrated in the figure by station 215 which is within an older LCE found in the northwestern Gulf. The second type of distribution is illustrated in the figure by station 165 which was located within a cyclone in the northwestern Gulf; there the salinity maximum at the SUW core is much reduced by vertical mixing (characteristic of open Gulf waters outside of the Loop Current and of LCEs) and temperatures and salinities are found higher in the water column than within the LCEs.

The pronounced subsurface salinity maximum associated with the SUW core together with the greater depth of isotherms serve as markers by which to easily distinguish LCEs from cyclonic rings or the background waters of the Gulf. Moreover, the salinity at the SUW core and the depth of upper layer (e.g., 15° to 20°C) isotherms are often plotted as horizontal distributions to indicate not only the signs and extents but also the intensities of Gulf eddies.

Robinson (1973) described the seasonal variability of the upper waters of the Gulf in terms of the monthly mean temperatures of the surface and upper 150 m and the depth to the top of the thermocline. Contoured fields of temperature at six levels and of the thermocline depth are pictured. Also shown are time series of temperatures at distinct levels averaged for each 2.5° x 2.5° square. Robinson's graphics illustrate the oceanic thermal response of the northern Gulf to the annual cycle of insolation (**Figure 4.4**). The surface waters warm in spring and summer, with maxima in July-August, and cool in fall and winter, with minima in February. Deeper waters of the upper 150 m also show warming, but with maxima smaller and later in the year with increasing depth. Minima are similar in time.

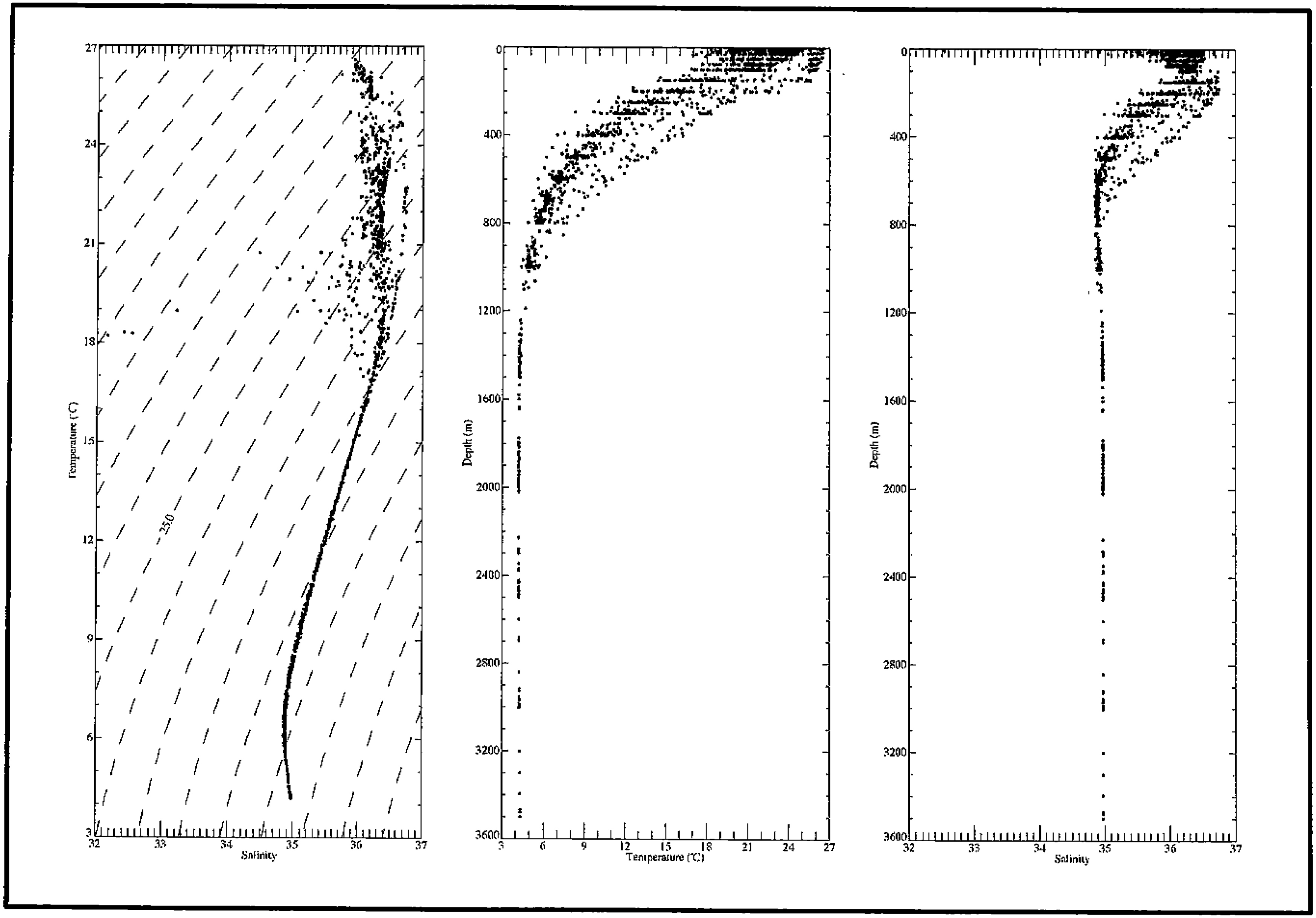


Figure 4.2. Temperature vs. salinity, temperature vs. depth, and salinity vs. depth based on all data collected during *Hidalgo* cruise 62-H-3, February-March 1962.

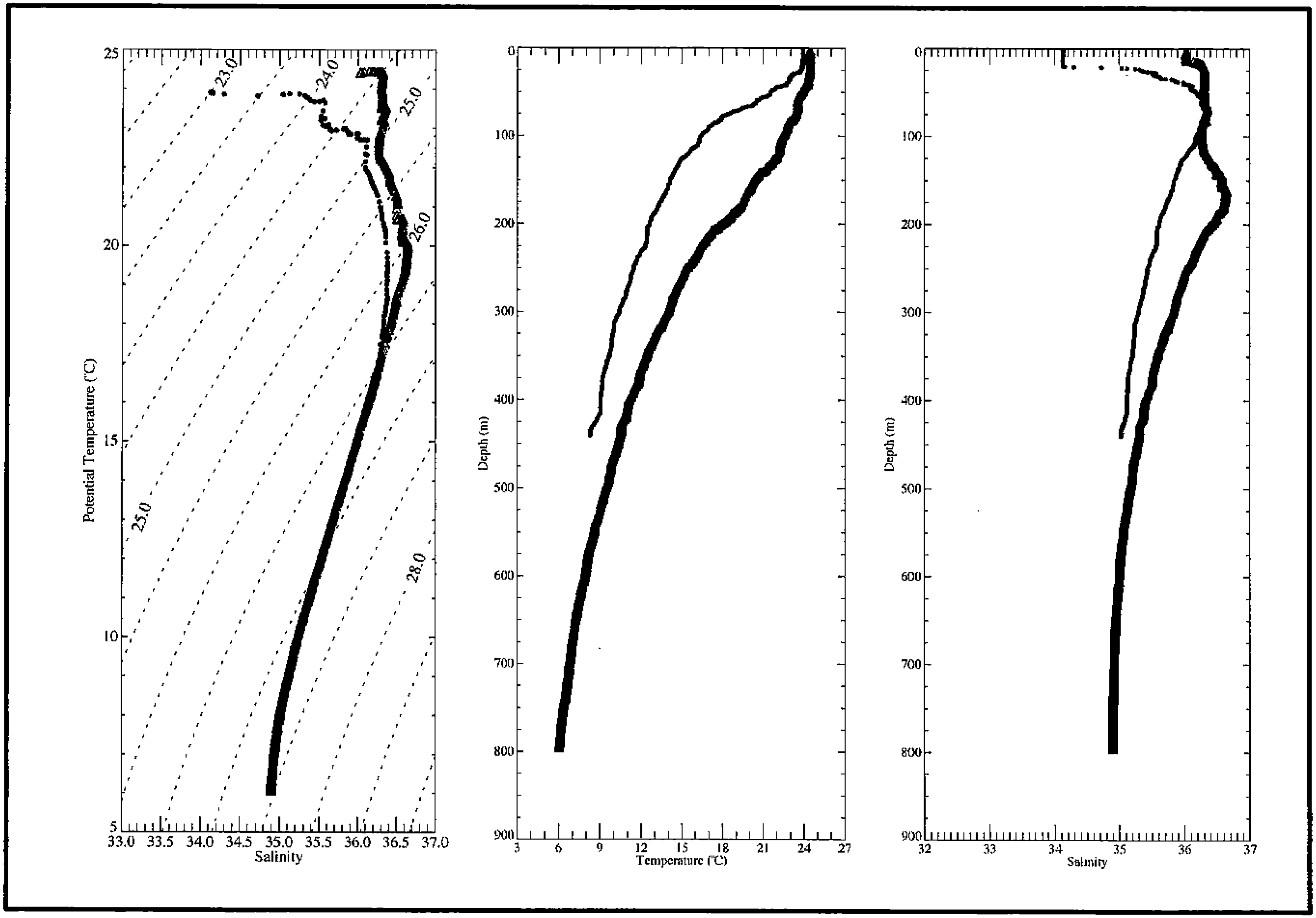


Figure 4.3. Temperature vs. salinity, temperature vs. depth, and salinity vs. depth for two stations made in early May 1993 over the continental slope off Texas. Station 215 (large triangles) was in the remnant of a Loop Current Eddy and station 165 (small circles) was in a cyclone. Station positions relative to sea surface height anomaly are shown in Figure 4.13.

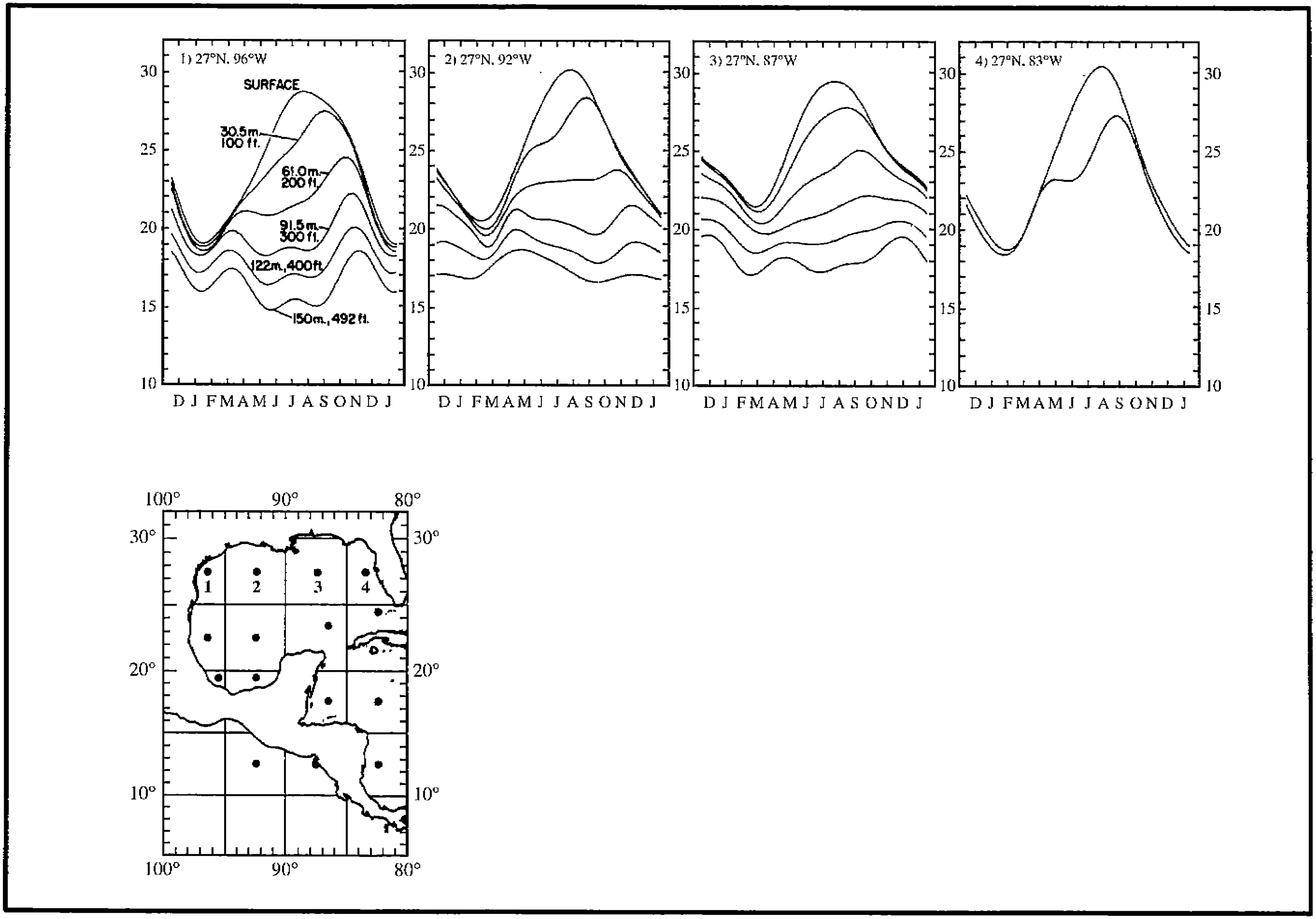


Figure 4.4. Annual time series of monthly averaged temperatures at six depths for four regions in the northern Gulf of Mexico (From: Robinson 1973). Locations of regions are shown.

## Low-Frequency, Local Wind Forcing

One permanent circulation feature in the deepwater Gulf thought to be locally wind driven is an anticyclonic (clockwise rotating) feature oriented about ENE-WSW with its western extent near 24°N off Mexico. It can be seen centered near 24.5°N, 95°W in **Figure 4.1**. This feature has been noted by Behringer et al. (1977), among others. There has been considerable debate regarding the causal mechanism for this anticyclonic circulation and the associated western boundary current along the coast of Mexico. Elliott (1979, 1982) attributed LCEs as the primary source of energy for the feature, but Sturges and Blaha (1975), Blaha and Sturges (1981), and Sturges (1993) argued that wind stress curl over the western Gulf is adequate to drive an anticyclonic circulation with a western boundary current. Sturges (1993) found annual variability in the wind stress curl corresponding to the strongest observed boundary current in July and the weakest in October. Based on ship drift data, he showed the maximum northward surface speeds in the western boundary current were 25 to 30 $cm{\cdot}s^{-1}$ in July and about 5 $cm{\cdot}s^{-1}$ in October; the northward transport in the western limb of the feature was estimated to vary from 2.5 to 7.5 x $10^6$ $m^3{\cdot}s^{-1}$. Sturges reasoned that the contribution of LCEs to forcing this anticyclonic feature must be relatively small. Vidal et al. (1999) attempted to attribute the presence of a northward flow along the western Gulf boundary to ring-slope-ring interactions, but their evidence does not seem convincing. The numerical circulation model of the Gulf reported by Oey (1995) shows a seasonal, wind-driven boundary current in the western Gulf. It is strongest in July and August some 1 to 2 months after the largest negative wind stress curl, in good agreement with the observations reported by Sturges (1993).

Geopotential anomaly, derived from temperature and salinity data, and SSHA, derived from satellite altimeter data, provide evidence of a permanent cyclonic circulation in the Bay of Campeche in the southwest Gulf of Mexico (18° to 22°N and 92° to 97°W) as noted by Vázquez (1975). Analyzing the geopotential anomaly of the surface relative to 450 db from 13 cruises in the southern Gulf of Mexico during the period 1958-1991 with empirical orthogonal functions, Vázquez (1993) showed the dominant mode represented 93% of the variance and yielded a cyclonic flow pattern. The pattern showed a central low of 4 ± 1 dyn cm below the basin mean with a mean central location of about 19.7°N, 94.5°W (**Figure 4.5**, after Vázquez 1993). Fields of SSHA from May 1992 through December 1998 also show a cyclonic gyre in the Bay of Campeche. Averaging one field per month yields a mean pattern consisting of a central low of 13 ± 5 dyn cm and a center located about 20.8°N, 94.5°W. The difference in the mean lows from the geopotential anomaly and SSHA suggests there is a strong barotropic component in the cyclonic gyre. The most plausible forcing for the cyclone is the positive wind torque, which is present in the area throughout the year (Velasco and Winant 1996). The seasonal pattern of SSHA shows the cyclone is at minimum strength in summer, consistent with the minimum positive wind torque that occurs in season.

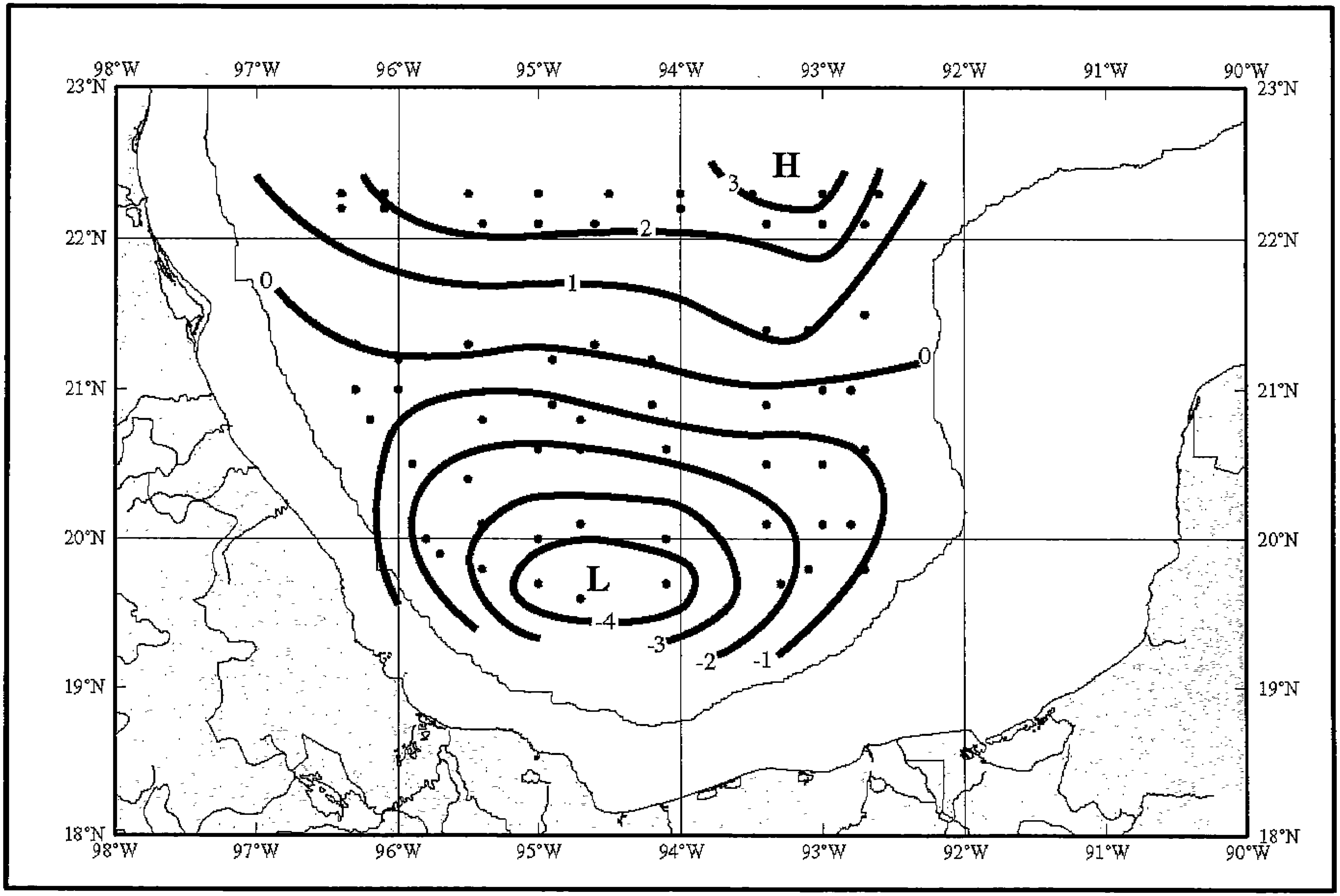


Figure 4.5. Contours of mean dynamic height (dyn cm) of surface relative to 450 db, constructed by averaging the first empirical orthogonal modes (EOF) obtained from an EOF analysis of the geopotential anomaly for 13 cruises covering the area (From: Vázquez 1993). The first mode contained 93% of the variance.

## Surface Wind Waves

Oceanic surface gravity waves with periods of 1 to 30 s contain large amounts of energy. Produced by wind acting at the air-sea interface, they consist of two types: sea (also referred to as wind waves) has typical periods of 0.2 to 9 s and is generated by local winds; swell, with periods of 9 to 30 s, are waves that have propagated from another region in which they were generated.

Because the fetch in the Gulf of Mexico is limited, surface gravity waves having large amplitudes and long periods (≥10 s) are rare (McGrail and Carnes 1983 and references therein) and are generally associated with extreme episodic weather events such as hurricanes (National Data Buoy Center [NDBC] 1990).

The NDBC of the National Oceanic and Atmospheric Administration maintains meteorological buoys in the Gulf of Mexico. Three of these are located along approximately 26°N latitude in waters with depths near 3,200 m. **Table 4.2** gives the locations of these buoys, together with water depths and the periods of records (~15 to 20 years) used by NDBC to compute the significant wave height and wave period from the buoys. Wave data are calculated by NDBC by applying spectral analysis to data from accelerometers or inclinometers that measure the heave acceleration or vertical displacement of the buoy hull during the wave acquisition time (Steele and Mettlach 1993). The significant wave height is calculated as the average of the highest one-third of all the wave heights measured during a 20-minute sampling period. The average wave period is the average period of all waves during the sampling period. The dominant wave period is the period with the maximum wave energy. Also shown in **Table 4.2** is information for one NDBC buoy (42020) located over the shelf off south Texas. **Table 4.3** gives the monthly and annual means of significant wave height, average wave period, and dominant wave period for the four buoys as computed by NDBC (data were obtained from NDBC Internet site, www.ndbc.noaa.gov).

Table 4.2. Location, water depth, and period of records, used for computations given in Table 4.3, for marine buoys in the Gulf of Mexico

| Buoy Number | Period of Record | Latitude (°N) | Longitude (°W) | Total water depth (m) |
|---|---|---|---|---|
| 42001 | 01/1976 - 12/1993 | 25.93 | 89.65 | 3,246.0 |
| 42002 | 06/1973 - 12/1993 | 25.89 | 93.57 | 3,200.0 |
| 42003 | 11/1976 - 12/1993 | 25.94 | 85.91 | 3,164.0 |
| 42020 | 05/1990 - 12/1993 | 26.92 | 96.70 | 78.6 |

Throughout the deep water Gulf of Mexico, the patterns of significant wave height and wave period are similar. The monthly mean significant wave heights average 1.1 m and range from 0.6 to 1.5 m, and the average wave period ranges from 4.1 to 5.2 s with a mean of 4.8 s (**Table 4.3**). Approximately 92% to 94% of the wave heights were 2 m or less at the deep water buoys. The patterns at the shallow water buoy were similar, and 92% of the wave heights were 2 m or less.

Table 4.3. Monthly and annual mean significant wave height (m) and extremes based on hourly observations from marine buoys (data from the National Buoy Data Center). Buoys 42001 (central Gulf), 42002 (western Gulf), and 42003 (eastern Gulf) are located in depths of approximately 3200 m; buoy 42020 (western Gulf) is located over the shelf in water depth of approximately 80 m.

| Buoy | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Mean Significant Wave Height (m)* | | | | | | | | | | | | | |
| 42001 | 1.3 | 1.4 | 1.4 | 1.2 | 1.0 | 0.8 | 0.6 | 0.6 | 0.9 | 1.2 | 1.4 | 1.4 | 1.1±0.7 |
| 42002 | 1.4 | 1.5 | 1.5 | 1.3 | 1.1 | 0.9 | 0.7 | 0.6 | 1.0 | 1.2 | 1.5 | 1.5 | 1.2±0.7 |
| 42003 | 1.3 | 1.4 | 1.4 | 1.1 | 0.9 | 0.8 | 0.6 | 0.6 | 0.8 | 1.1 | 1.4 | 1.3 | 1.0±0.7 |
| 42020 | 1.5 | 1.3 | 1.4 | 1.4 | 1.2 | 1.2 | 1.1 | 0.7 | 1.0 | 1.3 | 1.6 | 1.5 | 1.3±0.7 |
| *Maximum Significant Wave Height (m)* | | | | | | | | | | | | | |
| 42001 | 5.3 | 6.4 | 9.1 | 4.7 | 3.4 | 2.9 | 5.1 | 9.1 | 6.6 | 6.8 | 6.6 | 5.5 | 9.1 |
| 42002 | 5.2 | 7.4 | 7.8 | 5.9 | 3.4 | 5.1 | 3.1 | 6.9 | 9.7 | 7.2 | 8.4 | 5.0 | 9.7 |
| 42003 | 6.1 | 5.7 | 9.2 | 4.9 | 4.7 | 3.6 | 3.3 | 6.4 | 8.9 | 4.4 | 10.7 | 4.9 | 10.7 |
| 42020 | 5.0 | 3.8 | 6.1 | 3.9 | 3.3 | 4.6 | 2.4 | 2.7 | 3.4 | 3.8 | 4.9 | 4.6 | 6.1 |
| *Average Wave Period (seconds)* | | | | | | | | | | | | | |
| 42001 | 5.0 | 5.1 | 5.1 | 4.8 | 4.6 | 4.4 | 4.1 | 4.2 | 4.6 | 4.8 | 5.1 | 5.0 | 4.7±0.9 |
| 42002 | 5.1 | 5.2 | 5.2 | 5.0 | 4.8 | 4.7 | 4.4 | 4.3 | 4.7 | 5.0 | 5.2 | 5.2 | 4.9±0.8 |
| 42003 | 4.8 | 4.9 | 5.0 | 4.7 | 4.7 | 4.8 | 4.7 | 4.5 | 4.4 | 4.8 | 5.0 | 4.9 | 4.8±0.8 |
| 42020 | 5.1 | 4.9 | 5.1 | 5.1 | 4.8 | 4.7 | 4.5 | 4.1 | 4.5 | 5.0 | 5.2 | 5.1 | 4.8±0.8 |
| *Dominant Wave Period (seconds)* | | | | | | | | | | | | | |
| 42001 | 6.4 | 6.6 | 6.6 | 6.2 | 5.8 | 5.5 | 5.2 | 5.3 | 5.7 | 6.2 | 6.7 | 6.5 | 6.1±1.5 |
| 42002 | 6.5 | 6.7 | 6.8 | 6.4 | 6.2 | 6.0 | 5.5 | 5.3 | 5.9 | 6.5 | 6.8 | 6.7 | 6.3±1.5 |
| 42003 | 6.2 | 6.4 | 6.5 | 6.0 | 5.9 | 6.1 | 6.2 | 5.7 | 5.6 | 6.0 | 6.5 | 6.3 | 6.1±1.4 |
| 42020 | 6.7 | 6.4 | 6.6 | 6.7 | 6.2 | 6.1 | 5.8 | 5.1 | 5.7 | 6.6 | 6.8 | 6.7 | 6.3±1.4 |

The higher mean significant wave heights and longer average and dominant wave periods are seen to occur between November and March. As expected, the lowest heights and shortest periods occur in summertime, when fewer frontal passages or other storms occur (Nowlin et al. 1998a). Although the maxima significant wave heights for the period of record generally are smallest from April to July, there is a less regular seasonal pattern for the maximum heights than for the mean heights. This is because the maxima are associated with energetic, episodic wind events, such as hurricanes, which occur between June and November, or cyclogenesis events, which occur mainly between November and May (Nowlin et al. 1998a). With sufficiently long records, it is likely that the maximum significant wave height would increase to 9 m or more for all months since strong storms could occur in any month; but, because extreme events are rare, the mean significant wave heights likely would remain similar to those shown.

The energetic atmospheric events, which produce the larger waves, are of great concern in the design of offshore structures. Considerable effort has been spent to estimate these waves, both directional spectra and kinematics, from meteorological data through the use of hindcast modeling and to validate such models (e.g., Cardone et al. 1976; Forristall et al. 1978; Forristall et al. 1980). As part of model validation, Ward et al. (1978) developed a hurricane climatology covering the period 1900 through 1974 based on wave data from 48 Gulf of Mexico storms with a central pressure of 980 mb or less. They found maximum significant wave heights ranging from 4.6 to 15.5 m with an average of 9.7 m; 27 of the 48 storms exceeded 10 m. Using the Cardone et al. (1976) wave hindcast model validated by Ward et al. (1978), Haring and Heideman (1978) estimated rare wave heights associated with 22 severe hurricanes occurring in the Gulf of Mexico between 1900 and 1977. They found the model results varied little between the three sectors studied off the coasts of south Texas, east Texas-west Louisiana, and east Louisiana-Mississippi-Alabama. They found 100-yr significant wave heights of 12 to 13 m in water depths of 70 to 700 m and 11 to 12 m in shallower waters; the dominant spectral wave periods were 14 to 15 s in all water depths studied. Maximum 100-yr wave heights were estimated to be 20 to 22 m.

Tracy and Cialone (1996) reported that during Hurricane Opal, which was an intense category 4 hurricane in October 1995, the observed maximum significant wave height and maximum peak period in the central and east deepwater Gulf of Mexico reached 10 m and 13 s at buoy 42001, near which Opal passed by, and 8 m and 22 s at buoy 42003. In August 1992, Hurricane Andrew, which was within 2 mb of becoming a category 5 hurricane, generated significant surface waves that were well-documented over both the deep water and the Texas-Louisiana shelf. Stone et al. (1993) and Breaker et al. (1994) reported on measurements made at buoys 42003, which was ~50 km southwest of the hurricane at its closest, and buoy 42001, which was ~240 km southwest. Prior to the hurricane, seas at 42003 had wave heights of less than 1 m and wave periods of 4 to 8 s. As the hurricane passed near the buoy, seas reached a maximum significant wave height of over 6 m and peak wave periods of 17 s. Measurements from buoy 42001 also showed the influence of Hurricane Andrew with a time lag of approximately 9 hr (Stone et al., 1993). The significant wave height increased from less than 2 m before the hurricane to over 4 m, while the wave period increased from ~7 s to 17 s. Waves at buoy

42003 were generated primarily by the hurricane until it passed by; waves at buoy 42001, however, were primarily swell (Breaker et al. 1994).

Hurricanes, however, are not the only intense storms that can generate significant waves. Approximately 10 times each year, winter cyclones develop over the Gulf of Mexico in a process called cyclogenesis (Hsu 1988). On 12 March 1993, an intense extratropical cyclone, comparable to a category 1 hurricane, developed off the south Texas coast (Nowlin et al. 1998a). From 0600 to 1800 UTC on 12 March, it moved eastward along the Texas shelf edge before turning to the northeast. At about 0900 UTC 13 March, it exited the Gulf over Florida at about 85°W (Schumann et al. 1995). Maxima for significant wave height, average wave period, and dominant wave period were, respectively, 9.2 m, 9.7 s, and 14.3 s at eastern buoy 42003, 9.1 m, 9.8 s, and 12.5 s at central buoy 42001, and 7.8 m, 9.1 s, and 12.5 s at western buoy 42002. The peaks in height and period progressed in time from the western to eastern buoys. The significant wave heights were greater the farther east the buoys, reflecting the condition that for cyclones, the maximum wave heights occur to the right of the path of forward movement of the storm systems (U.S. Army Corps of Engineers 1984). The buoys in the central and eastern Gulf were on the right side of the storm for a longer time than was the buoy on the west. On the shelf off south Texas at buoy 42020 the maximum significant wave height was 6.1 m. The maximum record-length significant wave heights at buoys 42001 and 42020 were associated with this cyclone.

## Forcing By Energetic, Episodic Wind Events

Perhaps the currents of longest concern to oil and gas operators are those resulting from strong, episodic wind events, such as tropical cyclones (especially hurricanes), extratropical cyclones, and cold air outbreaks. Such wind events can result in extreme waves and cause currents with speeds of 100 to 150 $\mathrm{cm \cdot s^{-1}}$ over the continental shelves. Recent examples for the Texas-Louisiana shelf and upper slope are given in Nowlin et al. (1998a). Others (e.g., Molinari and Mayer 1982; Brooks 1983, 1984) have measured the effects of such phenomena down to depths of 700 (980) m over the continental slopes in the northwestern (northeastern) Gulf.

Tropical conditions normally prevail over the Gulf from May or June until October or November. The nominal hurricane season is 1 June through 30 November. **Figure 4.6** shows horizontal current vectors (hourly values from 3-hr low-passed records) during late August 1992 from two locations off Louisiana at approximately 90.5°W on the shelf edge and upper slope. **Figure 4.7** shows mooring locations discussed in this review. Moorings 13 and 12 were located in water depths of 200 and 504 m, respectively. Current meter depths are indicated. The eye of Hurricane Andrew passed on a northeastward track about 85 km north of mooring 13 at 0000 UTC on 26 August. Near-surface instruments recorded a large surge of water directed to the left of the storm's track just before the passage of the eye; maximum values at 10 m on mooring 13 reached 163 $\mathrm{cm \cdot s^{-1}}$. Following the initial surge, an oscillation with near inertial period was set up that penetrated, with diminished amplitude, to the deepest instrument on mooring 13 approximately 24 hours after the initial surge. Some time delay and considerable

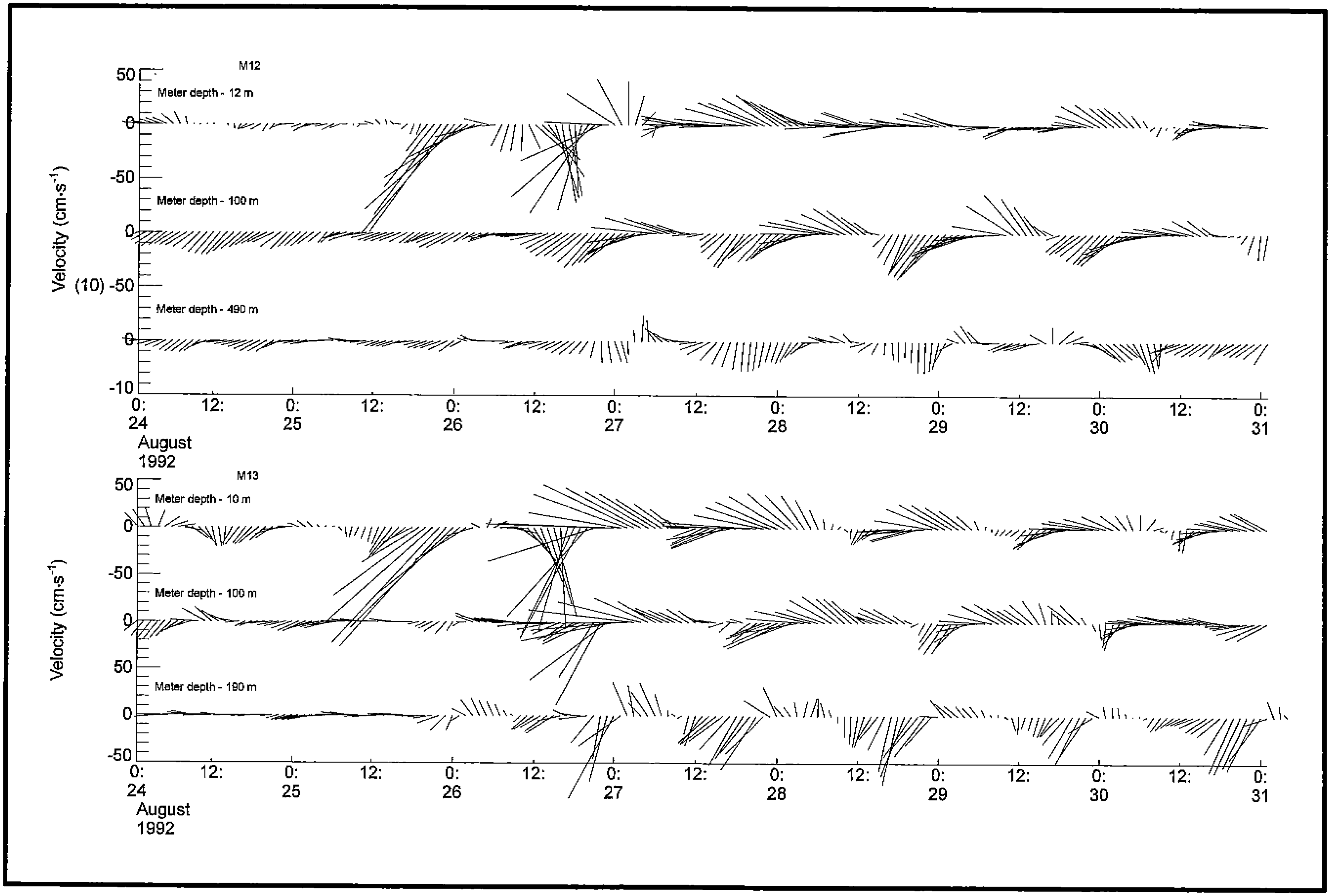


Figure 4.6. Horizontal current vectors (hourly values from 3-hr low-passed records) during late August 1992 from two locations off Louisiana at approximately 90.5°W on the shelf edge and upper slope. The cross-shelf components are oriented up and down (up is on shore) and along shelf components are oriented across the figure (generally eastward to the right). Moorings 13 and 12 were located in water depths of 200 and 504 m; current meter depths are indicated. The eye of Hurricane Andrew passed on a northeastward track approximately 85 km north of mooring 13 at about 0000 UTC on 26 August.

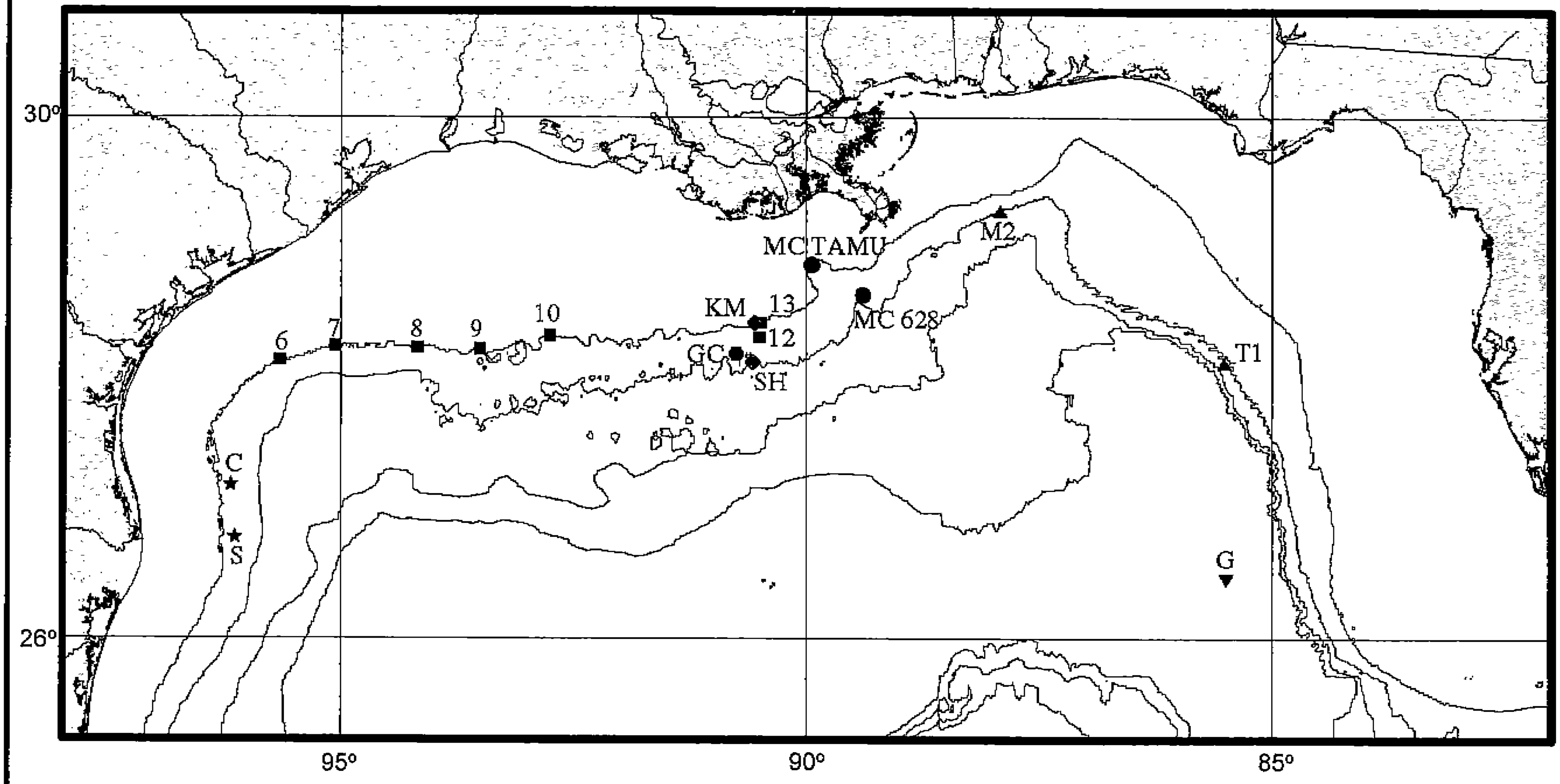


Figure 4.7. Locations of current measurements or model output used in figures within this review. Stars are moorings S and C; squares are LATEX moorings 6-10, 12, and 13; grey diamonds are locations for CCAR model output; triangles denote moorings T1 and M2 (Molinari and Mayer 1982); an inverted triangle is SAIC mooring G; circles denote moorings in the Mississippi Canyon (Block 628 and TAMU); and a hexagon is the Green Canyon Block 200 mooring. Bathymetry contours are 200, 1,000, 2,000, and 3,000 m.

decrease in amplitude with depth is seen, although the maximum speed at 190 m exceeded 100 cm·s$^{-1}$. There was a coherent but weak response at 490 m at mooring 12 (note change in velocity scale). The inertial oscillation continued for about a week with diminishing amplitudes. A review of shallow currents associated with Andrew is presented by Keen and Glen (1999).

Many studies of hurricane effects on the underlying ocean focus on surface wind waves or storm surges, but a number consider the effects on currents and thermal (and density) structures. Among those with a focus on hurricanes in the Gulf of Mexico are Leipper (1967), O'Brien and Reid (1967), O'Brien (1967), Forristall (1974), Forristall (1980), and Cooper and Thompson (1989a, 1989b). The papers by Sanford et al. (1987) and Price et al. (1994) give results of a study of direct current observations within hurricanes accompanied by model hindcasting and comparisons; they are summarized here. Although the hurricanes studied were Norbert (off western Mexico at ~20°N in September 1984) and Josephine and Gloria (off the southeast Atlantic coast at ~30°N in October 1984 and September 1985), the results should be equally applicable to the Gulf of Mexico for hurricanes of similar characteristics. These authors measured upper ocean (200 m) currents by deploying aircraft expendable current profilers (AXCP) in a pattern through each hurricane using a weather reconnaissance plane from which meteorological observations were taken. The oceanic reaction to a severe storm can be separated into the initial "forced response" with the arrival of the storm and the "relaxation stage response" with the passage and retreat of the storm. The AXCP measurements were analyzed to separate surface mixed layer and surface wave currents. The maximum vertically-uniform currents in the surface mixed layer (~50 m) in the three storms were found to be 73, 110, and 170 cm·s$^{-1}$, largest in the right quadrant. The vertical shear of the mixed layer currents seemed on the order of 20 to 30 cm/s. The maximum surface currents from combining both mixed layer and surface wave components were estimated at 133 to 346 cm·s$^{-1}$. These results are consistent with their model results. Their models could account for between 35% to 90% (with an average of 85%) of the variance of the mixed layer currents, the agreement increased with increasing current speed. The mixed layer currents showed patterns of divergence centered behind the eyes of the storms; these lead to upwelling at the base of that layer and a lowering of sea level above. The mixed layer divergence and the associated distortion of the thermal and density fields occur on near inertial periods, giving rise to inertial waves with wave lengths of several hundred kilometers and decay scales of 5 to 10 d (e.g., see Brooks 1983 results from Gulf of Mexico in next paragraph).

**Figure 4.8** shows hourly current components (u positive to the east and v positive to the north) measured at indicated depths from 200 to 700 m on moorings S (26°N, 96°17'W) and C (55 km north of S). Both moorings were approximately on the 730-m isobath. About 0000 UTC on 10 August 1980, the eye of Hurricane Allen passed some 65 km WSW of mooring S on a track toward the NNW. The effects of the hurricane passage were reported by Brooks (1983). Currents were stronger at mooring C than at S, although currents at both were affected—even to within 20 m of the bottom. A strong southward, along-shelf current occurred with the landward passage of the hurricane; maximum speeds exceeded 90 cm·s$^{-1}$ in the thermocline at 200 m and 15 cm·s$^{-1}$ at 700 m.

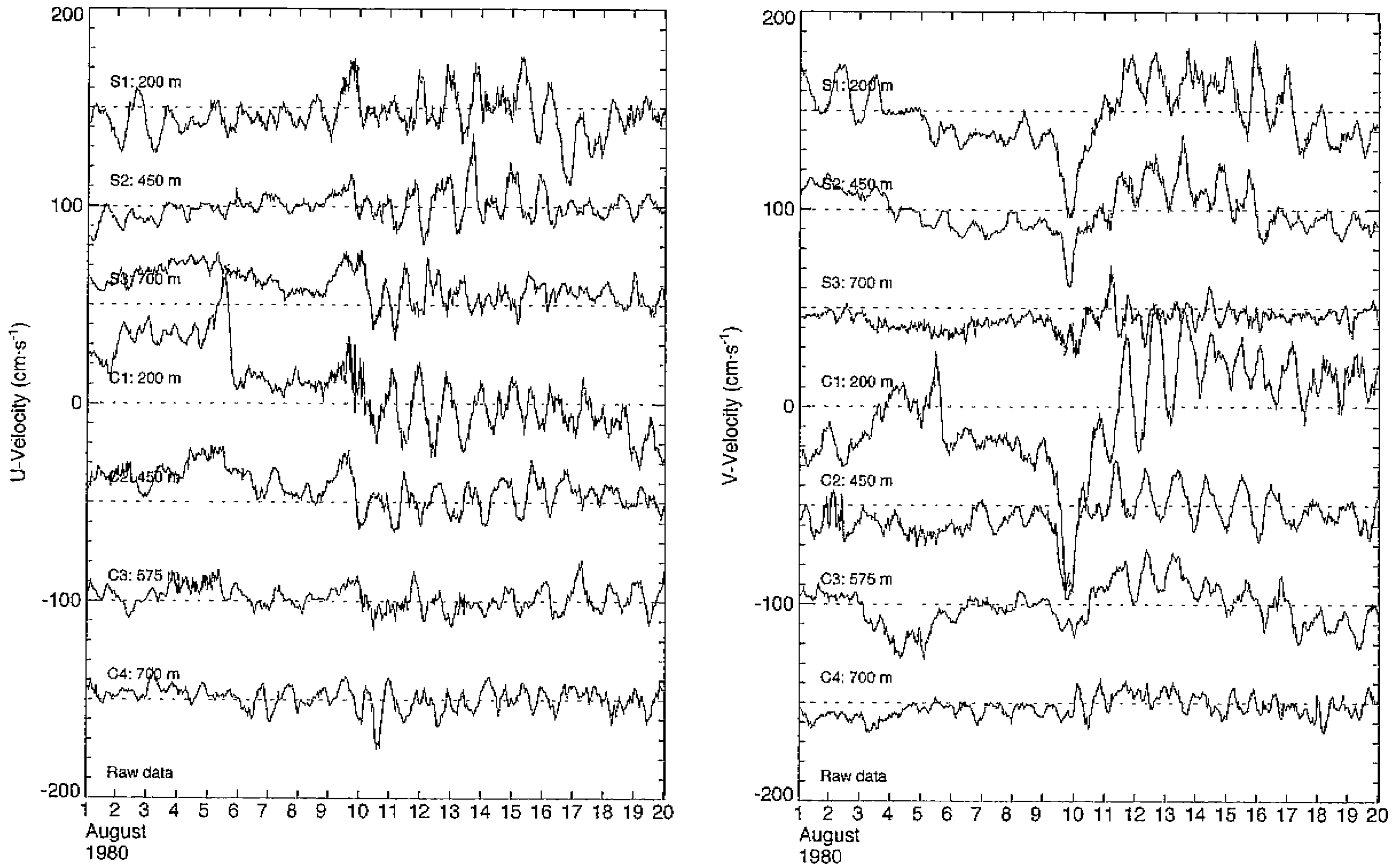


Figure 4.8. Components (u positive to the east and v positive to the north) of hourly currents measured at indicated depths on moorings S (26°N, 96°10'W) and C (55 km north of S). Both moorings were approximately on the 730-m isobath. The eye of Hurricane Allen, on a track toward the NNW, passed about 65 km WSW of mooring S at 0000 UTC on 10 August 1980.

This surge triggered a series of internal waves with near inertial period; these elliptical motions had maximum speeds along shore which reached a range of 50 $cm \cdot s^{-1}$ within about 3 days and then lasted for about 5 days with decreasing amplitudes. These oscillations were coherent over the scale of mooring separation (55 km) and with depth.

From October or November until March or April the Gulf experiences intrusions of cold, dry continental air masses. These result in the formation of extratropical cyclones and cold air outbreaks, both of which can cause quite energetic surface currents. On average about 10 to 12 extratropical cyclones are formed over the northern Gulf per year; the number of frontal passages varies from 0 to 2 per month in summer to order 10 per month in winter months. To illustrate the effects of an extreme extratropical cyclone, **Figure 4.9** shows eastward (u) and northward (v) components of currents (hourly values from 3-hr low-passed records) from two moorings located off Louisiana at approximately 90.5°W. Mooring 13 was in water of depth 200 m; mooring 12 was in water depth of 504 m. On 12 March 1993, a class 5 extratropical cyclone moved from west to east across the Texas-Louisiana shelf with its center approximately over the 1,500 m isobath. Initially the flow over the outer shelf and slope was toward the northeast as part of an induced cyclonic circulation over the Texas-Louisiana shelf. Following the passage of the storm out of the area, on 13 March, there occurred a surge to the southwest followed by a period (14 to 17 March) of strong motion toward the northeast, with diurnal modulation. This was followed by an energetic near-inertial oscillation with decreasing amplitude lasting for over a week. The maximum observed speeds associated with this event were: 65, 22, 67, 41, and 35 $cm \cdot s^{-1}$ at mooring/depth (m) 12/12, 12/100, 13/10, 13/100, and 13/190, respectively.

During the LATEX program of the early 1990's sponsored by MMS, a class of energetic surface currents previously unreported in the Gulf of Mexico were found over the Texas and Louisiana shelves (DiMarco et al. 2000). To illustrate, **Figure 4.10** shows eastward (u) and northward (v) components of currents from 3- to 40-hr band-passed records made in July and December 1992 at mooring 10 located off Louisiana at 27.94°N, 92.75°W in water of depth 200 m. The July sequence shows maximum amplitudes of 40 to 60 $cm \cdot s^{-1}$ at depth of 12 m for the situation of light winds. The period of diminished amplitudes followed an atmospheric frontal passage. These are near-circular, clockwise-rotating oscillations with period near 24.0 hr. They seem to be an illustration of thermally induced cycling (Price et al. 1986) in which large amplitude rotary currents can exist in thin mixed layers typical of summer. By contrast, the December sequence shown in **Figure 4.10** evidences no such behavior. Many examples of such currents, in phase at distinct locations, exist for the Texas-Louisiana shelf, and by implication they exist further offshore. Currents at 1-m depth have been observed to reach 100 $cm \cdot s^{-1}$.

Clearly episodic wind events can cause major currents in the deepwater Gulf. The initial currents give rise to inertial oscillations lasting for up to about ten days with decreasing amplitudes, superimposed on longer period signals. The number of direct measurements of energetic currents forced by episodic wind events is rather limited in the deepwater region of the Gulf of Mexico. Additional examples over the Texas-Louisiana continental shelf edge and slope are given in Nowlin et al. (1998a). The references contain other

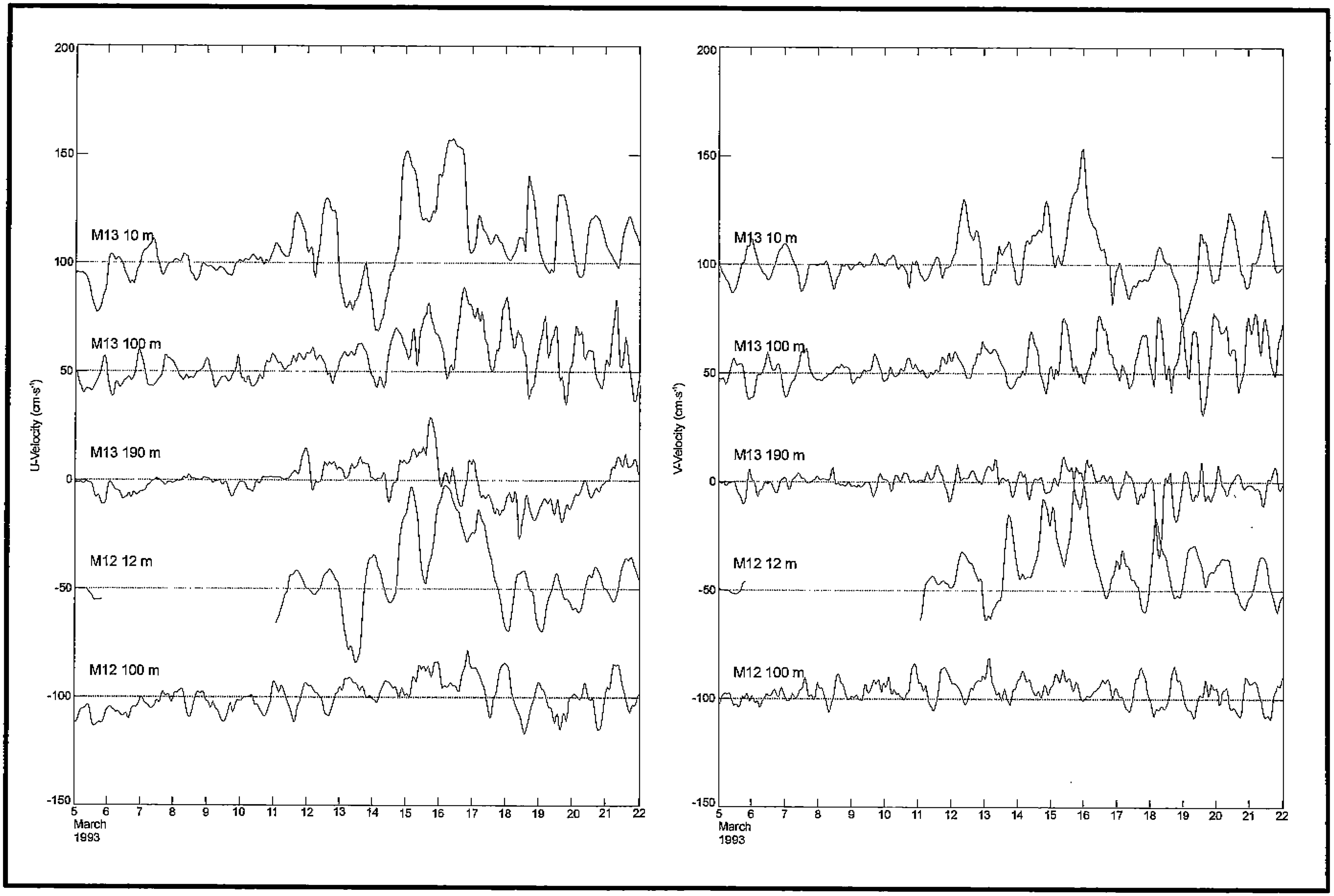


Figure 4.9. Eastward (u) and northward (v) components of currents (hourly values from 3-hr low-passed records) from moorings located off Louisiana at approximately 90.5°W. Mooring 13 was in water depth of 200 m; mooring 12 was in water depth of 504 m. On 12 March 1993, a class 5 extratropical cyclone moved from west to east across the Texas-Louisiana shelf with its center approximately over the 1,500-m isobath.

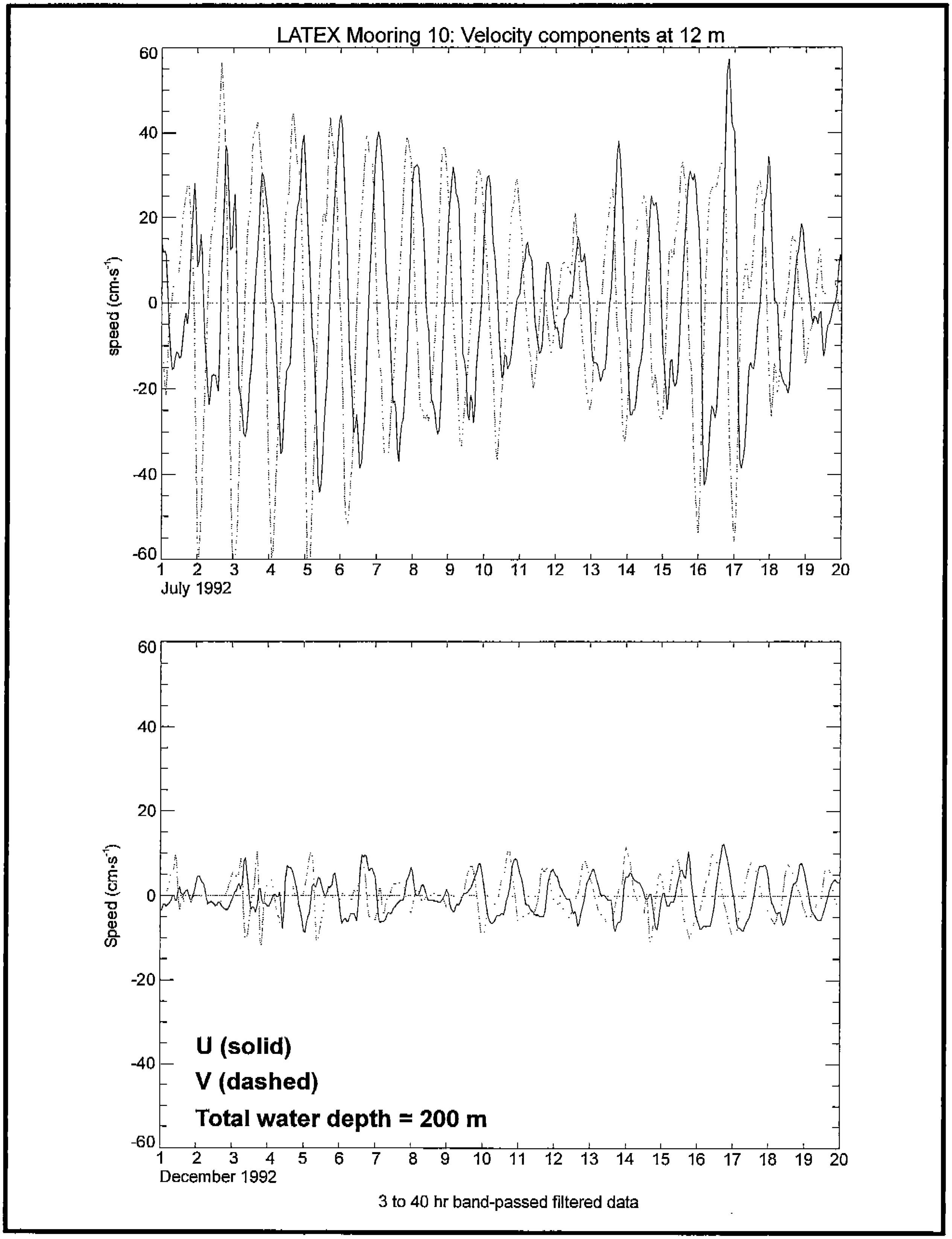


Figure 4.10. Eastward (u) and northward (v) components of currents from 3- to 40-hr band-passed records made in July and December 1992 at mooring 10 located off Louisiana at 27.94°N, 92.75°W in water depth of 200 m.

examples of measured currents, documentation of the effects on property distributions of energetic, episodic wind events, and models of such storms (e.g., see Leipper 1967, for effects of a hurricane passage on density and temperature distributions in the open Gulf or O'Brien 1967 or O'Brien and Reid 1967, for the modeled effects of hurricane passage).

## Loop Current Forcing and Eddy Activity

The phenomena of most concern in the past to deepwater operators in the Gulf of Mexico are surface-intensified currents associated with the Loop Current (LC), anticyclonic Loop Current eddies (LCEs) detached from the LC, and other eddies (both anticyclonic and cyclonic). Currents associated with the LC and LCEs extend into the water column to the of order 1,000 m.

The Loop Current enters the Gulf through the Yucatan Channel and exits through the Straits of Florida (**Figure 4.1**). As it enters (where it is called the Yucatan Current), the LC is westward intensified (e.g., Cochrane 1963). The surface currents that parallel the current core are approximately 200 $cm \cdot s^{-1}$ or more at the core and fall off to ~50 $cm \cdot s^{-1}$ or less within order 10 km to the west and order 100 km to the east of the core. They may reverse direction on the eastern side of the channel to flow from the Gulf into the Caribbean (Cochrane 1963; Maul et al. 1985). The deep flow at the sill in the Yucatan Channel is not unidirectional into the Gulf. In addition to tidal flows, there is significant variability between northward and southward flows at subtidal frequencies. Based on a 3-year current record at 1985 m (145 m above the sill) from an instrument moored halfway between Mexico and Cuba, Maul et al. (1985) showed an average southward drift of 1.8 $cm \cdot s^{-1}$ with significant energy near 19 d and 38 d. Moreover, they observed four periods of persistent southward flow with average 5 $cm \cdot s^{-1}$ speeds and bursts to 15 $cm \cdot s^{-1}$. These were separated by 8 to 10 months and appear to follow shedding of LCEs (R. O. Reid, personal communication), so they may be due to mass compensation as the Loop Current pushes into the Gulf following ring shedding.

As the LC moves into the Gulf, it tends to follow the topography along the Campeche Bank with meanders of small amplitude (Molinari and Cochrane 1972). Using the available data sets and an analytical model based on conservation of potential vorticity, Molinari and Cochrane (1972) noted the LC tends to go unstable north of 23.5°N where the topography changes rapidly from a north-south to east-west orientation; the current then may veer east and begin to meander. Reid (1972) found with a simple dynamic model that the variation of the Coriolis parameter could be responsible for the anticyclonic turn of the LC after it detaches from the Campeche Bank.

The LC then extends northward into the Gulf as a quasi-stationary meander (Hamilton 1997). The extent of the northward intrusion is variable (see e.g., Maul 1977; Vukovich et al. 1979; Sturges and Evans 1983; Molinari and Morrison 1988). The northward development of a LC intrusion was described by Leipper (1970) and by Maul (1977) using time series of contours of the 22°C isotherm at 100-m depth, which Leipper showed was a good indicator of the position of the LC. One example is schematically depicted in **Figure 4.11a**. The sequence shows the intrusion of the LC front from approximately 24.75°N in August 1972 northward into the Gulf; a year later it had extended to about 28.75°N. The contours for June and July show the development of an LCE associated with this intrusion. Note the July contours show the eddy pinching off at both the east and west sides. By September 1973, the LCE had detached and the LC front was at 25.5°N, about 3° latitude south of its position the month before. The percent of time during which warm LC water was located within various regions in the eastern Gulf is shown in **Figure 4.11b** (Science Applications International Corporation [SAIC] 1989). Although early investigations suggested that the northward extension was characterized by a seasonal cycle with minimum intrusion in winter and maximum in summer or fall (e.g., Leipper 1970; Maul 1977), subsequent investigations found the phasing was highly variable (Sturges and Evans 1983; Molinari and Morrison 1988). Data from 1974-1976, analyzed by Molinari and Morrison (1988), showed that the northward penetration of the LC into the Gulf was well correlated with the location of the current on Campeche Bank at the time of its separation. The LC did not intrude far in the Gulf when it was over the eastern part of Campeche Bank at time of separation; the degree of penetration into the Gulf increased for separations occurring farther west on the bank.

The LC influences the circulation in the deepwater region and over the slope of the eastern Gulf both directly as it intrudes northward and indirectly through the eddies and frontal features, such as filaments, associated with it (Kelly 1991). Maximum surface currents in the LC range from 100 to 200 $cm\cdot s^{-1}$ or more, as seen in **Figure 4.12** (Nowlin and Hubertz 1972). Hamilton (1997) reported on the velocity structure of the LC in the upper 1,500 m as obtained from air-deployed current profilers on 11 May 1984. The velocities normal to a nominally east-west transect across the LC at about 25°N showed strong northward and southward flows at, respectively, the west and east edges of the LC. Flows in the current core exceeded 120 $cm\cdot s^{-1}$ near-surface and were approximately 50 $cm\cdot s^{-1}$ at 200 m and 10 $cm\cdot s^{-1}$ at 700 m. Flows below 800 m, which is the sill depth of the Florida Strait, were ~10 $cm\cdot s^{-1}$ or less and generally in the opposite direction from the current core, suggesting the LC penetrates only to the depth of the Florida Strait sill. Hamilton (1990), however, showed that the LC may strongly influence currents below 1,000 m by the excitation of energetic currents associated with topographic Rossby waves (discussed later).

Strong current events that are associated with the nearby presence of the LC and its frontal features have been observed over the slopes and shelves of the eastern Gulf. Ebbesmeyer et al. (1982) attributed to LC forcing the peak currents of 30 to 50 $cm\cdot s^{-1}$ lasting 20 to 30 days that were observed at depths of 100 to 200 m over the upper slope off the Mississippi River delta. Filaments that protrude from the LC also influence currents over the slope. Huh et al. (1981) described an event in which an LC filament moved, at speeds of ~20 $cm\cdot s^{-1}$, up the axis of De Soto Canyon to within a few miles of the coast. Kelly (1991) and Vastano et al. (1991) describe types and effects of intrusions of the LC and its filaments onto the Mississippi-Alabama slope and shelves.

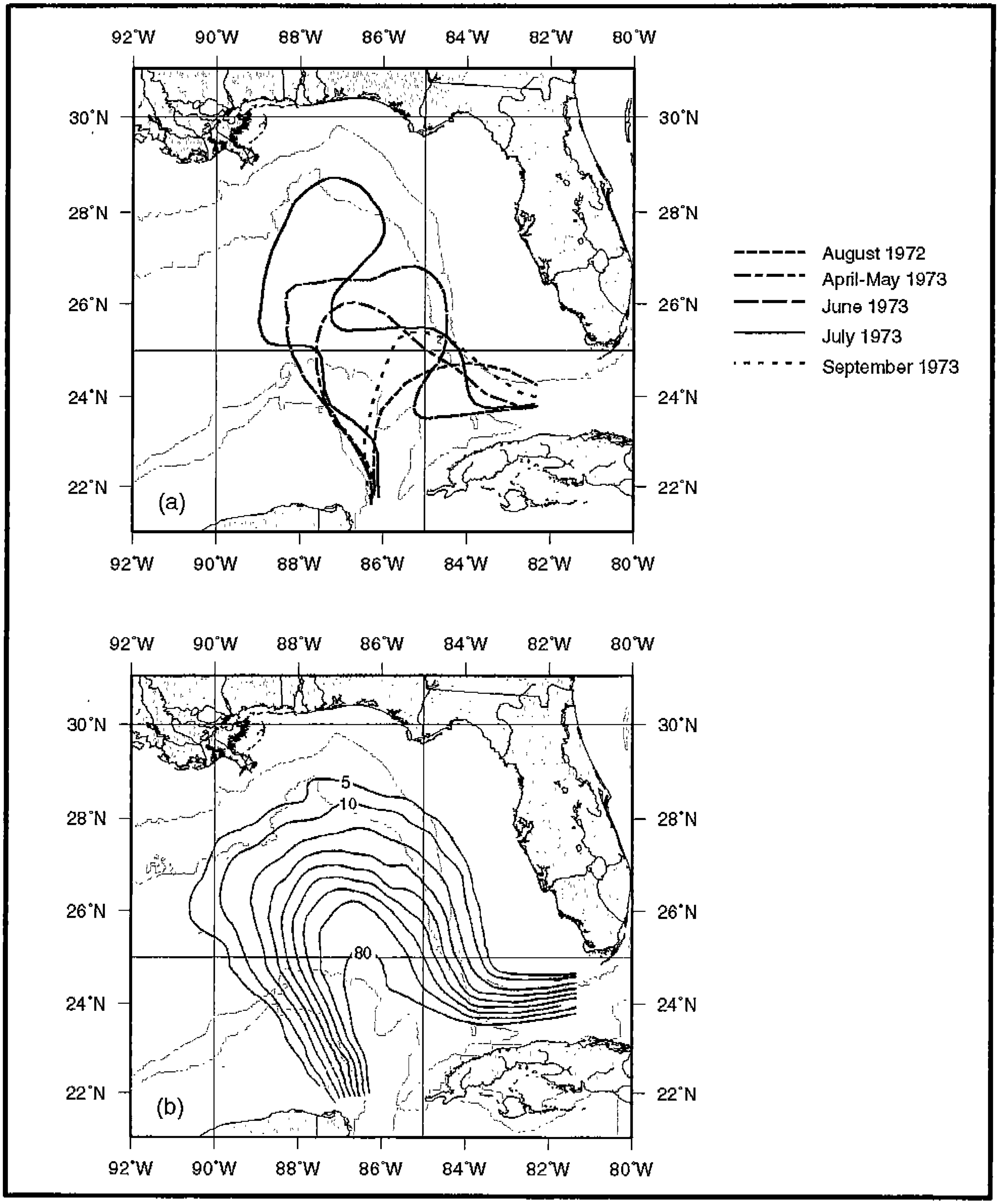


Figure 4.11. (a) An example of the development of an intrusion of the Loop Current into the eastern Gulf of Mexico is schematically depicted with contours of the 22°C isotherm at 100-m depth from hydrographic cruises conducted in August 1972 through September 1973 (Adapted from: Maul 1977). (b) Frequency of occurrence (%) of warm Loop Current water in the eastern Gulf of Mexico from monthly frontal analyses of AVHRR data from 1976 through 1985 (Adapted from: Science Applications International Corporation 1989). Percentage contour intervals are 10%.

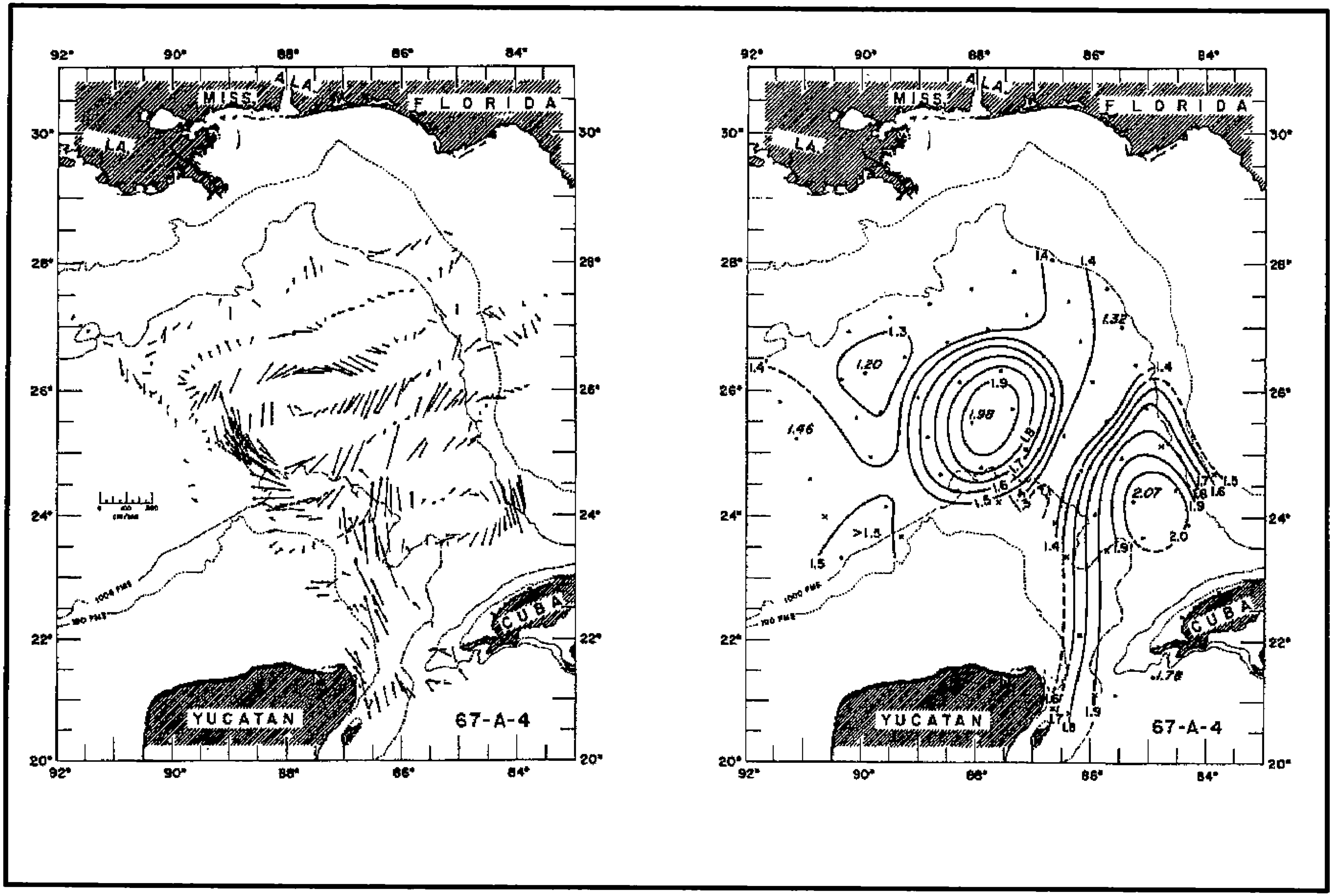


Figure 4.12. GEK surface current observations (left) and surface dynamic topography relative to 1,350 db (right) from *Alaminos* cruise 67-A-4 in June 1967 (Adapted from: Nowlin and Hubertz 1972).

Paluszkiewicz et al. (1983) describe the intrusion of an LC filament, propagating southeastward at 30 $cm{\cdot}s^{-1}$, onto the west Florida shelf.

When the LC penetrates into the Gulf, a LCE may separate from the LC itself. This process is complex, and the eddy can detach and reattach several times before fully separating from the LC (Vukovich 1995). Cochrane (1972) described a May 1969 separation event. It involved the formation of two cyclonic meanders, one protruding into the LC from Campeche Bank and the other from the west Florida shelf. The Campeche Bank meander grew until it joined the west Florida shelf meander, creating a cyclonic shear zone that separated the LCE from the LC. Vukovich and Maul (1985) observed, for the period 1978 to 1981, that the separation of large anticyclonic eddies was preceded by development of cyclonic eddies on the eastern side of the LC, but that development of such cyclonic eddies did not always result in separation of an LCE.

Periods between LCE detachments vary from 4 to 16 months with a primary mode at 8 to 9 months and a secondary near 13 to 14 months (Sturges 1994; results of an analysis by Vukovich 1995 are similar). Initially detached rings have diameters greater than 250 km, with typical values near 350 km, which decrease by 45% within 150 days and 70% within 300 days (Elliott 1982). They may have surface speeds of 150 to 200 $cm{\cdot}s^{-1}$ or more; speeds of 10 $cm{\cdot}s^{-1}$ are not uncommon at 500 m (Cooper et al. 1990). For more detail, see **Table 4.4**. After their separation from the Loop Current, LCEs move into the western Gulf, with average translation speeds of 5 km per day (range of 1 to 20 km per day), and in the process may interact with other eddies or with the continental margins to form additional eddies. They have typical lifetimes of 350 to 400 days (Elliott 1982), and decay by interactions with boundaries, ring shedding, and ring-ring interactions (e.g., Vidal et al. 1992). The net result is that at almost any given time, the Gulf is populated with numerous eddies, interacting with one another and with the margins. As an example, **Figure 4.13** shows sea surface height anomaly (cm) relative to a mean sea surface for 9 May 1993. It is based on satellite altimeter gridded data by Robert R. Leben, Colorado Center for Astrodynamics Research (CCAR), as described in Biggs et al. (1996). Clearly seen is the Loop Current, one semi-detached anticyclonic feature, the remnants of two LCEs, and many cyclonic features of various strength. Many of these separated anticyclonic and cyclonic features would be expected to have surface currents exceeding 50 or even 100 $cm{\cdot}s^{-1}$.

According to model results obtained by Oey (1995), transient shelf edge currents can be forced by the expansion of LC into the Gulf, the passage of a LCE in deepwater, or the collision of a LCE with the continental slope.

Although the LC and LCEs have been studied since the early 1960s, details of their velocity distributions and variability remain virtually unknown—only a few estimates of three-dimensional velocity fields have been reported (e.g., Cooper et al. 1990; Forristall et al. 1992). As an example, **Figure 4.14** shows components of velocity ($cm{\cdot}s^{-1}$) normal to a section extending from approximately 27.4°N, 90.6°W (station 64) to 24.8°N, 89.4°W (station 78). Measurements were made with a lowered Neil Brown acoustic current meter by Forristall et al. (1992); ship motion was estimated using Loran-C and

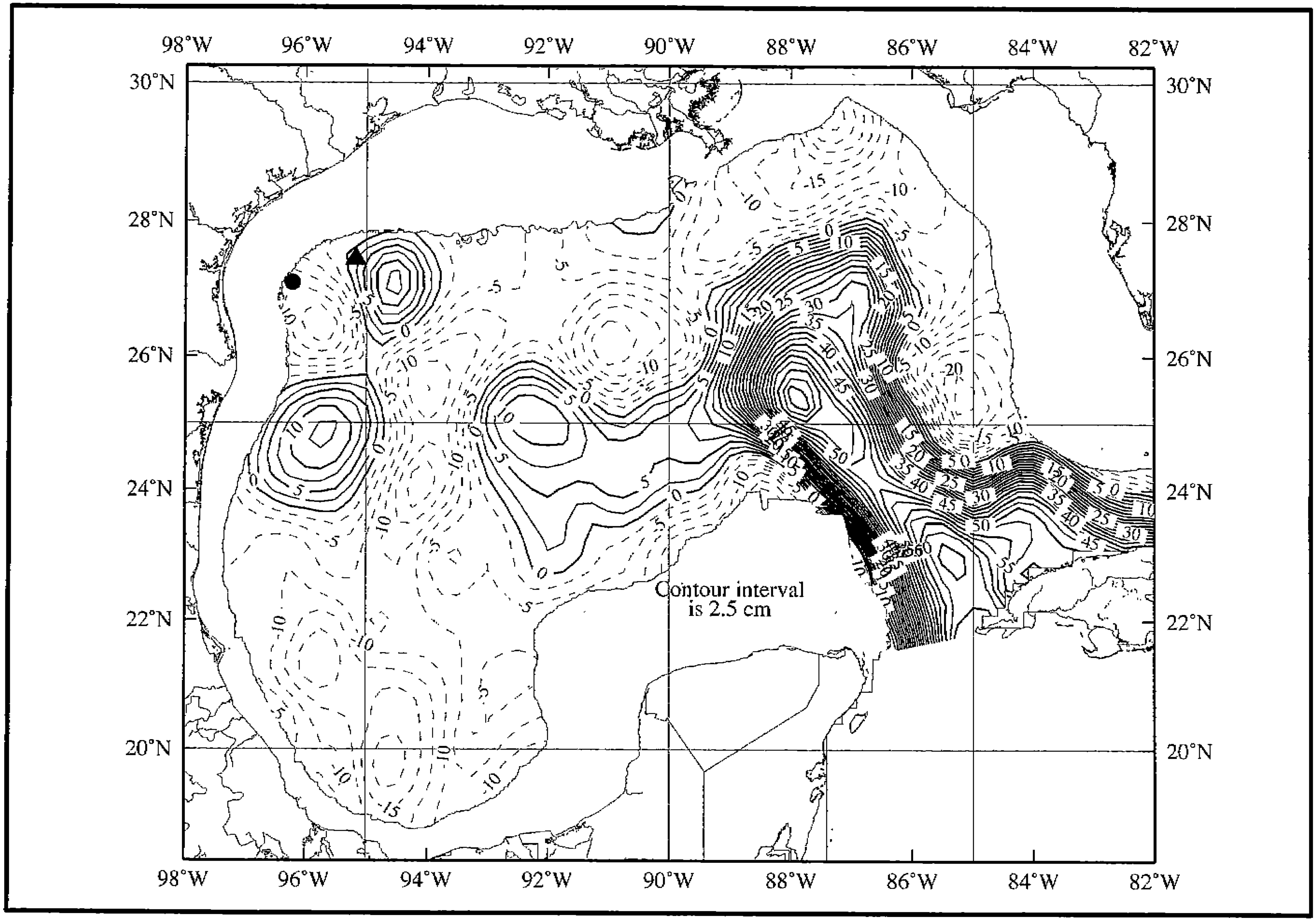


Figure 4.13. Sea surface height anomaly (cm) from satellite altimeter data for 9 May 1993. Based on gridded data from Robert R. Leben, Colorado Center for Astrodynamics Research, as described in Biggs et al. (1996). Locations of stations 165 (filled circle) and 215 (filled triangle) are shown.

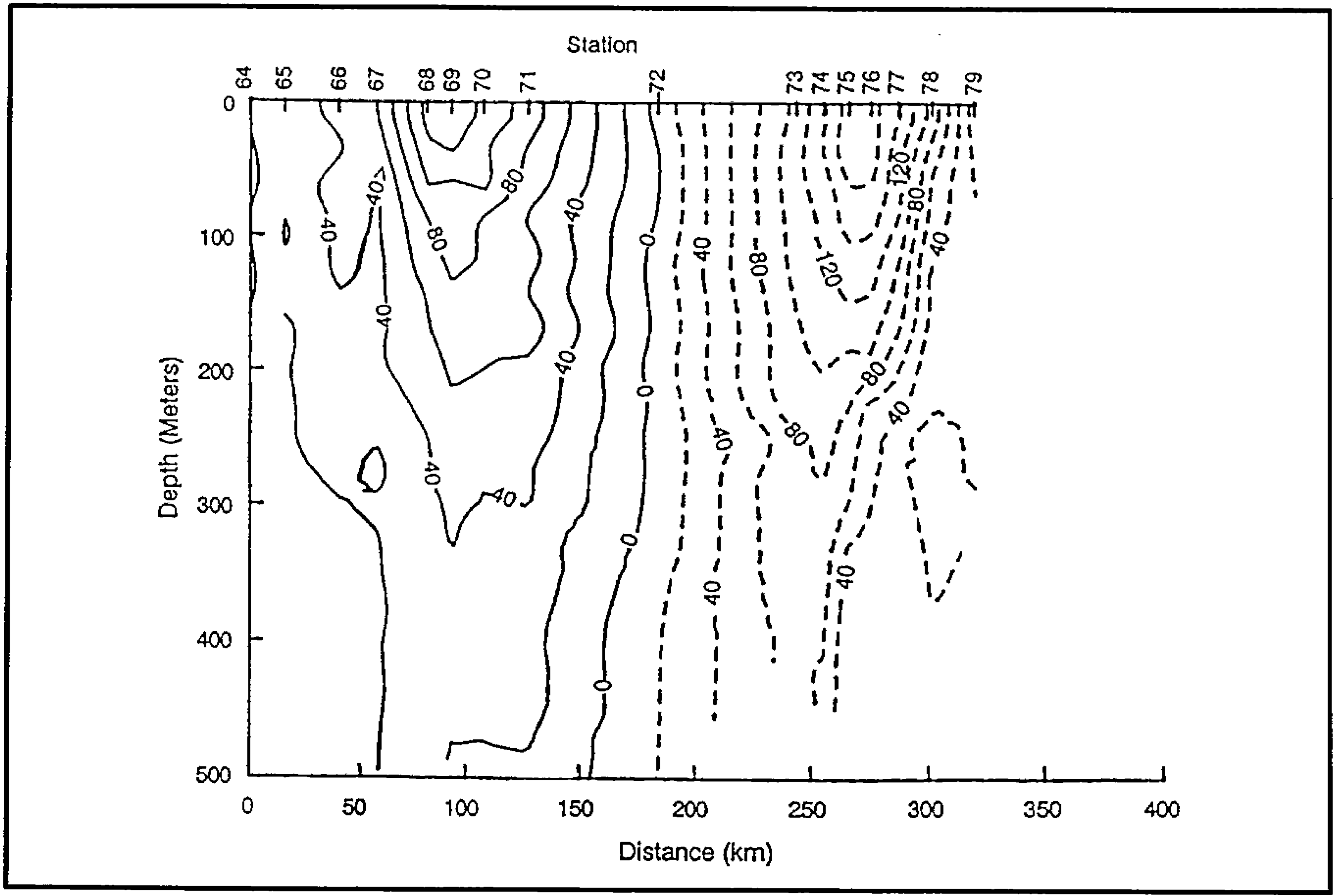


Figure 4.14. Components of velocity (cm·s-1) normal to a section extending from approximately 27.4°N, 90.6°W (station 64) to 24.8°N, 89.4°W (station 78). Measurements were made by Forristall et al. (1992) using a lowered Neil Brown acoustic current meter; ship motion was estimated using Loran-C and motion of the instrument relative to the ship was measured with an ultra-short baseline acoustic system. This section crossed the LCE called Fast Eddy during August 1985, and components are taken to represent azimuthal swirl speeds of the eddy. Positive components are directed toward 65°.

Table 4.4. Loop Current eddy properties

| | |
|---|---|
| Shedding frequency | Mean of about 10 months, with variations from 4 to 16 months (Sturges 1994) |
| Translation speeds | Vary over speeds of 1-14 km per day<br>Average speed of 5 km per day |
| Diameters of last closed circulation | Initially usually ≥ 250 km; typical value near 350 km<br>Decrease by 45% within 150 days; 70% within 300 days (Elliot 1982) |
| Swirl speeds | For new rings: 150-250 $\mathrm{cm \cdot s^{-1}}$ at surface; 10 $\mathrm{cm \cdot s^{-1}}$ at 500 m |
| Depths | Property distributions and motions extend to >1,000 m for new rings<br>Filaments are likely confined to the upper 50-300 m |
| Energy | Available potential energy for typical new ring is $15 \times 10^4$ $\mathrm{J \cdot m^{-2}}$ • Ratio of available potential energy to kinetic energy ~ 4.5 for new rings (Elliot 1979) |
| Lifetimes | 350 to 400 days (Elliot 1982) |
| Decay modes | Interactions with boundaries—formation of filaments<br>Ring shedding; ring-ring interactions |

motion of the instrument relative to the ship was measured with an ultra-short baseline acoustic system. This section crossed the LCE Fast Eddy during August 1985 and components are taken to represent azimuthal swirl speeds of the eddy. Positive components are directed toward 65°. Surface currents exceeded 160 $\mathrm{cm \cdot s^{-1}}$ on one side of this LCE and 120 $\mathrm{cm \cdot s^{-1}}$ on the other side. Speeds at 200 m reached 100 $\mathrm{cm \cdot s^{-1}}$ in this young LCE located in the north central Gulf.

To illustrate currents produced by LCEs in the northwestern Gulf, and at somewhat greater depths, in **Figure 4.15** are shown 40-hr, low passed current components from the same moorings C and S discussed in connection with hurricane effects (**Figure 4.8**). At mooring S large northward component, accompanied by reversing east-west components, are seen at the upper instrument commencing in late September and continuing into early November. During this period, northward speeds at 200-m depth averaged about 50 $\mathrm{cm \cdot s^{-1}}$, with bursts exceeding 70 $\mathrm{cm \cdot s^{-1}}$. This period of high speed flow resulted because of the presence of a clockwise rotating remnant of an LCE in the area (Brooks 1984). The vector velocities (not shown) reveal that the current varied in direction from NW to NE several times during this period; the implication is that the western edge of the

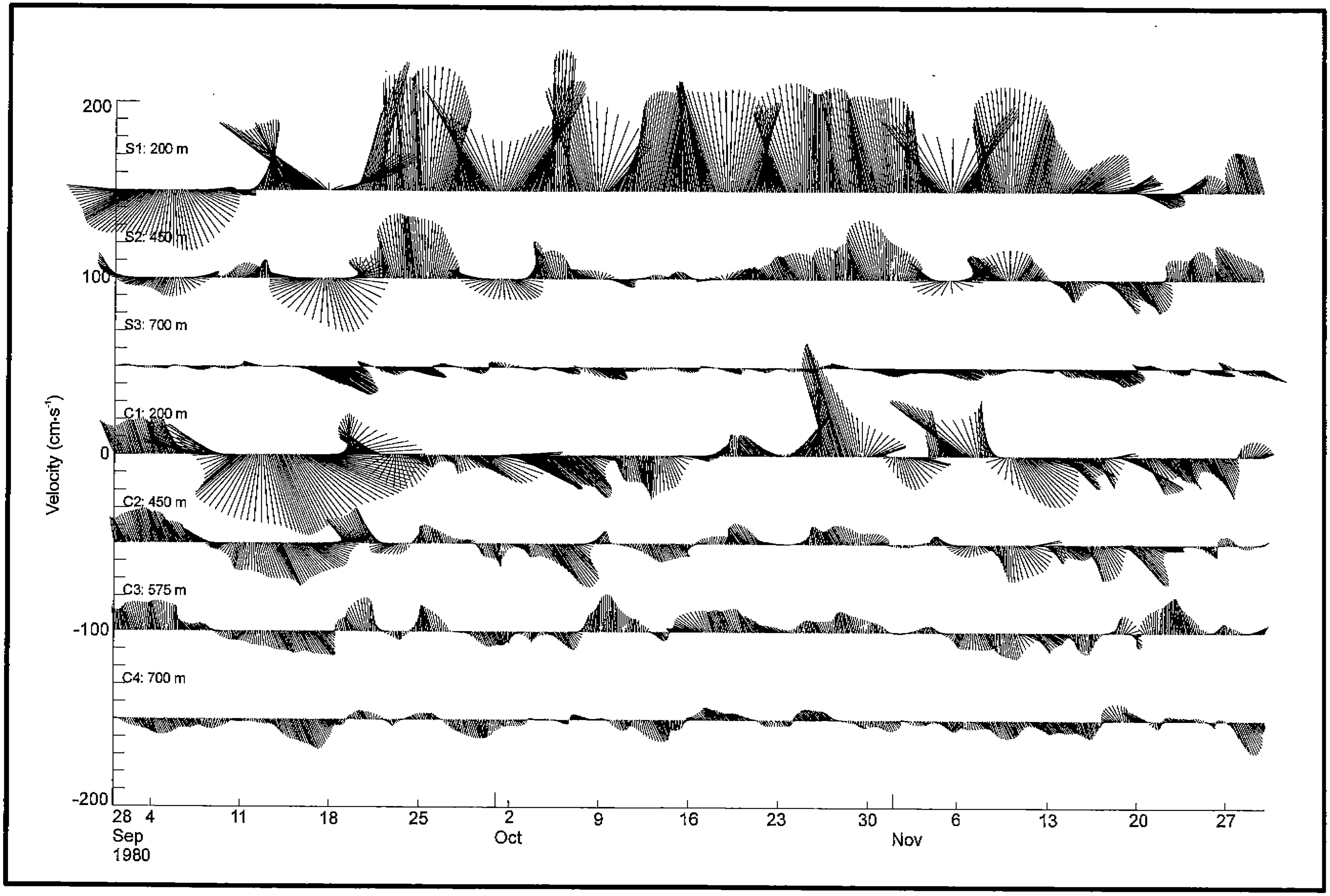


Figure 4.15. Components (u positive to the east and v positive to the north) of 40-hr, low-passed currents measured at indicated depths on moorings S (26°N, 96°10'W) and C (55 km north of S). Both moorings were approximately on the 730-m isobath. At mooring S, a long period of high northward components, accompanied by reversing east-west components, is seen to commence in late September and continue into early November; this was the result of the presence of an anticyclonic eddy over the mooring.

eddy repeatedly moved north and south over the mooring during the period. Maximum speeds associated with this LCE at 200 m reached 60 cm·s$^{-1}$; speeds at 450 m were considerably less, but nevertheless significant at values in excess of 35 cm·s$^{-1}$; even near the bottom at 700 m speeds reached 10 cm·s$^{-1}$. Velocities at mooring C were not correlated with those at mooring S. A cyclonic eddy (also noted to be in the area by Brooks 1984) was situated between moorings C and S from about 10 until 20 September, as seen by northwestward flow at S and southeastward flow at C.

**Figure 4.16** shows horizontal current vectors (hourly values from 3-hr low-passed records) from moorings located approximately equidistant along the 200-m isobath at the edge of the Texas continental shelf. Mooring 6 was at 27.71°N, 95.66°W; mooring 9 was at 27.81°N, 93.50°W. The influence of Loop Current Eddy V over the shelf edge is seen as it moves generally eastward past each mooring, beginning at mooring 6 from 22 July to 9 August. Maximum speeds at the upper instruments (~10 m) ranged from 50 to 100 cm·s$^{-1}$; those at mid-depth instruments (100 m) approached or exceeded 50 cm·s$^{-1}$. It should be noted that this LCE remnant was only the northern portion of an old ring that had been separated into two parts by interaction with another eddy.

Energetic, high frequency currents have been reported to occur with the passage of LCEs past structures, but they are not well documented; such currents would be of concern to offshore operators because they could induce structural fatigue of materials.

Only limited information is available concerning the velocity fields within cyclonic and ancillary anticyclonic eddies; reports include Vukovich and Maul (1985), Forristall et al. (1992), Hamilton (1992), and notably Berger et al. (1996). Hamilton (1992) reports the existence in the central Gulf and over the Louisiana continental shelf of cold cyclones with upper layer currents of 30 to 50 cm·s$^{-1}$, little surface temperature expression, the largest isotherm displacements in the depth range 200 to 800 m, diameters of 100 to 150 km, and long lifetimes.

Berger et al. (1996) reported on the existence over the continental slope and offshore of numerous eddies smaller than LCEs. Three small types of eddies can be identified from the results of that study: cyclonic eddies, anticyclonic eddies, and a submesoscale coherent vortex. The cyclones are probably the same features described over the slope by Hamilton (1992) and mentioned by Hamilton et al. (1999). These features are seen to affect the thermal fields to diameters of 150$^{+}$ km, although the observed radii of solid body rotation seems to extend only to 25 to 50 km. Maximum currents are 30 to 50 cm·s$^{-1}$ and occur somewhat beneath the surface, e.g. around 200 m. Velocities extend into the water column to depths of 800 to 1,000 m. Isotherms are sometimes observed to be depressed in the surface waters with the doming found in cyclones beginning around 200 m and increasing with increasing depth down to at least 1,500 m. (This is consonant with occurrence of maximum currents near 200 m.) The secondary anticyclones observed over the continental slopes of Texas and Louisiana seemed to have horizontal extents as small as or smaller than the cyclones. However, they were numerous and often found over the upper slope. Unlike the cyclones, they have their maximum thermal expression in the surface layers. There are only minimal measurements of the velocity

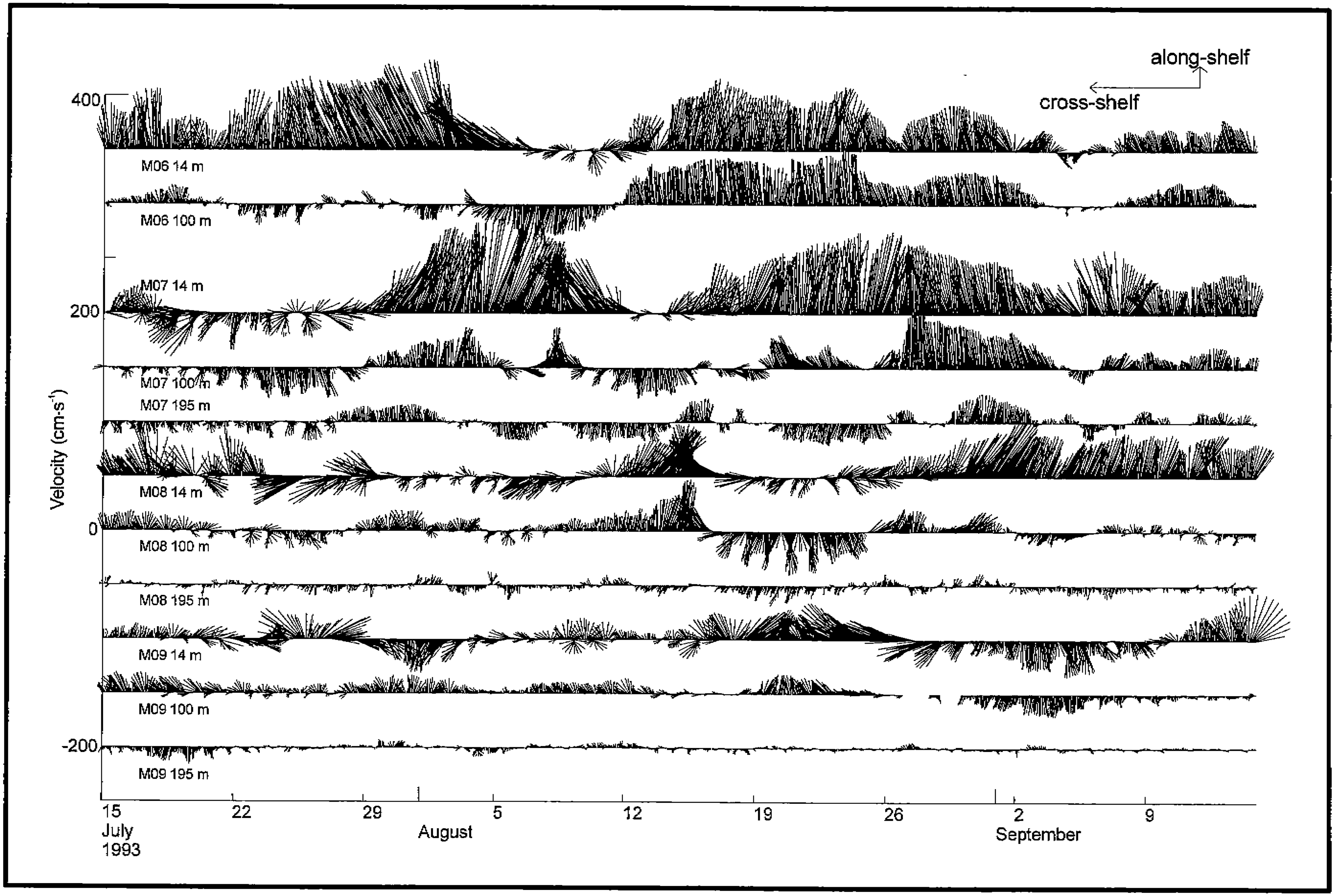


Figure 4.16. Horizontal current vectors (hourly values from 3-hr low-passed records) from moorings located approximately equidistant along the 200-m isobath at the edge of the Texas continental shelf. Along shelf components are oriented up-down (up is generally eastward); cross-shelf components are oriented across the figure (off-shelf to the right). Mooring 6 was at 27.71°N, 95.66°W; mooring 9 was at 27.81°N, 93.50°W.

structure in these features, though one can speculate that maximum velocities are $\leq 50\ \mathrm{cm \cdot s^{-1}}$. On one occasion in October of 1993, Berger et al. (1996) observed over the slope near 92.5°W an eddy not previously observed in the Gulf of Mexico, with thermal structure that was raised and lowered, respectively, above and below a subsurface level of about 350 m.

## Sea Level and Tides

Sea level is the elevation of the water surface relative to a fixed datum (Reid 1990). It fluctuates over many time and space scales. This section focuses on those sea level fluctuations that are due to seasonal thermal variations and to astronomical forces.

The seasonal cycle of heating and cooling induces thermally-forced seasonal sea level variability in the Gulf of Mexico. Pattulo et al. (1955) conducted a study of sea level oscillations over the world oceans, including observations from the Gulf of Mexico. They defined the component of sea level due to the density distribution as steric sea level. They noted that in the subtropical latitudes, the variations in steric level were mostly thermally-induced and quite large. Pattulo (1963) found the large sea level variations in the subtropics were due principally to variations in oceanic heat storage induced by seasonal variations in local heating.

Whitaker (1971) focused his study of the seasonal variations of steric sea level specifically on the Gulf of Mexico. He computed steric levels using available temperature data together with a constant salinity of 36.30, which he showed resulted in errors of the same order as those due to sampling and smoothing. His monthly maps of steric sea level relative to 150 m show a general Gulf-wide increase in steric height during spring and summer to maxima in September-October and a decrease during fall and winter to minima in February-March. The approximate range of steric levels through the year was 0.275 to 0.625 dyn m. The maps also show a higher steric level signature from the warmer water temperatures associated with the Loop Current and possible LCEs in the eastern Gulf and a "western high," possibly associated with LCEs, in the western Gulf.

Astronomically induced sea level variations in the northern Gulf of Mexico are dominated by the diurnal tidal components, rather than the semidiurnal components, except along the west Florida coast (Reid and Whitaker 1981; see also Reid 1990, for a review of tides, tidal forcing, and numerical modeling of tides). Tides in the Gulf are connected to tides in the Atlantic Ocean through the two ports at the Yucatán Channel and Straits of Florida. Reid and Whitaker (1981) reviewed tides in the Gulf of Mexico and developed a numerical tide model that agreed well with the observed $K_1$, $O_1$, $P_1$, $M_2$, and $S_2$ tidal constituents. **Table 4.5** shows their computations of tidally-induced volume influx from the two ports and the Gulf-wide mean response of water level. For comparison, **Table 4.5** also shows water level response to these five tidal constituents measured at a deep pelagic site (Mofjeld and Wimbush 1977). The results of Reid and Whitaker (1981) show diurnal tides have nearly uniform amplitudes and phases over the whole Gulf, with the $K_1$ and $O_1$ constituents significantly greater in amplitude than the semi-diurnal tidal amplitudes, and are driven mainly by in-phase forcing through the ports. This is in agreement with earlier investigators (Grace 1932, 1933; Marmer 1954; Zetler and Hansen 1972). The semidiurnal tides, however, are smaller than the diurnal tides and are driven mainly by the direct tide potential. Reid and Whitaker (1981) note that the response of the $M_2$ tide is nearly resonant to the direct forcing by the tide potential. They find the greatest response occurs on the west Florida shelf near Cedar Key, explaining the anomalously large $M_2$ tides along the west Florida coast compared to the rest of the Gulf. **Table 4.6** shows the percent of the total variance in sea level attributed to in-phase and out-of phase port forcing and to direct forcing by the tide potential.

Table 4.5. Summary of volume computations and mean response of water level (Reid and Whitaker 1981) and observed tidal constituents measured at a deep pelagic site located at 24.767°N, 89.648°W by Mofjeld and Wimbush (1977). The influx rate is for both ports combined. The phase lag is given relative to the time of transit of the maximum tide potential at Greenwich. The rms values are for the amplitude moduli for 20 observational stations, including that of Mofjeld and Wimbush (1977), for each given tidal component. Compare the tidal influx rates with the mean volume flux of ~30 x $10^6$ $m^3 \cdot s^{-1}$ into and out of the ports that is associated with the quasi-permanents currents.

| Tidal constituent | Influx rate | | Mean sea level response | | RMS station response | Observation at deep pelagic site | |
|---|---|---|---|---|---|---|---|
| | Amplitude ($10^6$ $m^3 \cdot s^{-1}$) | Phase (degrees) | Amplitude (cm) | Phase (degrees) | (cm) | Amplitude (cm) | Phase (degrees) |
| $K_1$ | 14.40 | 294.3 | 12.82 | 24.3 | 14.93 | 14.10 | 28.5 |
| $O_1$ | 12.73 | 289.7 | 12.23 | 19.7 | 14.43 | 14.90 | 18.9 |
| $P_1$ | 4.19 | 295.2 | 3.75 | 25.2 | 4.60 | 4.76 | 28.4 |
| $M_2$ | 5.18 | 105.7 | 2.39 | 195.7 | 15.29 | 1.30 | 225.8 |
| $S_2$ | 2.19 | 103.3 | 0.98 | 193.3 | 5.74 | 1.50 | 130.0 |

Table 4.6. Percent of observed variance in sea level attributed to various forcing factors by the model (Reid and Whitaker 1981)

| Forcing factor | % for $K_1$ | % for $M_2$ |
|---|---|---|
| In-phase port forcing | 83 | 35 |
| Direct forcing | 12 | 55 |
| Out-of-phase port forcing | 1 | 1 |
| Residual | 4 | 9 |

Tidal currents are induced by the changes in sea level elevation from astronomical tides. Schmitz and Richardson (1968) determined the tidal volume transport amplitudes of the Florida Current were 3.5 ±1 x $10^6$ $m^3 \cdot s^{-1}$ for the $K_1$, $O_1$, and $M_2$ tides and 1.5 ± 1 x $10^6$ $m^3 \cdot s^{-1}$ for the $S_2$ tide, in good agreement with estimates across the Straits of Florida by Werthiem (1954). Durham (1972) calculated the tidal current transports for the $K_1$ and $O_1$ tides across the Yucatan Channel to be 12.6 ± 4 x $10^6$ $m^3 \cdot s^{-1}$ and 11.3 ± 4 x $10^6$ $m^3 \cdot s^{-1}$, respectively.

Rezak et al. (1985) presented the major and minor axes of the $K_1$ and $M_2$ tidal current ellipses for the Gulf of Mexico as determined by the Reid and Whitaker (1981) model; these showed the tidal currents over the deepwater Gulf were much smaller than those over the shelves. Using a hydrodynamic model, Mungall et al. (1978) estimated the $K_1$ and $M_2$ tidal currents in the deepwater Gulf to be less than 1 $cm \cdot s^{-1}$ with higher values (5 to 20 $cm \cdot s^{-1}$) over the shelves. DiMarco and Reid (1998) conducted a tidal analysis of 81 current meter records over the Texas-Louisiana shelf and shelf break. They examined the principal diurnal constituents ($K_1$, $O_1$, $P_1$, and $Q_1$) and semi-diurnal constituents ($M_2$, $S_2$, $K_2$, and $N_2$). They found that, as expected, the tidal currents were larger over the shelf than in deeper water. For example, $K_1$ and $M_2$ tidal current amplitudes at about 10-m depth were, respectively, 3.2 $cm \cdot s^{-1}$ and 1.2 $cm \cdot s^{-1}$ from a mooring in water depth of 50 m as compared to 1.6 $cm \cdot s^{-1}$ and 0.5 $cm \cdot s^{-1}$ in water depth of 500 m. DiMarco and Reid (1998) showed the tidal vectors of both the diurnal and semi-diurnal constituents rotated anticyclonically. They found generally that the major axes of the semi-diurnal tidal current ellipses were directed across the isobaths and the diurnal tidal current ellipses were circular. Their results provided qualitative verification of the model results of Reid and Whitaker (1991).

Removed from Yucatan Channel, Straits of Florida, canyons, or other major bathymetric features, tidal currents in the offshore Gulf are small. In the upper 100 m, currents associated with the major tidal components may reach amplitudes of 1 to 2 $cm \cdot s^{-1}$. At greater depths they are much smaller. As an example over the upper slope, amplitudes of $M_2$, $K_1$, and $O_1$ components were 0.23, 0.32, and 0.26 $cm \cdot s^{-1}$ at 490 m on LATEX mooring 12 located in 500-m depth about 90.5°W off Louisiana. For a mooring in Atwater Canyon Block 618 currents at 16 levels were analyzed for principal tidal components. As expected, the principal components ($M_2$, $K_1$, and $O_1$) were 1 to 2 $cm \cdot s^{-1}$ in the upper 100 m, decreasing to vanishingly small values (~0.1 $cm \cdot s^{-1}$ or less than the level of analysis error) for depths between a few hundred meters and near bottom at 1,945 m.

## Currents in Deep Water

Discussed in previous sections were currents associated with energetic wind events and with the Loop Current and mesoscale eddies. In addition to those currents, several other classes of energetic currents are now known to occur in the deepwater region of the Gulf. For the most part they are not yet well documented and even less well understood.

**Figure 4.17** is a schematic of design current speeds in the deepwater Gulf of Mexico for three classes of phenomena: the Loop Current and surface-intensified eddies; topographic, barotropic Rossby waves; and subsurface-intensified, high-speed jets (shown by gray domain). The currents associated with anticyclonic eddies have been most often measured or estimated; those with cyclonic eddies are less well surveyed, but assumed to be of same or lesser magnitudes. The phenomena of deep barotropic currents, perhaps with bottom intensification, have been observed and reported in the open literature on one occasion, but are substantiated by model results and proprietary measurements. The subsurface-intensified, high-speed jets have now been documented in many data sets, but not yet reported in the open literature. The physical mechanisms responsible for those jets are not yet identified. Recently another class of deep currents was detected by documenting their effects in producing long, deep, linear furrows in the bottom sediments near the Sigsbee Escarpment. In this section are discussed deep, barotropic currents believed due to topographic Rossby waves, subsurface-intensified energetic jets, and currents responsible for the bottom furrows.

### Deep, Barotropic Currents

During the mid-1980s, barotropic (depth independent) currents were observed to extend from depths near 1,000 m to the bottom. Shown in **Figure 4.18** are 40-hr low passed current vectors from SAIC mooring G maintained in the eastern Gulf as part of an MMS-sponsored physical oceanography program. As described by Hamilton (1990), the northern edge (eastward currents) of the Loop Current was affecting the array during December 1984. Then, from January to March the mooring was influenced by the southward flow of the eastern limb of the LC as it extended further into the Gulf. Note that currents above 1,000 m were affected in a coherent, surface-intensified manner, but currents below 1,000 m were not affected. During the period April-June an eddy separated from the LC. At that time considerable energy appeared in the lower water column—vertical velocity coherence with slight near bottom intensification is seen. Hamilton (1990) concluded that such currents result from barotropic topographic Rossby waves triggered by the Loop Current—perhaps on separation of LCEs—and that their propagation speeds into the western Gulf are larger (perhaps 9 $km \cdot d^{-1}$) than the average propagation speeds (5 $km \cdot d^{-1}$) of the separated LCEs.

Sturges et al. (1993) observed similar phenomena from numerical model results for the Gulf. Deep circulation patterns distinct from those associated with the surface intensified eddies also were seen in numerical model studies by Inoue and Welsh (1997). Proprietary oil company measurements show some such barotropic currents with maximum speeds near 40 $cm \cdot s^{-1}$ and periods of weeks. Moreover, data give some indication of bottom current intensification. This class of barotropic currents, with possible bottom intensification, is of the high interest to offshore operators attempting oil production in water depths of 1,000 m and greater; measurements are ongoing in the north central Gulf by the MMS and by offshore operators.

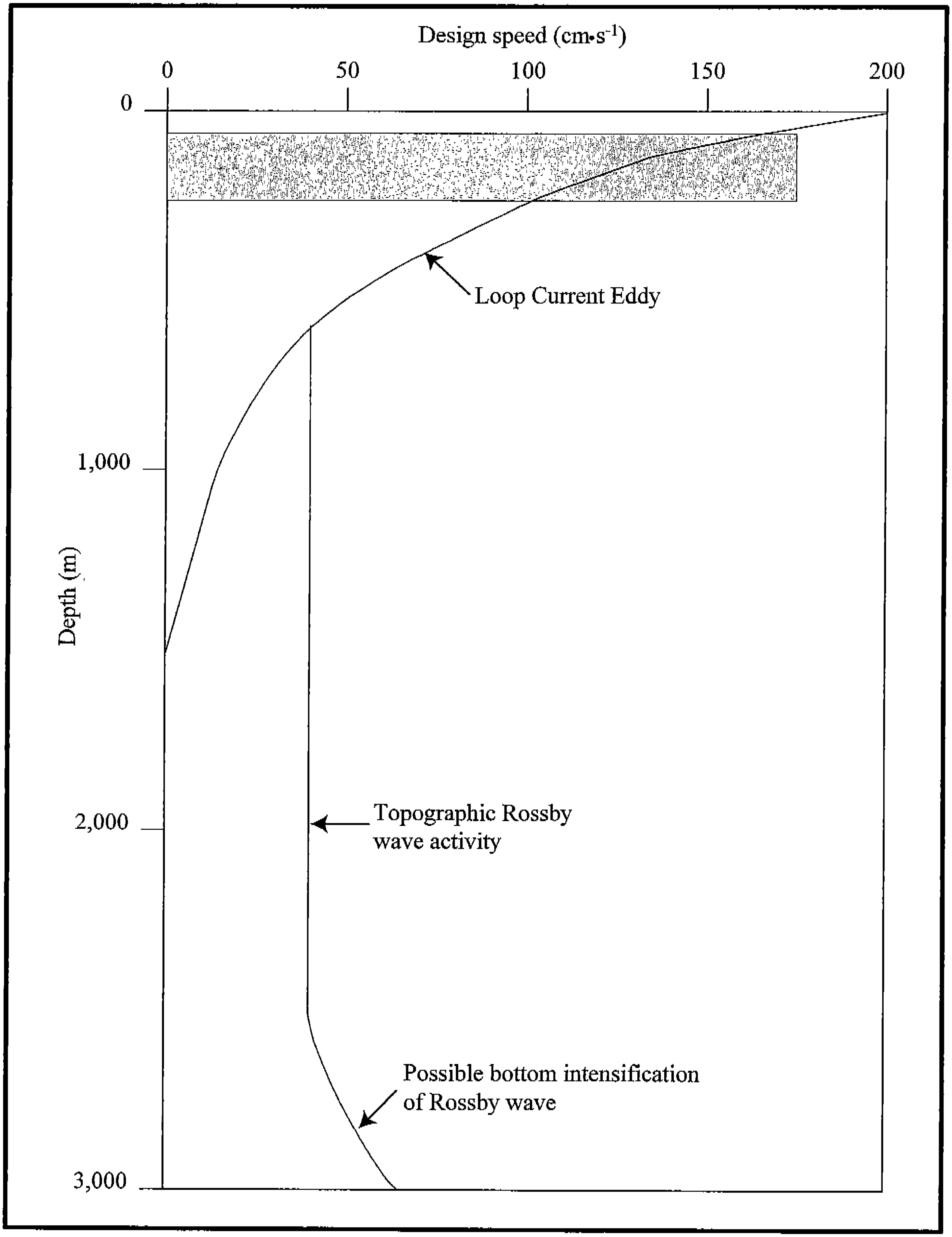


Figure 4.17. Schematic showing design currents in deepwater Gulf of Mexico for three classes of phenomena: topographic Rossby waves, Loop Current eddies, and subsurface-intensified, high-speed jets (shown by grey domain).

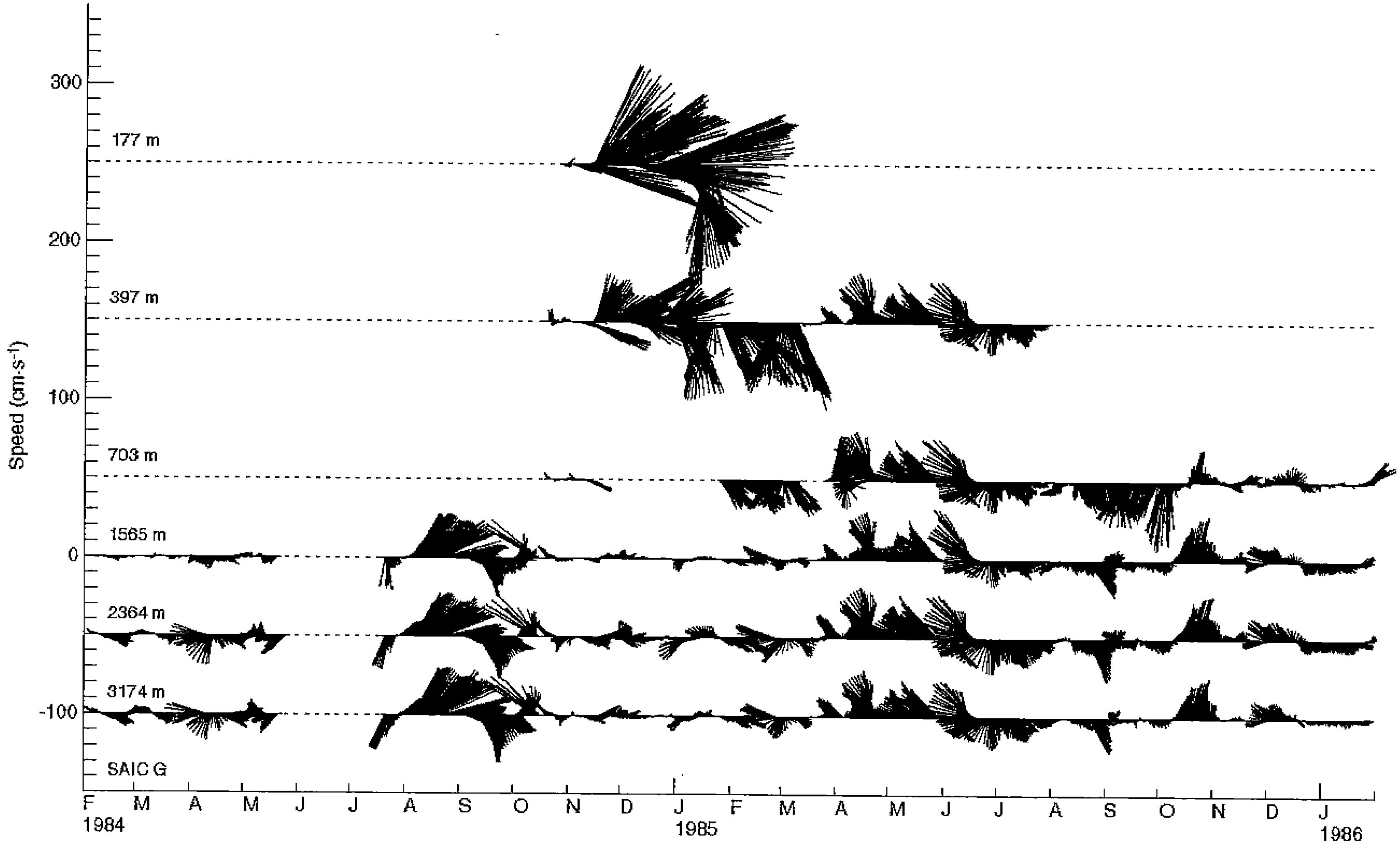


Figure 4.18. Current vectors (40-hr low-passed; north directed upward) from Science Applications International Corporation mooring G located in 3,200 m water depth at 25°36.2'N, 85°29.8'W off the southern West Florida Shelf. Position is shown in Figure 4.7.

### High-speed, Subsurface-intensified Currents

Several deepwater oil and gas operators have observed very high-speed, subsurface-intensified currents lasting of the order of a day at locations over the upper continental slopes. Such currents may have vertical extents of less than 100 m, with maxima observed generally within the depth range of 100 to 300 m. Maximum speeds exceeding 150 $\mathrm{cm \cdot s^{-1}}$ have been reported. **Figure 4.19** shows time-averaged current profiles before, during, and after the occurrence of such a subsurface jet in Mississippi Canyon in 1997. Total water depth at the location is estimated to be 800 to 900 m. The profiles in the upper 100 m are similar, showing a strong surface current with average speeds of about 30 $\mathrm{cm \cdot s^{-1}}$ at the surface decreasing to roughly 12 $\mathrm{cm \cdot s^{-1}}$ at 100 m. Below 100 m the profiles for the periods before and after the jet event were essentially barotropic at 8 to 10 $\mathrm{cm \cdot s^{-1}}$. The profile during the event shows a strong current at mid-depth with maximum averaged speeds greater than 30 $\mathrm{cm \cdot s^{-1}}$ near 300 m. Analyses of individual profiles shows that peak currents generally occurred between 250 to 300 m with a maximum speed of 56 $\mathrm{cm \cdot s^{-1}}$.

Examining data from locations in depths of 1,200 to 1,500 m, scientists at Texas A&M University have observed currents with subsurface maximum speeds of 50 $\mathrm{cm \cdot s^{-1}}$ lasting for about 1 day with bursts of speed peaking at more than 100 $\mathrm{cm \cdot s^{-1}}$. The higher speed currents appear to propagate upward, characteristic of baroclinic waves (either sub- or super-inertial). An example is shown in **Figure 4.20**. It seems possible that such phenomena could be intensified near topography. Causal mechanisms are being sought.

Model results also show short-period, subsurface-intensified currents over the Gulf slopes—but with maximum speeds approaching only 50 $\mathrm{cm \cdot s^{-1}}$. Examples are shown in **Figure 4.21**. More evidence for these phenomena is being sought in observations and in model results.

### Currents Responsible for Furrows

In early 1999, William Bryant of Texas A&M University (personal communication) discovered and mapped, using a deep towed acoustic system, a previously unexplored bedform just offshore of the Sigsbee Escarpment in the northwestern Gulf of Mexico. These are large, long furrows eroded into the Holocene deposits blanketing this region. These furrows have depths of 5 to 10 m, widths of several 10s of meters, are spaced on the order of 100 m apart, and extend unbroken for distances of 10s or more km. Generally they are oriented nearly along depth contours. Bryant has observed them in the region of 90°W just off the Sigsbee Escarpment and near the Bryant Fan south of Bryant Canyon from 91°W to 92.5°W. Depths in those regions range from 2,000 to 3,000 m. More recently, the existence of these features has been corroborated and they have been mapped more extensively in the area of Green's Knoll by offshore oil and gas operators. Observations of furrows demonstrate that such bedforms are widespread and important features in regions with cohesive, fine-grained sediments and directionally stable currents (Flood 1983).

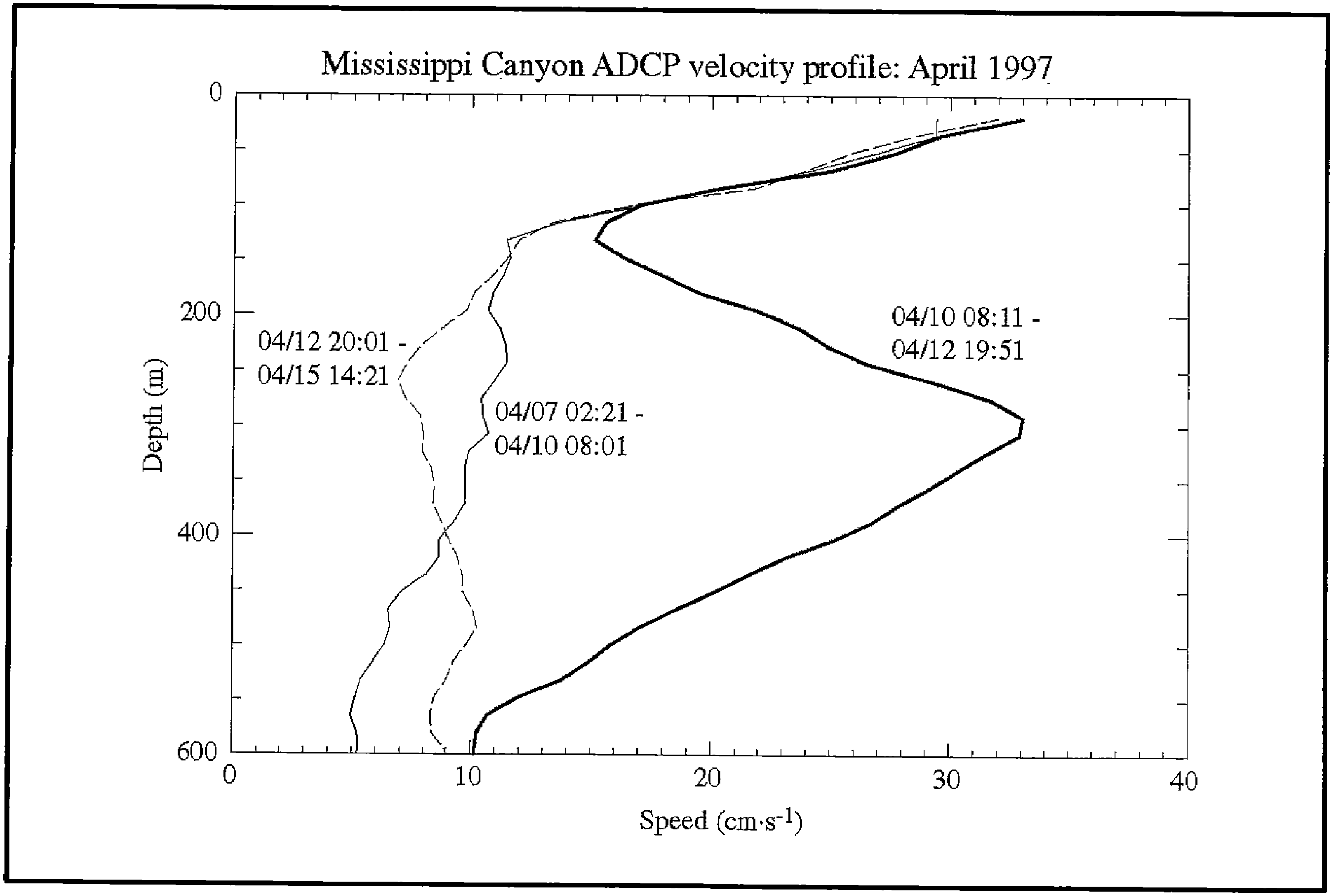


Figure 4.19. Average current profiles before (thin line), during (thick line), and after (dashed line) a subsurface jet event in Mississippi Canyon (data courtesy of Chevron).

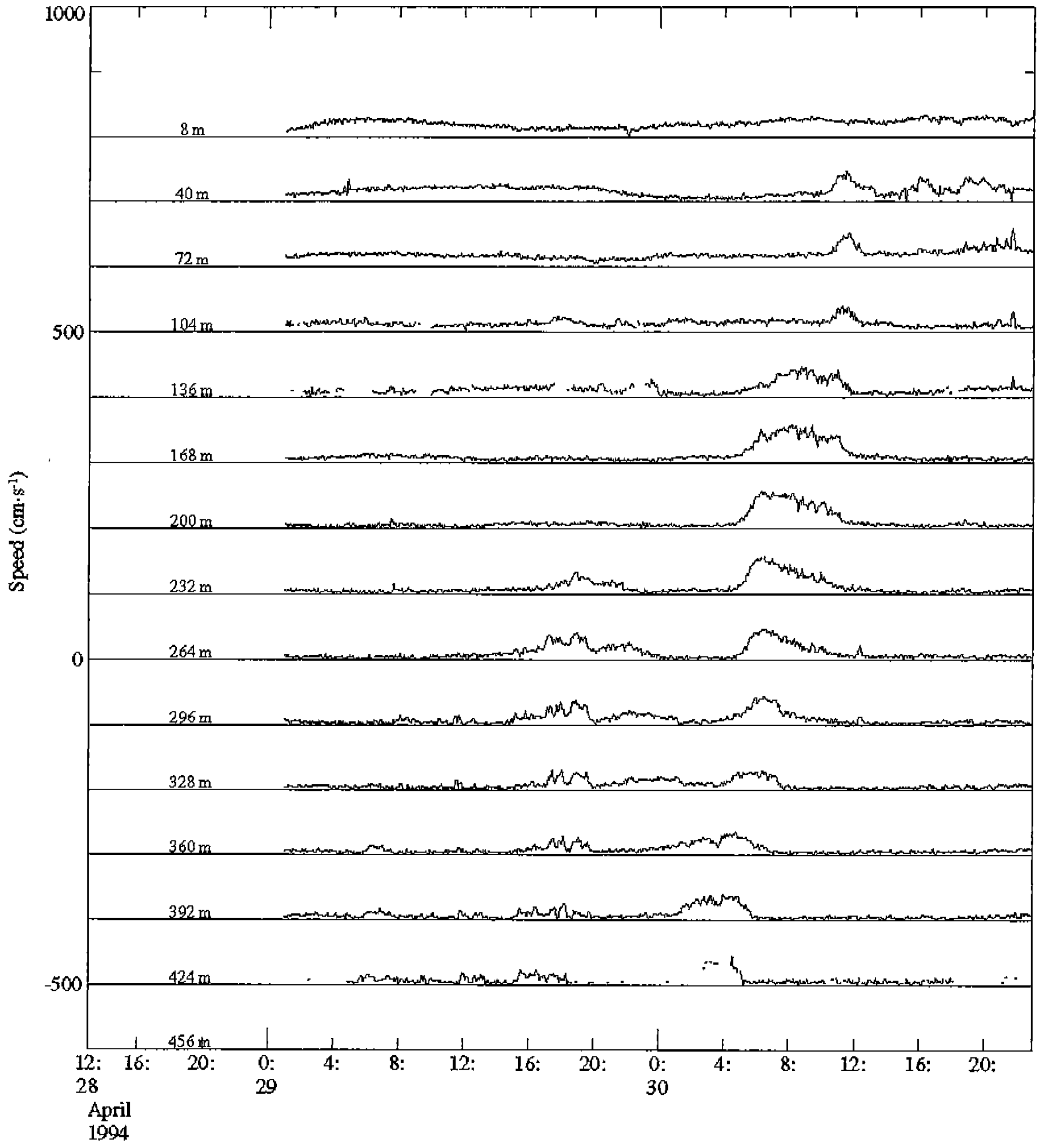
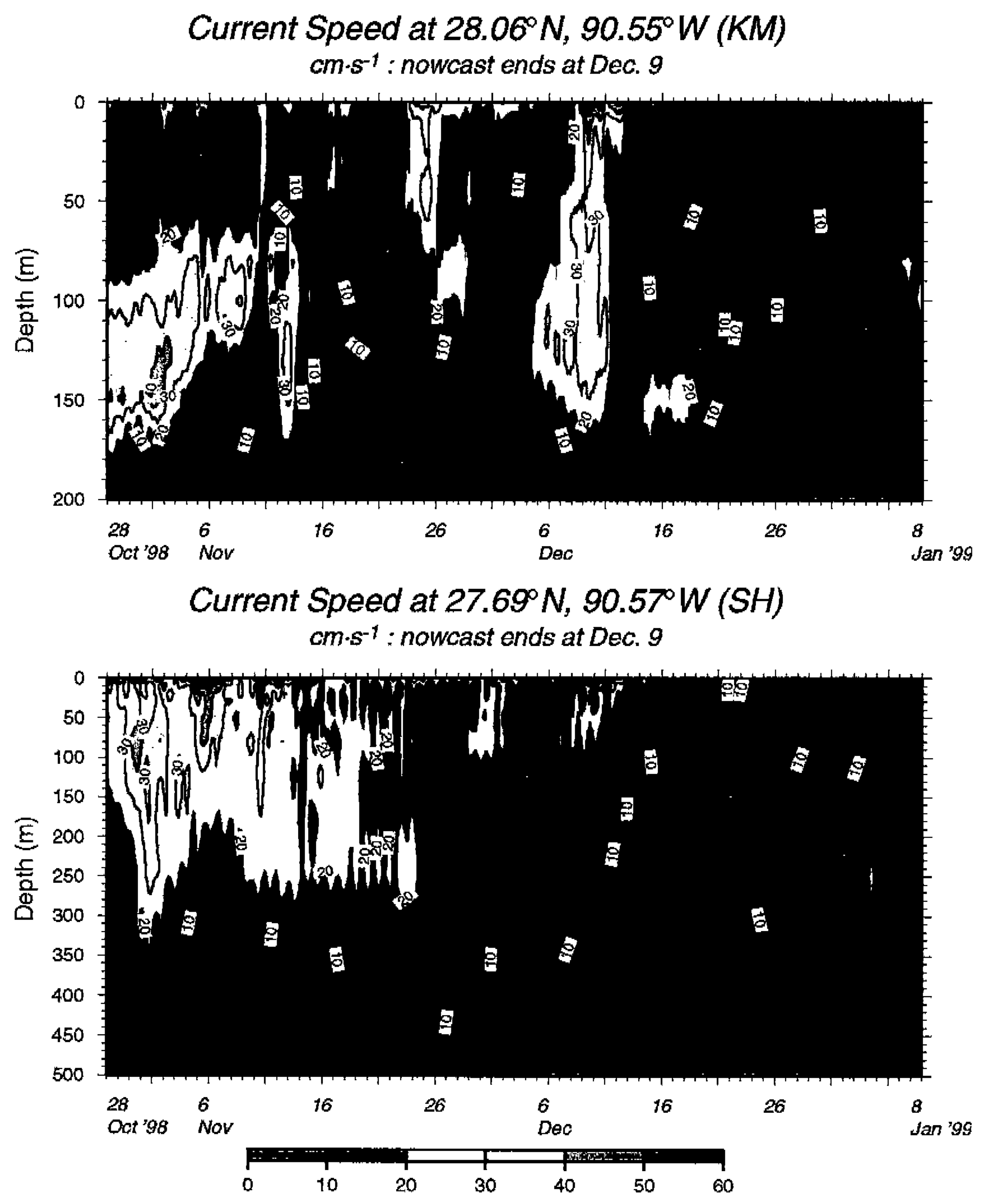


Figure 4.20. Acoustic Doppler current profiler current speed in Green Canyon Block 200 from 29 April through 30 April 1994, showing 50 cm·s$^1$ current event propagating upwards in the water column beginning about 30 April. Distances shown are in meters from the instrument, which was close to the surface. Data provided courtesy of Marathon.


Current Speed at 28.06° N, 90.55° W (KM)

cm·s-1 : nowcast ends at Dec. 9

Current Speed at 27.69° N, 90.57° W (SH)

cm·s-1 : nowcast ends at Dec. 9

Figure 4.21. Time series of vertical profiles of currentspeeds from the Kantha model. Shown are two Gulf of Mexico locations along 90.5°W in approximately 200 m (upper) and 1,000 m (lower) water depths (courtesy of CCAR, http://www-ccar.colorado.edu/~jkchoi/gomforecast.html).

It appears that the processes responsible for these furrows are active at present. Based on the change in character of these features from offshore toward the escarpment, and on the rather good agreement of that change with changes observed in published laboratory studies of submarine erosion (e.g., Dzulynski 1965; Allen 1969), the tentative conclusion is that bottom currents responsible for these features have along-isobath components and increase in strength toward the escarpment. Such work attributes the furrows to rows of counter-rotating helical currents generally directed along the furrows with rising parts of the helixes over the furrows. No direct measurements have been reported. The laboratory experiments indicate that furrows of different separation, wavelengths, and fundamental character occur for different flow rates. However, it is difficult to scale these model results to field conditions. Speculation is that near-bottom speeds of currents responsible for the inshore furrows might be 50 $cm{\cdot}s^{-1}$ or even in excess of 100 $cm{\cdot}s^{-1}$. These currents might be sporadic or quasi-permanent. These furrows and the currents responsible for them may also exist over a considerable part of the yet unexplored base of the continental slope in the Gulf of Mexico.

The implications of these furrows and currents for oil and gas production are manifold. These currents may represent a distinctly different phenomena, and thus problems, than the other classes of currents observed to date and presently under consideration.

## Effects of Shelf/Slope Canyons and Other Rough Topography

Submarine canyons may be conduits for exchanges of shelf and slope waters. Observations and model studies of canyons outside the Gulf of Mexico suggest that currents near the bottom tend to align with the canyon topography (e.g., Han et al. 1980) and that eddies which induce upwelling can form over the canyons near the shelf (e.g., Freeland and Denman 1982). The major canyons in the northern Gulf of Mexico are De Soto Canyon and Mississippi Canyon. De Soto Canyon is the broader of the two canyons. It nearly separates the Mississippi-Alabama shelf from the shelf off the Florida panhandle. The Mississippi Canyon is narrower and is located southwest of the Mississippi River Delta at about 90°W. Other rough topographical features of interest are the Sigsbee Escarpment and the many canyons inshore thereof off Texas-Louisiana and the Florida Escarpment off west Florida. The furrows and possible intense currents associated with them are located off the Sigsbee Escarpment (see discussion of deep currents).

Drennan (1968) summarized hydrographic investigations conducted from 1963 through 1965 over the east Louisiana-Mississippi-Alabama-west Florida panhandle shelves in the northeast Gulf of Mexico. He concluded that the De Soto Canyon bathymetry influences the horizontal circulation over the vicinity of the shelf edge in spring and early summer. During that time, a current flowed from the Mississippi Delta toward De Soto Canyon along the shelf edge. As this current moved over the canyon, it branched into a component that turned north in response to the bottom topography and a component that flowed toward the southeast. De Soto Canyon may act as a conduit for intrusion of deep waters onto the upper slope and shelf, as observed in May 1998 where cool water was pushed onto the shelf west of Cape San Blas (Nowlin et al. 1998a), and of energetic surface currents excited by the Loop Current or associated frontal eddies (e.g., Ebbesmeyer et al. 1982; Huh et al. 1981).

In a numerical modeling study of flow over shelf-canyon systems, Howard (1992) found that quasi-geostrophic flow across a canyon generates small scale eddies through vortex stretching processes and nonlinearities in the dynamics; these eddies freely propagate away from the canyon. He also found that wider canyons contain better organized eddy flows. During MMS-sponsored observations over the northeastern Gulf of Mexico shelves, both cyclonic and anticyclonic eddies were observed over the head of De Soto Canyon; similar eddies have been observed over other canyons and in numerical models (see e.g., Freeland and Denman 1982). A 1996-1999 study of the currents and hydrography over De Soto Canyon, being conducted for the MMS by SAIC, should provide added insights into the effect of De Soto Canyon on the circulation over the upper slope.

It was noted in discussing tidal currents that such currents in the deepwater region of the Gulf are very small. In the vicinity of canyons, however, the tidal currents may be more energetic. At the Mississippi Canyon mooring in 300 m water depth (indicated by MCTAMU in **Figure 4.7**), both the diurnal and semi-diurnal tidal currents were of amplitude >1 $cm{\cdot}s^{-1}$ at 50 m off the bottom as compared to <0.1 $cm{\cdot}s^{-1}$ (in the noise level) away from the canyon. The orientation of the tidal currents was along the canyon axis at the mooring location. The diurnal tidal current amplitudes appeared to be bottom intensified, being >2 $cm{\cdot}s^{-1}$ at 5 m off the bottom.

Direct current measurements in Mississippi Canyon are sparse. However, Lo (1999) conducted a modeling study of the buoyancy-driven flow over the Texas-Louisiana shelf that included the Mississippi Canyon. He found that a near-surface, offshore westward current split into two branches as it approached the canyon: one branch flowed across the canyon toward shore and the other formed a slope current along isobaths. He further found that an anticyclonic eddy was located near the head of the canyon and induced upwelling at the head of the canyon as water moved from depth onto the shelf along the canyon axis, consistent with the linear theory of geostrophic adjustment (see e.g., Freeland and Denman 1982; Klinck 1989; Howard 1992) and similar to observations over De Soto Canyon noted above.

## Numerical Modeling

### Types of Models and Studies

Numerical studies of the three-dimensional (3-D) circulation in the Gulf of Mexico (GOM) have employed primarily three generic types of models based upon the primitive equations of motion (enforcing mass, momentum, and energy conservation). The first type is the n-layer, quasi-Lagrangian model as in the studies of Hurlburt and Thompson (1980) and Murphy et al. (1999), and is most useful when thermohaline aspects are of secondary concern to the dynamics. Eulerian models (those employing a fixed 3-D grid) can most easily accommodate both thermodynamic and dynamic aspects. Such models using fixed z-levels are of the Bryan-Cox type (Sturges et al. 1993; Inoue and Welsh 1997) or the Sandia-type (Dietrich 1992; Dietrich and Lin 1994). Finally the most widely used Eulerian model in GOM applications is the Princeton Ocean Model (POM), developed by Blumberg and Mellor (1983) and adapted to a curvilinear grid by Blumberg and Herring (1984). The POM employs fixed values of the depth-following "sigma" coordinate (z/h, where h is water depth). Applications of this model have been used in GOM process studies (Oey 1995), climatological studies (Herring and Patchen 1997; Herring 1999), and hindcast, nowcast, and forecast studies by (Kantha and Piacsek 1993; Choi and Kantha 1997; and Herring 1999).

**Table 4.7** gives a capsulization, including the horizontal and vertical grid resolution for the different models in the GOM applications. One concern regarding the use of the sigma coordinate is the possible error in rendition of the horizontal pressure gradient and associated error in current (Haney 1991; Mellor et al. 1994). In order to minimize such error the vertical resolution over the steep continental slope must be consistent with the horizontal resolution. Specifically the number of cross-slope intervals on the slope should be compatible with the number of vertical intervals (as in the stair-step rendition of the seabed in a z-coordinate model). It is not clear how close this condition is met in all applications for the Gulf of Mexico, so this could be a source of difference among models. Another is differences in the parameterization of the sub-grid-scale along- and cross- isopycnal mixing of properties. The latter has an important impact on the shedding of eddies from the Loop Current.

The model studies discussed herein differ in their focus and in their domain. The emphasis in the studies by Oey (1995) using the POM model and Dietrich (1992, 1997) using the Sandia type model is on processes, including shelf dynamics, eddy-eddy and eddy-slope interaction. The early focus of the Dynalysis GOM studies was in hindcasting and climatology, and more recently in forecasting (Herring and Patchen 1997; Herring 1999). The Kantha model applications emphasize nowcasting/forecasting, including satellite altimeter and MCSST data assimilation (Choi and Kantha 1997). Although all of these model applications included local wind stress over the GOM, they are primarily driven by specified inflow to the GOM (or to the northwest region of the Caribbean Sea), and outflow from the Straits of Florida that is constrained to have the same volume transport as the inflow. The other studies considered here employ large *closed* domains over which the forcing is primarily by winds.

The focus of Sturges et al. (1993) and of Inoue and Welsh (1997), using the Bryan and Cox type model, was on relation of mesoscale variability in the upper to that in the lower layers of the GOM. The model domain in those studies includes a subregion of the North Atlantic and all of the Caribbean Sea, closed by walls at 36°N, 49°W, and 9°N. Hence the forcing was via North Atlantic winds. Finally, the study by Murphy et al. (1999), employing the NRL n-layer model (Wallcraft 1991), was also wind driven and of global domain. But its primary focus was on anticyclonic eddies that are spawned by the eastern retroflection of the North Brazil Current. These eddies grow within the Caribbean Sea, and some even squeeze through the Yucatan Channel to affect the evolution of the Loop Current. This raises the question as to real time monitoring of inflow to the GOM for predictive models. We address this question in a later section.

Table 4.7. Comparison of relevant properties of several ocean circulation models applied to the Gulf of Mexico

| Model | Reference | Horizontal Resolution | Levels or layers | Shedding period (mo) | Maximum current (cm·s$^{-1}$) | Typical flow near 2,000 m | Remarks |
|---|---|---|---|---|---|---|---|
| 2-layer | Hurlburt and Thompson 1980 | 20 km | 1.5 & 2 layers | 10.8 (327 d) | 73 | At rest for most runs | Extensive sensitivity tests |
| Bryan-Cox type | Sturges et al. 1993 | 1/4° | 12 fixed z levels | 6.9 (30 wk) | 100 | Cyclone-anti cyclone pairs | Closed domain |
| Bryan-Cox type | Inoue and Welsh 1997 | 1/8° | 33 fixed z levels | 6.9 (30 wk) | 100 | Cyclone-anti cyclone pairs | Closed domain |
| Sandia SOMS | Dietrich and Lin 1994 | 20 km | 16 fixed z levels | 9.9 (300 d) | 75 | Cyclonic basin scale | Eddy shedding tests |
| POM Oey version | Oey 1995 | 20 km | 20 fixed z/h sigma levels | Irregular 8 to 13 | Order of 100 | Not available | Shelf process study |
| POM Dynalysis version | Herring and Patchen 1997 | 4–14 km except in SW region | 15 fixed sigma levels | 7 to 20 for different conditions | Order of 100 | Cyclonic basin scale | Hindcast and climate study |
| POM Kantha version | Kantha and Piacsek 1997 | 1/5° and 1/12° | 21 fixed sigma levels | Order of 10 | Order of 100 | Not available | Assimilation of SSH and SST |
| N-layer NRL version | Murphy et al. 1999 | 1/4° in Gulf and Caribbean | 5.5 & 6 layers | Not applicable | Order of 100 | Not available | Global domain |

## Eddy Shedding Aspects

Clearly the cycle of intrusion of the Loop Current and the shedding of energetic eddies is the most important aspect of the GOM circulation which a realistic numerical simulation should get right. The numerical experiments in the early 1970's with linear and/or f-plane models of the GOM could not pass this test. Hurlburt and Thompson (1980) were the first to simulate the shedding of anticyclonic eddies (i.e., warm core rings) from the Loop Current, using a *nonlinear* two-layer numerical model that allowed planetary vorticity tendency (*beta effect*). Hurlburt and Thompson also demonstrated that the mean shedding period depends inversely on the square root of the maximum inflow speed and inversely on the buoyancy parameter (thermal stability). Their experiments showed that a periodic eddy shedding could occur with the lower layer at rest, even with *steady* inflow conditions in Yucatan Channel. Hurlburt and Thompson attributed the mechanism for shedding of eddies to barotropic instability, while the periodic property they related to the time for the Loop Current to reach its maximum intrusion after the spawning of an eddy. However, the shedding can be shut down if the horizontal mixing of momentum is too large, as in the earliest POM applications for the GOM (Blumberg and Mellor 1985).

Unlike the characteristics of warm core and cold core rings shed from the Gulf Stream in the North Atlantic (Chassignet 1992; Sturges et al. 1993), the LCEs are always warm core and are always shed in about the same place. Recognizing this, Pichevin and Nof (1997) now attribute the shedding of eddies associated with the retroflection of any major current system (like the Loop Current) to the requirement for a momentum balance for the system, in a time average sense. An important aspect of their analytic study is that it predicts the size of the eddies to be significantly larger than that deduced from the baroclinic radius of deformation. This may explain the greater size of the LCE compared with the North Atlantic warm core rings (beyond that due to the latitude difference).

All of the GOM model applications given in **Table 4.7** produce eddy shedding. The mean period of shedding varies from one application to another and is tunable to a certain degree, dependent upon the inflow conditions, the buoyancy parameter, and the lateral mixing coefficient for momentum. The application by Oey (1995) indicates a desired chaotic character of the shedding with a period range from 8 to 13 months. The Dynalysis 12 year climatological run, using a Smagorinsky (lateral mixing) coefficient of 0.05, exhibits a range of shedding from 9 to 23 months (Vukovich 1996). As discussed in an earlier section, the observed range is from about 4 to 16 months (Sturges et al. 1993). Further adjustment of the Smagorinsky coefficient could bring these POM models more in agreement with the observations, but even the latter is only about a 25 year sample, and hence is subject to uncertainty. The encouraging thing is that these two applications do demonstrate a chaotic character of shedding, similar to the real observed conditions.

Both the Dynalysis and Oey model domains include the northwestern part of the Caribbean Sea, while most applications of the Kantha model do not. In the study by Oey (1995), he found that eddy separations were often followed by a reversal in the flow of deep water near the Yucatan sill, so as to return water to the Caribbean Sea (Oey, personal communication). We speculate that this interaction of the two basins may be important in the separation process and its chaotic character. It may also be important in governing the circulation in the layer between 800 and 2,000 m (the sill depths for Straits of Florida and Yucatan Channel, respectively). The results of the Dynalysis climatological study show that this layer has a mean cyclonic circulation in the eastern Gulf, in opposition to the mean anticyclonic circulation of the Loop Current in the upper 800 m (Herring and Patchen 1997). The studies based on the Bryan-Cox type model (Sturges et al. 1993; Inoue and Welsh 1997) support this result.

## Other Skill Assessment

The MMS funded the LATEX measurement and data analysis program for the northwestern Gulf of Mexico as well as the numerical hindcast and climatology study of GOM circulation carried out by Dynalysis of Princeton. Skill assessment of the Dynalysis model results was addressed by an independent team including C. N. K. Mooers from the University of Miami, P. P. Niiler from Scripps Institution of Oceanography, M. Inoue and W. J. Wiseman from Louisiana State University, and F. M. Vukovich from SAIC at Raleigh, NC. They addressed the model skill with respect to response to synoptic time and space scale wind forcing, including a simulation of hurricane Andrew, as well as extratropical storms which occurred during the LATEX measurement time window (April 1992 to December 1994). They also addressed the monthly and seasonal climatology, including of course the Loop Current and LCE characteristics. Final reports have presumably been submitted to MMS from the skill assessment group, but were not available to the authors at the time of writing this literature survey. However, an interim report by Vukovich (1996) on eddy shedding skill (discussed earlier), and one by Mooers (1996) on near coastal current skill, were available to one of the authors from a project meeting at Dynalysis in March 1996. Some important aspects of Mooers' analysis are discussed below.

Included in the many runs of the Dynalysis model were hindcasts using synoptic wind fields employing point specific buoy data blended with ECMWF wind fields, for a time window encompassing the LATEX current measurement period (April 1992 to December 1994). The Mooers (1996) interim report provides results of auto- and cross-spectra of the simulated eastward and northward current components at 100 m depth, for the shelf break LATEX current meter moorings 7 to 11 (between 92° and 95°W along the 200-m isobath). The spectra are based on a time window spanning the three calendar years 1992 to 1994, and cover the frequency range from about 0.01 to 12 cpd. The autospectra for all of the simulated mooring positions are very similar for given current component. They show statistically significant peaks at about 0.2, 1.0, and 5 cpd. Moreover, the coherence among the five mooring positions is high with westward propagation indicated for the 0.2 cpd peak.

Visual comparisons between observed between observed and simulated time sequences of currents at the Texas-Louisiana shelf break indicated low correlation (presumably related to the influence of the LCE impacting the shelf differently in the model versus the observations). However, the current spectra deduced from the LATEX observations

(DiMarco et al. 1997) for the middle meter (at 100 m depth) for moorings 7 to 11 do indicate a peak at about 0.2 cpd. For mooring 9 the observed peak at 0.2 cpd and that simulated by the Dynalysis model are both about the same magnitude. Although the coherence among the observed shelf break currents data was low, the studies of Hamilton (1990) using current meter data on the continental slope support the existence of westward propagating topographic Rossby waves.

## Status of Nowcast/Forecasts

Two operational nowcast/forecasts of GOM circulation are presently in existence and available on the world wide web. One is for the coastal region north of about 25°N being carried out by Dynalysis as part of the NOPP Ocean Monitoring Program (Herring 1999). The other is the Gulf wide nowcast/forecasts carried out by the Kantha, Choi, Leben team at CCAR (Choi et al. 1995; Choi and Kantha 1997). The latter effort is supported by the petroleum industry Consortium for Analysis Studies of Eddies (CASE) because a knowledge of the position and strengths of LCEs is vital in offshore drilling and recovery operations for oil and gas.

An important finding of the LATEX program (Nowlin et al. 1998a) was that about 50% of the variance of subtidal observed currents on the Texas-Louisiana inner shelf (water depths of 50 m or less) can be explained by the winds. We would therefore expect that the coastal nowcasts of currents by the Dynalysis operational model would have a skill that at least matches this finding for that region. The skill for forecasts, however, is heavily dependent upon the skill of the wind forecast model used to locally drive that model. Real time observations of near surface currents at several sites over the Texas shelf are available from the Texas Automated Buoy System (TABS), which is jointly supported by the Texas General Land Office and the MMS of the Department of Interior. Spot checks of the Dynalysis near-surface current predictions over the Texas shelf indicates reasonable skill for the daily average current. The observed TABS currents show large near inertial motion superimposed on the low frequency along shelf flow. Reversals in flow from upcoast to downcoast or vice versa can follow reversals of local winds within a day. The model predictions track such changes well as long as the wind predictions are correct. The wind fields used in the predictions are supplied by the NCEP mesoscale ETA forecast model.

The CCAR (Choi et al. 1995) data assimilative model is reasonably accurate in nowcasts of the Loop Current and large energetic eddies. The SSHA deduced from satellite altimeter data represents a blending over time and space of TOPEX and ERS-2 data, and is most accurate for large scale features. The method of assimilation of the SSHA and of SST data is discussed in the application of the Kantha-Piacsek model by Horton et al. (1997). A primary limitation in the forecasting of changes in the Loop Current and associated LCE is the present lack of real time monitoring of inflow to the GOM. Motivated by this need, the Eddy Joint Industry Program (EJIP) together with the NOPP Ocean Monitoring Program are carrying out a series of aerial and ship surveys along one of the TOPEX tracks (number 65) across the western Caribbean Sea. The purpose is to provide the calibration of that track so as to allow real time estimates of the SSHA and associated geostrophic inflow to the western Caribbean and hence to the GOM. In the meantime, the CCAR model domain has been extended into the Caribbean, with the TOPEX track 65 serving as the new open boundary (personal communication with Choi). By monitoring inflow in real time along this track, forecasts of changes within the GOM should be improved, since the advection of the boundary information into the Gulf requires several weeks.

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# Chapter 5: Chemical Oceanography

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## Introduction

The Gulf of Mexico is a semi-closed sea that receives the bulk of its water from inflows from the Caribbean Sea through the Yucatan Channel with outflow through the Straits of Florida. The origins of the water establish the initial chemical characteristics of water masses within the basin. After inflow, the chemical composition of these water masses are then modified by a number of processes including *in situ* processes such as biological activity (which transforms nutrients to biomass and produces oxygen), mixing, and upwelling. In addition, large amounts of runoff enter from the river systems that ring the basin. Runoff from approximately two-thirds of the United States and more than half of Mexico empties into the Gulf of Mexico. These discharges regularly introduce a range of dissolved and particulate materials to the basin. Atmospheric transport, through wet and dry deposition, is another pathway that introduces chemicals to the basin. These processes can also introduce contaminants to the basin. In addition, activities occurring within the basin proper (shipping, oil and gas exploration and production, etc.) can introduce contaminants to the water and sediments.

This review summarizes what is known about the chemistry of the open water Gulf of Mexico (GOM) between water depths of 300 and 3,000 m. Geologic setting is important when considering the chemical oceanography of the deep GOM. The basin is characterized by wide continental shelves effectively isolating the deeper GOM from the direct influences of many coastal processes. The slope is characterized by steep inclines and a complex topography. Once deposited, sediments can be redistributed by mass wasting and slumping. These basinal features are important influences on the chemical composition of deep sea water and sediments. Another important feature of the deepwater GOM is that this region is underlain by large accumulations of salt, oil, and gas that have migrated nearly vertically into surficial sediments. The salt in contact with porewaters produces brines that migrate into near-surface sediments. Salt movement creates the tectonic forces that influence local topography. This same salt movement also creates subsurface conduits that allow liquids and gases to seep into near-surface sediments and the overlying water column. The active petroleum system that underlies the deep northern GOM has an important effect on the chemical characteristics of the slope environment as well. The leaky nature and immense volumetrics of the petroleum system allow the introduction of large amounts of petroleum hydrocarbons into the basin from below. Imprinted over these natural introductions of chemicals are inputs from anthropogenic activities.

The interactions of sources and sinks mediated by complex biogeochemical processes are the framework that establishes the spatial and temporal patterns of chemicals in the water and the sediments of the deepwater northern GOM.

## Dissolved Gases

The water overlying the deepwater GOM contains a range of dissolved constituents whose distributions lend clues to the relative importance of various biochemical processes in establishing the observed chemical distribution. Dissolved constituents include gases and solids. The dissolved gases include carbon dioxide ($CO_2$), oxygen, nitrogen, and other trace gases such as methane and hydrogen. The basic control on the concentrations of gases in near-surface waters is exchange with the atmosphere. Secondarily, gases such as oxygen, $CO_2$, and methane have their distributions altered by biological and/or other processes, i.e., they are non-conservative. The distribution of inert gases (such as nitrogen) are primarily affected by physical redistribution processes including mixing and diffusion, i.e., they are conservative.

A complete discussion of the $CO_2$ system is beyond the scope of this review. However, the salient points of the $CO_2$ system that are operative in the water masses of interest to this review are briefly discussed. Carbon dioxide concentrations are the end result of the interaction of biological processes (photosynthetic uptake and respiratory production), water transport, and surface heating and cooling that drives the air/sea partitioning of $CO_2$ (Riley and Chester 1971). Carbon dioxide concentrations in surface waters vary temporally on scales from hours to months (seasonal). In the open deepwater GOM, the equilibrium concentrations of $CO_2$ are predictable since the overall size of the carbon pool is large and the concentration of living organisms is relatively low compared to more isolated and smaller bodies of water where $CO_2$ concentrations and speciation can be highly variable in space and time. Below the thermocline, $CO_2$ concentrations are affected only by advection, diffusion, and the biological oxidation of organic matter. Total $CO_2$ rises sharply below the thermocline and increases to a maximum at a depth of 500 to 1,000 m coinciding with the oxygen minimum.

Dissolved oxygen is another biologically active gas and is an important product of photosynthesis. As for $CO_2$, the initial control on dissolved oxygen concentrations is exchange with the atmosphere. Near-surface oxygen levels are augmented by photosynthesis. Below the surface layer, a layer of oxygen supersaturated water tends to develop as this is the site of intense biological activity. Below the photic zone, respiration, which produces $CO_2$ and consumes oxygen, increases to a point where it exceeds the oxygen production and an oxygen minimum develops. The GOM oxygen minimum layer develops outside of the GOM and enters the GOM as an established water mass property through the Yucatan Channel (Wust 1964). This low oxygen layer spreads across the GOM and can intersect the seabed on the continental slope. Typical oxygen values are 3.5 to 4.5 $mL{\cdot}L^{-1}$ in the upper 200 m, 2.5 to 3.5 $mL{\cdot}L^{-1}$ at 200 to 500 m, and 2.5 to 5.5 $mL{\cdot}L^{-1}$ in water depths >500 m (Nowlin 1972).

Trace gases in the deepwater GOM can have an atmospheric and a biological source. In particular, methane exhibits near surface water maxima similar to dissolved oxygen. Methane is believed to be biologically produced *in situ*. An additional source of methane is water advected from the adjacent shelf where sedimentary porewater methane diffuses into the overlying water column. Methane concentrations have been shown to be associated with indicators of phytoplankton biomass (ATP) and with suspended particulate matter maxima (Brooks et al. 1981). Methane appears to be formed *in situ* in the reducing microenvironments associated with suspended particulates, some of which are advected into deeper water from the shelf (Brooks et al. 1981). Typical methane values are 50 to 250 $nL{\cdot}L^{-1}$ in the upper 200 m of the water column and 10 to 40 $nL{\cdot}L^{-1}$ in deeper waters distant from natural gas seeps. Significant amounts of methane and higher molecular weight hydrocarbons are introduced to the water column from natural seepage. In deeper waters, methane is stored in gas hydrate and the methane can have a biologic or thermogenic origin.

## Dissolved Solids

In addition to dissolved gases, deepwater GOM water masses contain dissolved solids. The most obvious is "sea salt," which is primarily sodium chloride with smaller amounts of a range of cations and anions. Salinity distributions in the study area are discussed elsewhere. In addition to salt, the water masses contain dissolved nutrients, dissolved organic carbon, and dissolved metals. The primary nutrients are nitrate, phosphate, and silicate and are essential elements for the growth of organisms. Dissolved organic matter (DOM) and metals are derived from several sources. In deepwater areas, the DOM can be quite old, reflecting the long term accumulation of microbially resistant DOM from marine and riverine sources. DOM can be both natural and anthropogenic in origin. Dissolved metals can be derived from riverine inputs and resuspension of sediments. As for DOM, dissolved metals also can be natural or anthropogenic in origin.

### Nutrients

Nutrient concentrations and distributions in the deepwater Gulf of Mexico are controlled by a combination of biogeochemical and physical processes (Armstrong 1974). The processes that control nutrient concentrations—river discharges, coastal currents and winds, upwelling, biological activity, and rainfall—are operative to some degree in the deepwater GOM. In near-bottom waters, remineralization of organic matter can liberate nutrients into the overlying water column. Excess or enhanced nutrient levels can contribute to plankton blooms followed by oxygen depletion due to organic matter decay. On the outer continental shelf and in deeper waters, differences in nutrient concentrations between surface water and bottom waters are substantial. Nutrient concentrations increase from below the detection limit in surface waters to maximum values in the deepwater GOM. Waters as deep as 70 m tend to be nutrient-poor. An abrupt increase in nutrient concentrations occurs between 70 and 100 m water depth. This vertical structure develops as a result of the fixation of nutrients into biomass by phytoplankton in the euphotic zone and remineralization of organic matter in deeper waters. These processes occur basin-wide and are key to establishing the chemical characteristics of the water masses in the deepwater GOM.

Nitrogen is essential for life and provides an important chemical building block for many organic compounds such as amino acids and proteins. Nitrogen occurs in seawater as dissolved molecular gas ($N_2$) and inorganic and organic compounds. The principal inorganic forms of nitrogen in seawater are nitrate ($NO_3^-$), nitrite ($NO_2^-$), and ammonia. Seawater also contains minute amounts of other inorganic compounds as well as dissolved and particulate organic nitrogen compounds. The distribution of the major inorganic nitrogen species in the deepwater GOM is controlled by biological processes. Once incorporated into biomass, nitrogenous materials are redistributed in the water column due to sinking of the detrital remains of dead organisms and upwelling of deeper waters to the near surface. These processes, operating in unison, establish a "nitrogen cycle." While phytoplankton normally synthesize proteins from nitrate, nitrite and ammonia, bacteria preferentially incorporate organic nitrogen. During metabolism, nitrogenous material, mainly in the form of urea, is excreted by living organisms. The nitrogen cycle is not a closed system in that nitrogenous material is deposited in sediments and various forms of nitrogen enter the GOM in river and rain water. Important processes that control the distribution of nitrogen in the open water GOM include nitrogen fixation, assimilation of fixed nitrogen, and regeneration of nitrogen. Most nitrogen assimilation occurs in the euphotic zone whereas regeneration of nitrate occurs throughout the water column and in the sediments. This offset in the spatial juxtaposition of these processes establishes the commonly observed vertical heterogeneity observed in water column profiles of inorganic nitrogen. Because the distribution of nitrogenous materials is primarily influenced by biological processes, there is a strong seasonal variation in concentrations. Typical nitrate concentrations are 0 to 20 $\mu$M in the upper 200 m of the water column and 20 to 30 $\mu$M in waters deeper than 200 m.

As another nutritive element required by living organisms, the same input and removal processes control the distribution of phosphorus in the open waters of the GOM as do nitrogen. Phosphorus occurs in seawater in a variety of dissolved and particulate forms. Inorganic phosphorus is predominantly in the form of orthophosphate ions ($PO_4^{-3}$). Dissolved phosphorus in seawater also occurs as organic compounds mostly derived from the decomposition of organismal remains and excretion from living organisms. Phosphorus occurs in the particulate form in seawater in association with living organisms and detrital remains from dead organisms. As for nitrogen, a "phosphorus cycle" has developed in the open waters of the GOM. Removal mechanisms include sedimentation and inputs are derived from riverine discharges, rainfall, and regeneration in the water column and sediments. Phytoplankton usually satisfy their phosphorus needs by direct assimilation of dissolved orthophosphate followed by metabolic transformation to organophosphorus compounds (phospholipids, phosphonucleotides, etc.). In the open water GOM, phosphorus is generally available in amounts exceeding the needs of the resident organisms. Bacteria satisfy their nutritional needs for phosphorus from detritus and are an active component, in addition to intracellular enzymes, in the process of regeneration of phosphorus. The close coupling of phosphorus to biological processes results in strong temporal variations usually associated with the seasons. Vertical and spatial heterogeneity in phosphate distributions reflects the dynamic interplay of sources and removal processes. Differences in the locations where these processes occur establish the observed spatial gradients and patterns in phosphate concentrations. Typical phosphate concentrations are 0 to 1.0 μM in the upper 200 m of the water column and 1.0 to 1.8 μM in waters deeper than 200 m.

Silicon is present in seawater in both dissolved and particulate forms. The dissolved form is commonly determined as silicate ($SiO_4$). A major source of silicon to the GOM is the subaerial weathering of rocks followed by riverine transport to the sea. Within the water column there are many organisms, including diatoms and radiolarians, that have skeletons composed of hydrated silica-opal. Upon their demise, the siliceous skeletons slowly dissolve in seawater as they sink to the underlying sediments. High concentrations of silicon are observed in inshore regions and can account for as much as 60% of the water column particulate matter depending on geographic location. Seawater is undersaturated with respect to silicon and therefore dissolution is almost always an ongoing process. The incorporation of silicon into biological structural components is an efficient mechanism of removing silica from seawater. These materials are also efficiently transported and deposited to the sediments due to the rapid settling and slow dissolution rates. The open water GOM contains several groups of plants (diatoms) and animals that require silicon to maintain their structural integrity. The concentration of silicon in open surface waters is generally low except in regions of upwelling due to the uptake by organisms in the euphotic zone. As with the other nutrients, the close coupling of silicon with biological processes produces spatial and temporal variations in its distribution and patterns. The "silicon cycle" produces heterogeneous patterns in time and space that reflect the balance of sources and removal processes. Each process can be more or less important depending on the local setting producing significant regional variations in silicon distributions. Typical silicate concentrations are 0 to 10 μM in the upper 200 m of the water column and 10 to 24 μM in waters deeper than 200 m.

### Dissolved Organic Matter

DOM is defined as that material which passes through a 0.5 micron filter and includes truly dissolved material as well as colloidal matter. The primary origin of DOM is biological organisms either through exudates or decomposition of detrital remains. The dissolved portion of organic matter can include a wide range of anthropogenic compounds such as hydrocarbons and other man-made chemicals (DDT, etc.). DOM in the study area arises from riverine and atmospheric transport, decay of dead organisms, algal metabolic exudates, and zooplankton and larger animal excretions. Riverine derived DOM is primarily composed of leachates from humic materials and the decomposition of vegetable matter. Riverine DOM can also include sewage and industrial effluents. In open GOM waters, *in situ* biological activity is an important source of new DOM. Two processes that produce DOM in the open water GOM are the lysis of cells and the bacterial degradation of organic matter. Algae are known to produce appreciable amounts of excretion products. Zooplankton and other marine animals excrete DOM as well. The excretion products are generally nitrogenous in nature including urea, purines, and amino acids.

DOM is usually measured as dissolved organic carbon (DOC). Few measures of DOC in the deepwater GOM have been reported. Deepwater GOM DOC concentrations vary from 0.5 to >2.0 $mg{\cdot}L^{-1}$ (Fredericks and Sackett 1970). DOC values are highest on the shelf, lower in the surface waters of the open Gulf, and lowest in the deep open GOM. Open GOM surface water (0 to 90 m) concentrations ranged from 0.45 to 1.07 $mgC{\cdot}L^{-1}$ with a mean of 0.79 and deepwater (90 to 3,600 m) DOC concentrations varied from 0.33 to 0.94 $mgC{\cdot}L^{-1}$ with a mean of 0.52. Other observations at a few slope stations reported DOC concentrations ranging from 45 to 130 micromolar, with 30% to 60% of the DOC being high molecular weight depending on location and season (Bianchi et al. 1997). As in the previous study, DOC generally decreased from shelf to slope waters and from surface to bottom waters. These and other studies suggest that a large portion of terrestrially derived DOC is preserved and transported to open GOM waters. DOC generally exceeds particulate organic carbon (POC) concentrations by a factor of 10 to 20, accounting for most of the organic carbon in a typical water column.

DOM is believed to be primarily complex macromolecules that are resistant to bacterial degradation thus accounting for the old age of DOM in deep GOM waters. DOM can contain amino acids, carbohydrates, lipids, and vitamins. In addition, anthropogenic chemicals can occur in a dissolved state as well. One class of compounds of interest is the hydrocarbons. Lower molecular weight hydrocarbons are at least sparingly soluble in seawater. In particular, those compounds referred to as volatile organic compounds (VOC) will be dissolved if they are present. In the deep sea portions of the GOM, these hydrocarbons can be derived from ship traffic, tanker discharges, discharges from offshore platforms (produced waters), spills, and natural seepage. In general, dissolved VOC and higher molecular weight hydrocarbons are below detection limits other than in areas close to discharge points. VOC rapidly equilibrate and degas to the atmosphere. Hydrocarbons are also labile being subject to relatively rapid microbial degradation.

Most studies of dissolved hydrocarbons in the GOM have been restricted to shallow waters and will not be reviewed here. Early studies by Iliffe and Calder (1974) detected concentrations of extractable non-polar dissolved hydrocarbons in the GOM ranging from trace amounts to 75 $\mu g{\cdot}L^{-1}$ with the highest concentrations occurring in the Straits of Florida. The hydrocarbons were primarily n-alkanes containing 15 to 20 carbons. Atmospheric fallout and tanker traffic were mentioned as possible sources. It is also unclear whether these hydrocarbons were truly dissolved. Sauer et al. (1978) and Sauer

(1980) found open GOM surface waters to contain 60 $ng \cdot L^{-1}$ or less of volatile liquid hydrocarbons (VLH) of mostly a biological origin. This contrasts with more polluted coastal and shelf waters with concentrations of more than 500 $ng \cdot L^{-1}$. VLH were composed of normal alkanes, cycloalkanes, and aromatic hydrocarbons. Brine discharges, tanker washings, and the underwater venting of waste gases were identified as sources of VLH. In general, open water GOM dissolved hydrocarbons are at least an order of magnitude lower in concentration than nearby shelf waters. No appreciable levels of dissolved hydrocarbons have been detected in the open water GOM; however, deepwater areas are not well studied. In areas of natural seepage, hydrocarbon concentrations can be significantly elevated and sea slicks are known to form in these areas as well.

It is generally believed that biological organisms are primarily affected by exposure to dissolved contaminants. In addition, organisms can ingest particulate contaminants and/or in the case of hydrocarbons, be externally coated if the levels are high enough (i.e., spills). As the main mechanism of bioaccumulation, dissolved contaminants and the associated organismal body burdens are often used to indicate exposure. A confounding factor in recognizing organismal exposure to organic contaminants is that many organisms, such as fish, are efficient at depurating toxic compounds. In particular, aromatic hydrocarbons are transformed by enzymatic modifications and are excreted in the bile. Therefore, contaminant body burdens may or may not reflect contaminant exposure history. There are few studies of the concentrations of hydrocarbons in organisms from the open GOM. Those organisms obligately associated with natural oil and gas seeps are discussed elsewhere in this chapter. In one report, the levels of benzene, toluene, ethylbenzene, phenol, fluorene, benzo(a)pyrene, and bis(2-ethylhexyhl)phthalate were either not detected or below the detection limit in tissues from representative fish species at two platform sites in about 300 m of water (Offshore Operators Committee 1997). While the amount of data in the open waters of the GOM is limited, it is expected that most if not all organisms will be free of significant anthropogenic contamination.

## Dissolved Metals

Metals have both natural and anthropogenic sources in the deepwater GOM. Metals are released during the weathering and decomposition of rocks (minerals, soils, etc.) and are then transported to the basin in dissolved and particulate forms. Human activities can also introduce metals to the water column from dumping of wastes, oil and gas exploration and production activities, construction, and shipping. Few studies have analyzed the concentration of dissolved metals in the deepwater GOM. Dissolved metals that have been detected in riverine runoff include copper, nickel, chromium, and molybdenum. It has been estimated that less than 10% of the metals transported to the sea are in the dissolved form (Trefry and Presley 1976). Atmospheric transport of metals can also be a pathway that introduces metals to the basin. Direct anthropogenic introduction of contaminants to the open water GOM occurred during the 1970's when approved dumpsites were used to dispose of industrial wastes at one location 90 km offshore off Southwest Pass in 1,000 m of water and a second site 220 km south of

Galveston. Exploration and production platforms are also known to discharge cuttings and produced waters that contain dissolved and particulate metals to the adjacent waters.

Open GOM surface waters had concentrations of 0.082 ppb for copper, 0.11 ppb for nickel, and 0.0005 ppb for cadmium (Boyle et al. 1984). These levels were approximately five times lower than those observed in coastal regions. For a second sampling of surface waters in the northwestern GOM in water depths from 100 to 1,000 m, similar concentrations of dissolved copper, cadmium, and nickel were observed. Higher values were indicated nearer to shore and nickel, copper, and cadmium concentrations increased with water depth as a result of organic matter degradation. Dissolved cadmium increased sharply with water depth and some deep samples were 10 times higher than near-surface samples. Other metal concentrations increased with depth but the increases were less regular and were usually not more than by a factor of two. Dissolved metal data in general suffers from artifacts due to the lack of clean methods for sample collection because of the very low concentrations encountered. It is also been noted that pore water dissolved metal concentrations are generally higher than the overlying water suggesting that diffusion of metals into the overlying water may be an important source of some dissolved metals (Presley and Trefry 1980; Trefry and Presley 1982). Dissolved metals have not been well studied in the deepwater GOM, but the few reports suggest that dissolved metals occur at very low (>ppb) levels.

As for organic contaminants, it is generally believed that the most biologically available component of metals is the dissolved fraction. As can be seen above, the levels of dissolved metals in the open water GOM are expected to be extremely low in concentration. As such, metals in organismal tissues would be expected to be low as well. This was the conclusion of a study of trace metals in organism associated with two platforms in about 300 m water depth in the northern GOM (Offshore Operators Committee 1997). In representative fish species, collected in close proximity to platforms, arsenic varied from 2 to 59 $\mu g \cdot g^{-1}$, cadmium from not detectable to 0.82 $\mu g \cdot g^{-1}$, and mercury from 0.036 to 0.33 $\mu g \cdot g^{-1}$. The fishes were collected at sites that were discharging produced waters and sites that were not discharging produced waters. No statistical differences could be detected between the sites, suggesting that natural processes and not produced water discharges were responsible for the metal concentrations observed in tissues. The concentrations detected were considered natural background levels for fishes collected throughout the GOM.

## Particulate Matter

In addition to the dissolved constituents described above, water masses in the deepwater GOM also contain significant amounts of particulate matter. Particulate matter in the water column of the open water GOM can be organic or inorganic, living or dead, and natural or anthropogenic in origin. Particulate matter is defined as those materials that are retained on a 0.5 micron filter. Particulate matter is often expressed as the weight of total suspended matter (TSM). Typical TSM values range from 50 to 200 $\mu g \cdot L^{-1}$ in the upper 200 m of the water column and 20 to 100 $\mu g \cdot L^{-1}$ in deeper waters (Feely et al. 1971) of the open water northern GOM.

## Particulate Organic Matter

In the deepwater GOM, the particulate organic matter (POM) in the upper water column is primarily detritus and phytoplankton. There are few studies of the distribution of POM in the open water of the GOM. Phytoplankton are the living portion of POM and generally account for 25% or less of the total particulate organic matter but this can be highly variable in the euphotic zone. The living fraction may also contain bacteria, fungi, and yeasts, with bacteria in some instances being a significant fraction of the biomass. With increasing depth below the euphotic zone, the living fraction of the POM decreases rapidly. POM is usually 10 to 20 times lower in concentration than the DOM. POM is usually measured as POC. Typical POC concentrations range from 50 to 100 $\mu g \cdot L^{-1}$ in the upper 200 m of the water column and 30 to 50 $\mu g \cdot L^{-1}$ in waters deeper than 200 m in the open water GOM (Feely et al. 1971).

Live phytoplankton are confined to the euphotic zone and the water lying immediately beneath it (Riley and Chester 1971). The composition of this portion of the POM can vary widely and the biological communities found in the water column are discussed elsewhere. The living portion of the POM is composed of a wide array of biochemicals including proteins, carbohydrates, fats, and pigments. The non-living POM is also a complex mixture of chemical compounds that varies with water depth. In the euphotic zone, biochemical metabolites are a major fraction of the POC. Many of these biochemicals are subject to rapid degradation as they settle through the water column. The residual POM at depth is materials that are resistant to degradation such as cell walls and exoskeletons. In the deepwater GOM, most of the water column POM will be derived from phytoplankton but terrestrially-sourced POM contributes as well.

POC in the euphotic zone is spatially and temporally highly variable due to it primary origin in biological organisms. POC is high in the upper water column and decreases with depth due to remineralization as the particulates sink through the water column. Below a depth of 200 m, POC values become relatively constant. An estimate of the amount of living POC can be based on chlorophyll a concentrations. Plankton biomass in the open Gulf of Mexico is considered to be low with values of 100 to 150 $mg \cdot m^{-3}$ compared to regions near the Mississippi River of 200 to 1,000 $mg \cdot m^{-3}$ (Khromov 1965; Bodganov et al. 1968). Profiles of chlorophyll *a* show low values near the surface followed by maximum concentrations at 50 to 110 m coinciding with the bottom of the euphotic zone, the pycnocline, or the nutricline (El-Sayed 1972; Hobson and Lorenzen 1972). Similar distributions of POC and chlorophyll *a* are expected in the open water GOM.

Included in the POM are anthropogenic chemicals including hydrocarbons and metals. The higher molecular weight hydrocarbons are non-polar and often occur primarily adsorbed onto particulates. Few studies are available on the distribution of seawater particulate hydrocarbons in the study area. It is expected that the concentrations will be lower than those for adjacent coastal and shelf waters. Water column particulate hydrocarbons originate from spills, platform discharges, and shipping activities. Some small, but unknown, input of atmospherically transported POM might also contribute terrestrial hydrocarbons (i.e., plant biowaxes). Resuspension of sediments is another important mechanism for introducing particulates into the water column, especially hydrocarbon-rich particulates in areas of known oil and gas seepage.

A special class of POM is pelagic tars. A summary of the distribution of pelagic tarballs in the GOM indicates that they are ubiquitous (Geyer 1980; Brooks 1981; Van Vleet et al. 1984). Tarballs are found in most surface neuston tows in the GOM (Jeffrey 1973, 1977, 1979; Jeffrey et al. 1973, 1974; Parker et al. 1979). Jeffrey (1979) determined that the average floating tar concentration in the GOM was 1.35 $mg \cdot m^{-2}$, based on 220 neuston tows between 1972 and 1976. No apparent change in tarball concentrations was observed during this period. The highest tar concentrations were observed in the western portions of the GOM. Koons and Monaghan (1973) estimated the standing crop of tarballs in the GOM to be about 2,000 metric tons (using a concentration of 1.0 $mg \cdot m^{-2}$). There is also one report of extensive benthic tars recovered in bottom trawls across the deepwater regions of the northern GOM (Alcazar et al. 1989).

The principal sources of tarballs in the GOM are natural seepage, tanker transportation activities, and oil spills (e.g., IXTOC blowout). Jeffrey (1979) found that approximately 30% of the tarballs analyzed were tanker sludge residues, about 2% were identified as fuel oil residues, and 65% were crude oils from many origins. Only 20% of the floating tar had sulfur content greater than 3% and these were found primarily in the western and southwestern Gulf. Based on the sulfur content of pelagic tars, Jeffrey et al. (1974) estimated that possibly as much as 60% of the tars originated from foreign crude oils spilled during tanker operations.

## Particulate Inorganic Matter

Particulate inorganic carbon can be derived from either the inorganic remains of organisms (carbonate or silicate tests) or from riverine transport of land-derived materials. As mentioned above, resuspension of bottom sediments can also contribute to water column particulates. There are few studies of the distribution of inorganic particulate matter in the study area. However, it is suspected that the amount of particulate matter decreases with increasing water depth and that the majority of the particulate matter is derived from the remains of biological organisms in the open water GOM.

One portion of the particulate inorganic matter is particulate metals. As for the dissolved metals, particulate metals will have their origins in terrestrial materials transported by rivers and the air as well as a range of potential anthropogenic sources. As mentioned above, more than 90% of the metals detected in the water column are in the particulate form (Presley et al. 1980). While little is known about particulate trace metal levels in the study area itself, the metal content in Mississippi River suspended material was similar to the original rocks in Fe, Al, V, Cr, Cu, Co, Mn, and Ni content but was enriched in Zn, Cd, and Pb content. Enrichments in lead and cadmium were believed to be the result of anthropogenic influences.

Another source of particulate metals to the open GOM is discharges during oil and gas exploration and production (Boothe 1979; Boothe and Presley 1979, 1987, 1989). Large amounts of drill muds are discharged that contain a range of trace metals. In the deepwater GOM, there are few measurements of water column particulate metal concentrations. In one study, increased concentrations of particulate iron were found in the nepheloid layer above the sea bottom caused by sediment resuspension (Betzer and Pilson 1971). A study of the distribution of particulate aluminum in the GOM concluded that the average concentration of Al was 2.0 $\mu g \cdot L^{-1}$ (Feely et al. 1971). Aluminosilicate accounted for 14% of the surface water particulate matter decreasing to 8% in the middle of the euphotic zone and then increasing to 30% at depths down to 1,000 m. The authors concluded that the total suspended matter was 50% organic, 20% aluminosilicate, and 30% other inorganic material.

## The Chemistry of Natural Seepage

Several features of the benthic environment are important influences on the fluxes of chemicals in the northern Gulf of Mexico deep-sea. A review of sediment characteristics is provided elsewhere. As previously mentioned, one of the unique features of the deepwater northern Gulf of Mexico is the extensive oil and gas seepage documented in the last 15 years. These seeps have important effects on the benthos and serve as a unique source of chemicals to the GOM basin. The area is underlain by a thick layer of salt that has produced a complex topography due to salt movement. This has also set the stage for migration of deeply generated thermogenic hydrocarbons to the near-surface sediments and into the overlying water column by producing conduits for fluid flow. The most recognized impact of this unique geological setting are the "cold seep" chemosynthetic communities of mussels and tubeworms (Brooks et al. 1987; MacDonald 1992; MacDonald et al. 1996; see also Chapter 8 of this report). This dynamic setting also affects the chemistry of the basin as these same processes introduce salt (brine seepage) and hydrocarbons (gases, liquids and solids) to deepwater regions. At some seep locations, gas hydrate is known to outcrop on the seafloor, disrupting adjacent sediments. Barite chimneys identified in some areas can be a natural source of barium in sediments (as contrasted with an anthropogenic origin in drilling muds). These processes are important to consider in any description of biogeochemical cycles in the deepwater northern GOM. It is also clear that the background of hydrocarbons in these areas can be quite high and these natural inputs need to be considered when attempting to recognize anthropogenic disturbances in the area.

### Brine Seepage

While first discovered on the shallow continental shelf, it is now known that hypersaline brines often breach the seafloor in the deep sea northern Gulf of Mexico (Shokes et al. 1977; Brooks et al. 1979; Roberts and Carney 1994; Roberts and Carney 1997). If the topographic setting is right, brine pools have been known to develop. Elevated salinities in pore waters are common at hydrocarbon seep sites and often brine seeps are associated with temperature anomalies (Nagihara 1992; Kaluza et al. 1996). These brines can be brackish to saturated solutions. In addition to the brine pools discovered along the mid-slope in water depths from 500 to 800 m (NR-1 Brine Pool), a large brine containing basin was identified in the 1970's called the Orca Basin (Sackett et al. 1979; Addy and Behrens 1980; Ishizaka et al. 1986; Aharon et al. 1992; Aharon et al. 1997; Van Cappellen et al. 1998). The Orca basin is a 400 $km^2$ basin at a water depth of 2,400 m in the central northern Gulf of Mexico. Salinities as high as 238 ppt have been measured.

### Hydrocarbon Seepage

Large areas of the northern Gulf of Mexico continental slope are known to contain seeps of gaseous and liquid hydrocarbons (Brooks et al. 1984, 1985, 1986a,b, 1987; Kennicutt et al. 1987, 1988). Sediments in the deep-sea regions of the northern Gulf of Mexico contain a mixture of terrigenous, petroleum, and phytoplanktonic hydrocarbons (Kennicutt et al. 1987). The relative importance of these inputs varies in space and time (LGL Ecological Research Associates, Inc. and Texas A&M University 1985, 1986; Kennicutt et al. 1987; Gallaway 1988). Background sediment hydrocarbon concentrations in the deepwater GOM are generally lower than those reported for GOM shelf and coastal sediments. The influence of land-derived materials decreases from the central to the western to the eastern deepwater GOM. Petroleum inputs are detectable at many locations. Natural seepage of hydrocarbons is an important source of petroleum hydrocarbons to slope sediments in localized areas. Background hydrocarbon concentrations can vary by 1 to 2 orders of magnitude along an isobath due to changes in sediment texture and hydrocarbon inputs. Variability along an isobath can be as great as that observed across isobaths from 300 to 3,000 m of water depth. In seep areas, hydrocarbon levels in near-surface sediments can reach concentrations of several percent by weight. Background hydrocarbon concentrations in deepwater GOM sediments are on the order of 50 to 100 ppm by weight. The movement of hydrocarbons from deep seated reservoirs to the shallow sediments, and into the water column followed by slick and tarball formation, has been documented in the open water GOM (Kennicutt et al. 1988). Visual observations from submersibles have confirmed active and on-going gas and liquid seepage at many locations on the central GOM continental slope. Near-surface hydrocarbons are often extensively altered due to microbial degradation. Seep locations are characterized by the presence of extensive microbial mats and extensive hard bottoms formed from authigenic carbonate precipitation incorporating $CO_2$ derived from the oxidation of hydrocarbons.

Analysis of organisms from areas of natural seepage has shown that animal tissues collected close to seeps contain significant amounts of hydrocarbons (Wade et al. 1989). Polynuclear aromatic hydrocarbon (PAH) concentrations were higher in sedentary organism than in the more mobile species. Tissue PAH concentrations demonstrated that these populations are chronically exposed to hydrocarbons of a natural origin.

## Conclusions

In general, the chemistry of the deepwater Gulf of Mexico is not well studied. In many ways, the deep Gulf is buffered from the direct influence of coastal waters and processes. This is reflected in the low levels of anthropogenic contaminants present in the dissolved and particulate phases of the water column. However, oceanographic mechanisms can transport low-salinity, nutrient-rich waters across the shelf and into the deepwater environment. This has been shown to occur off the Mississippi River mouth, for example, when a seaward-moving surface flow confluence is created by deepwater cyclone-anticyclone circulation pairs (Chapter 6). Riverine input of dissolved and particulate materials is important to the chemistry of the deepwater basin. Secondary movement of materials downslope is an important process as well. The sparse information on sediments in the area suggests that the benthic environment is mostly unaffected by anthropogenic impacts. One important feature of the study area is the widespread occurrence of natural seepage of oil, gas, and brines in near-surface sediments and up through the water column. This unusual "natural background" of hydrocarbons and other disturbances is important to consider when attempting to detect impacts related to oil and gas exploration and production activities in the area.

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# Chapter 6: Water Column Biology

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## Primary Productivity and Chlorophyll Standing Stocks

### Introduction

Phytoplankton distribution and abundance in Gulf of Mexico waters has been reviewed at decadal intervals over the last 30 years, first by Bjornberg (1971), then by Iverson (in Iverson and Hopkins 1981), and most recently by Vargo (in Vargo and Hopkins 1990). However, most of the reports these reviewers featured focused primarily on the continental shelf and Vargo, in particular, noted that much of the information for his review came from studies conducted 10 to 20 years before 1990. In fact, data collected by expeditions in the 1960's and 1970's remain the basis for the general paradigm that standing stocks and productivity of plankton are both quite low seaward of the shelf-slope break in the Gulf of Mexico. The present review will support that description of the mean state but will also show that research carried out since 1987 indicates "hot spots" in primary production occur when/where nutrient availability is locally enhanced, even in deepwater (water depths greater than 300 m). Fundamental nutrients-phytoplankton-zooplankton (NPZ) food chain theory forecasts that enhanced primary production, if sustained, will lead to increased animal (zooplankton and micronekton) production. In this review we will summarize the available evidence from the Gulf of Mexico that deepwater "hot spots" that are temporally persistent (even if they are spatially variable) have higher stocks of zooplankton and micronekton.

## Mean Condition

The Gulf of Mexico (GOM) is a subtropical ocean basin located within the circulation regime generally called the Intra-Americas Sea. The near-surface circulation pattern of the eastern GOM is dominated by the anticyclonic flow of the Loop Current (LC). East of 90°W, upper layer flow enters through the Yucatan Channel and leaves through the Florida Straits. Since this current enters from the Caribbean, it acts as a biological conveyor belt to maintain the exchange of pelagic species between the Caribbean and the GOM. This conveyor does not fertilize downstream plant plankton, however, since LC surface waters are among the most oligotrophic in the world ocean. Nitrate, phosphate, and other essential plant nutrients are usually below the analytical detection limit ($<0.05\ \mu M \cdot L^{-1}$) in LC inflow water from the surface to depths of 80-90 m. The extinction coefficient, "k", that describes how rapidly irradiance decreases with depth according to the exponential equation $I_z = I_o * e^{-kz}$, is usually <0.05 in LC surface water. As a consequence, the LC inflow into the GOM is almost swimming pool clear and therefore is deep blue in color.

In the central and western deepwater GOM as well, the standing stocks and biological productivity of the plant and animal communities living in the upper part of the water column are in general those that might be expected in a nutrient-limited ecosystem. In the late 1960's, as part of a review of plankton productivity of the world ocean, Soviet scientists characterized the deepwater GOM as very low in standing plankton biomass (Bogdanov et al. 1968), with mean primary productivity of just 100 to 150 mg $C \cdot m^{-2} \cdot d^{-1}$ (Koblenz-Mishke et al. 1970). A few years later, extensive surveys of phytoplankton chlorophyll and primary production that span the period 1964 to 1971 were summarized by El-Sayed (1972) in atlas format, as averages within 2° squares of latitude and longitude. These atlas maps show that surface chlorophyll generally ranges from 0.06 to 0.32 $mg \cdot m^{-3}$ in deepwater central and western GOM. Subsurface there is usually a "deep chlorophyll maximum" (DCM) within which concentrations are two- to three-fold higher, and so the atlas reported that chlorophyll in deepwater could reach 21 $mg \cdot m^{-2}$ when integrated from the surface to the base of the photic zone. Most values, though, ranged from 5 to 17 $mg \cdot m^{-2}$ when averaged in squares where water depth >2,000 m (El-Sayed 1972). Low values of primary production ($<0.25$ mg $C \cdot m^{-3} \cdot h^{-1}$) are typical for surface waters at the majority of the oceanic stations in this atlas, equivalent to <10 mg $C \cdot m^{-2} \cdot h^{-1}$ when integrated from the surface to the base of the photic zone. If there are on average 12 hours of sunlight per day, this rate is equivalent to <120 mg $C \cdot m^{-2} \cdot d^{-1}$ and so is in good agreement with the characterization by Koblenz-Mishke et al. (1970). Allowing for primary production to proceed 300 days a year in the GOM because of its subtropical climate, this rate of primary productivity is <36 g $C \cdot m^{-2} \cdot y^{-1}$. As a consequence the deepwater GOM is usually placed at the low end of the estimated range of 50 to 160 g $C \cdot m^{-2} \cdot y^{-1}$ that is generally accepted for the annual gross primary production in open-ocean ecosystems (Smith and Hollibaugh 1993).

Size fractionation of chlorophyll and primary production was done on subsequent cruises to deepwater. Early data were summarized by El-Sayed and Turner (1977). They noted that the <20 µm size fraction accounted for on average 83% of the standing crop and 83% of the total production. These values emphasize the importance of the nano-plankton size fraction in the phytoplankton community and further reinforce the paradigm that low nutrient surface waters are characteristically dominated by small-size phytoplankton and by blue-green algae like *Trichodesmium*. Vargo and Hopkins (1990) emphasized the importance of this blue-green alga in the deepwater GOM, for when abundant in the top 20 m of the water column, *Trichodesmium* may have photosynthetic rates of tens of mg $C{\cdot}m^{-2}{\cdot}d^{-1}$ (Carpenter 1983). After the potential importance of phytoplankton even smaller in size than nanoplankton became widely recognized, subsequent researchers working in the GOM and elsewhere have size fractionated chlorophyll and primary production into pico (<2 μm), as well as nano (2 to 20 μm), and net (>20 μm) fractions (Al-Abdulkader 1996; Gonzalez-Rodas 1999).

When it became known that even low concentrations of trace metals that may inadvertently be introduced into sampling bottles or into light-dark incubation bottles can greatly depress measured rates of gross primary production, biogeochemists advocated the use of trace-metal clean techniques to remeasure primary production in oceanic ecosystems (Fitzwater et al. 1982). After about 1980, such "clean techniques" were used routinely to remeasure primary production in the GOM and elsewhere. In their review, Vargo and Hopkins (1990) noted three such studies. Ferguson and Sunda (1984) reported rates of 0.11 mg $C{\cdot}m^{-3}{\cdot}h^{-1}$ for a LC station. Ortner et al. (1984) measured similar values in the LC and calculated that integrated production rates (0 to 90 m) ranged from 14 mg $C{\cdot}m^{-2}{\cdot}h^{-1}$ (temperature-stratified conditions) to 62 mg $C{\cdot}m^{-2}{\cdot}h^{-1}$ (after wind-mixing to 110 to 120 m). Yoder and Mahood (1983), who measured primary production from the shelf out into deepwater during the Southwest Florida Shelf Ecosystems Study, found that production averaged 0.1 g $C{\cdot}m^{-2}{\cdot}d^{-1}$ in deepwater outside an eddy-induced upwelling area. On average, then, it appeared that remeasurements using clean techniques in the 1980's yielded results that were comparable to those that were obtained during the more extensive surveys of the 1970's.

**Figure 6.1** shows the location of primary production measurements using clean techniques that have been made in deepwater after the Vargo and Hopkins (1990) review, by Texas A&M University and by the Universidad Nacional Autonomia de Mexico (UNAM) during the period 1987-1997. The primary productivity data from UNAM stations made in summer 1997 have not yet been published although a summary is available from Dr. Elva Escobar-Briones (escobri@mar.icmyl.unam.mx). The 1987-1988 measurements were discussed by Biggs (1992), and the 1990 deepwater measurements made in support of the Nutrient Enriched Coastal Ocean Productivity (NECOP) program were reported by Biggs and Sanchez (1997). Three dozen deepwater measurements made from 1992-1994 in support of the Texas-Louisiana Shelf Circulation and Transport Processes Study (LATEX) have recently been reported by Al-Abdulkader (1996) and Gonzalez-Rodas (1999).

During LATEX, size fractionation of chlorophyll and primary production was done along cross-margin transects that extended from shallow water to the shelf edge, and also at sampling sites along and seaward of the 200-m isobath of the western and central GOM. Ten LATEX cruises fielded from 1992 to 1994 sampled the continental margin in May (1992, 1993, 1994), August (1992, 1993, 1994), November (1992, 1993, 1994), and

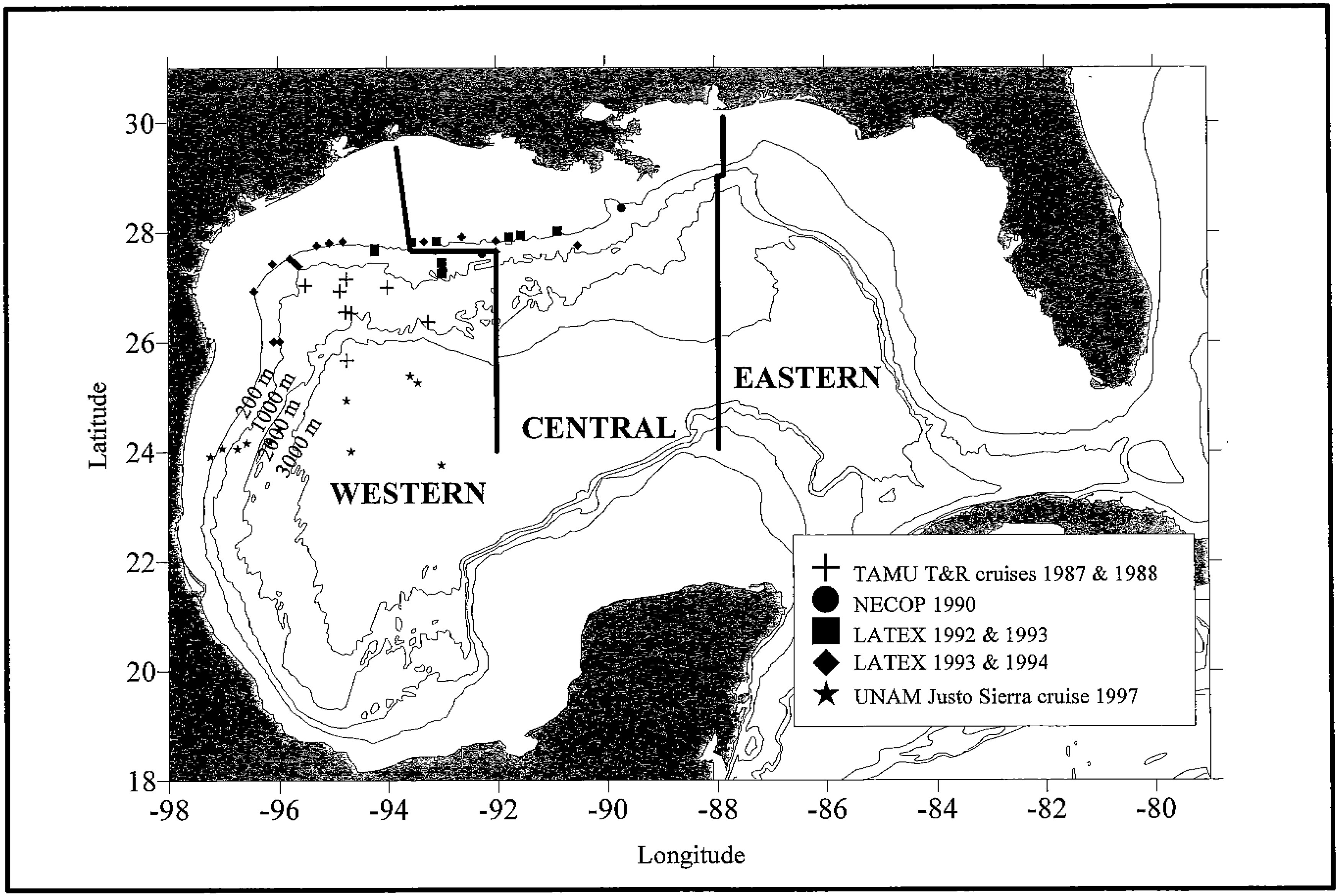


Figure 6.1. Deepwater locations of recent measurements of primary production, 1987-1997, on oceanographic cruises by Texas A&M University (TAMU) and the Universidad Nacional Autonoma de Mexico (UNAM).

February (1993 only). Nowlin et al. (1998) summarized the circulation and transport processes; phytoplankton pigment concentrations and species counts were reported by Neuhard (1994) and Bontempi (1995), and also by Al-Abdulkader (1996) and Gonzalez-Rodas (1999). In general, the LATEX results support the findings of El-Sayed and Turner (1977) in that on most cruises, pico+nano plankton averaged more than 3/4 of deepwater cell counts and accounted for >2/3 of the primary production. The exception was the "winter" cruise in February, when diatoms of the genera *Leptocylindrus* and *Chaetoceros* comprised >50% of phytoplankton numbers not just in deepwater but across the outer, middle, and inner shelf as well.

## Seasonal Changes

Even in a subtropical ocean there are seasonal changes. Pigment concentration at the surface in the deepwater GOM undergoes a well-defined seasonal cycle that is generally synchronous throughout the region. Muller-Karger et al. (1991) reviewed monthly climatologies of near-surface phytoplankton pigment concentration from multiyear series of coastal zone color scanner (CZCS) images for the period 1978-1985. They reported that highest surface concentrations of chlorophyll occur between December and February and lowest values occur between May and July. There is only about three-fold variation between the lowest (~0.06 $mg \cdot m^{-3}$) and highest (0.2 $mg \cdot m^{-3}$) deepwater surface pigment concentrations, however. Model simulations show that the single most important factor controlling the seasonal cycle in surface pigment concentration is the depth of the mixed layer (Walsh et al. 1989). Muller-Karger et al. (1991) concluded because of this dependence, annual cycles of algal biomass are one or more months out of phase relative to the seasonal cycle of sea surface temperature.

## Deepwater "Hot Spots" from Entrainment of Freshwater

Since essential plant nutrients are limiting, any process that increases the nutrient concentrations available to phytoplankton in the deepwater GOM will increase their primary productivity. It is well known that freshwater inputs carry high nutrient loads, but in the GOM these high nutrient inputs are usually measurable only close-in to rivers and estuaries (Lohrenz et al. 1990, 1994). An exception occurs, however, when surface currents set up off-shelf flow that carries the river water seaward past the shelf-slope break and into deepwater. Biggs and Muller-Karger (1994) combined CZCS data with ship data to document that high-chlorophyll "plumes" do form in the western GOM when a seaward-moving surface flow confluence is created by deepwater cyclone-anticyclone circulation pairs. Analogous to a pair of anticlockwise-rotating and clockwise rotating gears, these circulations entrain coastal water from the western and central GOM and draw this offshore when the cyclone (anticlockwise circulation) lies immediately to the north or east of the anticyclone (clockwise circulation).

Both types of these mesoscale features can be detected by the topography of the 15°C isotherm; this is domed upward in the cyclones and pushed locally deep within the anticyclones. Both types of features can now be located with satellite altimetry, as well, since GOM cold-core eddies (15°C isotherm domed) show up as 10 to 20 cm local depressions in sea surface height, whereas warm-core eddies (15°C isotherm pushed locally deep) show up as 20 to 70 cm local elevations in sea surface height (Leben et al. 1993). As one recent example, **Figure 6.2** shows dynamic topography, gridded upper layer geostrophic velocity, and surface salinity and surface chlorophyll concentrations over deepwater of the northeast GOM in mid-summer 1997. Low salinity Mississippi River water was entrained into the flow confluence created by a gradient of >80 dyn cm in geopotential anomaly between a cyclone located to the north-northeast of a Loop Current eddy (LCE). Note that low salinity patches of river water were wrapped anti-clockwise around the periphery of the cyclone. A comparison of the salinity and chlorophyll fields shows that surface chlorophyll concentrations in this river water reached 2.0 $mg{\cdot}m^{-3}$, and that especially in the concentration range 0.1 to 0.4 $mg{\cdot}m^{-3}$, the patches of highest surface chlorophyll correspond spatially to the patches of lowest surface salinity.

As a second example, **Figure 6.3** shows sea surface height anomaly, surface salinity, and surface chlorophyll over the same region the next summer, in August 1998. This time, there is not a well-developed cyclone-anticyclone modon pair. Rather, it is the clockwise circulation around the periphery of a small anticyclone that was located close off the Mississippi River delta that has entrained river waters eastward along its edge. In the periphery of the anticyclone, patches of low salinity, high chlorophyll waters got transported from the inner shelf eastward across the continental margin to deepwater depths >500 m. For example, note that the irregular-shaped patch of high chlorophyll (>1 $mg{\cdot}m^{-3}$) seaward of the 200-m isobath between 86° and 88°W corresponds, spatially, to a freshwater patch in the core of which surface salinity is <28.

### Deepwater "Hot Spots" from Cross Isopycnal Mixing

Recent fieldwork has shown these mesoscale oceanographic features have additional impacts upon deepwater plankton and micronekton communities, for locally high nutrients are also introduced to the surface of deepwater ocean regions at eddy edges where there is enhanced vertical mixing. In fact, the periphery regions of high velocity surface currents that surround both the cyclonic and the anticyclonic eddies are zones of locally high vertical shear. Lee et al. (1991) have shown that meanders and eddies in the Gulf Stream are often marked by local aggregations of phytoplankton, and elevated fish stocks appear to concentrate in such areas (Atkinson and Targett 1983). The presence of multiple cyclonic and anticyclonic features in the Gulf of Mexico can result in strong frontal gradients between these features.

In the CZCS ocean color climatology from 1978-1985 and in imagery from the current generation ocean color sensor (the Sea Wide-Field Scanner, or SeaWiFS, in orbit since October 1997), the periphery of the LC and of the anticyclonic LCEs of diameter 200 to 300 km that are shed from the LC are often seen to be outlined by surface pigment concentrations that are two- to three-fold higher than the extremely low concentrations (0.04 to 0.06 $mg{\cdot}m^{-3}$) in the interior of these circulations. **Figure 6.4**, which illustrates a "halo" of locally high chlorophyll standing stock around the LC in mid-January 1998, is one such example. Two other examples from recent fieldwork are presented as **Figures 6.5** and **6.6**.

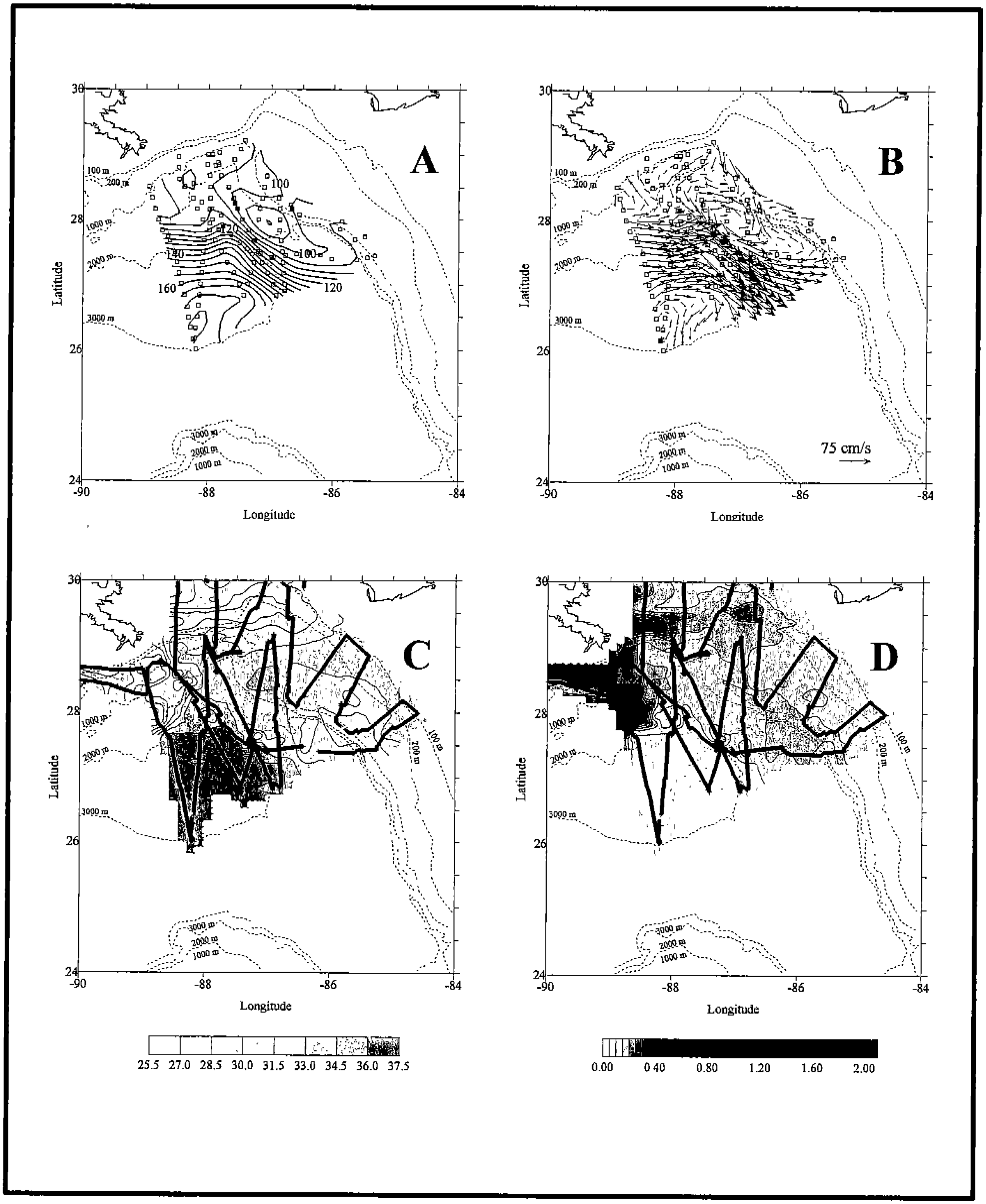


Figure 6.2. A: Dynamic topography (cm, 0 m relative to 800 m) of the deepwater GulfCet II focal area, as determined from 107 hydrographic stations made on R/V *Gyre* cruise 97G08. B: Gridded upper layer geostrophic velocity (0 m relative to 800 m) computed from the dynamic topography data in A. C: Sea surface salinity map, superimposed on ship track lines of 97G08. D: Sea surface chlorophyll map, superimposed on ship track lines. All four figures are from Chapter 2 of the GulfCet II Final Report (Davis et al. 2000a).

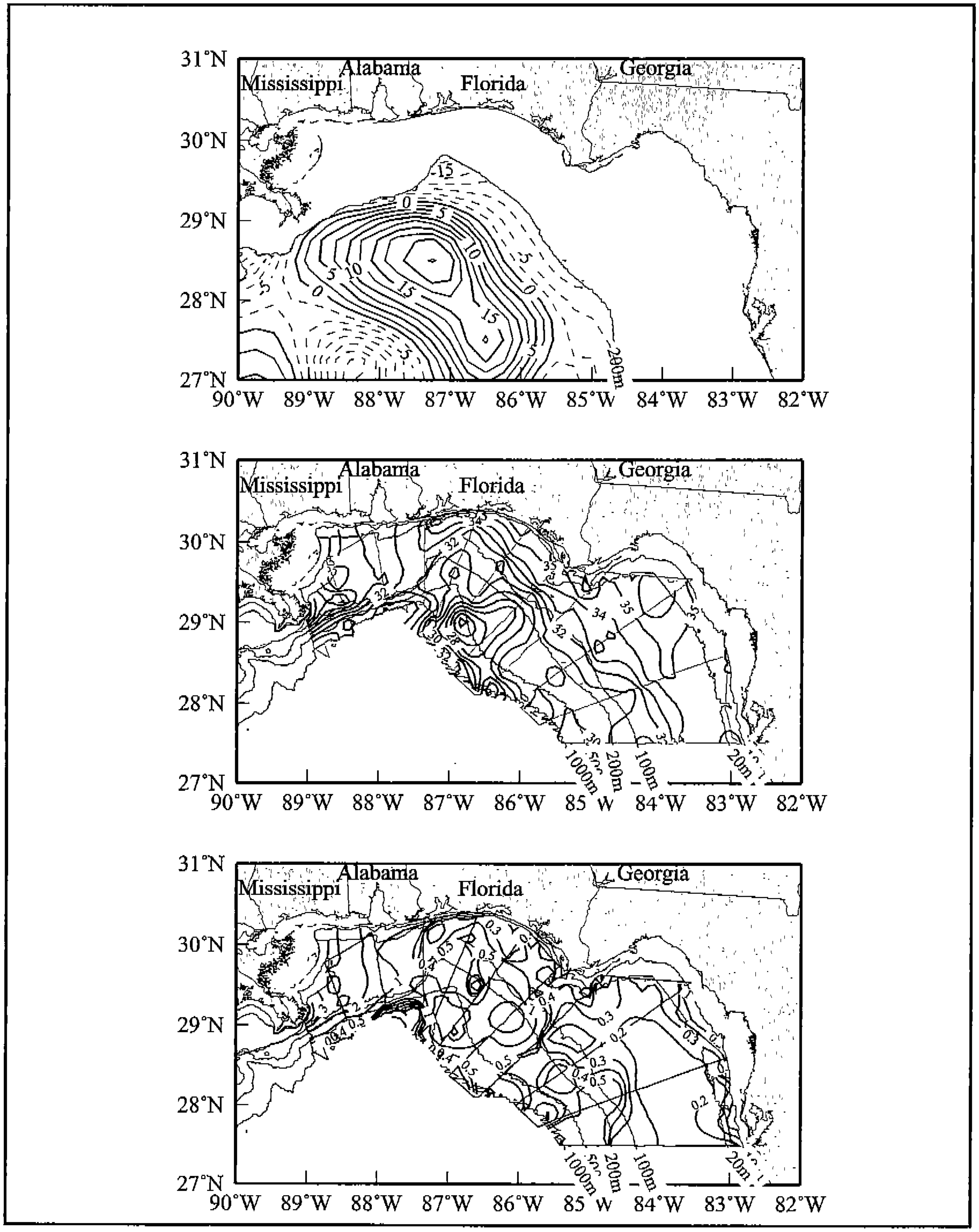


Figure 6.3. Top panel: Sea surface height anomaly for water depths > 200 m from satellite altimeter data for the NEGOM study area for 29 July 1998 (hindcast data). Middle panel: Salinity at ~3 m from thermosalinograph observations on NEGOM cruise N3, 26 July - 6 August 1998. Bottom panel: Chlorophyll ($\mu g \cdot m^{-3}$) at ~3 m calculated from flow-through fluorescence on NEGOM cruise N3. All panels are from the NEGOM Annual Report, Year 2 (Jochens and Nowlin 1999). Shading indicates patches of low salinity, high chlorophyll river water being entrained anticyclonically around the eddy centered in deepwater of De Soto Canyon.

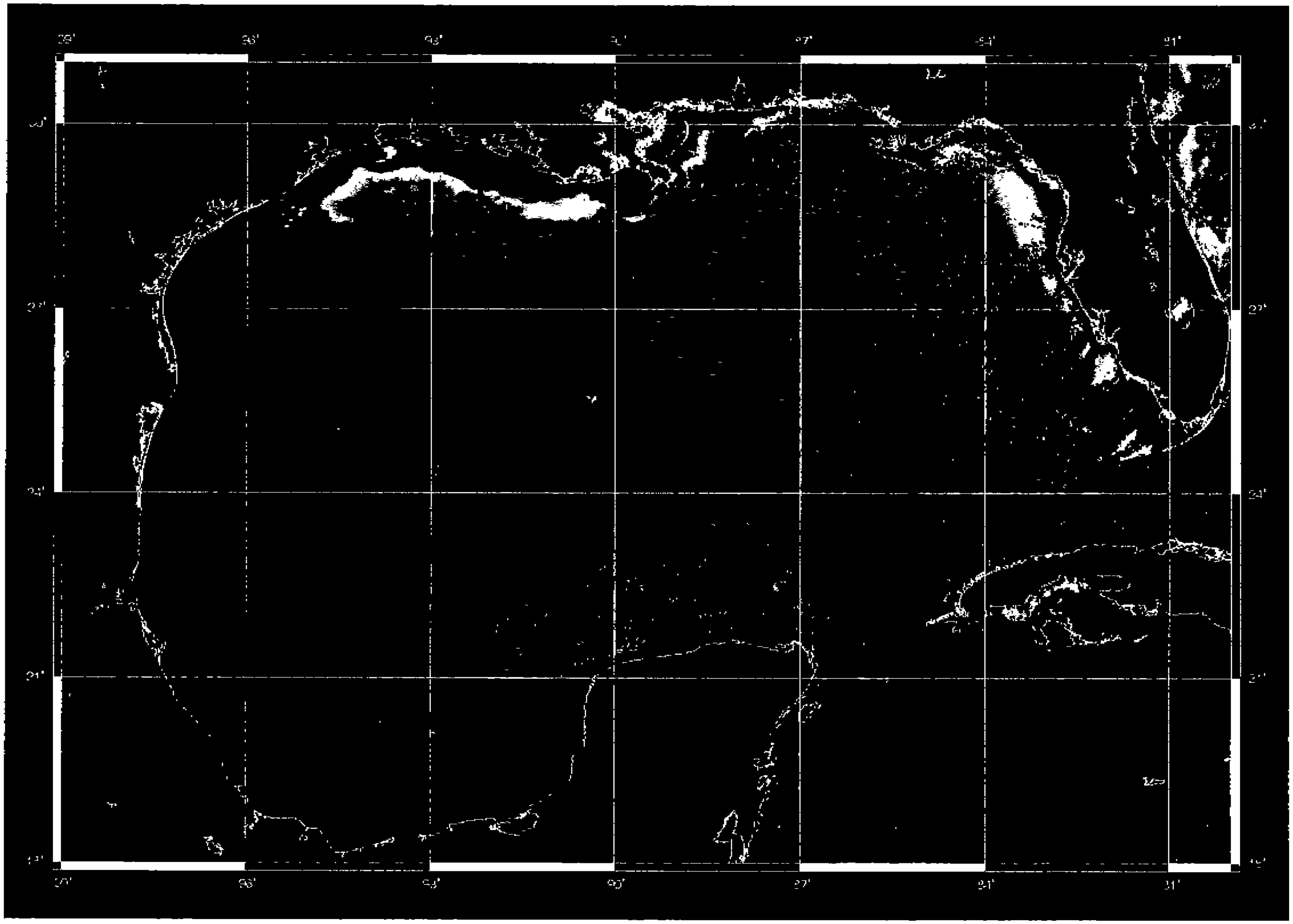


Figure 6.4. SeaWiFS ocean color image for 16 January 1998, processed by the Department of Marine Science, University of South Florida. Note the "halo" of locally high pigment concentration (light blue color) along the western and NW periphery of the Loop Current. In this image, the Loop Current (medium blue color) extends north of 27°N between 88.5°W and 85.5°W. Land and clouds are masked in black. Data courtesy of OrbImage and NASA.

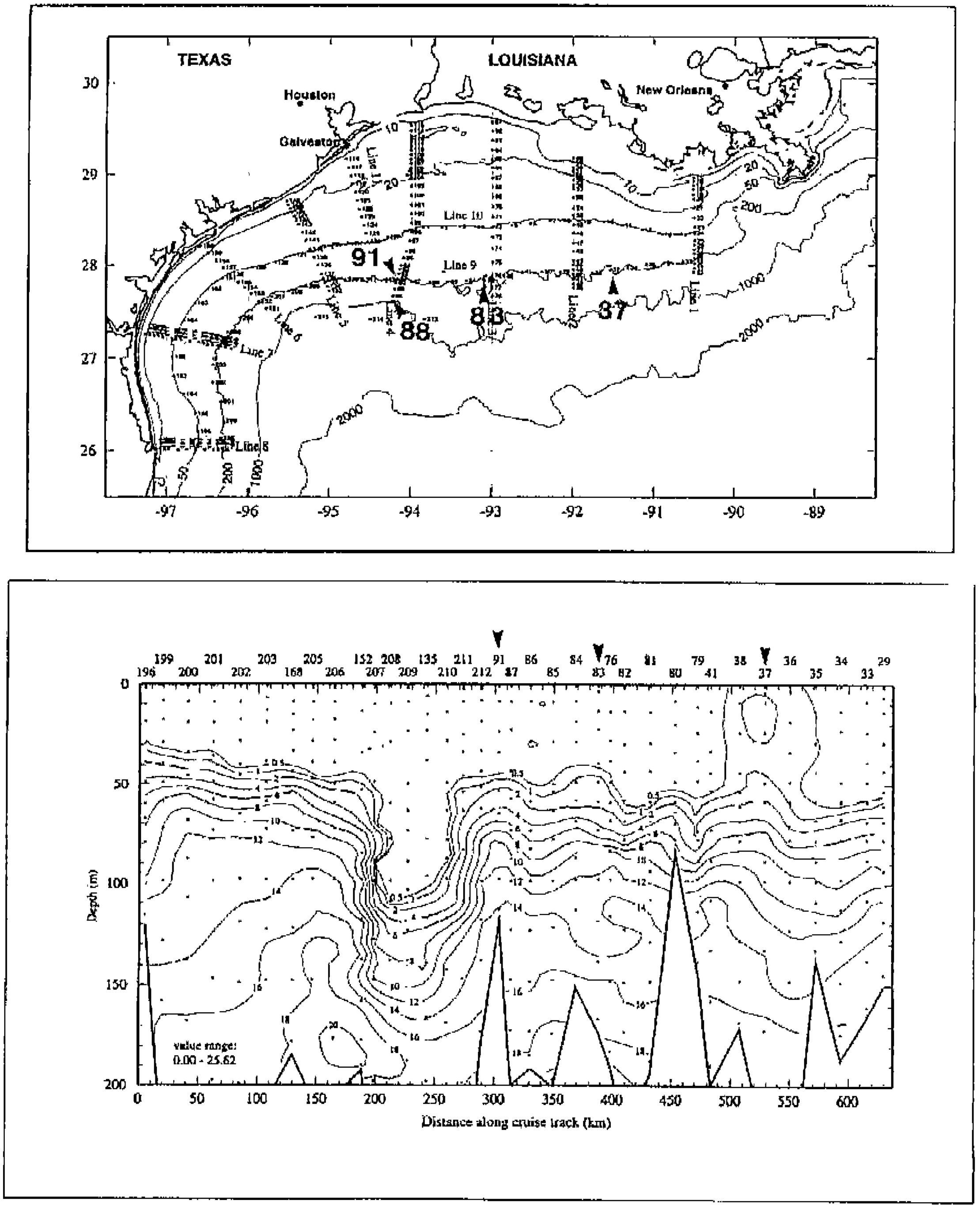
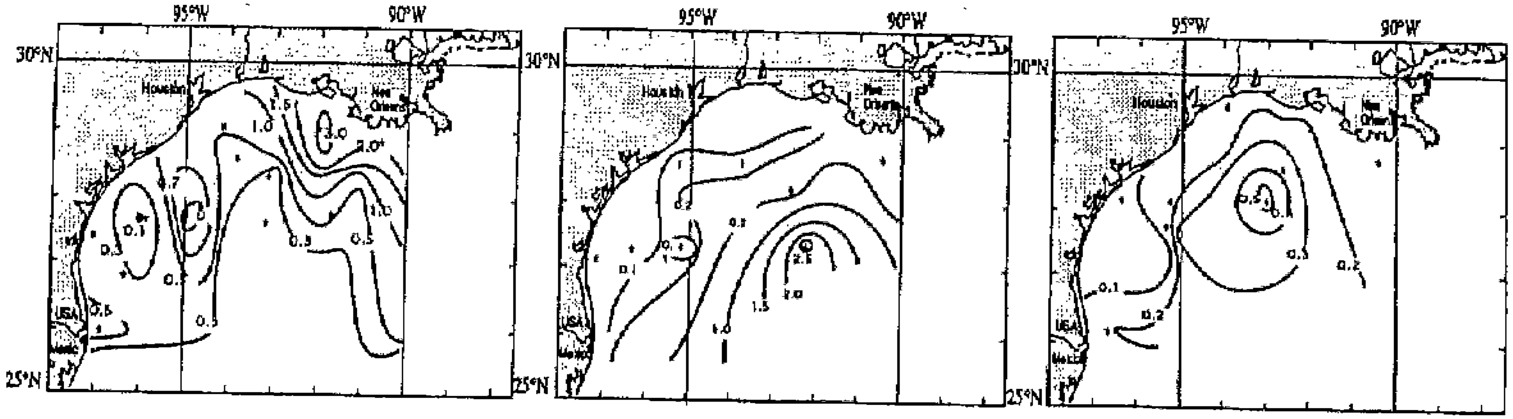


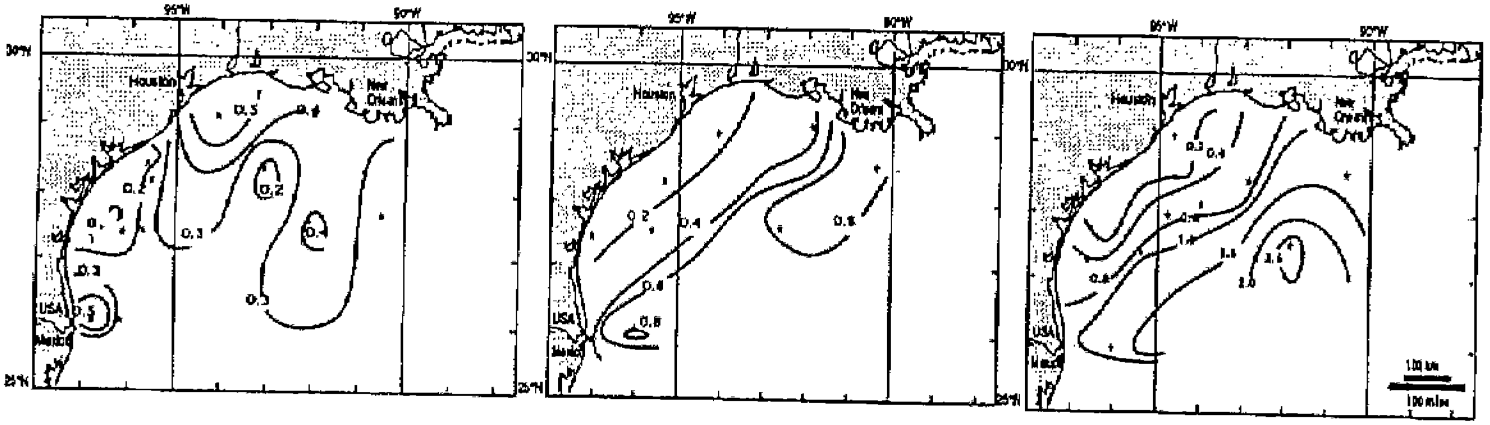
Figure 6.5. Top panel: Cruise track and station locations for LATEX hydrographic survey H05, April-May 1993. Bottom panel: Vertical contours of bottle nitrate (µmol·L$^{-1}$) along 200-m isobath during cruise H05. Dots indicate sample locations. Both panels are from the LATEX data report (Jochens et al. 1996).



Integrated productivity, May 1993

Integrated productivity, Aug. 1993

Integrated productivity, Nov. 1993



Integrated productivity, May 1994

Integrated productivity, Aug. 1994

Integrated productivity, Nov. 1994

Figure 6.6. Primary productivity (g C·m$^{-2}$·d$^{-1}$) of the LATEX continental margin in May, August, and November of 1993 and 1994 (From: Gonzalez-Rodas 1999). Asterisk symbols show location of primary productivity stations.

**Figure 6.5** shows a hot spot of anomalously high nitrate concentration in surface waters between 91° and 92°W along the 200 m isobath that was encountered in May 1993. At stations 36, 37,and 38 on LATEX hydrographic survey H05, nitrate concentrations >0.5 $\mu M \cdot L^{-1}$ occurred at the surface, just south of a strong surface front where salinity increased from 32.0 to 36.3. This hot spot of nitrate apparently arose from strong vertical shear that developed in this frontal zone, for the surface salinity and silicate data and the vertical contours shown in **Figure 6.5** strongly suggest that it was fueled by cross-isopycnal mixing from below rather than from entrainment of freshwater from the Atchafalaya Bay or Mississippi River to the north and east. Farther west along the 200 m isobath, an anticyclone (LCE "V") was interacting with the continental margin. Note as well from **Figure 6.5** that the extremely low nutrient interior of the eddy was apparently drawn onshore between stations 207 to 210.

Al-Abdulkader (1996) measured chlorophyll stocks and primary productivity at station 37 within the hot spot of anomalously high surface nitrate, and at station 83 some 140 km to the west along the 200 m isobath, and also further west at station 88 at the deepwater end of LATEX line 4 which reached the NE periphery of LCE "V". Data from his table 21 show that near-surface chlorophyll at station 37 ranged from 0.4 to 0.5 $mg \cdot m^{-3}$, or three-fold higher than the concentrations of 0.15 to 0.17 $mg \cdot m^{-3}$ at station 83 west of the hot spot. Al-Abdulkader's data show that primary productivity in the upper 50 m of the hot spot ranged from 0.2 to 0.3 $mg\ C \cdot m^{-3} \cdot h^{-1}$; integrated to the 0.2% $I_o$ depth and knowing that photosynthesis proceeds 12 h per day in May, this is a production of 220 $mg\ C \cdot m^{-2} \cdot d^{-1}$. This is 1.4 times higher than the measured production integrated to the same irradiance level at his station 83 (158 $mg\ C \cdot m^{-2} \cdot d^{-1}$). At station 88 in the NE periphery of LCE "V", locally low salinity surface water was present (33.6 to 33.8 in the upper 10 m). This surface water was low in nitrate and near-surface chlorophyll concentrations in it were similar to those at station 83, but high silicate levels in the upper 10 m at station 88 indicate this low salinity cap was probably entrained Mississippi River outflow. Data from Al-Abdulkader's table 20 show that primary productivity in the low salinity surface water was locally high (0.3 to 0.4 $mg \cdot m^{-3}$) and that even below this low salinity layer productivity averaged 0.16 $mg \cdot m^{-3}$ to a depth of 100 m. When integrated to the 0.2% $I_o$ depth, this is a production of 226 $mg\ C \cdot m^{-2} \cdot d^{-1}$, equivalent to that in the nitrate "hot spot."

A recent dissertation by Gonzalez-Rodas (1999) summarized primary productivity measurements that were continued and extended on subsequent LATEX cruises. **Figure 6.6** shows Gonzalez-Rodas' summary of integrated primary productivity for the LATEX continental margin in May, August, and November of 1993 and 1994. Note that hot spots in deepwater primary production (>2.5 $g\ C \cdot m^{-2} \cdot d^{-1}$) were present near 27.5°N and 92°W in August 1993 and also in November 1994. In summer 1993, the northern edge of LCE-W was interacting with the continental margin between 91° and 93°W; the locally high shear there apparently fueled a region of anomalously high deepwater primary production. This eddy had a diameter of some 250 km and at the location where the productivity was measured, the geopotential anomaly was about +20 cm and current speeds were about 60 $cm \cdot s^{-1}$ (see Table 5 in Gonzalez-Rodas 1999). In fall 1994, the northern edge of another anticyclone, LCE-Y, was interacting with the continental margin again between 91° and 92°W. This eddy was even larger in diameter (320 km) and presented a geopotential anomaly of +36 cm (from Table 5 in Gonzalez-Rodas 1999).

## Deepwater "Hot Spots" from Mesoscale Divergence

Because the interiors of the anticyclones are areas of convergence, the upper 100 m or so of the water column in both LC and LCEs are areas in which surface waters are infrequently renewed and so they are impoverished in nitrogen and phosphorus nutrients. The interiors of these regions of convergence are generally regarded as biological "ocean deserts." Measurements of chlorophyll standing stocks, primary productivity, and zooplankton standing stocks within an LCE sampled in 1988 are in good agreement with this premise (Biggs 1992). However, the cyclonic cold-core eddies (local areas of divergence) that are frequently associated with these anticyclones represent areas of higher biological productivity.

Subsurface sampling of these GOM eddies from ships showed there was a highly predictable negative first order relationship between temperature <22°C and nitrate concentration. Temperature could thus be used as a proxy for nitrate concentration, and in particular the depth of the 19°C isotherm was a good estimation of the depth of the 10 $\mu M \cdot L^{-1}$ nitrate concentration (Biggs et al. 1988). Within one cyclone sampled in 1996, the nitracline was domed 40 to 60 m shallower than within the LCE that was sampled concurrently (see Figure 6 in Zimmerman and Biggs 1999). Because this doming facilitated a higher flux of new nitrogen into surface waters in cyclone than in anticyclone, the DCM was locally shallower and chlorophyll reached higher maximum concentration in the cyclone than in the LCE. Because this resulted in higher standing stocks of chlorophyll in the upper 100 m in the cyclone, the cyclones are generally regarded as biological "oases" while the interior of the LCEs are biological "deserts."

At six conductivity, temperature, and depth (CTD) stations made during a survey of a mesoscale cyclonic eddy that was centered near 26°N and 94°W in November 1987, integrated chlorophyll standing stock averaged $38 \pm 9$ $mg \cdot m^{-2}$ (Biggs et al. 1988), or two to three times greater than the mean for the oceanic GOM. Primary productivity averaged 12 mg $C \cdot m^{-3} \cdot d^{-1}$ in the upper 10 m and integrated production to the 1% light level was equal to 250 mg $C \cdot m^{-2} \cdot d^{-1}$ (Biggs 1992), or double the mean of 100 to 150 mg $C \cdot m^{-2} \cdot d^{-1}$ reported by Koblenz-Mishke et al. (1970). Similarly, Yoder and Mahood (1983) reported that for stations located seaward of the 200-m isobath off the West Florida shelf within an area of eddy-induced upwelling, the top of the nitracline domed to depths of just 40 to 60 m below the surface. They measured the average water column production there at 0.6 g $C \cdot m^{-2} \cdot d^{-1}$, whereas for three other stations located outside the eddy-induced upwelling area, production averaged 0.1 g $C \cdot m^{-2} \cdot d^{-1}$ (Yoder and Mahood 1983). Thus, Yoder and Mahood concluded that subsurface upwelling may enhance deepwater phytoplankton primary production by as much as six-fold. Subsequent studies of cyclonic gyre formation off the Southwest Florida shelf found that a cold recirculation, approximately 200 km in size, develops off the Dry Tortugas when the LC flow overshoots the entry to the Florida Straits and that this persists over time scales of about 100 days (Lee et al. 1994). The "Tortugas Gyre" formation provides enhanced food supply, retention, and shoreward transports for successful recruitment of locally spawned snapper and grouper larvae in the western and lower Florida Keys.

In summary, when/where anticyclonic and cyclonic hydrographic features occur over deepwater in the GOM, it is expected they will play an important role in determining biogeographic patterns and controlling primary productivity in the Gulf of Mexico.

## Deepwater Zooplankton, Micronekton, and Ichthyoplankton

### Introduction

Historically, the Gulf of Mexico has been considered an oligotrophic, biologically impoverished ocean since on average the deepwater standing stocks of plankton there are lower than those found in temperate and higher latitude regions. Soviet-Cuban fisheries investigations in the 1960's reported that zooplankton standing stocks were low across much of the GOM (Bogdanov et al. 1968; Khromov 1969a) and subsequent reviewers have reinforced this perception (Hopkins, writing in Iverson and Hopkins 1981, and in Vargo and Hopkins 1990). The zooplankton and micronekton fauna of the deepwater GOM are similar in energy content, taxonomic composition, and food habits to those of other low-latitude oceans (Stickney and Torres 1989; Hopkins and Gartner 1992; Hopkins et al. 1994, 1996), and the ichthyoplankton fauna of the GOM have been grouped along with those of the western tropical Atlantic Ocean and Caribbean Sea (Richards 1990). Thus in several biologically important ways the GOM resembles other oligotrophic subtropical oceans.

Relegating secondary production in the GOM to oligotrophic status is nevertheless an oversimplification, because the generally low standing stock levels are not uniformly so but are instead punctuated by spatial and temporal variation greater than that found in most other oligotrophic oceans. This variability may be manifested as spatial "hot spots" and temporal peaks in biomass. For example, Khromov (1969a,b) reported that while zooplankton standing stocks in the tropical oligotrophic Caribbean Sea were almost always low and did not exceed 10 mL wet displacement volume (WDV) per 100 $m^3$ in waters offshore of the shelf/slope break, GOM stocks exhibited more seasonal, interannual, and spatial variability, with biomass levels as high as 35 mL WDV per 100 $m^3$ (range <5 to 35). Also, Hopkins and Lancraft (1984), who compared integrated wet weight biomass of zooplankton and micronekton in three tropical-subtropical locations (Caribbean Sea, Gulf of Mexico, and Pacific Ocean near Hawaii), found that the GOM was the highest in terms of zooplankton and intermediate in rank (above the Caribbean) in terms of micronekton, exceeding the next greatest by a factor of two in both cases. If gelatinous plankton were included in the micronekton biomass comparison, GOM then ranked highest of all three locations in both categories. Finally, although studies of GOM biomass do generally reveal low standing stocks, reported estimates can vary by a factor of 10 or more from the minima within a given study (Biggs et al. 1988; Richards et al. 1993; Wormuth et al. 2000).

Richards and McGowan (1989) note the considerable commercial fisheries resources in the GOM: this is perhaps the strongest contradiction to the dogma that the GOM has low secondary production. The northern Gulf supports the largest volume fishery in the

United States, the Gulf menhaden, *Brevoortia patronus* (Dagg et al. 1991). In 1998, 5 of the top 10 U.S. fishing ports in terms of commercial landings were located in Gulf Coast states, and the GOM accounted for the highest number of fish caught by recreational fishers of any U.S. subregion (O'Bannon 1999). The deepwater Gulf of Mexico is also habitat for substantial populations of marine mammals, sea turtles, and seabirds (Mullin et al. 1994; Davis et al. 2000a). The presence of sizeable populations of these apex predators in the deepwater GOM implies a reliable supply of lower trophic level prey resources (Biggs et al. 1988) and suggests that underlying physical processes allow "oases" of biological productivity to develop in the mostly oligotrophic deepwater GOM. In this review, we will show that when/where they occur over deepwater in the GOM, anticyclonic and cyclonic hydrographic features will play an important role in determining biogeographic patterns of and controlling secondary productivity. The fisheries potential of the cyclones and of the frontal zones of both types of eddies is becoming better understood, now that these have been identified as deepwater concentrating mechanisms for higher trophic levels and apex predators. Continued study and assessment of zooplankton and nekton abundance within these mesoscale circulation features is warranted, since these organisms ultimately serve as food stocks for higher trophic levels.

### The Available Database

Modern investigations of the overlapping categories of "zooplankton," "micronekton," and "ichthyoplankton" of the Gulf of Mexico began in the 1950's. Since then, knowledge of the composition, standing stock biomass levels, and environmental factors affecting each has been accumulated. For convenience, information on the deepwater GOM zooplankton, micronekton, and ichthyoplankton community summarized in this review is broadly divided into three categories, none of which are mutually exclusive:

- previous reviews;
- studies of the systematics, biology, or ecology of particular taxonomic groups of zooplankton, micronekton, and ichthyoplankton; and
- studies of the standing stock biomass of zooplankton, micronekton, and ichthyoplankton over time, depth, and location.

The primary focus of the present review will be upon studies of biomass and abundance (rather than on studies of specific groups), including an assessment of what is known and some recommendations for future research.

### Previous Reviews

There have been several major reviews of Gulf of Mexico zooplankton, micronekton, and ichthyoplankton since the 1950's (**Table 6.1**). Their focus and content varied, from catalogues of plankton collections yet to be analyzed to lists of known taxa to summarized results of studies of specific regions. Several of the reviewers note that significant portions of the research done in the GOM have often not reached the published literature but instead reside in government or contracting agency technical reports and documents.

Table 6.1. Previous reviews of the zooplankton, micronekton, and ichthyoplankton of the Gulf of Mexico (GOM).

| Year | Author | Descriptor |
|---|---|---|
| 1954 | Galtsoff (ed.) | An edited volume containing reviews of GOM zooplankton and micronekton; first major synthesis |
| 1970 | Pequegnat and Chace (eds.) | Texas A&M University Oceanographic Studies Volume 1; contains reviews of some groups of zooplankton and micronekton; emphasis is upon benthic/demersal rather than pelagic taxa |
| 1971 | Bjornberg and Rass | Reviews of Caribbean and GOM regions by Bjornberg (zooplankton) and Rass (deep-sea fish), in UNESCO-FAO proceedings of a 1968 meeting in Curaçao |
| 1973 | Hopkins and Briggs | Summary of knowledge of the eastern GOM; contains reviews by Hopkins (zooplankton) and Briggs (nekton) |
| 1981 | Iverson and Hopkins | GOM phytoplankton/zooplankton review in Environmental Research Needs in the Gulf of Mexico (GOMEX) symposium proceedings |
| 1990 | Darnell and Defenbaugh | GOM environmental overview and history of research, from a special session on the ecology of the Gulf of Mexico published in *American Zoologist* |
| 1990 | Vargo and Hopkins | Hopkins' portion reviewed zooplankton and micronekton + ichthyoplankton. The area of interest was Florida south of the Keys and the deepwater Gulf to the west of the Florida coast in MMS's Eastern Planning Area |

The earliest overview was by Galtsoff (1954), who assembled a volume of reviews written by leading government and university specialists about GOM zooplankton and micronekton under the auspices of the U.S. Fish and Wildlife Service. A general review of the state of knowledge of zooplankton was provided by H.B. Moore, to supplement specific reviews by other specialists of planktonic foraminifera, cnidarians, ctenophores, salps, chaetognaths, crustaceans, mollusks, and fishes. While some detailed information was available, the general conclusion was that there was still much to be learned about the GOM zooplankton/micronekton community. In fact, Moore concluded that on balance "next to nothing of the zooplankton of the Gulf of Mexico" was known at the time.

Sixteen years later, Pequegnat and Chace (1970) edited a volume on the biology of the Gulf of Mexico that contained a historical overview, locations, and discussion of investigations of water column sampling using midwater trawls and meter nets by Texas A&M University Department of Oceanography investigators in the 1960's. Although the emphasis of the volume is upon benthic/demersal rather than pelagic taxa, some chapters summarized the state of knowledge of particular holoplanktonic groups (penaeid and caridean shrimp, euphausiids, and heteropods) in the deepwater GOM. Around the same time, the proceedings of "A Symposium on Investigations and Resources of the Caribbean Sea and Adjacent Regions" were published, which included two reviews of interest. Bjornberg (1971) reviewed phytoplankton and zooplankton of the Caribbean and adjacent regions, including the GOM. The state of the knowledge of various taxonomic categories of zooplankton and micronekton was given, including protozoa, medusae, siphonophora, ctenophora, rotifera, polychaeta, nemertinea, mollusca, copepoda, cladocera, ostracoda, mysidacea, amphipoda, isopoda, euphausiacea, decapoda, chaetognatha, hemichordata, urochordata, and cephalochordata. Bjornberg concluded that the copepods and chaetognaths were the most well-studied groups, remarked that much of the study of GOM zooplankton to date had been concentrated in coastal waters and the Florida Current, and finally noted the need for large-scale, coordinated study of the zooplankton in shelf and oceanic waters of the Gulf of Mexico. In the same volume, Rass (1971) reviewed deep-sea fish fauna (members of the micronekton community) of what he termed the "American Mediterranean Region." Rass provided a list of 203 species from the GOM and estimated that deepwater fish represented about one-third of the total number of fish species in the open Gulf of Mexico.

In a compendium entitled "A Summary of Knowledge of the Eastern Gulf of Mexico," Hopkins (1973) reviewed Gulf of Mexico zooplankton. There had been increasing work in estuarine and coastal systems, but Hopkins noted there was still little published work on zooplankton in the oceanic GOM. However, knowledge of eastern GOM physical oceanography had increased considerably, and its potential biological effects were pointed out by Hopkins. The Loop Current and associated upwelling were cited as the most important factors affecting plankton production in the oceanic GOM, while in coastal areas runoff from terrestrial sources and seasonal temperature changes were the most important. Biomass was known to be low in the oligotrophic open Gulf and thought to vary seasonally with the movement of the Loop Current. The use of zooplanktonic indicator species as water mass tracers was mentioned in this review, as well as the ongoing plankton collections that were taking place as part of the EGMEX (Eastern Gulf of Mexico) program. Hopkins' own quantitative studies of biomass and taxonomic composition of zooplankton and micronekton in the eastern central Gulf of Mexico were mentioned as "in progress." Briggs (1973) reviewed midwater fishes of the GOM in the same volume, but he noted that the ichthyofauna of waters overlying the continental slope and abyssal plain was still not well known.

In 1981, a review of Gulf of Mexico phytoplankton and zooplankton by Iverson and Hopkins was included in the proceedings of a 1979 symposium on "Environmental Research Needs in the Gulf of Mexico." Hopkins'section on zooplankton reviews work on the shelf, slope, and in the open Gulf subsequent to previous reviews of GOM zooplankton, micronekton, and ichthyoplankton. Hopkins noted that except for published work on zooplankton taxonomy, much of the research done remained in "gray literature" government reports and theses/dissertations. However, Hopkins featured several major research programs that sampled zooplankton in water depths of 200 m or greater in the review, including:

- Ocean Thermal Energy Conversion (OTEC), a program sponsored by the U.S. Department of Energy . The zooplankton were studied off Mobile Bay (29°N, 88°W) and off Tampa Bay (27°38'N, 85°34'W). The investigators were able to observe taxonomic composition and biomass levels as a function of depth and time, although the sampling strategy did not allow them to completely resolve diurnal or seasonal trends.

- Hopkins' own National Science Foudnation-funded trophodynamic study of zooplankton and micronekton in the upper 1,000 m at a station in the eastern central GOM (27°N, 86°W). Diurnal patterns of zooplankton numbers and biomass were studied with trawling, net tows, and bottle sampling. Vertical migration was documented for a "significant portion of the zooplankton and micronekton in the east-central Gulf." Hopkins estimated that the zooplankton biomass at this reference station turned over once every 30 to 90 days, supported by the relatively low primary production in the oligotrophic open GOM. Some inferences were made about trophic interactions based on the data collected there, and Hopkins includes a list of important zooplanktonic and micronektonic predators and prey in the system. (Hopkins and colleagues at the University of South Florida would later publish many papers in peer reviewed journals detailing the work on GOM zooplankton and micronekton at this location.)

From the studies cited in Hopkins' review for the 1979 symposium, the temporally and spatially patchy nature of the zooplankton and micronekton had become evident. However, Hopkins emphasized the general lack of basic physiological data for GOM zooplankton, and argued such data were urgently needed to better understand the flow of energy and/or pollutants through the deepwater ecosystem.

In 1987, a special session on the ecology of the Gulf of Mexico was held at the annual meeting of the American Society of Zoologists. In 1990, selected papers from that session were published in an issue of the journal *American Zoologist.* Darnell and Defenbaugh (1990) reviewed the history of environmental research in the GOM, noting that in the 15 years preceding their review, federal agencies (most notably the Department of the Interior) had spent more than $75 million in research studies of the northern GOM. As had previous reviewers of the GOM zooplankton/micronekton field of study, these authors reported that much of the results of GOM research remained "locked up in the various technical reports submitted to the sponsoring agencies, and only a small fraction [had] appeared in the professional journal literature." However, although this review provided a list of early historical investigations of the GOM and of major interdisciplinary investigations since 1960, the bulk of these studies had been targeted to the continental shelf and not to deepwater.

In 1990, Vargo and Hopkins provided a review of GOM phytoplankton, zooplankton, and ichthyoplankton in a report to MMS. The area of interest was South Florida, mostly south of the Florida Keys but also including the deepwater Gulf to the west of the Florida coast (in the MMS Eastern Planning Area). Hopkins' portion of the review includes GOM hydrography and circulation relevant to zooplankton and micronekton/ichthyoplankton populations, as well as tabular data and a discussion regarding the taxonomic dominants and seasonal trends in abundance and biomass in GOM waters deeper than 200 m.

## Ecology, Biology, and Systematics Studies

Many studies of the diverse zooplankton, micronekton, and ichthyoplankton of the Gulf of Mexico have concentrated upon the ecology, biology, or systematics of one particular species or group of organisms. Appendix 6-A is a chronological list of these, including author and description of subject. Some of the studies are master's theses or doctoral dissertations that focus upon a particular group (e.g., a 1971 dissertation about two species of decapod crustaceans that could be used as a water mass tracer in the eastern GOM). Others are papers that were written about the abundance or distribution of a species or category of particular importance (e.g., several papers estimating the stock of larval bluefin tuna during different years in the GOM). However, many are stand-alone taxonomic technical descriptions of particular species (e.g., 1970's descriptions of copepods, by Park).

The scope of these individual works may be narrow, but in ensemble they are very important to an understanding of GOM zooplankton, micronekton, and ichthyoplankton communities. Such research provides the means to identify and enumerate specimens found in collected samples; without knowing 'who' is there, we cannot hope to understand the GOM as a system. To understand the flow of energy and nutrients through the deepwater biological system, Hopkins (1982) has argued, knowledge of taxon-specific trophic interactions is often helpful. Thus, we have included Appendix A because these works provide the taxon-specific ecological information needed to interpret studies of biomass and abundance and to allow the identification of species or groups of particular importance.

In brief, the dominant groups of GOM deepwater *zooplankton* in terms of biomass are holoplanktonic calanoid copepods, euphausiids, and chaetognaths; meroplanktonic larvae are "relatively scarce in the oceanic" zooplankton community but become more numerous closer to shore (Vargo and Hopkins 1990). In terms of feeding, the zooplankton community includes herbivorous, detritivorous, and omnivorous members (Hopkins 1982). The top three groups of deepwater *micronekton* in order of biomass are scyphomedusae, fishes (myctophids and gonostomids), and crustaceans (decapods and euphausiids) (Hopkins and Lancraft 1984). Zooplanktonic crustaceans comprise the greater part of the diet of micronektonic midwater fishes (Hopkins and Baird 1977; Hopkins et al. 1996) and crustaceans (Hopkins et al. 1994), and gelatinous carnivores are also known to be important zooplanktonic predators (Biggs et al. 1984; Vargo and Hopkins 1990). Further, areas of enriched deepwater zooplankton biomass have been shown to be correlated with increased abundance of squid paralarvae and myctophid fishes (Wormuth et al. 2000). The major components of the deepwater *ichthyoplankton* community are larval myctophids, gonostomids, mackerels, tunas, and flyingfishes (Vargo and Hopkins 1990). The presence of increased abundance of larval fish in areas of enriched zooplankton biomass implies that their diets include zooplankton (Govoni et al. 1989; Lamkin 1997a). However, the available information on the feeding habits of ichthyoplankton is limited, except as the category overlaps with micronekton and zooplankton.

## Biomass and Abundance

The standing stock biomass of zooplankton, micronekton, and ichthyoplankton in the GOM has been observed to vary in both space and time, but despite numerous studies on the ecology and systematics of particular taxonomic groups, a much smaller amount of work has been done to determine the scales of the variability at the coarse-to-mesoscale level and how these determine the patterns in biomass over time. Most of the work has been done using traditional net sampling techniques: a survey of bulk biomass values from the literature reveals up to 10-fold and higher variability in standing stock levels (see **Table 6.2**).

**Figure 6.7** includes two maps showing the locations of major collections of plankton biomass data. Despite fairly extensive sampling coverage in many deepwater parts of the GOM over the last 30-odd years, there has been no overall summary of the biomass results. Arnold (1958) offered only a cursory analysis of plankton biomass; the deepwater points supplied by Houde et al. (1976) were almost incidental to an ichthyoplankton study that concentrated on the west Florida shelf; and there has been little published analysis of the extensive set of bulk biomass data collected by the SEAMAP program. There have however been numerous publications and analyses of the amount, composition, and variability of the biomass at particular locations in the deepwater GOM (Commins and Horne 1979; Flock and Hopkins 1981; Hopkins 1982; Hopkins and Lancraft 1984) and regions (Houde and Chitty 1976; Houde et al. 1976 and 1979; Biggs et al. 1988; Richards et al. 1989; Grimes and Finucane 1991; Biggs 1992; Richards et al. 1993; Cummings 1984; Gasca et al. 1995; Biggs et al. 1997; Zimmerman and Biggs 1999).

Table 6.2. Estimates of plankton standing stock in the deepwater Gulf of Mexico (GOM) (bulk biomass as mL wet displacement volume per 100 $m^3$)

| Year | Author | Descriptor | Biomass |
|---|---|---|---|
| 1958 | Arnold | GOM-wide, upper 10 m, silk mesh in metal tube, horizontal tows | 5.2 - 5.4 |
| 1958 | Arnold | GOM-wide, upper 10 m, all-metal sampler, horizontal tows | 10.9 - 13.5 |
| *1969a | Khromov | GOM-wide, vertical hauls, upper 100 m, silk Juday meter nets with 38 meshes per inch (0.5 mm aperture), 'inedible forms removed' | <5 - 35 |
| 1973 | Hopkins | in review article, mentions biomass estimates for the eastern central GOM that were obtained during EGMEX (eastern Gulf of Mexico) investigations | 1 - 10 |
| 1976 | Houde et al. | eastern GOM from multiple years and seasons, upper 200 m, 61 cm diameter bongo nets with 333 µm mesh, oblique hauls | 2.20 - 9.86 |
| 1981 | Iverson and Hopkins | Tampa OTEC site in eastern GOM, upper 200 m, 0.75 m open nets with 202 µm mesh, vertical and oblique hauls; average value reported here | 6.17 |
| 1988 | Biggs et al. | western GOM, upper 100 m, open meter nets with 333 µm mesh, oblique hauls during two months (April and November) of the same year | 4 – 40 |
| 1989 | Richards et al. | northeast GOM, upper 200 m, 61 cm diameter bongo nets with 333 µm mesh, oblique hauls, data from SEAMAP program | 2.3 - 12.3 |

Table 6.2. Estimates of plankton standing stock in the deepwater Gulf of Mexico (GOM) (bulk biomass as mL wet displacement volume per 100 $m^3$) (Continued)

| | | | |
|---|---|---|---|
| 1991 | Grimes and Finucane | front between Mississippi plume and ocean water, neuston tows, 947 µm mesh, horizontal tows | 1 – 12 |
| 1992 | Biggs | western GOM, upper 200 m, open 70 cm diameter bongo nets with 333 µm mesh, oblique hauls, range of average day – night values is reported here | 4 – 6 |
| 1993 | Richards et al. | northeast GOM, upper 200 m, 61 cm diameter bongo nets with 333 µm mesh, oblique hauls, data from SEAMAP program | 1.50 - 33.05 |
| 1997 | Biggs et al. | western GOM, upper 100 m, open meter nets with 333 µm mesh, oblique hauls | 3.6 - 9.0 |
| 1997a | Lamkin | upper 200 m, 61 cm diameter bongo nets with 333 µm mesh, oblique hauls, data from SEAMAP program; range between averages for the eastern and western Gulf (respectively) are reported here | 10 - 13 |
| 1999 | Zimmerman and Biggs | central GOM, various discrete intervals in the upper 125 m, 1/4 m mouth area MOCNESS with 333 µm mesh nets | 4.0 - 32.5 |
| 2000b | Davis et al., Volume III: Data Appendix | northeast GOM during two different years, various discrete intervals in the upper 400 m, 1 $m^2$ mouth area MOCNESS with 333 µm mesh nets | <0.1 - 33.5 |

Notes: A comparison of literature biomass values is difficult because of differences in gear, sampling technique, and measurement methods. The values above are a sampling of those values reported in wet displacement volume per volume of seawater or similar, with equipment and sampling technique as noted. Volume units were converted as necessary into mL•100 $m^{-3}$. The implicit assumption is that these bulk values are useful in describing the general biomass patterns of various sizes and kinds of zooplankton, micronekton, and ichthyoplankton in the deepwater GOM. *= values in this paper were originally reported as g/$m^3$, but a footnote indicated that they were volume values that had been converted to weights by assuming a zooplankton 'specific weight' of ~1.

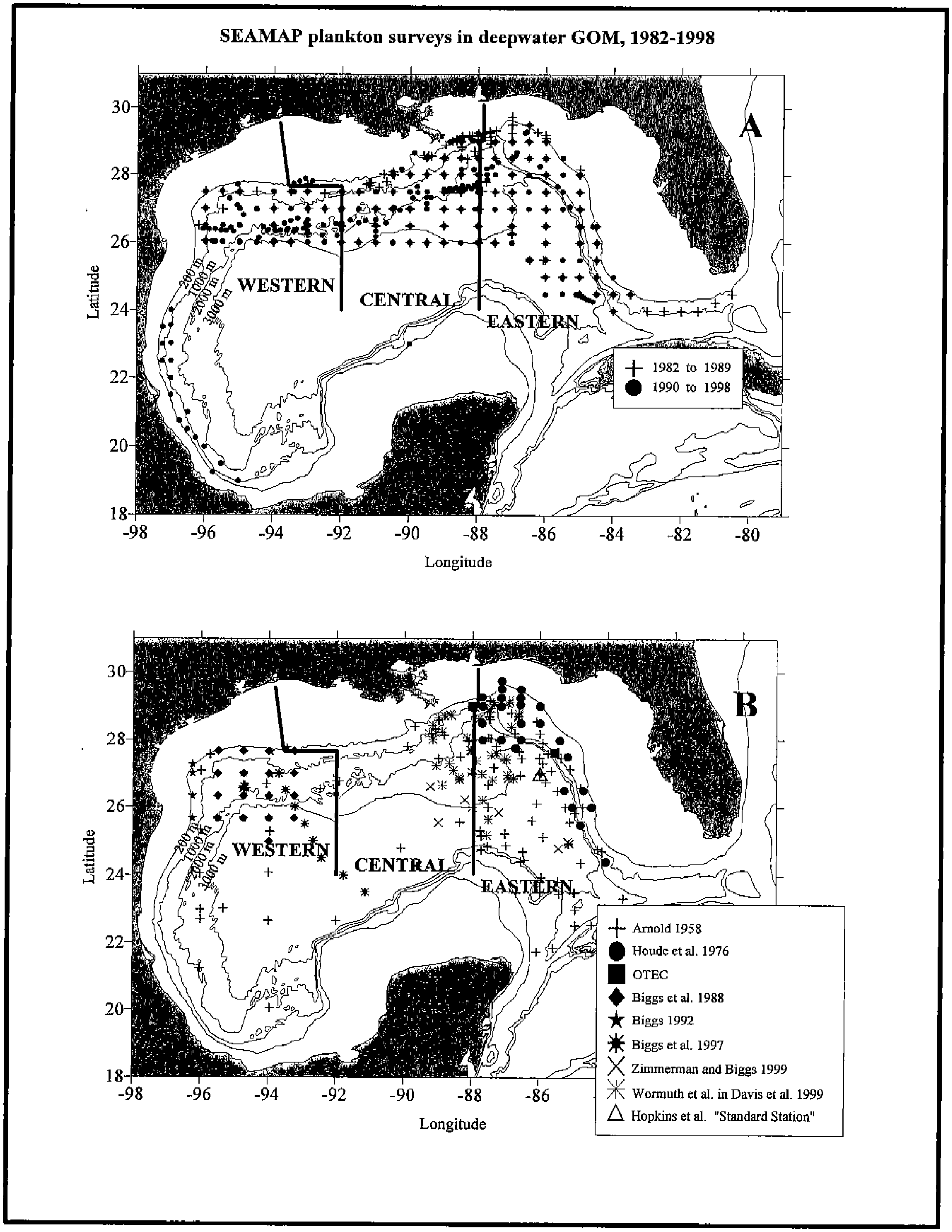


Figure 6.7. Top panel: Deepwater locations of SEAMAP plankton surveys, 1982-1998. Bottom panel: Deepwater locations of plankton collection stations (excluding SEAMAP), 1958-1999.

## Spatial and Temporal Variability

The analyses that are available indicate that while overall biomass levels are low, there is mesoscale spatial variability in biomass across the Gulf. The combined standing stock of zooplankton, micronekton, and ichthyoplankton generally varies with distance from shore (shelf areas are generally enriched as opposed to the deepwater areas: Khromov 1969a; Iverson and Hopkins 1981), depth in the water column (highest in the upper 200 m and decreasing with depth: Vargo and Hopkins 1990), and the proximity to riverine input (enriched areas downstream: Bogdanov et al. 1968; Khromov 1969a). Regions of upwelling, high current shear, or physical aggregation are "hot spots" that have greater standing stocks (Wormuth 1982; Vargo and Hopkins 1990; Lamkin 1997a; Wormuth et al. 2000).

There is also evidence for temporal variability in deepwater stocks, both between years and within a given year. In general, two- to four-fold increases in zooplankton standing stock appear to follow closely in time after changes in local forcing factors (Bogdanov et al. 1968, Khromov 1969a). These forcing factors may range from changes in river outflow (Dagg et al. 1991) to upwelling due to the passage of deepwater eddies. Variation in overall plankton biomass may also result from turnover of the deepwater zooplankton standing stock, estimated at 30 to 90 days for zooplankton in the eastern GOM (Iverson and Hopkins 1981). The biomass in a given depth interval also varies on the time scale of a day by a factor of two or more because of diel vertical migration. Although generally a small portion of the total plankton biomass (Richards 1985), ichthyoplankton distributions are especially variable, for many taxa exhibit pronounced seasonality and year- to-year variation in abundance. Much of this variation appears tied to length and time of year of spawning (Houde and Chitty 1976; Ditty et al. 1988; Vargo and Hopkins 1990).

Details of the OTEC sampling off Mobile and Tampa Bays were reported by various groups (Lawrence Berkeley Laboratory 1980a, b, c; Flock and Hopkins 1981) and summarized by Commins and Horne (1979) as well as by Iverson and Hopkins (1981). In addition to taxonomic and size frequency data, Commins and Horne (1979) reported a peak in zooplankton abundance in October and a minimum in June 1978 at the Tampa site, while at the Mobile site abundance was greatest in June and least in August. Approximately 98% of the zooplankton were found to occur in the upper 200 m of the water column. Diel vertical migration was evident at both sites.

A very extensive analysis of the zooplankton and micronekton community of the so-called 'Standard Station' in the Eastern GOM (27°N, 86°W) has been done by T.L. Hopkins and colleagues. Trends in biomass and abundance over depth and time at this location were elucidated in addition to the ecological information gathered about groups of zooplankton and micronekton found there. Biomass results from these studies were not included in **Table 6.2** because they were usually reported in dry-weight units based on length-weight regressions for particular groups of organisms, rather than in bulk WDV. However, because spatial variation was not the focus of Hopkins' study, it is unclear whether conclusions drawn from the data collected at this single location are generally applicable to the rest of the GOM.

Probably the most complete and systematic sampling of the standing stocks of zooplankton, micronekton, and ichthyoplankton in the deepwater GOM is being carried out as part of an ongoing state-federal project administered by the Gulf States Marine Fisheries Commission. Known as SEAMAP-Gulf of Mexico (Southeast Area Management and Assessment Program), the primary goal has been to census the abundance of eggs and ichthyoplankton larvae of commercially important fish stocks. **Figure 6.7A** shows the station locations where SEAMAP cruises collected deepwater plankton, primarily using 333 μm mesh bongo nets and 947 μm mesh neuston tows according to standard fisheries methods but supplemented with Tucker trawls on more recent cruises. Samples are collected one to three times per year on a 1/2 x 1/2 degree grid in different seasons. Although many of the samples collected by SEAMAP have been from the continental shelf, so far about 2,100 have been tows in water depth >200 m.

Data reports for the SEAMAP program are produced each year, and aliquots of the plankton collected (both sorted and unsorted) are available for loan. Even more helpful, though, are the summaries of sampling locations, biomass values, and the environmental data collected at each plankton station that are available from the SEAMAP data manager (for more information on SEAMAP data products, see http://www.gsmfc.org/seamap.html). So far there has been no summary of the interannual or decadal variability of these data. However, some published studies have used SEAMAP collections from particular regions or over certain periods of time. Grimes and Finucane (1991) attributed increased abundance of larval fish caught in SEAMAP neuston tows taken in the front between Mississippi River plume and oceanic waters to enriched primary and secondary production there, as indicated by elevated chlorophyll *a* and zooplankton WDV. Richards et al. (1993) reported that both zooplankton WDV and several taxa of larval fish varied across the LC boundary, being lower in abundance in LC interior than in the periphery or outside. Recently, Lamkin (1997a) used 6 years of SEAMAP data 1983-1988, in an investigation of the frontal zones associated with the northern excursions of the LC. Lamkin found a positive correlation between the abundance of larval nomeid fish and the location of the northern edge of the LC. In particular, *Cubiceps pauciradiatus* has adult spawning grounds and larval habitats closely related to sharp temperature gradients. Larvae of apex predators like bluefin and yellowfin tuna seem to be most abundant along LC frontal zones and within eddy peripheries, where zooplankton biomass and myctophid larvae numbers in SEAMAP bongo collections were also elevated (Richards et al. 1989). Adult tuna, as well, can be caught in such frontal zones (Roffer Offshore Fish Finding Service, personal communication).

Locations of other studies that produced the biomass estimates listed in **Table 6.2** are plotted in **Figure 6.7B**. Work by Houde and Chitty (1976) and Houde et al. (1976) included a study of eastern GOM ichthyoplankton: bulk plankton displacement volumes were reported, but most of the analyses concentrated upon shelf waters and ichthyoplankton composition and stock estimates for species of interest, rather than deepwater biomass. As in most studies, bulk biomass was greater on the shelf than in the deepwater part of the study area. There appeared to be a positive relationship between bulk displacement volume and egg/larval abundance, although the association was not always strong. Also notable is the "distinct seasonality" in the data (especially the eggs and fish larvae, due to seasonal spawning), with highest biomass and numbers of eggs and larvae during the spring-summer versus fall-winter, but these seasonal fluctuations were much more apparent on the shelf than in the deepwater part of the study area.

The studies of Biggs et al. (1988) and Biggs (1992) report opportunistic sampling during cruises to study LC eddies in the deepwater western GOM. The results provide further evidence that the upper 200 m of LCEs are low in plankton stocks, especially in contrast to LCE periphery. Using a 1/4 $m^2$ Multiple Opening/Closing Net Environmental Sensing System, or MOCNESS (for a description of gear see Wiebe et al. 1985), Zimmerman and Biggs (1999) collected samples in a transit through a cyclone, an LCE, and the LC itself. This sampling documented higher standing stocks of zooplankton and micronekton in the cyclone than in the LC or the LCE. Recently, Wormuth et al. (2000) reported on extensive 1 $m^2$ MOCNESS sampling, which they supplemented with IKMT (Isaacs-Kidd midwater trawl) collections, as a part of the GulfCet II multidisciplinary study of marine mammal, sea turtle, and seabird abundance and distribution. Their trawling carried out in support of this recently completed research program, which was co-sponsored by the U.S. Geological Survey and MMS, also documented that cyclones had locally higher standing stocks of zooplankton and micronekton than did LCEs.

## Acoustic Sampling of Zooplankton and Micronekton Biomass

Besides traditional net sampling, acoustic methods are also currently recognized as an important way of studying zooplankton and micronekton (Greene and Wiebe 1990; Wiebe et al. 1997; Greene et al. 1998). Under typical open ocean conditions and using frequencies on the order of $10^2$ kHz, the particles responsible for acoustic volume backscattering ($S_V$) are assumed to be zooplankton and micronekton (Stanton et al. 1994; Medwin and Clay 1998). There are several approaches to making standing stock measurements of zooplankton and micronekton using acoustics (for a survey, see Hersey and Backus 1962; Greene and Wiebe 1990; Wiebe and Greene 1994). One of the simplest is to use a single-frequency echosounder to measure acoustic backscattering from a volume of water, and to then relate this measurement to number or biomass of sound-scattering organisms in that volume as determined by direct sampling with nets.

To date, there have been few acoustic surveys of deepwater zooplankton, micronekton, or ichthyoplankton in the Gulf of Mexico. After the early work of van Schuyler and Hunger (1967) and Thompson (1971) on acoustic volume backscattering, no studies using special purpose acoustics to measure zooplankton, micronekton, or ichthyoplankton in the deepwater GOM have reached the published literature. However, both moored and vessel-mounted acoustic doppler current profilers (ADCPs) are routinely used to measure the velocity of near-surface currents, and recently several volume backscattering studies using ADCPs have been completed and published (Biggs et al. 1997; Zimmerman 1997; Ressler et al. 1998; Wormuth et al. 2000; Zimmerman and Biggs 1999). The ADCP transmits a sound pulse into the water and then awaits the return of sound scattered back by passively drifting particles in the water column. The Doppler shift of this backscattered sound is then used to estimate current speed and direction. However, the ADCP also measures the intensity of the backscattered acoustic return, which is proportional to the number and backscattering cross sections of the particles in a given ensonified volume of water (Clay and Medwin 1977; Medwin and Clay 1998). Although the ADCP was not designed as a scientific echosounder (Brierly et al. 1998), ADCPs have been successfully used to estimate the concentration of sound scatterers (Flagg and Smith 1989; Ashjian et al. 1994; Zhou et al. 1994; Griffiths and Diaz 1996; Ressler et al. 1998). Some of the studies cited above (Ressler et al. 1998; Wormuth et al. 2000) have employed 'sea-truth' sampling of zooplankton and micronekton using a 1 $m^2$ mouth area, 333 μm mesh size MOCNESS. With 1) information about the acoustical properties of the ADCP and relevant hydrographic data, 2) net sampling of sound scattering zooplankton and micronekton concurrent with ADCP surveys, and 3) some acoustic theory to refine the estimate of what is being measured and how different sizes, abundances, and taxa of zooplankton and micronekton are impacting the signal, it is possible to produce ADCP-derived estimates of standing stock biomass and map zooplankton and micronekton biomass distribution over depth, space, and time (**Figure 6.8**).

### Optical Sampling of Zooplankton and Micronekton Biomass

Underwater optical techniques, such as the video plankton recorder (VPR), provide another more recently developed means of surveying zooplankton. Deepwater VPR studies have not taken place in the GOM, but in other regions such observations have been used in concert with net and acoustic sampling to study the coarse-scale abundance and composition of zooplankton populations (Benfield et al. 1996; Davis et al. 1996; Benfield et al. 1998).

### A Combined Approach to Biomass Surveys

Traditional direct sampling and alternative acoustic and optical techniques are complementary approaches. Net sampling provides taxonomic information that cannot currently be gathered with acoustical or optical techniques; it also provides necessary 'sea-truth' information needed to interpret acoustical and optical data. However, acoustics and optics can make nearly continuous measurements over various temporal and spatial scales, providing zooplankton-micronekton-ichthyoplankton data with sufficient resolution to examine temporal and spatial trends in a manner impossible with net sampling at single discrete locations. This capacity is also useful given the growing amount of coarse to mesoscale oceanographic data available from satellites. A combination of net, acoustical, and optical techniques appears to be the optimum way to study variations in zooplankton and micronekton standing stock biomass, and such a unification of technologies will lead to better understanding of the interaction of hydrography and ecology in the deepwater Gulf of Mexico.

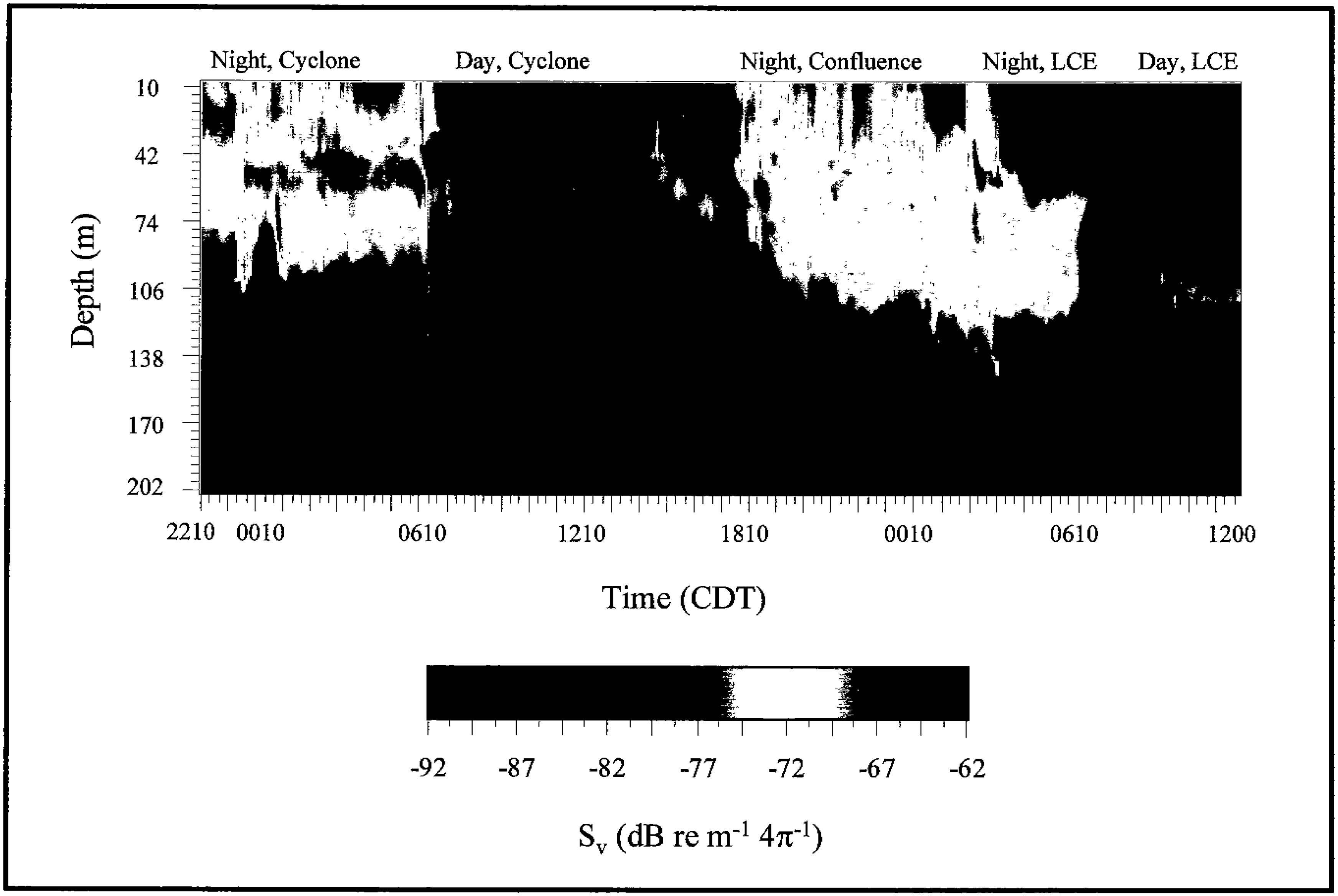


Figure 6.8. Grayscale running plot of $S_v$ collected with an ADCP along a north-south transect line from the deepwater ofthe Mississippi River, through a cyclone, and into a Loop Current Eddy (LCE-C) during October 1996 (Adapted from: Wormuth et al. 1999). Lighter areas on the plot indicate higher $S_v$, while dark colors indicate less intense returns. Since local time and location are both changing along the x-axis, such field survey data include temporal variability (higher $S_v$ at night than in the daytime) as well as spatial variability (higher $S_v$ in the cyclone than in the anticyclone).

**Acknowledgments**: A number of people helped us with the technical aspects of this review. Rezneat Darnell (Texas A&M University) and Dennis Emiliani (National Marine Fisheries Service) were helpful sources of information for the expeditions of the 1950's and 1960's, and Mark McDuff (SEAMAP Data Manager) provided the location of the deepwater SEAMAP stations. Gloria Guffy and the microtext and reference staff at Texas A&M University Sterling C. Evans Library helped with interlibrary loans of source material, and Joel Ortega made the base maps with bathymetry that we have used in Figs 6.1, 6.2, and 6.7.

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## Appendix 6A: Deepwater Water Column Biology

Some studies of the systematics, biology, or ecology of particular taxonomic groups of zooplankton, micronekton, and ichthyoplankton

| Year | Author | Descriptor |
|---|---|---|
| **1950's** | | |
| 1956, 1957a, 1957b, 1957c, 1959 | Fleminger | Thesis and publications about copepods in the Gulf of Mexico (GOM), primarily using 1951-1953 near-surface collections from U.S. Bureau of Commercial Fisheries vessel M/V *Alaska* |
| 1956 | Voss | Extensive review cephalopods of the GOM, although it contains only limited information about the smaller planktonic or micronektonic species |
| 1957 | Gonzalez | Thesis about the distribution of copepods off the Mississippi delta in GOM during 1956 |
| **1960's** | | |
| 1968 | Jones | Paper on planktonic foraminifera of Caribbean and limited areas of GOM; taxonomy, distribution, standing crop, use as hydrographic indicator species |
| 1969 | Bright and Pequegnat | Paper on deep-sea hatchet fishes of the GOM; known species are listed along with observation on abundance, distribution, behavior, and taxonomy |
| 1969 | Grice | Paper on calanoid copepods of GOM and Caribbean Sea, mainly taxonomic work |
| 1969 | Taylor | Texas A&M thesis on heteropod distribution and taxonomy in the GOM (first investigation of GOM heteropod fauna per se) |
| **1970's** | | |
| 1970, 1975 | Lipka | Thesis and dissertation about systematics, biology, and zoogeography of GOM cephalopods |

Appendix 6A: Deepwater Water Column Biology
Some studies of the systematics, biology, or ecology of particular taxonomic groups of zooplankton, micronekton, and ichthyoplankton
(Continued)

| Year | Author | Descriptor |
|---|---|---|
| 1970, 1974, 1975a, 1975b, 1975c | Park | Taxonomic work regarding calanoid copepods from the GOM and Caribbean Sea |
| 1971 | Austin | Dissertation about the use of pteropods and foraminifera as indicator organisms of eastern GOM water masses |
| 1971 | Cruise | Thesis in which two species of the decapod genus *Lucifer* are examined and suggested as hydrographic indicator species in the eastern GOM |
| 1971 | Schroeder | Dissertation on the distribution of euphausiids in the oceanic GOM, Yucatan Strait, and Caribbean; includes Longhurst-Hardy sampling |
| 1973 | Ferrari | Dissertation on the distribution of epipelagic cyclopoid copepods in the GOM and Yucatan Strait; includes Longhurst-Hardy sampling |
| 1973 | Hopkins and Baird | Paper about the diet of the GOM hatchetfish *Sternoptyx diaphana* |
| 1974 | Minello | Thesis on the vertical distribution and feeding relationships of calanoid copepods in the western GOM |
| 1976 | Berkowitz | Thesis on neuston and near-surface zooplankton in the northwest GOM, including taxonomic composition |
| 1977 | Hopkins and Baird | Paper on the feeding ecology of midwater fishes; topics include diet composition, feeding chronology, daily food ration, prey choice, resource partitioning, and bioenergetics |
| 1977 | Nafpaktitis et al. | Large multi-authored volume about groups of fishes and zoogeographic provinces of the western north Atlantic, including the GOM; of special interest is the section on the myctophid fishes |

## Appendix 6A: Deepwater Water Column Biology
## Some studies of the systematics, biology, or ecology of particular taxonomic groups of zooplankton, micronekton, and ichthyoplankton
## (Continued)

| Year | Author | Descriptor |
|---|---|---|
| **1980's** | | |
| 1980a, b | Richards and Potthoff | Two papers on distributions of a) bluefin tuna larvae and b) other scombrid larvae and swordfish in the GOM during the spring of 1977 and 1978 |
| 1981 | Flock and Hopkins | Paper on zooplankton collections near an Ocean Thermal Energy Conversation site off of Tampa Bay, including taxonomic analysis and abundance of six particular groups |
| 1981 | Heffernan and Hopkins | Vertical disribution and feeding ecology of the penaeid shrimp genera *Gennadas* and *Bentheogennema* |
| 1982 | Smith | Dissertation on the abundance and foraging ability of physonect siphonophores the subtropical waters in the western GOM and off the Bahamas |
| 1983 | Murdy et al. | List of midwater fish collections in the GOM during the period 1965-1973 by the R/V *Alaminos*, including locations and species accounts |
| 1984 | Cummings | Paper describing the vertical structure and taxonomic composition of calanoid copepods in the western GOM |
| 1984 | Michel | National Oceanic and Atmospheric Administration technical report on chaetognatha in "Caribbean Sea and Adjacent Areas," including GOM; includes information on distribution and identification |
| 1984 | Richards et al. | Distribution and abundance of nine groups of GOM ichthyoplankton, from 1982 SEAMAP bongo and neuston collections |
| 1985a | Hopkins and Baird | Paper about trophic ecology of the GOM myctophid *Lampanyctus alatus* |

## Appendix 6A: Deepwater Water Column Biology
Some studies of the systematics, biology, or ecology of particular taxonomic groups of zooplankton, micronekton, and ichthyoplankton
(Continued)

| Year | Author | Descriptor |
|---|---|---|
| 1985b | Hopkins and Baird | Paper on the feeding ecology of four species of GOM hatchetfish |
| 1986 | Kelley et al. | Distribution and abundance of 10 groups of GOM ichthyoplankton, from 1983 SEAMAP bongo and neuston collections |
| 1986 | McGowan and Richards | Distribution and abundance of bluefin tuna larvae in the GOM for 1982 and 1983, and spawning stock biomass estimates for 1977-1978 and 1981-1983 |
| 1987 | Gartner et al. | Paper about myctophids of the eastern GOM; information includes vertical distribution, species composition, and abundance |
| 1987 | Shuert and Hopkins | Vertical distribution and feeding ecology of the copepod *Euchaeta marina* in the eastern GOM |
| 1988 | Dagg et al. | A study of copepod nauplii in northern GOM, primarily from the continental shelf, but including some deepwater stations |
| 1988 | Ditty et al. | Paper on seasonal and depth distribution of larval fishes in the northern GOM includes tables of seasonal occurrence, depth of occurrence, and previous studies for specific taxa |
| 1988 | Gartner et al. | Paper about escapement of myctophids from midwater trawls, including size-selectivity (in terms of catch) of net mesh size |
| 1988 | Lancraft et al. | Paper on the trophic ecology of a GOM stomiid, *Gonostoma elongatum* |

Appendix 6A: Deepwater Water Column Biology
Some studies of the systematics, biology, or ecology of particular taxonomic groups of zooplankton, micronekton, and ichthyoplankton
(Continued)

| Year | Author | Descriptor |
|---|---|---|
| 1989 | Bennett and Hopkins | Paper on the copepod genus *Pleuromamma* in the eastern GOM |
| 1989 | Hopkins et al. | Caridean shrimp in the eastern GOM |
| 1989 | Ortner et al. | Correspondence analysis of zooplankton community structure and copepod species composition in GOM |
| **1990's** | | |
| 1990 | Grimes et al. | A review of information about larval king mackerel in the GOM, including information gained from SEAMAP collections |
| 1990 | Passarella | Thesis on oceanic cephalopods in the eastern GOM |
| 1990 | Kelley et al. | Distribution and abundance of ten groups of GOM ichthyoplankton, from 1986 SEAMAP bongo and neuston collections |
| 1990 | Richards | List and drawings of fishes of the 'western central North Atlantic' (which includes GOM) by family. includes species information and whether eggs, juvenile, or larval stages are known |
| 1991 | Dagg and Whitledge | Paper about concentrations of copepod nauplii in the Mississippi plume, primarily at the edge of the continental shelf |
| 1991a, 1991b | Gartner | Life histories, age and growth patterns of three species of eastern GOM myctophids using analysis of otoliths |
| 1991 | Goldman and McGowan | Distribution and abundance of paralarval squid south of Florida keys |

## Appendix 6A: Deepwater Water Column Biology

Some studies of the systematics, biology, or ecology of particular taxonomic groups of zooplankton, micronekton, and ichthyoplankton
(Continued)

| Year | Author | Descriptor |
|---|---|---|
| 1991 | Grimes and Finucane | Includes frequency and percent frequency of occurrence of families of ichthyoplankton from SEAMAP neuston tows across a front between Mississippi River water and oceanic water |
| 1991 | Passarella and Hopkins | Paper on the species composition and food habits of micronektonic cephalopods in the eastern GOM |
| 1992 | Cheng and Wormuth | Paper about the marine insect *Halobates* in the GOM and Caribbean Sea |
| 1992 | Flock and Hopkins | Paper describing species composition, vertical distribution, and food habits of sergestid shrimp in the eastern GOM |
| 1992 | Hopkins and Gartner | Paper about resource partitioning and predation of eastern GOM myctophids |
| 1993 | Gartner | Paper on reproductive patterns of myctophids in the eastern GOM; includes abundance estimates for several GOM myctophid genera |
| 1993 | Kelley et al. | Distribution and abundance of 10 groups of GOM ichthyoplankton, from 1984-1985 SEAMAP bongo and neuston collections |
| 1993 | Richards et al. | Principal component analyses of larval fish assemblages across a Loop Current Boundary in the GOM, using SEAMAP bongo collections |
| 1994 | Kinsey and Hopkins | Paper about euphausiids in GOM, including cluster analysis of vertical distribution, diet and morphology |

## Appendix 6A: Deepwater Water Column Biology
Some studies of the systematics, biology, or ecology of particular taxonomic groups of zooplankton, micronekton, and ichthyoplankton
(Continued)

| Year | Author | Descriptor |
|---|---|---|
| 1994 | Hopkins et al. | Paper about decapod and mysid assemblage in GOM, including cluster analysis of vertical distribution, diet and morphology |
| 1994 | Suárez | Distribution of pteropods in the GOM, Florida Current, and Caribbean Sea; checklist of species in addition to brief information about the geographical and vertical distribution, biogeography, and ecology of each |
| 1996 | Hopkins et al. | Trophic structure and predation of eastern GOM midwater fish |
| 1996a, 1996b | Sutton and Hopkins | Papers about stomiid fish assemblage in the eastern GOM, including species composition, abundance, vertical distribution, diet |
| 1997a | Lamkin | Paper about the abundance of the larval fish *Cubiceps pauciradiatus* in the Loop Current of the GOM |
| 1997b | Lamkin | Paper describing larval stages of the stromateoid fish *Ariomma melanum* in the GOM |
| 1997 | Scott and Turner | Index for estimating bluefin tuna abundance based on larval surveys (SEAMAP surveys) in the GOM |
| 1998 | Hopkins and Sutton | Diets and resource partitioning of micronekton (midwater fishes and shrimps) in the Gulf of Mexico |
| 2000 | Wormuth et al. | Included in a survey of zooplankton biomass in the northeast GOM are ongoing studies of the taxonomy, distribution, and abundance of cephalopod paralarvae and myctophid fish |

# Chapter 7: Non-Seep Benthos

*Gilbert T. Rowe*

## Introduction

The study of the deep benthos of the GOM can be divided into three eras. Early studies prior to the 19th century were exploratory zoogeographic investigations. In the 1960's, Willis E. Pequegnat initiated modern investigations of the standing stocks of the megafauna. In the 1980's, the MMS supported an investigation of the continental slope that encompassed state-of-the-art quantitative sampling of the meiofauna, macrofauna, and megafauna. Considerable work also has been initiated in the 1990's, but little of it has been published yet.

The earliest explorations were concerned mostly with dredging the deep-sea floor. The most extensive work is summarized by Agassiz (1888). Few generalizations could be made in these works; they dealt mostly with lists of species and descriptions of new species. Publications resulted on a broad suite of invertebrate taxa. None of the early studies penetrated the western Gulf. These early investigations have been reviewed by Galtsoff (1954) and Geyer (1970).

The second important period of deep Gulf studies was initiated by Willis E. Pequegnat in the mid-1960's. A diverse series of investigations employed the R/V ALAMINOS. Efforts were made to characterize all geographic areas of the deep Gulf and the far western Caribbean. The composite samples were divided up by taxon or by specialized ecological problem among the graduate students at Texas A&M University working with Pequegnat. The individual studies are available at Texas A&M University or at University Microfilms. Many sampling trips extended well into what is now recognized as Mexico's Exclusive Economic Zone (EEZ) because at the time, no restrictions had been placed on scientific sampling of these international waters. A similar geographic distribution of studies would not be possible today without permission from Mexico. These studies have been summarized by Pequegnat (1983) in a volume submitted to the

MMS. The work concentrated on samples taken with a sampling device developed by Pequegnat called a "skimmer" (Pequegnat et al. 1970). It was equipped with an odometer wheel to estimate distance covered. The anterior "mouth" of the skimmer measured 3 m wide by 1 m high. The anterior frame of the rigid, hour glass-shaped structure was covered with 1.25 cm galvanized wire mesh but its bulbous cod end was covered with 0.6 cm mesh. The distances traveled averaged several kilometers. The original meter wheel data are available in the field notes taken aboard ship at the time of sampling. This method sampled "megafauna," principally, and not other size categories. It had the advantage that the samples were protected by the rigid posterior framework, and thus fragile forms were damaged less than in conventional otter or beam trawls.

Faunal groups studied from the deep Gulf included the crustaceans (L. Pequegnat 1970; Roberts 1970; Firth 1971), echinoderms (Booker 1971; Carney 1971), mollusks (James 1972), and fishes (Bright 1968), among others. Tabulation of fish gut contents was intended to link the megafauna to its food source (Rayburn 1975). Kennedy (1976) compared the species composition of the eastern and western Gulf faunas and concluded that they were not the same. The macrofauna appeared to be grouped into assemblages that were distributed within zones down the slope onto the abyssal plain (Kennedy 1976; Roberts 1977), but no justification was found for separating the abyssal plain fauna into zoogeographic provinces by latitude or longitude. That is, even though the fauna along the slope changed with increasing depth and these changing faunas differed in the eastern and western Gulf, down on the basin floor the fauna showed little in the way of east-west differences.

The stations occupied by the ALAMINOS also incorporated bottom multi-shot photography to quantify areas of the seafloor. The principal rationale for this was to quantify the densities of the epibenthic megafauna captured by the skimmer and other miscellaneous trawls and dredge samples. It also allowed the users to count "lebenspuren" (animal tracks and burrows) and qualitatively categorize the types of sediments present. Although a 70 mm format camera was used on occasion, a 35 mm camera built by Alpine Geophysical seems to have produced more good film. It was rigged to take photographs on bottom contact of a trigger switch. The advantage of such an approach is that distance between the camera and the bottom is always known and this allows the operator to calculate the area each photograph covers with a given lens angle. This technique can be calibrated with a grid in shallow water, if necessary. The records available indicate that on the order of up to 50 photographs were taken per lowering and each photograph covered an area of approximately 1 $m^2$. An appendix in Pequegnat (1983) features a large number of the photographs.

In addition to the biological studies, photographs of an "iron stone bottom" north of the Yucatan Channel suggested deep bottom currents can be strong enough in the eastern Gulf to sweep large areas free of sediments (Pequegnat 1972). The photographic negatives of the entire collection of lowerings are archived in the Oceanography Department at Texas A&M University (with the present exception of a station on loan to the Universidad Nacional Autonomia de Mexico (UNAM).

Abyssal plains constitute a significant proportion of the surface of the earth. Although generally acknowledged as the ultimate sink of detritus from the continents, their biota has long been considered sparse and depauperate. The abysso-benthic communities of the Sigsbee Deep in the western Gulf of Mexico, known as one of the flattest surfaces on the deep ocean floor, is less well known than many other abyssal plains, in spite of its modest depth (3.6 to 3.8 km) and proximity to the United States and Mexico. The works of Pequegnat remain the most extensive on the Sigsbee Deep plain.

The third historical timeframe represents the most extensive sampling of the sediment biota of the continental slope of the northern Gulf of Mexico to date. The Northern Gulf of Mexico Continental Slope (NGOMCS) study was conducted in the 1980's by LGL Ecological Research Associates, Inc. with support from the MMS. This consisted of paired Gray-O'Hara or GOMEX box cores (Boland and Rowe 1991), bottom survey camera lowerings, and bottom trawling. The stations studied included three transects down the continental slope off Texas, Louisiana, and Florida (**Figure 7.1**). Sampling stopped at depths just shy of 3 km and therefore did not extend out onto the abyssal plain. Thus, comparison with shelf and abyssal plain samples was not possible.

The work on deepwater benthos at Texas A&M University beginning in the 1960's up through the MMS-supported studies of the 1980's has been published in a concise summary by Pequegnat et al. 1990). The focus was on the northern continental slope. Other documentation of the studies of the slope include reports to MMS (Gallaway 1988; Gallaway et al. 1988a,b) and a dissertation on the polychaete annelid worms (Hubbard 1995).

Considerable work has been initiated in the 1990's, but little of it has been published yet. The Instituto Ciencias del Mar y Limnologia of UNAM initiated extensive studies in the southern Gulf of Mexico with the acquisition of the deep ocean research vessel JUSTO SIERRA. Mexican biologists are conducting studies of megafauna, demersal fishes, macrofauna, and meiofauna from the continental shelf down across the slope onto the Sigsbee Abyssal Plain. Stable C and N isotopes have been used to infer pathways through a benthic food chain (Soto and Escobar 1995). Studies in deep water across the Cordilleras Mexicanas or "Mexican Ridges" of the upper continental rise out onto the Sigsbee Abyssal Plain have identified regions that contain enhanced biomass under surface water masses characterized by accelerated rates of primary production (Escobar-Briones and Soto 1997; Escobar-Briones et al. 1999). Polychaetes dominated the infauna; they encountered a mid-slope maximum in abundance similar to that described in the northern Gulf (Pequegnat et al. 1990). The fauna could be partitioned into three groups that conformed to depth intervals of >3 km, intermediate depths of 1.5 and 3 km, and shallow waters <1.5 km. This contrasts with the view of Pequegnat et al. (1990) that the continental margin is characterized by five zones.

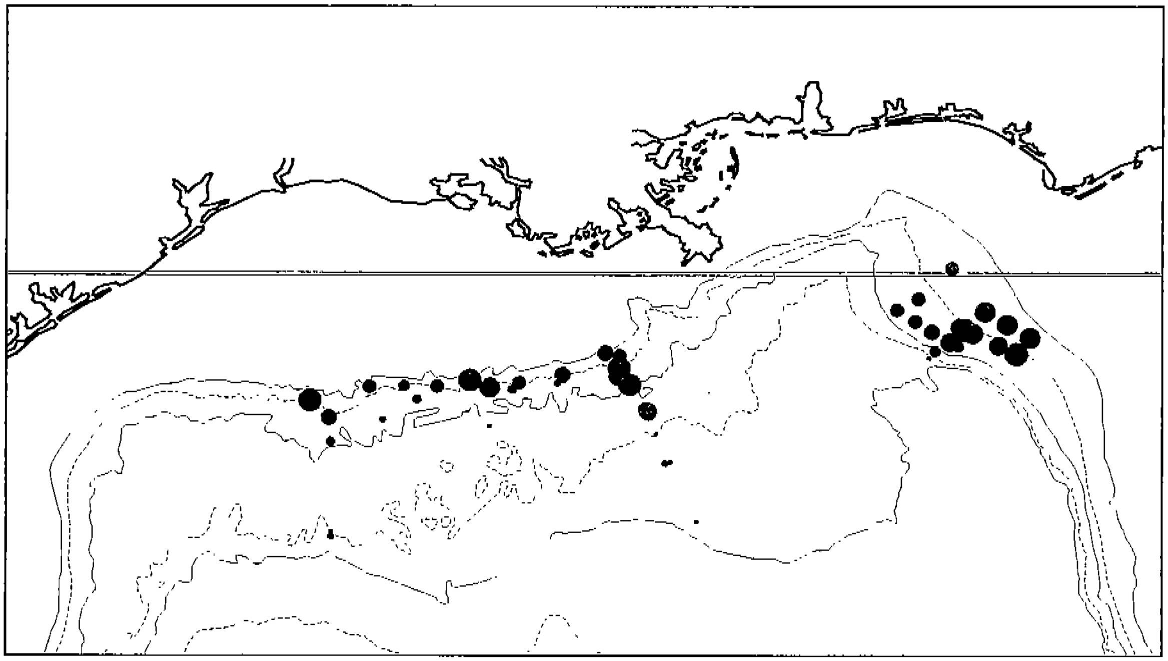

Figure 7.1. Station locations for the MMS-supported Northern Gulf of Mexico Continental Slope (NGOCMS) Study conducted by LGL Ecological Research Associates, Inc. (Gallaway 1988). Log transformed polychaete densities (individuals·m$^{-2}$) are shown from Hubbard (1995). Ranges of densities from smallest to largest circles are as follows (numbers in parentheses are numbers of occurrences): 250-630 (8); 630-1,000 (7); 1,000-1,340 (6); 1,340-1,560 (7); 1,560-1,800 (8); 1,800-2,040 (6); 2,040-2,270 (6); 2,270-2,470 (5); 2,470-2,860 (6).

In 1997, a two-ship operation by Texas A&M University and UNAM was conducted at a common station (25°15'N, 93°26'W) on the northern Sigsbee Abyssal Plain, at a depth of 3.65 km. The JUSTO SIERRA traveled up from Tuxpan, sampling along an east-west line across the Cordillera Tampiquena or Mexican Ridges (Escobar-Briones et al. 1999), while the GYRE went due south out of Galveston, directly to the site. As this site is well within the Mexican EEZ, all sampling conducted from the GYRE had to be approved *a priori* by a suite of Mexican federal agencies. It is nestled within several nearby locations that Pequegnat sampled with the skimmer and bottom photography..

Total sediment community respiration was measured using a benthic lander containing a pair of automatically operated benthic incubation chambers used to measure fluxes of metabolic gases across the sediment water interface. The lander and its operation have been described previously by Rowe et al. (1994) and Rowe et al. (1997). Oxygen consumption by the bottom and its contained biota is calculated from the decline of oxygen within the chamber over time, the volume of the chamber, and the area of the seafloor it covers. It was deployed once in the western Sigsbee Deep at a depth of 3.6 km.

## Community Description

The standing stocks of the size categories of the biota have been grouped together, in terms of biomass and numbers per square meter, for comparison (**Table 7.1**).

### Microbiota

The microbiota of the deep Gulf sediments is not well characterized. While direct counts have been coupled with some *in situ* and re-pressurized metabolic studies have been made in other deep ocean sediments (Deming and Baross 1990), none has been made in the deep Gulf. Direct counts using a fluorescing nuclear stain have been made at several depths down the slope, thus allowing the bacterial biomass to be estimated from their densities and sizes (Cruz-Kaegi 1998). Mean biomass was estimated to be 2.37 g $C{\cdot}m^{-2}$ for the shelf and slope (combined), and 0.37 g $C{\cdot}m^{-2}$ for the abyssal plain. These data indicated that the bacteria are the most important component of the functional biota in terms of biomass. Comparisons are not yet possible with other ocean basins. Cruz-Kaegi (1998) developed a budget for carbon cycling based on her estimates of biomass and metabolic rates in the literature. Her budget illustrates that on the deep slope of the Gulf, a large fraction of the organic carbon supplying the benthos with energy is cycling through the bacteria.

### Meiofauna

The extensive sampling by the NGOMCS study discovered that the meiofauna appears to have a biomass that is higher than that of the macrofauna. The regressions of $\log_{10}$ numbers per square meter and biomass (as micrograms wet weight per square meter) were the following (from Gallaway et al. 1988b):

$\mathrm{Log}_{10}$ density = 5.87 – 0.00018 (depth in meters), and

$\mathrm{Log}_{10}$ biomass = 6.4 – 0.0002 (depth in meters).

Unfortunately, no estimates of biomass were made directly. Biomass was estimated from conversion factors for each group in both the macrofauna and the meiofauna. The densities were 2.5 log units higher than macrofauna, which is not unusual. The biomass was 0.5 log units above macrofauna, which is a reversal with the relationship found in shallow water environments. If true, this confirms earlier studies in the Atlantic (Thiel 1983; Rowe et al. 1991) that implied that meiofaunal-sized organisms increase in importance (in terms of biomass) at deep-sea depths relative to the macrofauna. Cruz-Kaegi (1998) also observed this in her studies. No information is available on the species composition or diversity of the meiofauna of the deep Gulf.

### Macrofauna

**Abundance and Biomass**. Anchor dredge samples across the Sigsbee Deep and van Veen grabs from the northern continental slope shelf suggested that deep biomass in the Gulf was depauperate in numbers and biomass, similar to that in other ocean basins, but that the mean size of the macrofauna was in general smaller than that in the Atlantic at similar depths (Rowe 1971, 1983; Rowe and Menzel 1971; Rowe et al. 1974). The lognormal relationship between abundance and depth (**Figure 7.2**) and biomass and depth (**Figure 7.3**) has been confirmed now for numerous ocean basins (Rowe 1983), but the slope of the line (biomass as a function of depth) for the Gulf appeared to be steeper than that in most basins. It was suggested that this is due to the Gulf's low primary productivity.

Table 7.1. Standing stocks of various size categories of benthic biota on the northern Sigsbee Abyssal Plain of the Gulf of Mexico. The JUSTO SIERRA and GYRE data are from a two-ship operation in 1997 by Texas A&M University and the Universidad Nationale Autonoma de Mexico at a common station at a depth of 3.65 km. ALAMINOS megafaunal numbers are from Pequegnat (1983); biomass was recently estimated based on preserved specimens from the "systematics working collection" at Texas A&M University. Values are means, with standard deviation and number of samples given where available.

| Parameter | Ship | | |
|---|---|---|---|
| | JUSTO SIERRA | GYRE | ALAMINOS |
| Bacterial numbers | NA | $6.9\text{x}10^8$ cells/mL<br>± $1.2\text{x}10^8$ (n=5) | NA |
| Bacterial biomass | NA | 406 mg $\text{C}\cdot\text{m}^{-2}$ | NA |
| Meiofaunal numbers | $288\text{x}10^3\cdot\text{m}^{-2}$<br>± $81\text{x}10^3$ (n=25) | NA | NA |
| Meiofaunal biomass | 83 mg $\text{C}\cdot\text{m}^{-2}$<br>± 22 (n=25) | NA | NA |
| Macrofaunal numbers | 1,281 $\text{ind}\cdot\text{m}^{-2}$<br>± 635 (n=5)<br>(125 μm sieve) | 318 $\text{ind}\cdot\text{m}^{-2}$<br>± 159 (n=5)<br>(macrofaunal taxa)<br>490 $\text{ind}\cdot\text{m}^{-2}$<br>± 147 (n=5)<br>(nematodes)<br>808 $\text{ind}\cdot\text{m}^{-2}$ (total)<br>(250 μm sieve) | NA |
| Macrofaunal biomass | 32.2 mg $\text{C}\cdot\text{m}^{-2}$<br>± 15.3 (n=5) | NA | NA |
| Megafaunal numbers | NA | NA | $10.5\cdot\text{ha}^{-1}$<br>*Dytaster insignis*<br>(seastar)<br>*Benthodytes typica*<br>(sea cucumber) |
| Megafaunal biomass | NA | NA | 0.15 mg $\text{C}\cdot\text{m}^{-2}$ |
| Scavengers | NA | 21 per 24 hour<br>trap deployment<br>*Eurythenes grillus*<br>(amphipod) | NA |
| Fishes | NA | NA | NA |

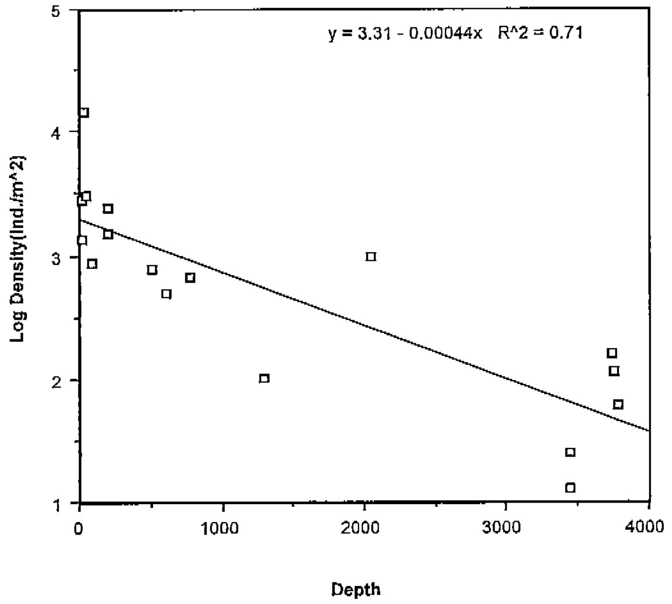

Figure 7.2. Density of macrofauna in the Gulf of Mexico (From: Rowe et al. 1974).

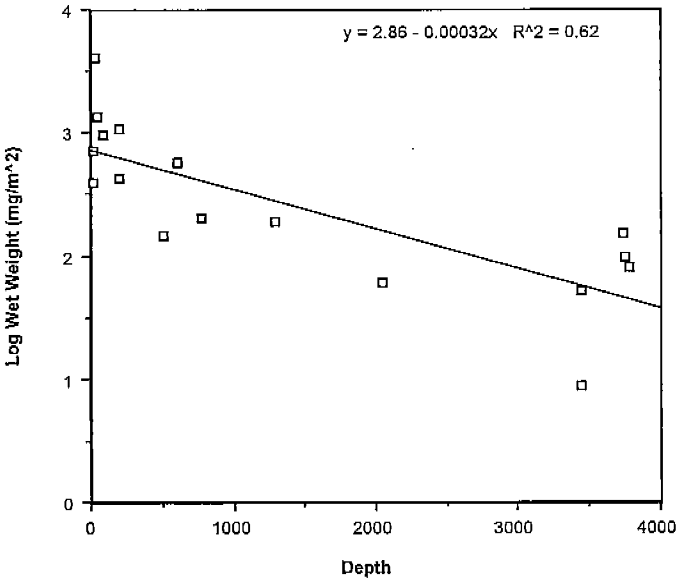

Figure 7.3. Biomass of the macrofauna in the Gulf of Mexico (From: Rowe et al. 1974).

Abundance values are a function of sieve size. The NGOMCS study used 300 micron sieves and the studies aboard JUSTO SIERRA used 125 micron sieves. It might be expected that they both sampled far more individuals per square meter than the earlier studies by Rowe, who used a 420 micron sieve. The values for the NGOMCS samples, however, ranged from 518 to 5,369 individuals$\cdot$m$^{-2}$, which is similar to that encountered by Escobar-Briones et al. (1999) in the southwestern Gulf and by Rowe et al. (1974) in the northern Gulf.

Regressions of biomass and abundance as a function of depth from the NGOMCS study (Gallaway et al. 1988b) follow:

$\text{Log}_{10}$ individuals$\cdot$m$^{-2}$ = 3.52 – 0.000109 (depth in meters), and

$\text{Log}_{10}$ micrograms wet weight$\cdot$m$^{-2}$ = 5.88 – 0.000227 (depth).

**Figure 7.1**, which shows polychaete densities at the NGOMCS stations, also illustrates this decline in abundance with depth (Hubbard 1995).

It has become clear that deep offshore abyssal plains in other oceans may have somewhat fewer organisms than the Sigsbee Deep, but they are at much greater depth (Glover et al. in press). The deep Gulf has on the order of 150 to 500 individuals$\cdot$m$^{-2}$, depending on sieve size, taxa included, and region studied. Escobar-Briones et al. (1999) for example suggested that the southern Gulf in the region of the Bay of Campeche had fewer macrofauna than the northern Gulf. They suggested that this was due to higher primary production that resulted from the interaction of warm eddies and shelf water.

**Diversity**. Macrofaunal diversity was studied extensively in the NGOMCS study. The general pattern was a decline in diversity from the upper slope down to the lower slope, as reviewed by Lohse (1999). She suggested, by comparison with other studies on the outer shelf, that a "diversity maximum" was located on the upper slope. This contradicts earlier work in other basins which suggested that a diversity maximum is routinely encountered at 2 to 3 km depth. Hubbard (1995) also utilized the polychaete annelid fraction of the NGOMCS study to assess Gulf diversity. The polychaete fraction was used because it was the most abundant taxon (65%) and he was confident that he could separate them at the species level.

The studies of diversity used several measures. The diversity index referred to as the Information Function, or H'(s), was calculated from the polychaete data because it is simple to use, relatively independent of sample size, and has been used in numerous other studies, including Gulf of Mexico benthos. Fragments were not included in the analysis. The equation used follows:

$$H'(s) = - \Sigma (\ln p_i \times p_i),$$

where p is the proportion of each species, i, to the total population sampled, i through n. Also, Hurlbert's (1971) revision of the Sanders "rarefaction" curve, or Expected Species (per 100 individuals), was calculated and plotted by Lohse, directly from the NGOMCS data reports, and by Hubbard from his own polychaete data.

In general, the Gulf slope macrofauna is very speciose. Dominants are few. Rare species are common. While shallow shelf studies in the Gulf typically encounter numerous individuals represented by 50 to 60 or so species, the slope data suggest that 100 or so species would be expected for a similar number of individuals. It has not yet been possible to compare the Gulf with other similar studies because of differences in technique.

There has been little attempt to uncover any seasonal variation in deep Gulf standing stocks or processes. Sets of samples along the central transect of the NGOMCS study were taken in spring and fall, which showed some change in animal abundances on the upper slope (**Figure 7.4**). Polychaete abundance was twice as high in spring than in two fall periods. Species composition did not appear to change, just densities. The best description of this is in Hubbard (1995).

### Megafauna

**Zonation**. Megafauna in the Gulf appears to occur in zones that are restricted to fairly predictable depth intervals (Pequegnat 1983; Pequegnat et al. 1990). These were designated 1) the Shelf/Slope Transition, down to about 500 m; 2) the Archibenthal Zone, Horizon A (500 to 775 m); 3) the Archibenthal Zone, Horizon B (800 to 1,000 m); 4) the Upper Abyssal Zone (1 to 2.3 km); 5) Meso-Abyssal Zone (2.3 to 3.2 km); and 6) Lower Abyssal Zone (3.2 to 3.8 km). These names were given earlier by Menzies et al. (1973) for similar zones encountered along several continental margins of the world oceans. In Pequegnat et al. (1990), percent similarities were presented of evidence that groups of fishes and megafauna in the region of the De Soto Canyon in the eastern Gulf occur in recurrent groups that could be considered zones. The rate of change in species composition of the bottom fishes also suggested that there are depth intervals that can be considered zones and other intervals that can be regarded as boundaries between zones. The authors mention the species that dominate each zone. Most of these can be found archived in the deep-sea systematic working collections at Texas A&M University. The predictability of zones such as this, regardless of what they are called, may be useful for understanding the effects of environmental variation, whether it is natural or the result of some alteration by human activities.

The deep Gulf summary by Pequegnat (1983) suggested that megafauna on the abyssal plain was substantially reduced in both numbers and species compared to the continental slope. The megafauna was dominated by the carnivorous sea star *Dytaster insignis* and the surficial deposit feeding sea cucumber *Benthodytes typica*. Both of these species had wide bathymetric distributions that extended well up onto the continental slope. Other, less abundant megafauna species also were observed with some regularity. This included the brittle star *Ophiomusium planum*, which reached high densities in isolated locations when encountered. Others observed were the sea cucumber *Psychropotes semperiana* and the penaeid crustacean *Benthesicymus cereus/iridescens*. A number of other large crustacean species were observed in these earlier studies, but it is not clear if they were associated with the bottom or were captured up in the water column (*Nematocarcinus ensifer*, for example). There was little evidence that many demersal fishes extended out onto the abyssal plain. Pequegnat (1983) suggested that the "terminal predator" on the abyssal plain was the sea star *D. insignis*; he inferred this because the predatory sea stars increased in abundance at depth intervals over which the demersal fishes were declining.

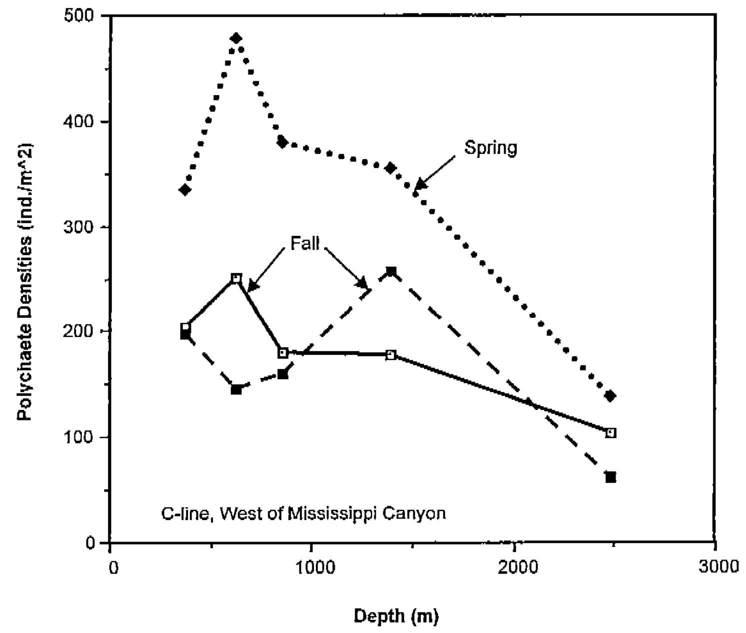

Figure 7.4. Comparison of polychaete densities at two different time periods on the upper slope of the northern Gulf of Mexico (Adapted from: Hubbard 1995).

**Abundance and Biomass**. The abundance of the dominant megafauna was estimated with two methods in the studies that Pequegnat (1983) has reviewed: multishot bottom photographic transects and use of the skimmer with an odometer wheel. The sea star *D. insignis*, according to Pequegnat, had mean densities of approximately 5 per hectare at depths of 3.6 km. *B. typica* reached similar values: from 4 to 7 individuals per hectare. Similar numbers were observed for the large crustaceans *B. cereus/iridescens*, *Nematocarcinus ensifer*, and the sea cucumber *P. semperiana*. It is not clear, however, if the crustaceans were caught on the bottom or in the water column; therefore, they have been left out of the assessment of total benthic standing stocks.

Biomass was not measured in these earlier studies. However, many of the specimens are archived in a "systematics working collection" originally established by Willis and Linda Pequegnat on the Texas A&M University campus. This enabled our review to find a representative number of the dominants, *B. typica* and *D. insignis*, and determine their mean biomass on preserved specimens approximately 30 years after they were captured. The *D. insignis* were dried specimens. They had a mean dry weight of 2.88 g per individual ($\sigma$=2.2, n=11). Mean disk diameter was 23.3 mm ($\sigma$=9, n=11). The holothurian *B. typica* individuals have been preserved in 70% ethanol and they were measured wet: mean=4.04 grams per individual ($\sigma$=1.4, n=13). They had a mean length of 6.6 cm ($\sigma$=1.1, n=13) and a diameter of 1.7 cm ($\sigma$=0.35, n=13). Thus, the sea star had a mean dry weight of 14.4 g per hectare and the holothurian had a mean wet weight of 22.2 g per hectare. The latter value would be equivalent to approx. 3.3 g per hectare dry weight (Rowe 1983). The two together would be equivalent to approximately $1.77 \times 10^{-3}$ g dry weight·m$^{-2}$.

Some megafauna are distributed in peculiar patches. The most consistent such animal patches in the Gulf appear to be the contagious distribution of the holothuroid *Peniagone* sp. These were rarely taken in trawls, but occurred as clumps of dozens of individuals in photographs, in the photographic surveys made in the NGOMCS study. The highest densities at a lowering were $1.6 \times 10^5$ per hectare at a depth of 1.25 km. The reasons for the patchiness are not known. Other patches have been attributed to the proximity to fossil hydrocarbon seeps. Odd "reefs" of sponges are seen occasionally, but the causes of these accumulations are not known. Densities estimated with photography were always far higher than that estimated with the trawls.

### Motile Scavengers

Little is known about deep-living scavengers in the GOM. On several occasions, baited traps have been used to capture organisms. None of the information in these studies has been published however. In the 1997 Texas A&M University/UNAM studies with GYRE and JUSTO SIERRA, a deep baited trap was deployed and a single species was captured: the cosmopolitan amphipod crustacean *Eurythenes grillus*. The numbers taken, however, appeared to be small (21 per 24 hour deployment) compared to similar trap deployments in other ocean basins. The significance of this group needs further study in the deep Gulf.

### Community Metabolism

Sediment oxygen consumption has been measured at a single site on the deep abyssal plain in the eastern Gulf, and the rate measured was equivalent to approximately 6.7 mg C·m$^{-2}$·d$^{-1}$ (Hinga et al. 1979). On the Sigsbee Abyssal Plain, an unpublished value of 4.1 mg C·m$^{-2}$·d$^{-1}$ was measured. At this time it is impossible to know if this difference is real or simply due to a difference in gear used. In any case, the two values are not remarkably different from values at similar depths and temperatures elsewhere in the world's oceans. Values listed by Smith and Hinga (1983) for this depth range go from 2.6 to 25 mg C·m$^{-2}$·d$^{-1}$, and so our rate falls at the low end of the range.

## Community Function – The Cycling of Organic Carbon

The information on the stock sizes and respiration rates of the biota have been put together into a carbon budget for the slope and abyssal plain (**Figure 7.5**; Rowe et al. 2000) based in part on previous work by Cruz-Kaegi (1998). A budget of this sort allows a comparison of how carbon is both stored and cycled within an ecosystem. Values for the boxes are standing stocks in units of mg C·m$^{-2}$, integrated to a depth of 20 cm, whereas the arrows are fluxes of carbon between the boxes, with units of mg C·m$^{-2}$·d$^{-1}$. The arrow at the upper left represents inputs of organic carbon to the system whereas the arrows that do not enter a box are losses of organic carbon from the system. Most of the

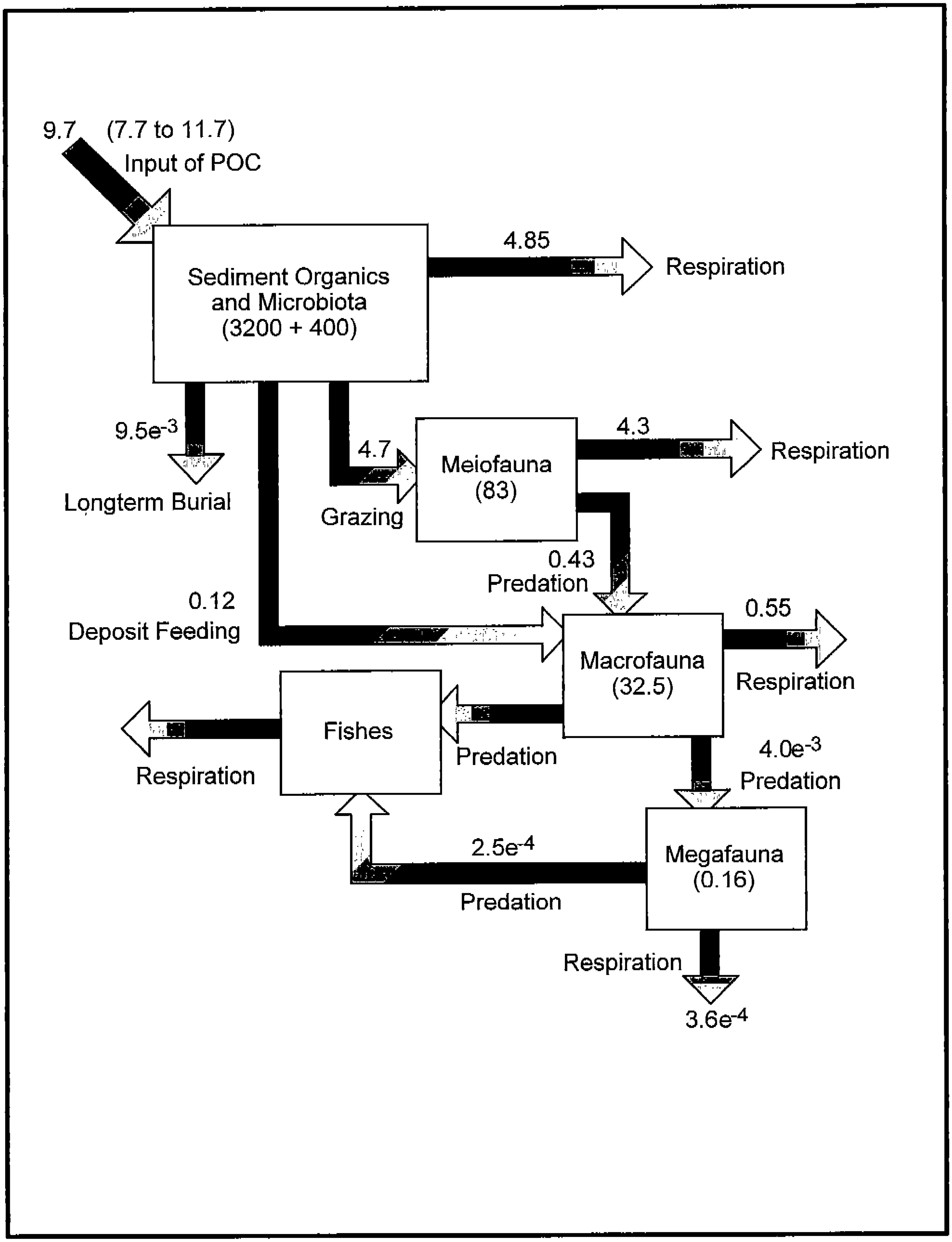

Figure 7.5. Preliminary carbon flow model for the deepsea benthos of the northern Gulf of Mexico (From: Rowe et al. 2000). Values in boxes are standing stocks of organic carbon in mg C·m-2, integrated to a depth of 20 cm. Arrows represent fluxes, with values expressed in mg C·m-2·d-1.

losses are the remineralization of organic matter to $CO_2$. The input term, in this case, is estimated from the sum of the respiration loss terms by the community, plus long-term burial. An independent estimate of input can also be derived from measures of primary productivity in the overlying water and then applying the "Suess relationship" (Suess 1980) to estimate arrival of particulate matter at the seafloor. We assume the input varied by a factor of two or so over an annual cycle, with the highest productivity occurring during the winter when the phytoplankton biomass is highest (Muller-Karger et al. 1991).

Most of the loss terms are respiration. Respiration remineralizes organic carbon to metabolic $CO_2$. It is the largest consumer of organics in any typical benthic community and it can be estimated from oxygen fluxes. The sum of the aerobic respiration by the sediment dwelling organisms (bacteria, meiofauna and macrofauna) is equal to the value measured with the incubation chambers. This can be converted to carbon by assuming a respiratory quotient (RQ) of 0.85 (moles of $CO_2$ produced per moles of $O_2$ consumed).

The respiration of the individual groups was estimated by Cruz-Kaegi (1998) independently from known size and temperature relationships in the literature (Mahaut et al. 1995). The regression produced by Mahaut et al. (1995) relating size and respiration rates was used to calculate a first-order respiration coefficient for the mean size of each size groups.

The estimates of respiration for each size category allow us to further partition the flow of organic matter through the food web. The sum of the arrows entering each standing stock must equal the sum of the arrows leaving each stock, for the system to be in steady state. Given the information generated on the respiration rates of each of the components above, we can then calculate exchanges between the boxes to maintain steady state. This is a step-wise analysis that has been utilized previously on benthos over a broad range of latitudes (Cruz-Kaegi 1998), in addition to the Demerara Abyssal Plain (Rowe and Deming 1985) and the continental margin off NE Greenland (Rowe et al. 1998). The resulting solutions for the predator-prey relationships are not always unique. As indicated, they are based on reasonable inferences of how the size classes are most probably partitioning their resources.

Cruz-Kaegi's (1998) relationships are close to several of the measurements described in Relexans et al. (1996). A value for bacterial efficiency that is high tends to "conserve" carbon within the system, rather than burning it off as metabolic $CO_2$. The production of the bacteria must be held in check by bactivory to maintain steady state and this has been directed primarily into the meiofauna, with a small fraction into the macrofauna. It was assumed the meiofauna had a 10% growth efficiency and thus the loss terms are respiration and predation by macrofauna, as indicated. The total meiofauna demand must therefore be met by bactivory and direct sediment consumption. Macrofauna fluxes are calculated in a similar fashion.

The megafauna was assumed to be growing at a very slow rate and this is transferred by predation to the fishes. Fish growth is assumed to be zero; thus, the megafauna growth rate is equal to fish respiration.

The standing stock of the organic matter was calculated from the concentration of organic carbon (0.6%), the porosity (85%), and the density of the sediment. Thus, organic carbon in the surface 5 cm of sediment is 3,600 mg $C \cdot m^{-2}$. The burial rate was estimated from long-term burial rates (William R. Bryant, pers. comm.), as follows. Approximately 1 to 2 m of Holocene pelagic sediments, composed primarily of foram ooze, are spread rather uniformly over the entire Sigsbee Deep. On the continental margins, the thickness of the Holocene material is 3 to 4 m deep. Thus, the rate of accumulation on geologic time scales are ca. 100 to 200 cm per 13,000 years; at the time scales of our budget this is ca. 0.015 $cm \cdot y^{-1}$. Multiplying this by the concentration in a 1 cm thick layer (225 mg $C \cdot m^{-2}$) gives a burial rate of ca. 3.5 mg $C \cdot m^{-2} \cdot y^{-1}$, or 0.0095 mg $C \cdot m^{-2} \cdot d^{-1}$, the appropriate units in the budget. This value is comparable to the low flux rates estimated for the larger sized groups of organisms (megafauna and fishes).

## Comparison of the Gulf Benthos with Other Oceans

The standing stocks of the principal components of the benthic community have been measured together for the first time at a site in the Sigsbee Deep in the northwest GOM (Rowe et al. 2000). The relationship of bacteria numbers in abyssal sediments from the limited data available for the world's oceans has been regressed on depth, organic carbon concentrations, and particulate organic carbon (POC) fluxes to the seafloor by Deming and Baross (1990). They found that the best predictor of $\log_{10}$ total bacterial biomass was $\log_{10}$POC fluxes. If we assume that our "input" term in our budget, estimated from the sum of the measured or estimated carbon demand, is equal to the POC fluxes measured in sediment traps in their study, then we can use this term in their regression. Our value for biomass (408 mg $C \cdot m^{-2}$-20 cm depth) suggests, based on their regression, that the POC flux should be on the order of 24 mg $C \cdot m^{-2}$ $d^{-1}$.

The abundance and biomass of the macrofauna was somewhat higher than previously estimated in the southern GOM (Rowe and Menzel 1971). Escobar-Briones et al. (1999) made comparisons with several similar ocean basins and noted that abundances were higher in the northern Gulf than in the Bay of Campeche. We suggest that this area experiences intensified surface primary production that results from the interaction of warm eddies (Muller-Karger et al. 1991). The differences with the measurements in the southern Gulf presented by Rowe and Menzel (1971) may be due to gear: the earlier studies used a semi-quantitative anchor dredge and not a spade or box corer.

The biomass of the macrofauna in the Sigsbee Deep was not statistically separable from a general mean for the "global" ocean at a depth of 3.7 km, based on more than 700 values measured with a wide variety of sampling gear (Rowe 1983). A regression of $\log_{10}$ biomass as wet preserved weight as a function of depth in meters suggests that biomass at 3.7 km depth at the deep end of the Gulf regression line would be expected to be approximately 0.64 $g \cdot m^{-2}$.

A fair number of trawls have been taken across extensive areas of the continental margin in both the northwest Atlantic (Haedrich and Rowe 1977; Haedrich et al. 1980), and the northeast Atlantic (Lampitt et al. 1986), thus making it possible to compare densities and biomass of megafauna and fishes with the Gulf. Lampitt et al. (1986) plotted $\log_{10}$ biomass of total invertebrate megafauna as a function of depth in the northeast Atlantic near the Porcupine Bight. Their regression line predicts that 0.31 g wet weight$\cdot m^{-2}$ should be encountered at 3.7 km depth. Haedrich et al. (1980) measured a wet preserved weight of approximately 0.08 $g \cdot m^{-2}$ of fishes and 0.05 $g \cdot m^{-2}$ of megafaunal invertebrates (echinoderms and crustaceans) between depths of 3.2 and 3.7 km, suggesting that the abundance and biomass of these groups is lower than in the Porcupine Bight of the northeast Atlantic. The lower value above is higher than we have estimated for similar depths in the Gulf (0.006 g wet preserved weight $m^{-2}$= approximately 0.155 $mg \cdot C\ m^{-2}$); thus, compared to the Atlantic, the deep Gulf megafauna appears to be relatively depauperate. The extensive data from both the east and west sides of the North Atlantic had ranges of as much as three orders of magnitude at any given depth.

The diversity of the polychaete fraction confirms that the Gulf of Mexico harbors a diverse fauna, as is typical for much of the deep-sea floor (Rex 1983). The numbers of species, H'(s) and the expected number of species per hundred individuals however are rather low compared to values on the upper continental slope and outer continental shelf (Lohse 1999). This pattern relative to depth is different from that in other basins: maximum diversity, regardless of "index" used, is found on the lower slope or the upper rise. The values we encountered were somewhat lower than that in other basins. Thus, a preliminary conclusion is that the pattern in the Gulf is different from most basins, with maximum diversities at the shallower depths of the upper slope and outer shelf (100 to 1,000 m), rather than at the slope base (2 to 3 km), as described by Rex (1983). The apparent decline with depth might be due to the limiting sill depth, the variability of the deepwater environment (seeps from fossil hydrocarbons buried deep in the sediments, temperature variations due to warm eddies originating in the Loop Current in the eastern Gulf, nepheloid layers associated originally with the Mississippi River, sediment slumps and turbidity flows), or inadequate sample size. The latter artifact cannot be discounted because we continued to add equal numbers of previously unencountered species with each additional box core, thus suggesting that many more species were present than we had actually sampled. This question can only be answered by more intense sampling.

The abyssal plain of the Gulf differs from those in the major ocean basins because it is shallower (3.6 to 3.8 km) and warmer (4.2°C). Thus, one might expect that the characteristics of communities of organisms might differ from "typical" oceanic abyssal plains.

## Conclusions

The study of the deep benthos of the Gulf of Mexico can be divided into three eras. Early studies prior to the 19th century were exploratory zoogeographic investigations. In the 1960's Willis Pequegnat initiated modern investigations of the standing stocks of the megafauna. In the 1980's the MMS supported an investigation of the continental slope that encompassed state-of-the-art quantitative sampling of the meiofauna, macrofauna, and megafauna.

Metazoan biomass is dominated by the meiofauna. The Eastern Gulf is not similar in species composition to the Western Gulf and this can attributed to a difference in substrate. The Western Gulf sediments are terrigenous whereas the Eastern Gulf substrate is carbonate. Faunal diversity of the macrofauna is high but it is not characterized by a mid-depth maximum. The low biomass of the macrofauna and the megafauna suggest that the biota is food limited. Budgets of carbon cycling on the slope suggest that most of the organic matter is cycled through the smaller animals of the communities.

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# Chapter 8: Seep Communities

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## Introduction

This is a review of publications relevant to the so-called seep fauna of the northern Gulf of Mexico. The objective is to provide the best citations for the most pertinent facts. Peer-reviewed articles are given priority where available, unless an important sequence in the knowledge base is captured by reference to reports or other secondary literature. Reports and dissertations are cited when nothing has yet been published in peer-review sources. Personal communications are avoided. An initial discussion of background biology mentions the seep fauna analogues at hydrothermal vents. This material is provided without any attempt to give comprehensive citation. The reader needing wider information on chemosynthetic fauna at hydrothermal vents should consult reviews by Tunnicliffe et al. (1998) for distribution and ecology or Nelson and Fisher (1995) for physiology and symbiont-host interaction. Nor does this discussion treat the worldwide occurrence and attributes of seep fauna outside the Gulf of Mexico. A recent review by Sibuet and Olu (1998) provides a reliable starting point for the cold seep literature.

# Background Biology

## Microbiology of Chemosynthesis

Chemosynthesis is a mode of life practiced by numerous groups of bacteria, which are able to oxidize simple compounds such as hydrogen sulfide ($H_2S$) and methane ($CH_4$) (Jannasch 1989). The sulfide-oxidizing forms use energy released by the oxidation process to drive the cellular machinery of carbon fixation. These bacteria produce carbohydrates, proteins, and other complex organic compounds starting with the basic building blocks of nutrients and water. Like photosynthetic plants, chemosynthetic bacteria are thus able to form new organic compounds at the base of the food chain.

Ecologically, chemosynthetic bacteria differ from green plants because they do not need light and do require free oxygen. In their free-living forms, chemosynthetic bacteria are found where a substrate is enriched with $H_2S$ or $CH_4$. Such conditions often occur in the anaerobic sediments of marshes or sewage treatment ponds where the decomposition of organic matter produces these chemically reduced compounds in abundance. Because they require the means for oxidizing their chemical nutrient source, chemosynthetic bacteria typically live at the interface between reduced sediments and oxygenated water (Nelson et al. 1986). A common form is *Beggiatoa*, which lives in long filaments that form pale-colored mats on sediment surfaces (Larkin et al. 1994; Nikolaus 1995). In shallow aquatic habitats, chemosynthetic bacteria are one component of complex systems comprising numerous pathways for producing and recycling organic matter.

Below the photic zone—in depths of 300 m or more—photosynthesis is no longer possible and nutrient limits sharply constrain the possibilities for community structure. Where seepage of hydrocarbons, venting of hydrothermal fluids, or other geological processes supply abundant reduced compounds, chemosynthesis becomes the dominant component of the ecosystem. In the northern Gulf of Mexico, these conditions are met where oil and gas seep into seafloor sediments at depths of ~400 m and greater. Although chemosynthesis remains an exclusively microbial process at the cellular level, chemosynthetic communities in the deep sea achieve prominence because of symbiotic partnership between chemosynthetic bacteria and invertebrate hosts (Fisher 1990).

## Symbiosis with Invertebrates

Free-living chemosynthetic bacteria are limited to interfaces because they simultaneously require oxygen *and* reduced compounds that would spontaneously oxidize in the presence of oxygen. Symbiotic partnership with invertebrate hosts greatly extends the possible habitat for the chemosynthetic mode of life (Tunnicliffe et al. 1998). Specific adaptations vary, but the basic arrangement is that the bacteria live within specialized cells in the host organism. The host physiology supplies oxygen and chemosynthetic substrates to the bacteria, often by means of specialized blood chemistry (Arp et al. 1984, 1987), and exploits the resulting bacterial productivity (Nelson and Fisher 1995).

## Discoveries of Chemosynthetic Communities

### Hydrothermal Vents

Awareness of chemosynthetic communities in the Gulf of Mexico came in a series of steps. The initial recognition that certain locations in the seafloor might harbor dense assemblages of invertebrates occurred in 1977, when anomalous concentrations of clam shells were photographed in the vicinity of hydrothermal vents in the eastern Pacific Ocean (Lonsdale 1977). The connection between chemical enrichment and this fauna was not made until Submarine ALVIN visited the area (Corliss et al. 1979) and discovered assemblages of vestimentiferan tube worms, *Riftia pachyptila*, which were unknown to science; the vent mussel, *Bathymodiolus thermophilis*; and a clam, *Calyptogena magnifica*. Interestingly, chemosynthetic tube worms, *Lamellibrachia barhami*, had already been described as a new species, but without recognition of their nutritional mode (Webb 1969). *Aceata bullisi*, a bivalve commonly associated with Gulf of Mexico tube worms, had also been described from material undoubtedly collected at an oil seep (Volkes 1963; Kohl and Vokes 1994). The importance of chemoautotrophic symbionts for these species was not elucidated until 2 years later (Cavanaugh et al. 1981; Felbeck et al. 1981).

### The Florida Escarpment

Because the Gulf of Mexico is not a tectonically active region and lacks hydrothermal venting, chemosynthetic fauna were not anticipated here. Another ALVIN cruise, this time to the base of the Florida Escarpment in the eastern Gulf, unexpectedly found vestimentiferans and *Bathymodiolus*-like mussels at so-called cold seeps near the location 26°02'N and 84°55'W and at a water depth of approximately 3,200 m (Paull et al. 1984; Hecker 1985). This site is a continental margin brine seep, also called a cold seep, where brines formed by dissolution of the limestone Florida Platform seep out into hemipelagic sediments at the base of the Florida Escarpment (Paull and Neumann 1987). The brines are enriched in sulfides and the stable isotope signature of the source fluid can be seen in the tissue of the chemosynthetic fauna (Paull et al. 1985). The vestimentiferans and their symbionts depend upon this sulfide source (Cavanaugh 1985; Cary et al. 1989), but it would be shown that the mussels possessed methylotrophic symbionts (Cavanaugh et al. 1987) that could be supported by methane dissolved in the brine. Because of its depth, the Florida Escarpment site can only be sampled with ALVIN, so the site has not been well sampled and was last visited during two dives in June 1992. The reader can review summaries of ALVIN dives in the Gulf of Mexico via the URL http://www.marine.whoi.edu/webpub/divelog/default.htm.

### The Northern Gulf of Mexico Continental Slope

Concurrent with discoveries on the Florida Escarpment, chemosynthetic fauna were found at hydrocarbon seeps on the northern Gulf of Mexico continental slope. The initial discovery came as a result of sampling by otter trawl, which targeted several known oil seeps (Kennicutt et al. 1985). The trawl recovered vesicomyid clams (*Calyptogena ponderosa* and *Vesicomya cordata*), a new species of mussel, *Bathymodiolus childressi*, and two still undescribed vestimentiferan species *Lamellibrachia* n. sp. c.f. *barhami*

Webb, and *Escarpia* n. sp. The first photographic evidence of these communities (Boland 1986) was obtained in the course of a research program sponsored by MMS (Gallaway 1988), which also sponsored the first submarine dives to Gulf of Mexico hydrocarbon seeps. These species and their associated benthic communities will be discussed in more detail below. Additional findings about hydrocarbon seep communities that were published during the initial discovery phase included the following: 1) demonstration that these fauna derived their nutritional requirements from hydrocarbons (Brooks et al. 1987); 2) demonstration of methanotrophy by the seep mussel (Childress et al. 1986); 3) recognition of the association of the fauna with specific seep attributes (Kennicutt et al. 1988a); and 4) the first submarine dives to visit a seep community (MacDonald et al. 1989).

## The Gulf of Mexico Seep Fauna

The following four sections provide a synopsis for each of the major invertebrate groups that live at fluid seeps and that host chemoautotrophic symbionts.

### Vestimentiferan Tube Worms

These unusual worms lack mouth, gut, and anus and were originally assigned to a new phylum, Vestimentifera (Jones 1985). Subsequently the vestimentiferan group has been re-understood as highly adapted polychaetes (Southward 1991). Vestimentiferans include the first tube worm species discovered at hydrothermal vents, *Riftia pachyptila* (Jones 1980), but are related to the Pogonophora, a group of small, thin tube worms that have a cosmopolitan distribution on reducing sediments (Southward and Southward 1987). All vestimentiferans occupy a tube composed of β-chitin (Gaill et al. 1992) and possess blood containing a unique hemoglobin that is capable of simultaneously and reversibly binding oxygen and sulfide; the latter is normally a powerful toxin (Arp et al. 1987). Vestimentiferan anatomy features a vascularized plume (red in color), which is the gas-exchange organ, that extends prominently from the anterior tube-end, and can be retracted in defense (Gardiner and Jones 1993). Additionally, a sac-like organ called the trophosome extends within the tube and harbors chemoautotrophic bacteria, which live in specialized host-cells (Nelson and Fisher 1995).

Two species are common in the Gulf of Mexico: *Lamellibrachia* n. sp. cf. *barhami* Webb and *Escarpia* n. sp. The life-mode of Gulf of Mexico tube worms was first described by MacDonald et al. (1989), who write that *Lamellibrachia* is the larger animal and forms bush-like clusters of several hundred individuals, typically 1 cm in diameter and often 2 m long. The tube is often held 1 m or more above the seafloor. **Figure 8.1** shows clusters of tube worms at a mid-slope seep site. *Escarpia* are smaller in total length and often live at the base of *Lamellibrachia* clusters. They are distinguished by a short, flared tube extended 10 to 15 cm above the sediment. Gulf of Mexico tube worms possess symbionts that utilize $H_2S$, which the tube worm absorbs from fine root-like structures that extend below the buried portions of the tubes (Julian et al. 1999). This is clearly an adaptation to life in a sedimentary environment, where sulfidic fluids are not venting vigorously, as they do at hydrothermal vents, but are instead dissolved in the pore volume of the upper sediment column. Buried tube length may be as much as 30% of total length. These animals grow at rates typically less than 1 $cm \cdot y^{-1}$, so that a large adult may

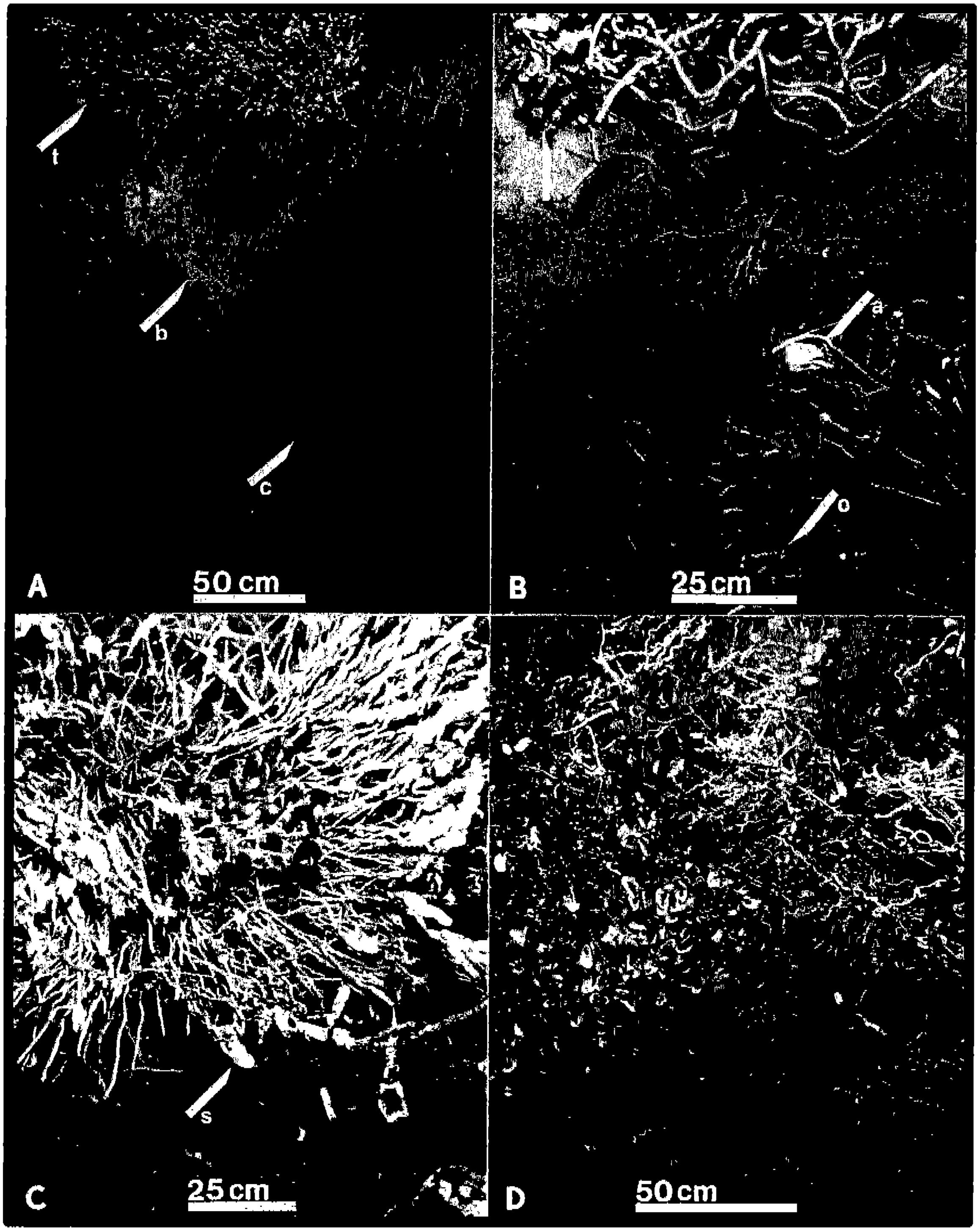

Figure 8.1. Photographs taken with vertically-mounted 35 mm camera (Figure 3 from MacDonald et al. 1989). A: Bush-like clusters of *Lamellibrachia* sp. (t), carbonate boulder (c), and bacterial mat (b). B: Small tangle of *Lamellibrachia* sp. with attached *Acesta bullisi* (a), obturacular plume of *Lamellibrachia* sp. (o), and an escarpiid vestimentiferan (e). C: Basket-like cluster of *Lamellibrachia* sp. with seep mussels in center, epifaunal sponge (s). D: Transition between a bed of seep mussels and sparse clusters of *Lamellibrachia* sp.; note dead mussel shells.

be 200+ years old. A single large cluster marks a location where hydrocarbon seepage has continued unabated for several hundred years or more (Fisher et al. 1997). Larvae of *Lamellibrachia* n. sp. and *Escarpia* n. sp. have been cultured *in-vitro* from fertilized eggs (Young et al. 1996), and were shown to be strong swimmers during a 2 to 3 week larval phase. This is interpreted as an adaptation to finding active seep habitats for settlement.

## Seep Mussels

Members of the mytilid genus *Bathymodiolus* harbor symbionts in specialized cells within their gill linings, but retain functional feeding grooves and a gut (Fisher et al. 1988b, 1992). The vent mussel, *B. thermophilus*, maintains symbionts that oxidize thiosulfate (Nelson and Fisher 1995). A key discovery in the history of the Gulf of Mexico seeps was that the seep mussel, *B. childressi*, possesses methanotrophic symbionts (Childress et al. 1986). Subsequently, other species of seep mussels were shown to possess both methane-oxydizing and sulfide-oxidizing symbionts (Fisher et al. 1992). An early experiment demonstrated that growth of juvenile *B. childressi* could be turned on or off by regulating the supply of gas to experimental specimens, effectively proving that the animal is able to supply its entire energy and carbon requirements from methane (Cary et al. 1988). Methane and oxygen are supplied to the symbionts through the ventilation of the gills (Nix et al. 1995). Because the requirement is for dissolved $CH_4$, seep mussels are restricted to locations where $CH_4$ concentrations are high, for example near active gas vents, as first described by MacDonald et al. (1989), but dissolved $CH_4$ can also be supplied in seafloor brines (MacDonald et al. 1990a,b). At such sites, mussels may completely cover the seafloor in mats that are bound together by byssal threads and extend for tens of meters or more. The maximum length of an adult is 12 to 13 cm. The growth rates are slow, with juveniles requiring possibly 20 years to reach maturity and large adults frequently surviving 40 years (Nix et al. 1995).

Taxonomy of Gulf of Mexico seep mussels was resolved by Gustafson et al. (1998), who described five new species. **Table 8.1** summarizes the names and pertinent aspects of these species. **Figure 8.2** shows outlines and relative sizes of these species.

Table 8.1. Summary of taxonomic designations of seep mussels from the northern Gulf of Mexico taken from original descriptions in Gustafson et al. (1998).

| Name | Locality | Comment |
|---|---|---|
| *Bathymodiolus brooksi* | Alaminos Canyon (2,250 m depth) | Possesses sulfide-oxidizing symbionts |
| *Bathymodiolus childressi* | Mid-slope hydrocarbon seeps | Common seep mussel |
| *Bathymodiolus heckerae* | Florida Escarpment | Methylotrophic symbionts |
| *Idas macdonaldi* | Single collection from GB386 | Found in coarse, oil-soaked sediment |
| *Tamu fisheri* | Mid-slope hydrocarbon seeps | Possesses sulfide-oxidizing symbionts |

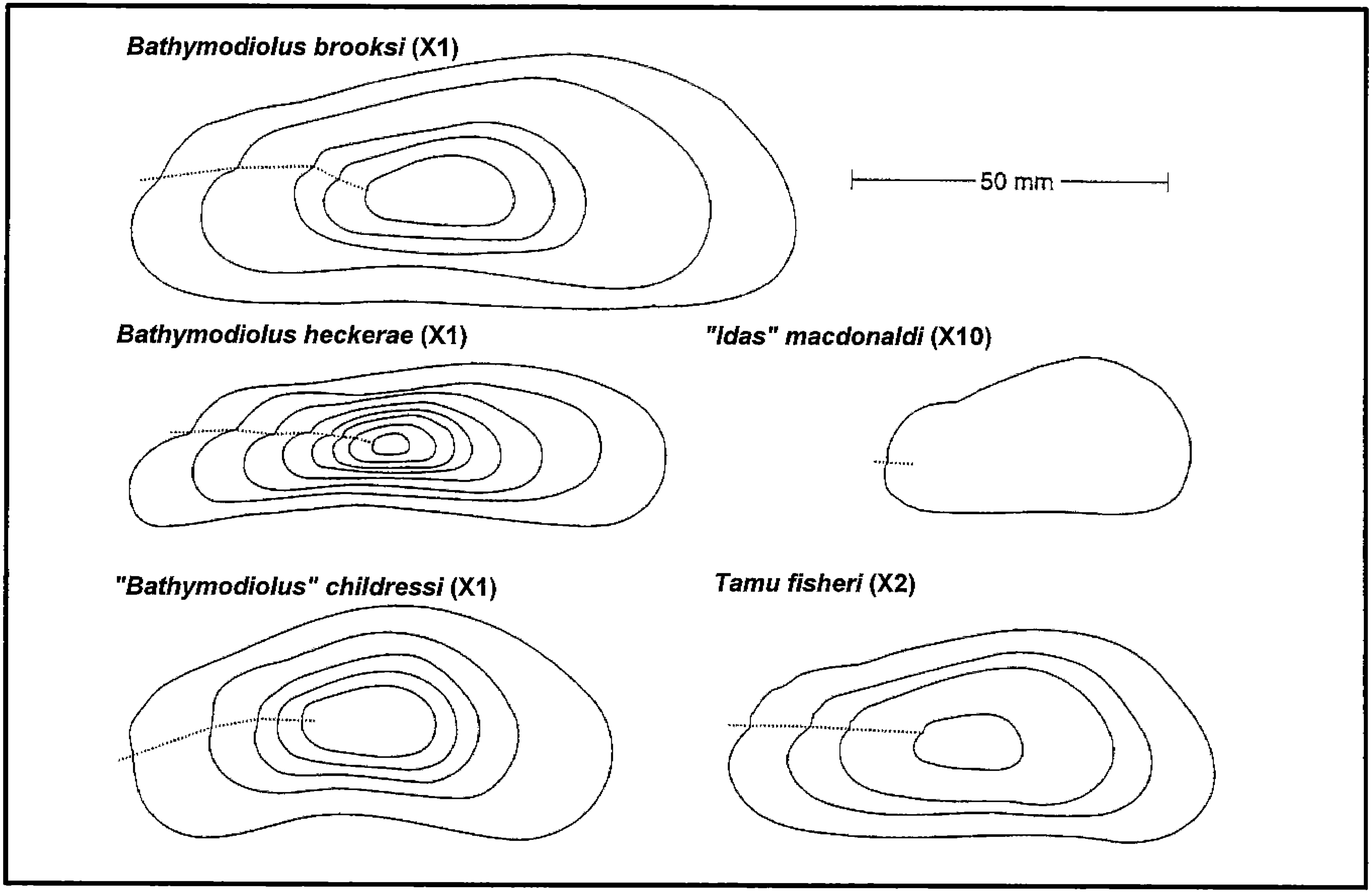

Figure 8.2. *Bathymodiolus heckerae, B. brooksi, B. childressi, Tamu fisheri, and Idas macdonaldi* (Figure 11 from Gustafson et al. 1998). Inset of a graded series of shell outlines illustrating change in shape with increase in size. Only one specimen of "*Idas*" *macdonaldi* is illustrated. Dottend lines connect the relative positions of the anterior edge of the umbones in specimens of different size. Note scale bar and magnifications.

## Vesicomyid Clams

The family Vesicomyidae is found in deep-sea settings worldwide. The species *Calyptogena magnifica* was among the specimens collected during the discovery dives at the Galopágos Rift (Boss and Turner 1980). The two species known from the Gulf of Mexico are *Calyptogena ponderosa* and *Vesicomya cordata,* which were originally described from material collected in the Gulf of Darien, Caribbean Sea (Boss 1968). These are surface-dwelling bivalves that plow long, curving furrows across the seafloor (Rosman et al. 1987). These "trails" and the accumulation of shell debris are distinctive features marking active seeps on the mid-slope (**Figure 8.3**). Most of what is known about vesicomyids comes from study of specimens at hydrothermal vents or cold seeps (Ohta et al. 1987) in other regions of the world. In the basic feeding mode, the foot is thrust forward and down into an anoxic substratum while the siphon is extended into the bottom water with the exposed portion of the shell (Hessler et al. 1985; Fisher et al. 1988a; Hessler and Kaharl 1995). This allows that animal to absorb $H_2S$ across the foot epithelium, from where it is transported to symbiont-lined gills via specialized blood chemistry (Arp et al. 1984). Adult vesicomyids from the Gulf of Mexico are 75 to 90 cm long, and have a deep, heavy shell, which is frequently stained by exposure to anoxic sediment (Fisher 1990). Nothing is known of the growth rates, but deep-sea bivalves are typically long-lived. Accumulations of dead shells with clusters of live individuals suggest persistent occupation of active seep sites (Rosman et al. 1987; Callender and Powell 1997). These aggregations have been found on the flow-fields where expulsion of oil-rich mud generates shallow anoxic layers (Lee 1995).

## Lucinid Clams

These are probably the most widely-distributed chemosynthetic invertebrates in the Gulf of Mexico (Powell et al. 1998). However, due to an infaunal habit, living adults are almost never seen in photo-surveys (MacDonald and Schroeder 1993), whereas accumulations of dead shells are common in and near seeps (Callender and Powell 1992). As with the vesicomyids, information on life-history comes primarily from work done outside the Gulf of Mexico. These animals live in deep, U-shaped burrows and manipulate the oxygen tension in their burrows by moving up and down in the passage to the surface (Fisher 1990). Common species in the Gulf of Mexico are *Lucinoma atlantis* and *Thiasira oleophila* (Callender and Powell 1997). The chalky shells are subcircular, shallow, and have a small but distinct beak at the hinge. Symbionts live in enlarged gills and utilize $H_2S$ (Dando et al. 1986). The stable carbon isotope signatures of *L. atlantis* are the best data supporting a chemoautotrophic nutritional source (Brooks et al. 1987). Growth rates and life-spans are unknown, although Powell et al. (1998) believe lucinids to be slow-growing.

## Polychaete "Ice Worms"

This polychaete, *Hesiocaeca methanicola,* received attention in the press following its discovery in 1997, but relatively little is published about its life history or ecology (Desbruyeres and Toulmond 1998). The worm inhabits shallow burrows on the surface

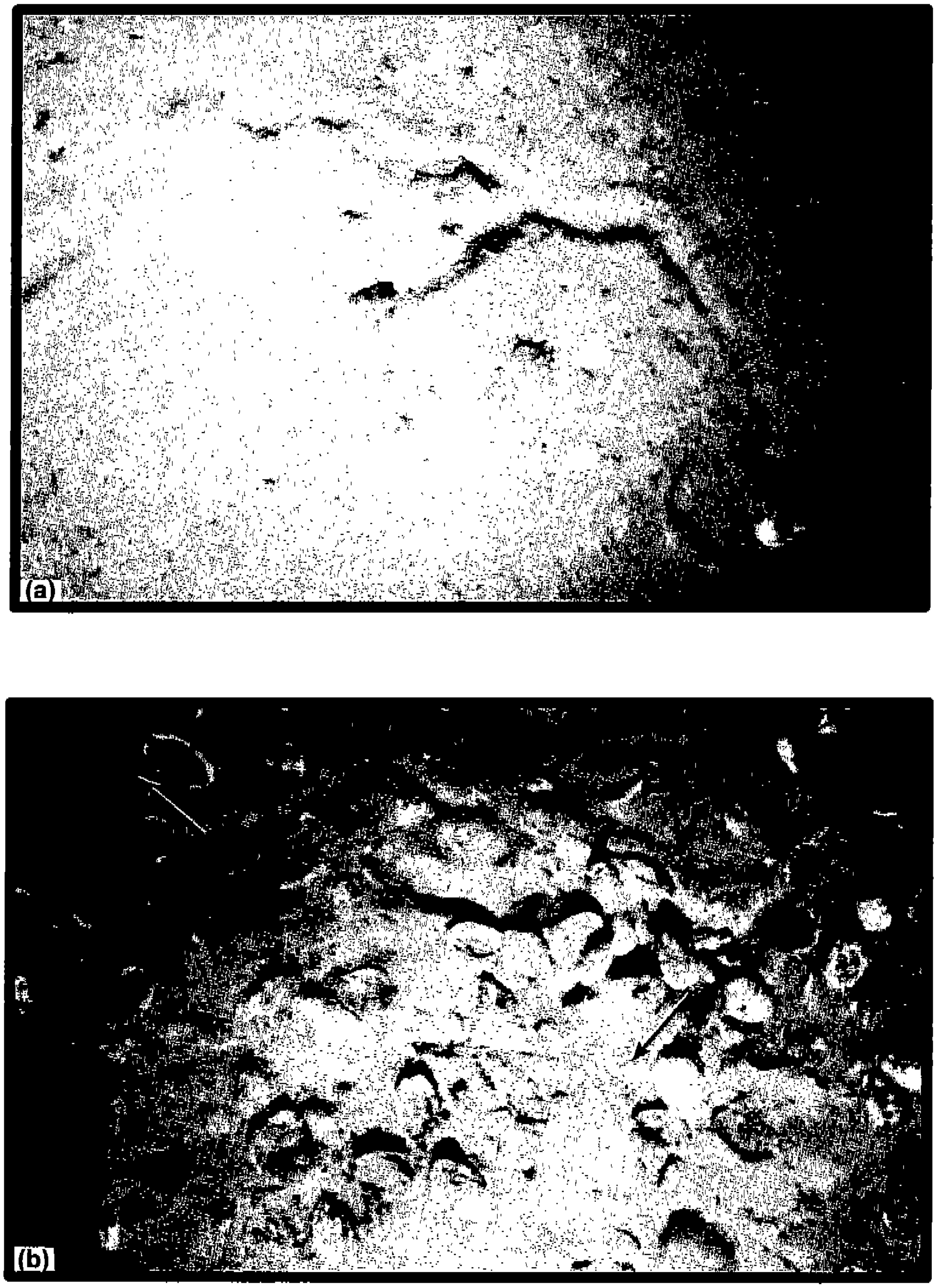

Figure 8.3. Photographs of the two types of trails observed in the aggregations of vesicomyids (Figure 3 from Rosman et al. 1987). The upper frame shows a vesicomyid in characteristic plowing position and its vee-shaped, curving trail. The lower frame shows the faint surface trails formed by a second trail-making organism that occurred in the aggregations (arrows). Only trails similar to those in the upper frame were included in the analyses.

of shallow gas hydrate deposits. It does not possess chemosynthetic symbionts, but the stable carbon isotope ratios of its tissue are consistent with a diet derived from chemosynthetic production (Fisher et al., in press).

## *Beggiatoa* Mats and Other Protozoans

Colonies of the free-living autotrophic bacteria *Beggiatoa* are found on reducing sediments in freshwater and marine environments (Nelson et al. 1986). The cells are vacuolated and inhabit large filaments (Larkin and Strohl 1983). Cell vacuoles function as storage compartments for nitrate; functionally, *Beggiatoa* migrate vertically between the sediment-water interface and as deep as 10 cm into anoxic sediments, using nitrate as an electron acceptor for the oxidation of hydrogen sulfide (McHatton et al. 1996). At Gulf of Mexico hydrocarbon seeps, *Beggiatoa* form mat-like colonies that extend for several meters in some cases (MacDonald et al. 1989; Larkin et al. 1994). Zonation in the mats is closely linked to sediment geochemistry, with orange and white mats overlying sediments with high concentrations of hydrocarbon gases and extractable liquid hydrocarbons (Sassen et al. 1993b, 1994). Nikolaus (1995) found two color phases in the *Beggiatoa* mats from Gulf of Mexico seeps. A white form was characterized by high activities of the enzyme RUBP-carboxylase, an indicator of Calvin cycle functions that implies autotrophic carbon fixation. A pigmented form did not test positive for RUBP-carboxylase, which Nikolaus interpreted as a possible indication of heterotrophic function in these colonies. Unusually high abundance of benthic Foraminifera were seen in samples of sediment from beneath *Beggiatoa* mats (Sen Gupta and Aharon 1994). LaRock et al. (1994) report high productivity in bacterioplankton in bottom waters at hydrocarbon seeps.

## Heterotrophic Fauna

A succinct description of the heterotrophic fauna found at a "typical" oil seep can be found in MacDonald et al. (1989) and is quoted in full below with updated taxonomic designations indicated in square brackets.

> "A diverse assemblage of common slope fauna was recorded in the still photographs and the video tapes [from Bush Hill]. Bathypelagic organisms included tunicates, squid and trichiurid fishes. The fish *Hoplostethus* sp. was frequently seen hovering over the tube worm clusters. Other fishes (including *Chaunax pictus*, *Urophycis cirratus* and *Peristedion greyae*) were frequently observed swimming near or resting on the bottom. Crustaceans included decapod crabs (*Geryon* sp. [*Chaceon*], *Bathyplax typhla* and *Rochinia crassa*), shrimp and the giant isopod *Bathynomus giganteus*."
>
> "Epifaunal organisms were observed on the tube worms and mussels. The bivalve *Acesta bullisi* (R. D. Turner, pers. comm; Boland 1986) was commonly attached to the ends of the tubes of *Lamellibrachia* sp. Examination of photographs and collected specimens showed that the tubes were inserted through a concave process in the posterior margin of the *A. bullisi* shells, and that the

> obturacular plumes of the *Lamellibrachia* sp. were extended within the mantle cavity of the bivalves.... Several photographs showed a galatheid crab, *Munidopsis* n. sp. (L. Pequegnat, pers. comm.), clinging to the ends of the tubes of the *escarpiid.* Other tubes of both species were encrusted with hydroids and sponges. Epifauna on the mussels included nerite gastropods [*Cataegis* cf *merloglypta*] (E. N. Powell, pers. comm.), an undescribed caridian shrimp, *Alvinocaris* n.sp. [*stactophila*] (A. Williams, pers. comm.) and the crab *Benthoschascon schmitti.* The hag fish, *Eptatretus* sp., was observed at rest in several mussel beds."

## Types of Seep Communities in the Northern Gulf of Mexico

Roberts and Carney (1997) distinguish among slowly seeping oil and gas seeps, rapid, mud-prone expulsion features (mud volcanoes), and quiescent, mineral-prone seeps. Reilly et al. (1996) categorizes complex communities, which comprise a mixture of tube worms and seep mussels, and simple communities, which consist of a single species—usually seep mussels or vesicomyid clams. MacDonald (1998a) and MacDonald et al. (in press) identify brine-pooling and sediment diffusion habitats, noting that so-called simple and complex communities can occur in close proximity. At slow oil and gas seeps, fluids migrate to the seafloor from deep (3,000 to 5,000 m subbottom) reservoirs that are broadly distributed across the continental slope. Near the seafloor is a layer of unconsolidated hemipelagic sediment that is several hundred meters thick. The upper sediment column diffuses and retains oil and gas over areas considerably larger than the fault axis (Reilly et al. 1996). In the upper meter or so of the sediments, microbial degradation of the labile carbon in the oil and gas depletes available oxygen and reduces seawater sulfate to $H_2S$. This provides chemosynthetic substrates for invertebrates with sulfide oxidizing symbionts, notably vestimentiferan tube worms. Increased alkalinity due to microbial productivity causes extensive precipitation of carbonate. Accumulating fluid and carbonate produces low mounds with basal diameters of 10 m to over 500 m and slopes of 10% or greater. At localized vents, methane bubbles through near-bottom waters and generates sufficient local concentrations to support seep mussels. Gas hydrates form where free gas is trapped beneath layers of rock or other shallow obstructions. The result is often a patchwork of tube worm clusters and carbonate boulders extending over the surface of the seep, with the greatest concentrations along fault axes.

At mud volcanoes (Neurauter and Roberts 1994), formation of chemosynthetic communities is controlled by the intensity and frequency of mud discharge (Roberts et al. 1990). Rapid fluid flux often includes abundant hydrocarbons, but burial of slow-growing fauna will limit community formation at active sites. Because the fluid flux is associated with shallow salt in most cases, halite dissolution produces concentrated brines and the increased density of these briny fluids tends to create pools or channels with distinct, stable interfaces (MacDonald et al. 1990a, b). Seep mussels can colonize the stable edges of mud-filled craters or channels. Repeated burial over thousands of years of activity is indicated by recovery of mussels shells in cores taken at mud-prone sites (MacDonald et al. 1995).

Mineral-prone seeps occur with decreased rates of venting and formation of surface domes capped with lithified layers. Lithified surface layers and crusts represent the terminal phase of seeps regardless of whether the active seepage mode was slow, oil and gas driven, or rapid and mud prone (Lee 1995; Sager et al. 1999). Lithification greatly reduces sediment porosity and limits seepage to faults and fissures in the crust. Layers of bivalve shell may remain over large areas for many years after most seepage and all chemosynthetic production has ceased.

Dependence upon seeping hydrocarbons places Gulf of Mexico chemosynthetic fauna in a deep-sea locality that may be affected by human activities (MMS 1988, 1992). The offshore energy industry has experienced several expansive episodes in the past 20 years. All of these have increased activities at ever greater depths. The amount of seafloor influenced by seepage is quite small compared to the extent of the subbottom hydrocarbon system and industry engineers generally strive to avoid the unstable substrate at seeps (Reilly et al. 1996). Current interest lies in improving the capacity to predict where seep communities will occur and in understanding processes that contribute to either stability or change in this environment so that anthropogenic changes could be distinguished from natural processes. Type cases of "typical" chemosynthetic communities are given below.

## Bush Hill

The "Bush Hill" site (27°47' N, 91°30.4' W) described by MacDonald et al. (1989) was the first hydrocarbon seep community to be sampled from a submersible. Reilly et al. (1996) describe it as the type-example of a *complex chemosynthetic community*. The Conoco tension leg work platform (TLWP) was installed <2 km west southwest from the mound and began producing oil in the late 1980's. The major seep area is a 300 m-EW by 500 m-NS mound with a crest depth of 570 m, rising about 40 m above the surrounding seafloor, and composed of mud, carbonate, and shallow gas hydrate. The N-S axis of the mound is situated along the surface trace of a west-dipping fault that is the conduit by which oil and gas reaches the surface from deposits located at approximately 1,200 m subbottom depth. Surface sediments contain, by weight, up to 10% liquid hydrocarbons, which Kennicutt et al. (1988b) described as having fingerprints identical to oil produced by the TLWP wells. However, reservoirs tapped by TLWP wells were located at subbottom depths of 3,000 m or greater by Cook and D'Onfro (1991), who suggest that the field comprises a complex of many reservoirs, charged from a common source, but seeping only from the shallowest strata. Sulfide concentrations in shallow sediments (<10 cm) associated with tube worm clusters have been measured in the 100 to 250 μM range with use of micro-electrode technique (Escorcia et al. 1999). Methane concentrations in near-bottom waters are 30 to 60 μM in the vicinity of active gas vents and below 1 μM elsewhere (MacDonald et al. 1989; Nix et al. 1995). Shallow gas hydrates have been recovered by coring at Bush Hill (Brooks et al. 1986). Layers of gas hydrate breach the sediment layer near the highest point of the mound (MacDonald et al. 1994a). Tube worm clusters extend over much of the mound crest while mussels are confined to the active gas vents.

### Brine Pool NR1

The focus of this chemosynthetic community is a small (190 m$^2$) pool of brine (salinity 121.35) found near 27°43.4'N and 91°16.5'W at a water depth of 650 m (MacDonald et al. 1990b). Brine fills a crater at the center of a ~100 m wide mound. The mound rises about 6 m above the surrounding seafloor, but the crater and its diatreme extend at least 30 m below the surface. The brine contains microbial methane ($\delta^{13}C = -63.8$) in concentrations that are supersaturated at standard temperature and pressure. Streams of $CH_4$ bubbles emanate continually from the center of the pool. The pool is ringed by a large (540 m$^2$) bed of seep mussels (MacDonald and Fisher 1996). Mussels settled on the "shoreline" of the pool include numerous juveniles, whereas the periphery of the bed comprised a single settlement class without juveniles. Sulfide levels are below levels of detection in the pool, but rise sharply in fluids collected beneath the surrounding mussel bed (Fisher, personal communication). The bed of seep mussels comprises a striking example of a mono-specific aggregation of chemosynthetic fauna, but numerous other species of heterotrophic animals are also commonly observed at the site (MacDonald 1992; MacDonald and Fisher 1996). Recent findings challenge the Reilly et al. (1996) designation that this Brine Pool NR1 is a "simple" community because small, but significant clusters of vestimentiferans are known to occur to the south of the pool (MacDonald et al., in press).

### Garden Banks 386

Located at 580 m water depths near 27°36.9'N and 92°15.5'W, this flat-topped mound is described as a mud volcano by Reilly et al. (1996), but active seepage in the form of gas venting and mud or fluid discharge does not occur over the mound (Reilly et al. 1996; Sager et al. 1999). A rubble-strewn crust of authigenic carbonate extends over the entire ~600 m wide area of the upper mound. Bivalve shells are common, but no living seep mussels or clams have been recovered from the site and tube worms are restricted to stunted individuals lining small fractures in the rocky substratum (MacDonald et al. 1995). Because active mud volcanoes similar of similar morphology are common in the region, and because of the accumulation of dead bivalve shells, one can surmise that this site was previously more active in terms of fluid expulsion and biological productivity. Mineral-prone seeps probably do not generally represent aggregations of biological activity requiring extensive protection. It would require careful study, however, to distinguish a mineral-prone, relatively inactive seep and biological assemblage like the mound in Garden Banks 386 from more active features.

### Alaminos Canyon

Chemosynthetic communities at this site comprise at least six aggregations of seep mussels (*B. brooksi*) and tube worms (*Lamellibrachia* and *Escarpia*) distributed along the northeastern wall of a submarine canyon in water depths of 2,250 m (Brooks 1990; Brooks et al. 1990). The largest aggregation, dubbed Neptune's Garden, is located near 26° 21'N and 94° 21' W. The mussels occupy beds as large as 10 $m^2$ on a rocky substratum (Fisher et al. 1992; MacDonald et al. 1994b). Elevated salinity observed in water samples indicates possible brine seepage at the site. Hydrocarbon seepage has been documented in piston core samples from the region (MacDonald and Schroeder 1993).

## Distribution of Seep Communities in the Northern Gulf of Mexico

Seeps and chemosynthetic communities can be detected with seismic survey methods by looking for migration conduits—also called seismic wipe-outs—that coincide with surface mounds and low-angle faults (Reilly et al. 1996; Roberts and Carney 1997). Side-scan sonar has also shown promise and may be more cost-effective in some applications (Sager and MacDonald 1998). As the discussion above indicates, the timing of migration and seepage is not necessarily predicted by structures that are detected with seismic data. The geochemistry of hydrocarbon seeps has been thoroughly described (Anderson et al. 1983; Brooks et al. 1984, 1986; Kennicutt et al. 1987, 1988a) and will reliably predict regional occurrence of chemosynthetic communities for at least the so-called "lush" communities of most concern for management (MMS 1988). However, brine-pooling communities like Brine Pool NR1 are not always associated with thermogenic hydrocarbons in the surface sediments. Submersible and photo-surveys have been executed haphazardly and with a definite bias toward sites <1,000 m depth, this due to the cost and depth limitations of available submersibles. Surveys of chemosynthetic communities need to be evaluated critically, therefore, with an eye to the underlying limits of the data and the motivating goals of the survey. The following briefly summarizes different evidence for the regional distribution of chemosynthetic communities in the Gulf of Mexico.

Sassen et al. (1993a) demonstrated that, where data permit comparison, most major oil fields in the deepwater Gulf of Mexico are associated with chemosynthetic communities. Recent exploration and production have not been thoroughly documented by submersible observations and there is some question about community development in water depths between 1,000 and 2,000 m where data are lacking (MacDonald 1998b). However, these authors and other authors (Abrams 1996; Kaluza and Doyle 1996) note that salt tectonism generates migration conduits across the entire Gulf of Mexico slope. All hydrocarbon fields are therefore highly susceptible to leakage. A map of oil discovery and production should, therefore predict the *general* localities where chemosynthetic communities might be found. First-hand observations are required to confirm community occurrence at scales of 1 km or less. **Table 8.2**, reproduced from MacDonald et al. (1996), compiles direct observations of chemosynthetic communities in the northern Gulf of Mexico.

Table 8.2. Sites where chemosynthetic megafauna have been collected by trawl (Trl) or submarine (Sub), or definitively photographed by submarine, remotely operated vehicle (ROV), or photosled (Photosl). Fauna indicates type of chemosynthetic megafauna found at site: V=vestimentiferan tube worms, M=seep mytilids, C=vesicomyid or lucinid clams, PG=pogonophoran tube worms. Lease block designators follow MMS standard abbreviations. Data sources give precedence to observations published in open literature.

| Fauna | Latitude (North) | Longitude (West) | MMS Lease Block | Depth (m) | Observation Method | Data source |
|---|---|---|---|---|---|---|
| V,M | 26°21.20' | 94°29.80' | AC0645 | 2200 | Sub | 1 |
| M | 27°23.50' | 94°29.45' | EB0602 | 1111 | Trl | 2 |
| P,G | 27°27.55' | 93°08.60' | GB0500 | 734 | Trl | 2 |
| V,C | 27°30.05' | 93°02.01' | GB0458 | 757 | Trl | 2 |
| M | 27°31.50' | 92°10.50' | GB0476 | 750 | Sub | 3 |
| M,C | 27°33.40' | 92°32.40' | GB0424 | 570 | Sub | 3 |
| V | 27°35.00' | 92°30.00' | GB0425 | 600 | Sub | 3 |
| V,C | 27°34.50' | 92°55.95' | GB0416 | 580 | Sub | 3 |
| V,C | 27°36.00' | 94°46.00' | EB0376 | 776 | Sub | 3 |
| P,G | 27°36.15' | 94°35.40' | EB0380 | 793 | Trl | 2 |
| M,C | 27°36.50' | 92°28.94' | GB0382 | 570 | Sub | 3 |
| V,C | 27°36.60' | 94°47.35' | EB0375 | 773 | Trl | 2 |
| V,C | 27°36.82' | 92°15.25' | GB0386 | 585 | Sub, Trl | 2, 3 |
| V,C | 27°37.15' | 92°14.40' | GB0387 | 781 | Sub, Trl | 2, 3 |
| V | 27°37.75' | 91°49.15' | GC0310 | 780 | Trl | 2 |
| V,C | 27°38.00' | 92°17.50' | GB0342 | 425 | Trl | 2 |
| C | 27°39.15' | 94°24.30' | EB0339 | 780 | Trl | 2 |
| V,C | 27°39.60' | 90°48.90' | GC0287 | 994 | Sub, Trl | 2 |
| C | 27°40.45' | 90°29.10' | GC0293 | 1042 | Trl | 2 |
| V,C | 27°40.50' | 92°18.00' | GB0297 | 589 | Trl | 2 |
| V,M,C | 27°40.88' | 91°32.10' | GC0272 | 720 | Sub, Trl | 2, 3, 4 |
| V,C | 27°42.65' | 92°10.45' | GB0300 | 719 | Trl | 2 |
| V | 27°43.10' | 91°30.15' | GC0229 | 825 | Trl | 2 |
| V,M | 27°43.30' | 91°16.30' | GC0233 | 650 | Sub | 5 |
| V,M,C | 27°43.70' | 91°17.55' | GC0233 | 813 | Trl | 2 |
| V,M | 27°44.08' | 91°15.27' | GC0234 | 600 | Sub | 3, 6 |
| V,M | 27°44.30' | 91°19.10' | GC0232 | 807 | Sub | 3 |
| V,M | 27°44.80' | 91°13.30' | GC0234 | 550 | Sub | 3, 7 |
| V,C | 27°45.00' | 90°16.31' | GC0210 | 715 | Sub | 3 |
| C | 27°45.50' | 89°58.30' | GC0216 | 963 | Sub, Photosl | 8, 2 |
| V,M,C | 27°46.33' | 90°15.00' | GC0210 | 796 | Sub | 3 |
| V,M | 27°46.65' | 91°30.35' | GC0184/5 | 580 | Sub, Trl | 2, 3, 9 |
| V,M | 27°46.75' | 90°14.70' | GC0166 | 767 | Sub, Trl | 2, 3 |
| V,M | 27°49.16' | 91°31.95' | GC0140 | 290 | Sub | 10 |
| V | 27°50.00' | 90°19.00' | GC0121 | 767 | Sub | 3 |
| V,M | 27°53.56' | 90°07.07' | GC0081 | 682 | Photosl | 11 |
| V,C | 27°54.40' | 90°11.90' | GC0079 | 685 | Trl | 2 |
| V,M | 27°55.50' | 90°27.50' | GC0030 | 504 | Sub | 3 |
| V,P,G | 27°56.65' | 89°58.05' | GC0040 | 685 | Trl | 2 |
| C | 27°57.10' | 89°54.30' | MC0969 | 658 | Trl | 2 |
| V | 27°57.25' | 89°57.50' | EW1010 | 597 | Sub, Trl | 2, 3 |
| V | 27°58.70' | 90°23.40' | EW1001 | 430 | Sub, Trl | 2, 3 |
| V,C | 29°11.00' | 88°00.00' | VK0826 | 545 | Sub, ROV, Trl | 3, 4, 12 |

Data sources: 1–Brooks et al. (1989), 2–Kennicutt et al. (1988a,b), 3–GERG unpubl. data, 4-Callender and Powell (1992), 5-MacDonald et al. (1990b), 6–MacDonald et al. (1990a), 7–MacDonald et al. (1990a), 8–Rosman et al. (1987), 9-MacDonald et al. (1989), 10–Roberts et al. (1990), 11–Boland (1986), 12–Boss (1968), Gallaway et al. (1990), Volkes (1963).

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# Chapter 9: Protected Species

*Stephen T. Viada*

## Introduction

Protected species that may occur within oceanic waters of the northern Gulf of Mexico (defined as the continental slope and abyssal regions) include 28 marine mammals and 5 sea turtles. All marine mammals are protected under the Marine Mammal Protection Act of 1972. Certain marine mammals and all sea turtles are also "listed species"; that is, they are classified as endangered or threatened under the Endangered Species Act of 1973.

This chapter discusses only those species of marine mammals and turtles that have been reported from the deepwater Gulf of Mexico or whose known ranges may include these waters. Other protected species occur in the Gulf of Mexico, but primarily in coastal or continental shelf waters, or within adjacent waters of the western Atlantic Ocean or Caribbean Sea. For example, the West Indian manatee (*Trichechus manatus*), which consists of two subspecies, the Florida manatee (*T.m. latirostris*) and the Antillean manatee (*T.m. manatus*), may be found in the northern Gulf of Mexico but inhabits only coastal marine, brackish, and freshwater habitats (Reeves et al. 1992; Jefferson et al. 1993; O'Shea et al. 1995). Similarly, the Gulf sturgeon (*Acipenser oxyrinchus desotoi*) is an anadromous fish that also inhabits coastal marine (including inner continental shelf), brackish, and freshwater habitats of the central and eastern Gulf of Mexico (Gilbert 1992; Mettee et al. 1996). The roseate tern (*Sterna dougallii*) is a seabird that commonly ventures into oceanic waters; however, its western Atlantic population is known to only approach the far southeastern Gulf to breed in scattered colonies along the Florida Keys. The Bermuda petrel (*Pterodroma cahow*) is a pelagic seabird that is limited to oceanic waters of the northwestern Atlantic and breeds in small colonies on Bermuda. The brown pelican (*Pelicanus occidentalis*) is commonly found in the northern Gulf of Mexico but occurs only within coastal habitats and waters of the inner continental shelf (Clapp et al. 1982a,b; Harrison 1983; Warham 1990; Olsen and Larsson 1995; Harrison 1996; Olsen and Larsson 1997; National Geographic Society 1999).

## Cetaceans

Whales and dolphins are members of the mammalian taxonomic order Cetacea, which includes two suborders: Mysticeti (baleen whales) and Odontoceti (toothed whales, and dolphins and their allies). Twenty-eight species of cetaceans comprising 7 mysticete whales and 21 odontocete whales and dolphins are known to occur in the Gulf of Mexico (**Table 9.1**) (Davis et al. 2000; Jefferson et al. 1992).

### Listed Species Accounts

Five mysticetes (the northern right, blue, fin, sei, and humpback whales) and one odontocete (the sperm whale) that occur or have been reported in the Gulf of Mexico are listed as endangered species. The sperm whale is the only endangered species that is considered to be common and perhaps a resident species in certain deepwater areas of the Gulf (Davis et al. 2000). Listed mysticetes do not normally enter the Gulf with any regularity (Jefferson 1995; Davis and Fargion 1996). Sightings of these species in the Gulf are rare or uncommon, and are believed to be in most cases representative of extralimital strays from their normal ranges in the western Atlantic Ocean where they may inhabit both deepwater habitats and waters of the continental shelf (Würsig et al. 2000). Consequently, there are insufficient sightings records to estimate numbers of individuals or "stocks" of mysticetes in the Gulf (Jefferson 1995). Brief species accounts of the listed cetaceans are presented below.

#### Mysticetes

The northern right whale (*Eubalaena glacialis*) primarily inhabits temperate and subarctic coastal and continental shelf waters. The western North Atlantic population, or stock, ranges between the Maritime Provinces of eastern Canada to northeastern Florida. Right whales forage primarily on subsurface and localized concentrations of zooplankton such as calanoid copepods (Leatherwood and Reeves 1983; Jefferson et al. 1993; Perry et al. 1999). Sparse, historical sightings and strandings records (one confirmed sighting from Florida and one confirmed stranding from Texas) suggest that this species is not a normal inhabitant of the Gulf of Mexico. The sightings records that do exist are considered to be those of extralimital strays from their wintering grounds off the southeastern United States (Jefferson 1995; Jefferson and Schiro 1997; Würsig et al. 2000).

The blue whale (*Balaenoptera musculus*) is an oceanic species that may move into selected habitats on the continental shelf to feed. Blue whales are distributed from the equator to polar regions of both hemispheres. Blue whales feed almost exclusively on localized concentrations of zooplankton, primarily euphausiid crustaceans (krill) (Yochem and Leatherwood 1985; Jefferson et al. 1993; Perry et al. 1999). Their presence in the Gulf of Mexico is considered to be very rare, as sighting records consist of two stranded individuals on the Texas coast and two nonconfirmed sightings (Jefferson and Schiro 1997; Würsig et al. 2000).

Table 9.1. Cetaceans of the Gulf of Mexico

| Scientific Name | Common Name | Status[a] |
|---|---|---|
| SUBORDER MYSTICETI | BALEEN WHALES | |
| Family Balaenidae | Right whales | |
| *Eubalaena glacialis* | Northern right whale | E, S |
| Family Balaenopteridae | Rorquals | |
| *Balaenoptera musculus* | Blue whale | E, S |
| *Balaenoptera edeni* | Bryde's whale | None |
| *Balaenoptera physalus* | Fin whale | E, S |
| *Megaptera novaeangliae* | Humpback whale | E, S |
| *Balaenoptera acutorostrata* | Minke whale | None |
| *Balaenoptera borealis* | Sei whale | E, S |
| SUBORDER ODONTOCETI | TOOTHED WHALES AND DOLPHINS | |
| Family Physeteridae | Sperm whales | |
| *Kogia simus* | Dwarf sperm whale | None |
| *Kogia breviceps* | Pygmy sperm whale | None |
| *Physeter macrocephalus* | Sperm whale | E, S |
| Family Ziphiidae | Beaked whales | |
| *Mesoplodon densirostris* | Blainville's beaked whale | S |
| *Ziphius cavirostris* | Cuvier's beaked whale | S |
| *Mesoplodon europaeus* | Gervais' beaked whale | S |
| *Mesoplodon bidens* | Sowerby's beaked whale | S |
| Family Delphinidae | Dolphins (Delphinids) | |
| *Stenella frontalis* | Atlantic spotted dolphin | None |
| *Tursiops truncatus* | Bottlenose dolphin | None |
| *Stenella clymene* | Clymene dolphin | None |
| *Pseudorca crassidens* | False killer whale | None |
| *Lagenodelphis hosei* | Fraser's dolphin | None |
| *Orcinus orca* | Killer whale | None |
| *Peponocephala electra* | Melon-headed whale | None |
| *Stenella attenuata* | Pantropical spotted dolphin | None |
| *Feresa attenuata* | Pygmy killer whale | None |
| *Globicephala macrorhynchus* | Short-finned pilot whale | S |
| *Grampus griseus* | Risso's dolphin | None |
| *Steno bredanensis* | Rough-toothed dolphin | None |
| *Stenella longirostris* | Spinner dolphin | None |
| *Stenella coeruleoalba* | Striped dolphin | None |

[a] Status: E = endangered under the Endangered Species Act of 1973; S = strategic stock under the Marine Mammal Protection Act of 1972, as indicated by Waring et al. (1999).

The fin whale (*Balaenoptera physalus*) is also an oceanic species of both hemispheres, and may be found from the tropics to polar zones. They are sighted near the coast in certain areas where deep water approaches the coast. Fin whales feed on localized concentrations of zooplankton, fishes, and squid. The predominant prey of fin whales varies greatly in different geographic locales, based on what is locally abundant (Leatherwood and Reeves 1983; Jefferson et al. 1993; Perry et al. 1999). There are seven reliable sightings and four unreliable sighting reports of fin whales from the Gulf of Mexico. From these data, they are not considered to be abundant in the Gulf. Sighted individuals may be extralimital strays from their western Atlantic population or, less likely, a small, resident, and relict population (Jefferson and Schiro 1997; Würsig et al. 2000).

The humpback whale (*Megaptera novaeangliae*) feeds and breeds in coastal waters, and migrates across oceanic waters from breeding areas in the tropics to polar or sub-polar regions. Humpback whales feed on localized concentrations of zooplankton, fishes, and squid (Winn and Reichley 1985; Jefferson et al. 1993; Perry et al. 1999). There are seven reliable sightings and two unreliable sightings reports of generally small, humpback whales from the Gulf of Mexico. The time of the year of the records suggest that these individuals may be extralimital strays during their breeding season or during their migrations, and their small body sizes suggest that they may be inexperienced yearlings on their first return migration (Jefferson and Schiro 1997; Würsig et al. 2000).

The sei whale (*Balaenoptera borealis*) is an oceanic species that is not commonly sighted near the coast. They occur from the tropics to polar zones in both hemispheres, but appear to be more common in mid-latitude temperate zones. Sei whales feed on localized concentrations of zooplankton, small fishes, and squid (Gambell 1985; Jefferson et al. 1993). Sparse sightings data in the Gulf of Mexico, consisting of one questionable sighting and three strandings from eastern Louisiana, suggest that their presence there is rare, or of accidental occurrence (Jefferson and Schiro 1997).

### Odontocetes

The sperm whale (*Physeter macrocephalus*) is the largest toothed whale and is distributed from the tropics to polar zones in both hemispheres. They are deep diving mammals and inhabit oceanic waters, although they may come close to shore in certain areas where deep water approaches the coast. Their distribution varies by gender and age composition. Mature females, and calves and immature whales of both sexes are found in social groups in temperate and tropical waters. Mature males are mostly solitary, and may travel into polar seas as high as 70° N or 70° S (Perry et al. 1999). Sperm whales are known to feed on cephalopods, demersal fishes, and benthic invertebrates (Rice 1989; Jefferson et al. 1993; Perry et al. 1999). The sperm whale is the only great whale that is considered to be common in the Gulf of Mexico (Jefferson 1995). Historical sightings records suggest a Gulf-wide distribution, primarily on the continental slope. During GulfCet I and II surveys, however, sperm whales on the slope were sighted almost entirely in the north-central and northeastern Gulf in loose groups of two to eight individuals (Davis and Fargion 1996; Davis et al. 1999). Congregations of sperm whales are also common inhabitants of waters over the shelf edge in the vicinity of the Mississippi River delta in water depths of 500 to 2,000 m. From these consistent sightings it is believed that there is a resident population of sperm whales in the Gulf consisting of adult females, calves, and immature individuals (Brandon and Fargion 1993; Mullin et al. 1994b; Sparks et al. 1996; Jefferson and Schiro 1997). Recent minimum population estimates of sperm whales within the oceanic northern Gulf of Mexico totaled 530 individuals from 1991-1994 surveys and 387 individuals from 1996-1997 surveys (Davis et al. 2000).

## Nonlisted Species Accounts

Two nonlisted mysticete whales and 20 nonlisted odontocete whales and dolphins are known to occur in the Gulf. Brief species accounts of these nonlisted cetaceans are presented below.

### Mysticetes

The Bryde's whale (*Balaenoptera edeni*) is the second smallest baleen whale and is generally confined to tropical and subtropical waters (between 40°N and 40°S latitudes). Unlike other baleen whales, it does not have a well-defined breeding season in most areas and thus calving may occur throughout the year. Resident populations may be common in certain areas. Bryde's whales feed on both fishes and invertebrates (Leatherwood and Reeves 1983; Cummings 1985; Jefferson et al. 1993). The Bryde's whale is represented by more sightings records than any other species of baleen whale in the Gulf. All Bryde's whale sightings made during recent surveys in the Gulf of Mexico were from the continental shelf edge in the vicinity of De Soto Canyon and along the 100 m isobath in the north-central Gulf. These data suggest that the Gulf may represent at least a portion of the range of a dispersed, resident population of Bryde's whale (Davis and Fargion 1996; Jefferson and Schiro 1997; Davis et al. 2000; Würsig et al. 2000).

The minke whale (*Balaenoptera acutorostrata*) is the smallest baleen whale and is widely distributed from tropical to polar habitats. Minke whales may be found in oceanic regions but appear to prefer coastal waters and waters of the continental shelf. Their diet consists of invertebrates and fishes (Leatherwood and Reeves 1983; Stewart and Leatherwood 1985; Jefferson et al. 1993). There are 10 reliable records and 2 questionable records of minke whales in the Gulf. All of these are stranding records from winter or spring. These records suggest that minke whales may migrate into Gulf waters in small numbers during the winter or, more likely, that sighted individuals represent strays from low-latitude breeding grounds in the western North Atlantic (Davis and Fargion 1996; Jefferson and Schiro 1997; Davis et al. 2000; Würsig et al. 2000).

### Odontocetes

Pygmy and Dwarf Sperm Whales. The pygmy sperm whale (*Kogia breviceps*) and its congener, the dwarf sperm whale (*K. simus*), are known from deep waters in tropical to warm temperate zones (Jefferson and Schiro 1997). They appear to be most common on the continental slope and along the shelf edge (Würsig et al. 2000). Little is known of their natural history. Data collected from stomach contents of stranded individuals suggest that these species feed on cephalopods, fishes, and crustaceans in deep water (Leatherwood and Reeves 1983; Jefferson et al. 1993). *Kogia spp.* has been sighted throughout the Gulf across a wide range of depths and bottom topographies, though they may more commonly be associated with water mass fronts along the continental shelf edge break and upper slope (Baumgartner 1995).

Beaked Whales. Two genera and four species of beaked whales are known to occur in the Gulf of Mexico. These include three species in the genus *Mesoplodon* (Sowerby's beaked whale [*M. bidens*], Blainville's beaked whale [*M. densirostris*], and Gervais' beaked whale [*M. europaeus*]) and Cuvier's beaked whale (*Ziphius cavirostris*). Generally, beaked whales appear to prefer deep water, though little is known of their respective life histories. Stomach content analyses suggest that these whales feed primarily on deepwater cephalopods, although they will also take fish and some benthic invertebrates (Leatherwood and Reeves 1983; Jefferson et al. 1993). In the Gulf, beaked whales have been sighted at depths between approximately 700 and 2,000 m. Cuvier's beaked whale is probably the most common beaked whale in the Gulf (Davis and Fargion 1996; Jefferson and Schiro 1997; Davis et al. 2000; Würsig et al. 2000).

Delphinid Whales and Dolphins. All remaining species of nonendangered and nonthreatened cetaceans found in the Gulf are members of the taxonomically diverse family Delphinidae.

The Atlantic spotted dolphin (*Stenella frontalis*) is endemic to the Atlantic within tropical to temperate waters. They feed on a wide variety of fishes and cephalopods. The Atlantic spotted dolphin is the only other species of cetacean (other than the bottlenose dolphin) that commonly occurs on the continental shelf of the Gulf of Mexico (Brandon and Fargion 1993; Jefferson and Schiro 1997). Current Gulf surveys sighted the Atlantic spotted dolphin primarily on the continental shelf and shelf edge at depths less than 250 m, although with some individuals sighted along the slope at depths of up to 600 m (Davis et al. 2000).

The bottlenose dolphin (*Tursiops truncatus*) is a common inhabitant of both continental shelf and slope. They are opportunistic feeders of a wide array of prey items (Brandon and Fargion 1993; Jefferson and Schiro 1997). Current data suggest genetically discrete, inshore and offshore stocks, or populations of bottlenose dolphins. Interaction between the two populations is thought to be minimal (Würsig et al. 2000). Bottlenose dolphins in the Gulf are commonly sighted at depths less than approximately 1,200 m (Mullin et al. 1994b; Jefferson and Schiro 1997; Davis et al. 1999).

The Clymene dolphin (*Stenella clymene*) is endemic to the Atlantic, and found only in tropical and subtropical waters. This species appears to feed on fishes and squid (Leatherwood and Reeves 1983; Jefferson et al. 1993; Mullin et al. 1994a). They are not considered to be rare in the Gulf, though current sightings have been made almost exclusively to the west of the Mississippi River at depths of 600 to 3,000 m (Mullin et al. 1994a; Jefferson 1995; Jefferson and Schiro 1997; Würsig et al. 2000).

The false killer whale *(Pseudorca crassidens)* is found in tropical to warm temperate zones in deep offshore waters. It feeds on primarily fish and cephalopods, although it has been known to also feed on cetaceans (Jefferson et al. 1993; Leatherwood and Reeves 1983). In the Gulf, most sightings of false killer whales have occurred along the continental slope, although some were sighted over the outer continental shelf (OCS) as well (Davis and Fargion 1996).

The Fraser's dolphin *(Lagenodelphis hosei)* has a pantropical distribution in oceanic waters and nearshore in areas where deep water approaches the coast. Fraser's dolphins feed on fish, cephalopods, and crustaceans (Leatherwood and Reeves 1983; Jefferson et al. 1993; Jefferson and Schiro 1997). In the Gulf, sightings of Fraser's dolphins have occurred in the western part at depths of around 1,000 m (Davis and Fargion 1996; Jefferson and Schiro 1997; Davis et al. 2000).

The killer whale (*Orcinus orca*) is probably the most cosmopolitan of all cetaceans and can be found in almost any marine region in all oceans. Generally, they appear to prefer nearshore, cold temperate to subpolar zones. Killer whales feed on marine mammals, marine birds, fishes, sea turtles, and cephalopods (Leatherwood and Reeves 1983; Jefferson et al. 1993). In the Gulf, most sightings of killer whales have been along the continental slope, within a broad area of the north-central Gulf (Jefferson and Schiro 1997; O'Sullivan and Mullin 1997; Würsig et al. 2000).

The melon-headed whale (*Peponocephala electra*) is a deep-water, pantropical species. It is known to feed on cephalopods and fishes (Leatherwood and Reeves 1983; Jefferson et al. 1993; Mullin et al. 1994c; Jefferson and Schiro 1997). In the Gulf, the melon-headed whale has been sighted in continental slope waters, west of the Mississippi River (Davis and Fargion 1996; Jefferson and Schiro 1997; Davis et al. 2000; Würsig et al. 2000).

The pantropical spotted dolphin (*Stenella attenuata*) is a tropical species known from the Atlantic, Pacific, and Indian Oceans. It is known to feed on epipelagic fishes and squid (Jefferson et al. 1993; Leatherwood and Reeves 1983). The pantropical spotted dolphin is the most common and abundant cetacean on the slope and especially outer slope waters of the Gulf at depths greater than 1,200 m (Brandon and Fargion 1993; Jefferson 1995; Jefferson and Schiro 1997; Würsig et al. 2000).

The pygmy killer whale (*Feresa attenuata*) is apparently widely distributed in tropical waters, though little is known of its biology. Its diet includes cephalopods and fishes, though reports of attacks on other delphinids are reported (Leatherwood and Reeves 1983; Jefferson et al. 1993). The pygmy killer whale does not appear to be commonly found in the Gulf of Mexico. Sightings of this species in the Gulf have been at depths of 500 to 1,000 m (Davis and Fargion 1996; Jefferson and Schiro 1997; Davis et al. 2000; Würsig et al. 2000).

The short-finned pilot whale (*Globicephala macrorhynchus*) is found in warm temperate to tropical waters of the world. Short-finned pilot whales feed primarily on squid and fishes. In the Gulf, it is most commonly sighted along the mid- to upper-slope at depths of 250 to 2,000 m and often in areas of steep bottom topography (Davis and Fargion 1996; Jefferson and Schiro 1997; Davis et al. 2000; Würsig et al. 2000).

The Risso's dolphin (*Grampus griseus*) is a pantropical species that inhabits deep oceanic and continental slope waters. Risso's dolphins feed primarily on cephalopods and secondarily crustaceans (Leatherwood and Reeves 1983; Jefferson et al. 1993; Baumgartner 1995). In the Gulf, it occurs at depths of 150 to 2,000 m, especially in areas along the upper continental slope (Baumgartner 1995). It is considered common in these areas of the Gulf (Davis and Fargion 1996; Jefferson and Schiro 1997; Davis et al. 2000; Würsig et al. 2000).

The rough-toothed dolphin (*Steno bredanensis*) is a circumtropical and subtropical species. This species feeds on cephalopods and fishes (Leatherwood and Reeves 1983; Jefferson et al. 1993). In the Gulf, they are sighted almost exclusively west of the Mississippi at depths of 900 to 2,000 m, and occur year-round (Davis and Fargion 1996; Jefferson and Schiro 1997).

The spinner dolphin (*Stenella longirostris*) is a pantropical species (Jefferson and Schiro 1997). They commonly associate with pantropical spotted dolphins. Spinner dolphins appear to feed on fishes and squid. In the Gulf, most sightings of spinner dolphins have been east of the Mississippi at depths of 500 to 1,800 m (Jefferson and Schiro 1997; Davis et al. 2000; Würsig et al. 2000).

The striped dolphin (*Stenella coeruleoalba*) is primarily a tropical species, though it may also range into temperate seas. Striped dolphins are known to feed on squid and fishes. In the Gulf, they are found at depths of 600 to 2,000 m (Jefferson and Schiro 1997; Würsig et al. 2000).

## Distribution and Abundance in the Oceanic Northern Gulf of Mexico

Prior to 1989, most historical study programs designed to assess the distribution and abundance of cetaceans within the Gulf of Mexico were conducted exclusively within waters of the continental shelf. The first systematic surveys for cetaceans within continental slope and abyssal waters of the Gulf began in 1989. During this period, systematic aerial surveys were conducted over selected survey blocks off Louisiana and Mississippi by the National Marine Fisheries Service (NMFS) (Mullin et al. 1991, 1994b). Subsequent, shipboard surveys for cetaceans within a broad area of the oceanic northern Gulf were conducted by NMFS in spring of 1990 and 1991 (Jefferson 1995). These early study efforts provided the first data pertaining to the distribution and abundance of oceanic cetaceans within the northern Gulf of Mexico but provided limited information regarding geographic coverage (Mullin et al. 1991, 1994b) or variability in seasonal distributions of cetacean populations (NMFS shipboard surveys) (Jefferson

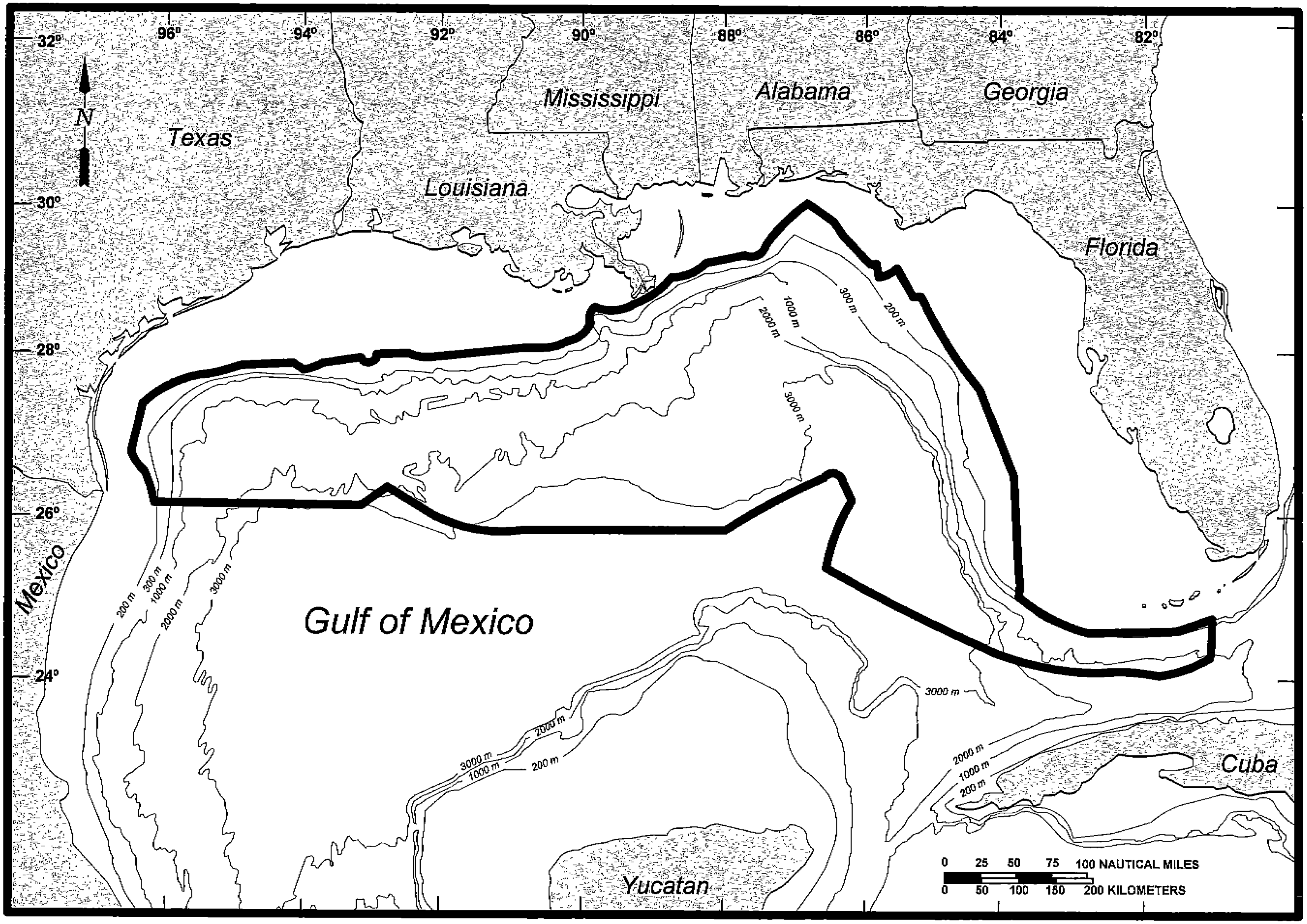

Figure 9.1. U.S. oceanic northern Gulf of Mexico as defined in the GulfCet II study (Davis et al. 2000).

1995). Texas A&M University began a series of extensive survey programs in 1992 within the OCS and continental slope waters of the northern Gulf of Mexico in an effort to determine seasonal and geographic distributions, and habitat associations of cetacean, sea turtle, and seabird populations. These programs, entitled GulfCet I and II, represent the most recent and systematic survey efforts within the oceanic northern Gulf of Mexico (Davis and Fargion 1996; Davis et al. 2000). Systematic shipboard and aerial surveys were conducted within waters from 100 to 2,000 m west of 87°30.0'W during the GulfCet I program and east of 88°10.0'W during the GulfCet II program. In addition, Gulf of Mexico waters within the U.S. EEZ greater than 100 m deep were surveyed by ship during the GulfCet II program (**Figure 9.1**). From these surveys, at least 17 species of cetaceans that typically inhabit deep, tropical waters were sighted throughout the oceanic northern Gulf. Sighting rates of cetaceans within this area were, however, approximately 80% greater east of 90.0°W longitude. Relative minimum abundance estimates of cetaceans known to occur in the oceanic northern Gulf were calculated from survey data collected during two survey periods (1991-1994 and 1996-1997) within the "oceanic northern Gulf" survey area (see **Figure 9.1**) and are presented graphically in **Figure 9.2**. Bottlenose dolphins were the most common species in terms of total numbers of sightings in the oceanic northern Gulf. Pantropical and spinner dolphins were the most abundant species, in terms of total numbers of individuals, and occurred in fewer but much larger groups than bottlenose dolphins (Davis et al. 2000).

Davis et al. 2000 suggest that the spatial and temporal distribution and abundance of cetaceans within the northern Gulf of Mexico may be strongly influenced by various circulation patterns. These patterns are generally driven by river discharge, wind stress, and the Loop Current. The major river system in this area is the Mississippi-Atchafalaya River (approximately 30% of the Mississippi discharge is diverted upriver into the Atchafalaya River). Most of the river discharge into the northern Gulf is transported to the west and along the coast. Circulation on the continental shelf is largely wind-driven, with localized effects from freshwater (i.e., river) discharge. Beyond the shelf, mesoscale circulation is largely driven by the Loop Current in the eastern Gulf. Meanders of the Loop Current create warm-core anticyclonic eddies (anticyclones) once or twice annually that migrate westward. The anticyclones in turn spawn cold-core cyclonic eddies (cyclones). Together, anticyclones and cyclones govern the circulation of the continental slope in the central and western Gulf (see Chapter 4). The Loop Current and anticyclones are dynamic features which transport large quantities of high-salinity, nutrient-poor water across the near-surface waters of the northern Gulf. Cyclones, in contrast, are dynamic features which contain high concentrations of nutrients and stimulate localized production. The combination of input of nutrients into the Gulf from river outflow and mesoscale circulation features enhances productivity, and thus the abundance of cetacean prey species such as fish and squid. The dynamics of these oceanographic features in turn affect the spatial and temporal distribution of prey species and ultimately influence cetacean diversity, abundance, and distribution (Mullin et al. 1994b; Davis et al. 1999).

Studies conducted during the GulfCet I program demonstrated correlations of the distributions of cetaceans with certain geomorphic features such as bottom depth or slope. These studies suggested that bottom depth was the most important variable in

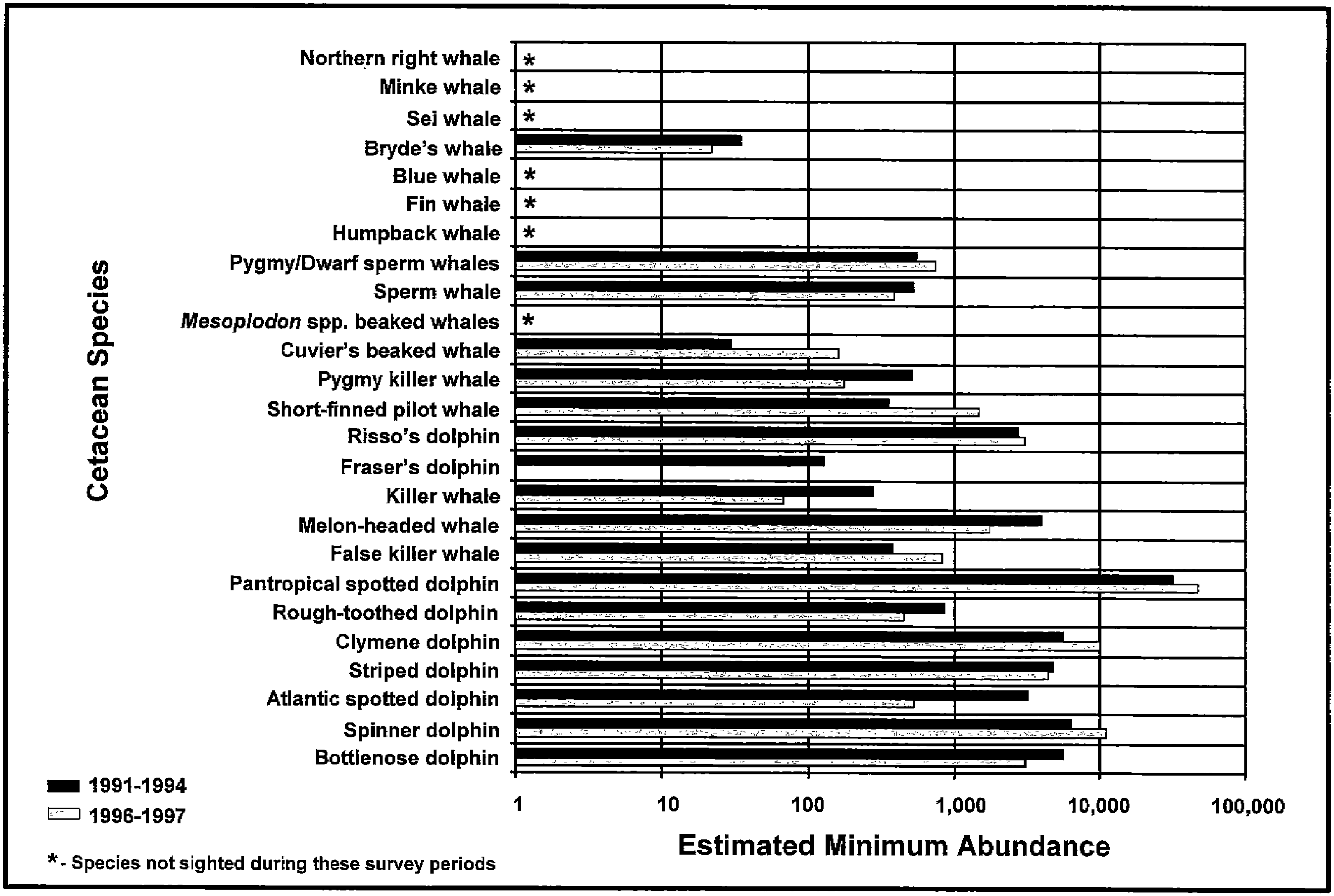

Figure 9.2. Minimum abundance estimates for species sighted within oceanic waters during two survey periods (From: Davis et al. 2000).

habitat partitioning among cetaceans in the Gulf, and stated that species in the northern Gulf were differentiated most clearly with bottom depth (Baumgartner 1995; Davis and Fargion 1996; Davis et al. 1998). For example, GulfCet I and II surveys, along with other historical surveys and opportunistic sightings of cetaceans within the U.S. Gulf of Mexico found that only the bottlenose dolphin and Atlantic spotted dolphin were common inhabitants of the continental shelf. The remaining species of cetaceans known to regularly occur in the Gulf (with possible exception of the Bryde's whale) were sighted on the continental shelf edge and slope (Mullin et al. 1994b; Jefferson 1995).

A major objective of the subsequent GulfCet II program was to correlate a number of environmental parameters, such as selected hydrographic features, with cetacean sightings data in an effort to characterize cetacean habitats in the Gulf of Mexico (Davis et al. 2000). From GulfCet II surveys, sightings of cetaceans along the slope were generally concentrated in cyclones (cold core rings) where production (in this case, measured chlorophyll concentration) was elevated. Sightings of these deepwater species were much less frequent in water depths greater than 2,000 m and in anticyclones (warm core rings). Sperm whales tended to occur along the mid-to-lower slope, near the mouth of the Mississippi River and, in some areas, in cyclones and zones of confluence between cyclones and anticyclones. From these data it was suggested that the greater densities of cetaceans sighted along the continental slope, rather than abyssal areas, of the northern Gulf probably result from localized conditions of enhanced productivity, especially along the upper slope, and as a result of the collisions of mesoscale eddies with the continental margin (Davis et al. 2000).

In the north-central Gulf, the relatively narrow continental shelf south of the Mississippi River delta may be an additional factor affecting cetacean distribution, especially in the case of sperm whales (Davis et al. 2000). Outflow from the Mississippi River mouth transports large volumes of low salinity, nutrient-rich water southward across the continental shelf and over the slope. River outflow may also be entrained within the confluence of a cyclone-anticyclone eddy pair and transported beyond the continental slope. In either case, this input of nutrient-rich water leads to a localized deep-water environment with enhanced productivity and may explain the presence of a resident population of sperm whales within 50 km of the Mississippi River delta in the vicinity of the Mississippi Canyon.

Temporal variability in the distribution of cetaceans in the northern Gulf of Mexico may also be primarily dependent upon the extent of river discharge and the presence and dynamic nature of mesoscale hydrographic features such as cyclones. Consequently, the distribution of cetacean species will change in response to the movement of prey species associated with these hydrographic features. GulfCet I and II survey data determined that most of the cetacean species that were routinely or commonly sighted in the northern Gulf apparently occur in these waters throughout the year, although seasonal abundances of certain species or species assemblages in slope waters may vary (Baumgartner 1995; Davis and Fargion 1996; Davis et al. 1998, 2000). For example, comparisons of summer and winter abundances of commonly sighted species from slope waters suggested that dwarf/pygmy sperm whales and pantropical spotted dolphins may be more abundant during summer, whereas Risso's dolphins may be more abundant during winter. In the case of sperm whales, sightings data indicated that concentrations of whales would shift spatially in association with the presence and dynamics of mesoscale features. Concentrations of sperm whales were sighted near the mouth of the Mississippi River during periods when this area was strongly cyclonic (late summer 1996). This concentration of whales subsequently shifted 100 to 200 km due east over the De Soto Canyon in mid-summer 1997 in response to a similar shift in the relative position of the cyclone (Davis et al. 2000).

## Sea Turtles

Five sea turtle species are known to inhabit the waters of the Gulf of Mexico (**Table 9.2**) (Pritchard 1997). These are the loggerhead, green, hawksbill, Kemp's ridley, and leatherback turtles.

As a group, sea turtles possess elongated, paddlelike forelimbs that are substantially modified for swimming and shells that are depressed and streamlined (Marquez 1990; Ernst et al. 1994; Pritchard 1997). They depend on the land only during the reproduction period, when females emerge to nest on sandy beaches. They are long-lived and slow-maturing. Generally, their distributions are primarily circumtropical, although the various species differ widely in their seasonal cycles, geographical ranges, and behavior. There are also considerable differences in behavior among populations of the same species (Marquez 1990).

Most sea turtles (except perhaps the leatherback) exhibit differential distributions among their various life stages (hatchling, juvenile, adult) (Marquez 1990; Hirth 1997; Musick and Limpus 1997). After reaching the sea, hatchling turtles actively swim directly away from the nesting beach until they encounter zones of water mass convergence and/or sargassum rafts, which are rich in prey and provide shelter (NMFS and FWS 1991b; Hirth 1997). Most then undergo a passive migration, drifting pelagically within prevailing current systems such as oceanic gyres. After a period of years (the number of which varies among species), the juveniles actively move into developmental habitats within shallow waters of the inner continental shelf. When approaching maturity, subadult juvenile turtles move into adult foraging habitats that, in some populations, are geographically distinct from their juvenile developmental habitats (Musick and Limpus 1997).

All sea turtle species that inhabit the Gulf are listed as either endangered or threatened species under the Endangered Species Act of 1973 (Pritchard 1997). It is believed that human activities are the cause of the collapse of sea turtle numbers. These activities impact every stage of their life cycle and include the loss of nesting beach and foraging habitats; harvesting of eggs and adults for consumption; incidental mortalities at sea through pelagic and ground fishing practices; and harm or mortality from increasing loads of nonbiodegradable waste and pollutants (Lutcavage et al. 1997).

Table 9.2. Sea turtles of the Gulf of Mexico

| Scientific Name | Common Name | Status[a] |
|---|---|---|
| Family Cheloniidae | | |
| *Caretta caretta* | Loggerhead turtle | T |
| *Chelonia mydas* | Green turtle | T/E[b] |
| *Eretmochelys imbricata* | Hawksbill turtle | E |
| *Lepidochelys kempi* | Kemp's ridley turtle | E |
| Family Dermochelyidae | | |
| *Dermochelys coriacea* | Leatherback turtle | E |

[a] Status: E = endangered, T = threatened under the Endangered Species Act of 1973.
[b] Green sea turtles are threatened except for Florida breeding populations, which are listed as endangered.

## Species Accounts

The loggerhead (*Caretta caretta*) is a large sea turtle that inhabits the continental shelves and estuaries of temperate and tropical environments of the Atlantic, Pacific, and Indian Oceans. Typically, this species wanders widely throughout the marine waters of its range and is capable of living in varied environments for a relatively long time (Marquez 1990; NMFS and FWS 1991b; Ernst et al. 1994). They may remain dormant during winter months, buried in moderately deep, muddy bottoms (Marquez 1990). Loggerheads are carnivorous and, though considered primarily predators of benthic invertebrates, are facultative feeders over a wide range of food items (Ernst et al. 1994). Loggerheads are considered to be the most abundant sea turtle in the Gulf of Mexico (Dodd 1988). Loggerhead nesting along the Gulf Coast occurs primarily along the Florida panhandle, although some scattered nesting has been reported along the Texas and Alabama coasts as well (NMFS and U.S. Fish and Wildlife Service [USFWS] 1991b). The loggerhead is currently listed as a threatened species.

The green turtle (*Chelonia mydas*) is the largest hardshell turtle and considered to be a circumglobal species. They are commonly found throughout the tropics and as stragglers in a far more extensive area, generally between 40°N and 40°S latitudes (NMFS and USFWS 1991a; Hirth 1997). In the continental United States, they are found from Texas to Massachusetts. Green turtles are omnivorous; adults prefer feeding on plants but juveniles and hatchlings are more carnivorous (Ernst et al. 1994; Hirth 1997). The adult feeding habitats are beds or pastures of seagrasses and algae in relatively shallow, protected waters; juveniles may forage in areas such as coral reefs, emergent rocky bottom, sargassum mats, and in lagoons and bays. Movements between principal foraging areas and nesting beaches can be extensive, with some populations regularly carrying out transoceanic migrations (Hirth 1997; Ernst et al. 1994; NMFS and FWS 1991a). Green turtles occur in some numbers over grass beds along the south Texas coast and the Florida Gulf coast. Reports of nesting along the Gulf of Mexico coast are infrequent, and the closest significant nesting aggregations are along the Florida east coast and the Yucatan Peninsula (NMFS and USFWS 1991a). The green turtle is currently listed internationally as a threatened species internationally and as an endangered species in Florida.

The hawksbill (*Eretmochelys imbricata*) is a small to medium-sized sea turtle that occurs in tropical to subtropical seas of the Atlantic, Pacific, and Indian Oceans. In the continental United States, the hawksbill has been recorded in all the Gulf states and along the Atlantic coast from Florida to Massachusetts, although sightings north of Florida are rare. They are considered to be the most tropical of all sea turtles and the least commonly reported sea turtle in the Gulf of Mexico (Marquez 1990; Hildebrand 1995). Coral reefs are generally recognized as the resident foraging habitat for juveniles and adults. Adult hawksbills feed primarily on sponges and demonstrate a high degree of feeding selectivity on a relatively limited number of sponge species (primarily demosponges) (Ernst et al. 1994). Nesting within the continental United States is limited to southeastern Florida and the Florida Keys. Juvenile hawksbills show evidence of residency on specific foraging grounds, although some migrations may occur (NMFS and USFWS 1993). Some populations of adult hawksbills undertake reproductive migrations between foraging grounds and nesting beaches (Marquez 1990; Ernst et al. 1994). The hawksbill is presently listed as an endangered species.

The Kemp's ridley (*Lepidochelys kempi*) is the smallest sea turtle. This species occurs mainly in the Gulf of Mexico and along the northwestern Atlantic coast as far north as Newfoundland. Juveniles and adults are typically found in shallow areas with sandy or muddy bottoms, especially in areas of seagrass habitat. Kemp's ridleys are carnivorous and feed primarily on crabs, though they also feed on a wide variety of other prey items as well (Marquez 1990; NMFS and USFWS 1992; Ernst et al. 1994). The major Kemp's ridley nesting area is near Rancho Nuevo, along the northeastern coast of Mexico (Tamaulipas). Some scattered nesting also has been reported in other areas of Mexico and Texas, Colombia, Florida, and South Carolina (Ernst et al. 1994). Adult Kemp's ridleys exhibit extensive internesting movements, but appear to travel relatively near the coast, especially within shallow waters along the Louisiana coast. The Kemp's ridley is currently listed as an endangered species.

The leatherback (*Dermochelys coriacea*) is the largest and most distinctive living sea turtle. This species possesses a unique skeletal morphology, most evident within its flexible, ridged carapace, and in cold water maintains a core body temperature several degrees above ambient. They also have unique deep diving abilities. This species is also the most pelagic and most wide-ranging sea turtle, undertaking extensive migrations from the tropics to boreal waters. Though considered pelagic, leatherbacks will occasionally enter the shallow waters of bays and estuaries. Leatherbacks feed primarily on gelatinous zooplankton such as jellyfish, siphonophores, and salps, though they may, perhaps secondarily, ingest some algae and vertebrates (Ernst et al. 1994). Data from analyses of leatherback stomach contents suggest that they may feed at the surface, nocturnally at depth within deep scattering layers, or in benthic habitats. Florida is the only site in the continental U.S. where the leatherback regularly nests (NMFS and USFWS 1992; Ernst et al. 1994; Meylan et al. 1995). The leatherback is currently listed as an endangered species.

## Distribution and Abundance in the Oceanic Northern Gulf of Mexico

As in the case of cetaceans, most historical surveys on the distribution and abundance of sea turtles within the Gulf of Mexico were conducted within coastal waters and on the continental shelf. In 1981, aerial surveys were conducted by the USFWS within relatively small, widely separated blocks which encompassed continental shelf and limited continental slope waters within the central and western Gulf (Fritts et al. 1983a,b). In 1989, systematic aerial surveys were initiated within selected survey blocks over the continental slope off Louisiana and Mississippi by NMFS (Mullin et al. 1991, 1994b). Subsequent, shipboard surveys within a broad area of the oceanic northern Gulf were conducted by NMFS in the springs of 1990 and 1991 (Jefferson 1995). These early study efforts provided the first data pertaining to the distribution and abundance of sea turtles within the OCS and oceanic waters of the northern Gulf of Mexico but provided limited information regarding geographic coverage (Fritts et al. 1983a,b; Mullin et al. 1991, 1994b) or variability in seasonal distributions of sea turtles (NMFS shipboard surveys) (Jefferson 1995). Systematic aerial and shipboard surveys conducted by Texas A&M University during the GulfCet I and II programs represent the most recent assessments of sea turtle distribution and abundance within the oceanic northern Gulf of Mexico (Davis and Fargion 1996; Davis et al. 2000).

During the GulfCet I and II surveys, only two species of sea turtles were sighted within the oceanic northern Gulf: loggerheads and leatherbacks (Davis et al. 2000). Other species of chelonid sea turtles (all species other than the leatherback turtle) were not sighted or identified on the slope during these surveys. However, because of the extensive geographic ranges of these sea turtle species and their known migratory movements between feeding and reproductive habitats, their absence in these survey data does not preclude the possibility of their presence in these deepwater areas. In addition, the presence and movements of juvenile turtles, especially Kemp's ridleys, within the oceanic waters of the Gulf of Mexico remains unknown.

GulfCet I and II surveys found the abundance of sea turtles in the Gulf of Mexico significantly greater within the eastern Gulf, east of Mobile Bay (Lohoefener et al. 1990; Davis et al. 2000). Sightings of loggerhead turtles were significantly higher on the continental shelf than the slope. The overall abundance estimate of loggerheads from GulfCet II surveys was 147 individuals. Loggerheads over the slope were about 12 times more abundant in winter than summer. This difference was considered statistically significant. There were also winter sightings of individual loggerheads over very deep waters (>1,000 m). The significance of the oceanic Gulf to loggerheads was not identified from these surveys, though it was suggested that they may traverse these waters in order to reach distant foraging sites or to seek warmer waters during winter (Davis et al. 2000). Historic sightings data suggest that leatherback turtles appear to spatially utilize both shelf and slope habitats in the Gulf of Mexico (Fritts et al. 1983a,b; Collard 1990; Davis and Fargion 1996). The overall abundance estimate of leatherbacks on the slope from GulfCet II surveys was 168 individuals. Leatherback densities were about 2.5 times more abundant in summer than winter surveys, though this difference was not considered statistically significant. Disjunct summer and winter distributions of leatherbacks suggest that specific areas may be important to this species, either seasonally or for short periods of time. For example, GulfCet I and II survey data show that the region from Mississippi Canyon to De Soto Canyon, especially near the shelf edge, may be an important habitat for this species. In addition, the high variability in the relative numbers of individual leatherbacks sighted within specific areas, such as concentrations of leatherbacks sighted during GulfCet I surveys, suggest that their distributional patterns were irruptive in nature (Davis et al. 2000).

## Sensitivity to Oil and Gas Exploration and Development

Major impact producing factors from deepwater oil and gas exploration and development on marine mammals and sea turtles include degradation of water quality resulting from operational discharges; noise from platforms, drillships, service vessels, helicopters, and seismic surveys; oil spills and oil spill response activities; discarded debris from OCS structures and service vessels; and collisions with service vessels. Sea turtles may be attracted to fixed offshore petroleum platforms and consequently may be at greater risk of impacts from OCS activities than marine mammals (Lohoefener et al. 1990).

The major operational discharges generated during offshore oil and gas exploration and development include drilling fluids, cuttings, and produced waters. Many operational discharges include components or compounds that may be injurious to marine mammals and sea turtles. However, most waste fluids are treated prior to discharge, and plumes of released wastes mix rapidly with ambient seawater and are thus diluted. These discharged fluids may, however, have sublethal effects on marine mammals or sea turtles either indirectly, as a result of their impacts on prey species (reduction in prey), or possibly directly through prolonged exposure to the discharge or through the ingestion of affected prey species (National Research Council 1983; American Petroleum Institute 1989; Kennicutt 1995).

Fixed production facilities and drillships, and OCS-related helicopter and service-vessel traffic produce a broad array of sounds at frequencies and intensities that may be detected by marine mammals and sea turtles (Geraci and St. Aubin 1987). These sounds could directly and adversely affect cetaceans by physically injuring their hearing; producing behavioral or physiological disturbances which may disrupt normal activities or lead to short- or long-term displacement from areas which may be important for feeding or reproduction; or masking their ability to utilize (i.e., receive) sounds produced for echolocation or communication (Richardson et al. 1995). Sound may also disperse potential cetacean prey species (National Research Council 1994). Studies involving turtle hearing sensitivity or noise-induced stress are limited (Geraci and St. Aubin 1987). Impacts related to OCS-related sounds on sea turtles may include behavioral disruption, temporary or permanent displacement from the area near the sound source, and potential long-term effects such as hearing loss.

Seismic activity may affect the distribution of marine mammals and sea turtles. During the GulfCet I field surveys, it was noted that groups of sperm whales were displaced from or moved away from an area for several days subsequent to the onset of a seismic survey (Mate et al. 1994; Davis and Fargion 1996). These observations suggest that this group of sperm whales was temporarily displaced as a result of activities associated with the seismic survey. Acoustic surveys conduced during the GulfCet II program measured pulsed signals from a seismic survey vessel. These data suggest that these low frequency signals (2.5 kHz with little energy below 1 kHz) were probably audible to sperm whales or mysticete whales in the area. In addition, acoustic and visual data were examined from periods when seismic surveys were underway in an effort to detect whether these seismic signals affected cetacean distribution. Results from these analyses suggested that there were no significant differences between overall sighting rate (and distribution) and sound level for cetaceans, including sperm whales (Davis et al. 2000). However, seismic signals used during this study were measured from distant vessels and the received seismic pulses were thus relatively low in intensity and frequency. Many cetaceans and sea turtles habituate to low level background noise and coexist with human activities. Historical records show the presence of sperm whales near the mouth of the Mississippi over a period of many years. During this period, this area has been exposed to a variety of sources of anthropogenic noise and recently is the site of intense oil and gas industry activity and heavy seismic exploration. The continued presence of sperm whales near the mouth of the Mississippi River suggest either tolerance or insensitivity to various sources of anthropogenic noise in sperm whales (Davis et al. 2000).

OCS service helicopters and surface vessels can affect cetaceans and sea turtles from machinery noise and/or visual disturbances (Richardson et al. 1995). The degree of impacts associated with helicopter and service vessel traffic appear to be highly variable, though transient, and cause short-term behavioral changes such as disruption of activities or departure from the area of disturbance (Davis and Fargion 1996). Areas with heavy vessel traffic may be avoided by cetaceans and sea turtles, although generally most cetaceans exhibit considerable tolerance to ship and aircraft noise.

Spilled oil may affect marine mammals and sea turtles through various pathways: direct contact; inhalation of oil or related volatile distillates; ingestion of oil (directly, or indirectly through the consumption of oiled prey species); and impairment of feeding by fouling of baleen (in mysticetes) or ingestion of floating tar by turtles (Geraci 1990). Studies have shown that direct contact of oil with sensitive tissues such as eyes and other mucous membranes produce irritation and inflammation. Cetacean skin may also experience irritation when exposed to oil or petroleum products such as fuels in high concentrations or long exposure (Geraci and St. Aubin 1987). However, under less extreme exposures (concentrations or durations) or contact, oil does not appear to readily adhere to or be absorbed through cetacean skin. Cetacean skin may therefore serve somewhat as a barrier to substances such a allergenic hydrocarbons in the marine environment (Harvey and Dahlheim 1994). Nevertheless, cetaceans observed in or within the proximity of surface oil associated with the *Exxon Valdez* spill showed no evidence of avoidance or abnormal behavior when swimming near or within oil. Their lack of response may then subject them to increased levels of exposure to spilled surface oil (Harvey and Dahlheim 1994). Oil can adhere to turtle skin or shells; however, no evidence of resultant tissue damage exists. Marine mammals or turtles surfacing within or near an oil spill may inhale petroleum vapors. Small doses of oil, when aspirated, have been shown to cause acute fatal pneumonia in mammals. Studies on effects of petroleum vapors on terrestrial mammals and seals showed (in cases of prolonged exposures and high concentrations) absorption of hydrocarbons in organs and other tissues, and damage to the brain and central nervous system. However, short-term inhalation of petroleum vapors at concentrations similar to those found in oceanic oil spills may not be necessarily detrimental either in terms of structural tissue damage or respiratory gas exchange. Sea turtles have shown apneic response when confronted with disagreeable odors and may thus be able to minimize their exposure to inhaled petroleum vapors. Ingested oil, particularly the lighter fractions, can be toxic to marine mammals and sea turtles. Ingested oil can remain within the gastrointestinal tract and be absorbed into the bloodstream and thus irritate and/or destroy epithelial cells in the stomach and intestine. Certain constituents of oil, such as aromatic and polycyclic aromatic hydrocarbons, include some well-known carcinogens. These substances, however, do not show significant biomagnification in food chains and are readily metabolized by many organisms. Hatchling and juvenile turtles feed opportunistically at or near the surface in oceanic waters, and are especially sensitive to spilled oil and oil residues such as floating tar (Lutz and Lutcavage 1987; Lutcavage et al. 1995). Tar found in the mouths of turtles may have been selectively eaten or ingested accidentally while feeding on organisms or vegetation bound by tar (Geraci and St. Aubin 1987; Geraci 1990). Spilled oil may also foul the baleen fibers of mysticete whales, thereby impairing food-gathering efficiency or result in the ingestion of oil or oil contaminated prey (Geraci and St. Aubin 1987). Oil spill response activities that may affect both cetaceans and sea turtles involve the application of dispersant chemicals to spilled surface oil. These dispersant chemicals contain toxic constituents that are considered to be low when compared to toxic constituents of spilled oil (Wells 1989). There are currently little available data regarding the effects of oil dispersants or coagulants on marine mammals or sea turtles (Tucker and Associates, Inc. 1990). Certain species or stocks of marine mammals or sea turtles may be at greater potential risk from spilled oil, based on their relative exposures. These include those species or stocks that may inhabit or frequent restricted areas such as bays and estuaries (e.g., coastal bottlenose dolphins or Kemp's ridley turtles), or those with particular feeding strategies or a dependence on selected localized habitats for feeding, shelter, or reproduction (e.g., surface-feeding baleen whales, sperm whales off the Mississippi River mouth, and post-hatchling sea turtles in offshore debris lines [convergence zones]) (Würsig 1990; B.E. Witherington 2000, personal communication, Florida Marine Research Institute, Melbourne Beach, FL).

Ingestion of, or entanglement with, solid debris can adversely impact marine mammals and sea turtles (Carr 1987). Ingestion of plastic debris can impact the alimentary canal or remain within the stomach. Certain species of sea turtles, such as loggerhead and leatherback turtles, appear to ingest more debris than other species (Lutcavage et al. 1995). Recent survey data suggest that these species are the most commonly sighted adult sea turtles in the oceanic waters of the Gulf of Mexico (Davis et al. 2000). Entanglement in plastic debris can result in reduced mobility, drowning, and constriction of and subsequent damage to limbs (Lutcavage et al. 1995). Currently, the discharge or disposal of solid debris from both OCS structures and vessels is prohibited by the MMS to lessees (30 CFR 250.40) and the U.S. Coast Guard (MARPOL, Annex V, Public Law

100-220 [101 Statute 1458]). Therefore, debris from OCS activities is not expected to significantly adversely affect marine mammals or sea turtles in the Gulf.

Increased service vessel traffic associated with offshore OCS activities may increase the probability of collisions between vessels and cetaceans and sea turtles, especially at night and during periods of reduced visibility. Certain marine mammals, such as deep diving species that spend extended periods of time at the surface (such as sperm whales), may be particularly vulnerable to collisions with offshore vessels. Because of their relatively small size and dark coloration on their dorsal surfaces (especially in the case of rafting hatchlings and small juveniles), sea turtles resting on the surface or just below the surface may be difficult to sight from moving vessels. Individual turtles that may be attracted to offshore platforms are also at greater risk of collision with OCS service vessels.

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# Chapter 10: Fishes and Fisheries

*David B. Snyder*

## Deepwater Fishes

### Introduction

The Gulf of Mexico with its great variety of estuarine, coastal, and shelf habitats supports a diverse ichthyofauna. Several general reviews, compilations, and taxonomic guides exist for fishes of the inshore and shelf regions of the Gulf (Rivas 1954; Briggs 1973; Walls 1975; Darnell and Kleypas 1987; Hoese and Moore 1998). But until recently, there have been no comprehensive taxonomic or ecological accounts of the Gulf's deepwater fishes—those inhabiting the pelagic and demersal habitats beyond the continental shelf break. Potts and Ramsey (1987) produced a guidebook for deepwater fishes of the Gulf of Mexico, and more recently, McEachran and Fechhelm (1998) published the first of a two volume systematic summary of Gulf of Mexico fishes that included deepwater species. With this taxonomic foundation now in hand, the stage is set for an ecological summary of knowledge concerning Gulf of Mexico deepwater fishes.

This section reviews the available information on the taxonomic composition and ecological characteristics of fish assemblages inhabiting pelagic and demersal components of the Gulf of Mexico deepwater (>200 m) environment. The pelagic component may be further subdivided into three depth-related layers: epipelagic (0 to 200 m), mesopelagic (200 to 1,000 m), and bathypelagic (>1,000 m) (**Figure 10.1**). These subdivisions reflect to some degree concomitant patterns in physical environmental variables such as light, temperature, and dissolved oxygen. In some cases, the distinction between mesopelagic and bathypelagic is blurred, so the term midwater is used when referring to these two zones collectively. The demersal component simply consists of the

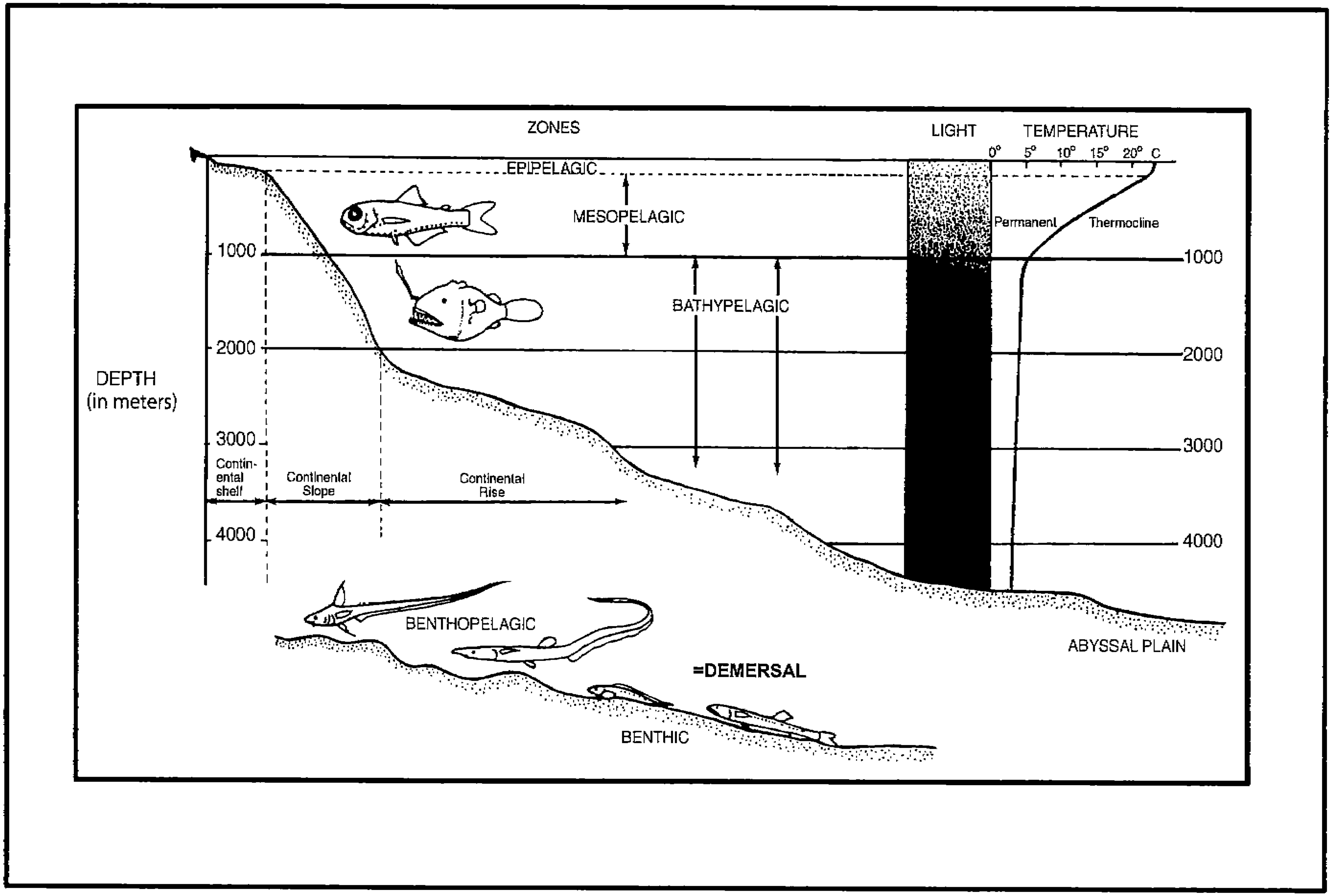

Figure 10.1. Diagram of the environmental framework used to describe deepwater fishes of the Gulf of Mexico (Adapted from: Helfman et al. 1997).

seafloor seaward of the continental shelf break (or about 200 m) including, where applicable, the continental slope, continental rise, and abyssal plain. This general pelagic/demersal scheme has been effectively used to frame discussions of deep-sea fishes in other regions (e.g., Marshall 1979; Haedrich 1997; Merrett and Haedrich 1997).

## History of Deepwater Fish Sampling in the Gulf of Mexico

Biological sampling in the deep-sea is costly and time-consuming, requiring large vessels equipped with specialized gear. Despite the onerous nature of deepwater investigations, numerous sampling programs have been conducted in the Gulf of Mexico over the past 100 years that either directly or indirectly targeted deepwater fishes. During the first such program, which extended from 1877 to 1880, A. Agassiz aboard the U.S. Coast Survey steamer BLAKE collected the first samples of deepwater (to 3,658 m) fishes from the Gulf of Mexico (Pequegnat 1976). These efforts consisted mainly of bottom trawling and dredging, but midwater fishes were collected as trawls were retrieved through the water column. In 1884, the U.S. Fish Commission vessel ALBATROSS also made some deepwater collections in the Gulf of Mexico. Goode and Bean (1896) later described many of the fishes collected in Gulf waters by the BLAKE and the ALBATROSS. With the exception of a few collections made near the Dry Tortugas in the late 1930's by W.H. Longley (Longley and Hildebrand 1941), there was a hiatus in sampling of the deep Gulf until the 1950's. At this time, the Bureau of Commercial Fisheries vessel OREGON and to a lesser extent the vessels SILVER BAY, COMBAT, and PELICAN began exploratory fishing in the Gulf of Mexico. Although these vessels mostly sampled shelf waters, some deepwater stations were sampled with pelagic and bottom tending gear types, and these efforts continue today with the NMFS vessel OREGON II. Most of the early efforts were under the direction of H.R. Bullis and S. Springer (Springer and Bullis 1956; Bullis and Thompson 1965). Many of the fishes collected during these surveys contributed to publications on deepwater demersal fishes (Grey 1956, 1958, 1959; Nelson and Carpenter 1968; Gutherz 1967; Rohr and Gutherz 1997) and epipelagic fishes (Bullis 1955a,b; Iwamoto 1965).

The next series of deepwater collections were made from 1964 to 1973 under the supervision of W.E. Pequegnat of Texas A&M University (Pequegnat 1976, 1983). Pequegnat's sampling program, conducted aboard the research vessel ALAMINOS, primarily focused on the demersal environment. Bottom trawls, dredges (including a skimmer dredge), and benthic photographs were taken at 264 stations in water depth ranging from 81 to 3,493 m across the northern Gulf of Mexico. Samples collected during these cruises provided an information base from which several dissertations and theses were produced, some of which focused directly (Bright 1968; Rayburn 1975; Martin 1978) or indirectly (Roberts 1977) on fishes. Also during the same period, 38 midwater (0 to 3,600 m) fish collections were made throughout the Gulf of Mexico with an Isaacs-Kidd midwater trawl (Bright and Pequegnat 1969; Murdy et al. 1983). Other collections of midwater fishes were made in the 1960's by Russian and Cuban investigators aboard the ALEXANDER KOVALEVSKII (Rass 1971) and by Woods Hole Oceanographic Institution (Backus et al. 1977).

In 1971, T.L. Hopkins at the University of South Florida began a sampling program that focused on mesopelagic fishes and invertebrates (micronekton). His program continued for 20 years with 24 sampling cruises made aboard various research vessels to the same "standard station" in the eastern Gulf of Mexico (27°N Lat, 86°W Long). Using nets capable of being closed at discrete depths (Tucker trawls and MOCNESS nets), Hopkins and his students amassed considerable information on species composition, life histories, vertical migration, and feeding ecology of mesopelagic fishes (e.g., Hopkins and Lancraft 1984; Gartner et al. 1987; Sutton and Hopkins 1996a,b; Hopkins et al. 1997).

Finally, in the early 1980's the MMS funded a series of studies investigating the continental slope biota of the northern Gulf of Mexico. These studies were conducted by LGL Ecological Research Associates, Inc and Texas A&M University (LGL and TAMU 1985, 1986; Gallaway 1988; Gallaway et al. 1988). Bottom trawl samples were collected during five cruises made from 1983 to 1985. In all, 59 stations were sampled along three downslope transects and along selected depth contours in the western, central, and eastern Gulf. Information on the density, diversity, distribution, and food habits of demersal fishes was obtained during the biological sampling portion of these efforts.

## Epipelagic Fishes

A diverse assemblage of epipelagic fishes inhabits the euphotic zone, the upper 200 m layer of the Gulf of Mexico. The most recognizable members of this assemblage are tunas, billfishes, dolphins, and sharks. Lesser known representatives include driftfishes, oarfishes, opahs, flyingfishes, and molas. A phylogenetic listing of epipelagic fishes reported from the Gulf of Mexico is given in **Table 10.1**. The overall assemblage is composed of 10 orders with 34 families containing 120 species. The most diverse orders are Perciformes (perch-like fishes), Beloniformes (flyingfishes and halfbeaks), and Tetraodontiformes (molas, triggerfishes, and puffers).

As mentioned above, there has been little direct scientific investigation into any aspect of the epipelagic assemblage. Not surprisingly, much of what is known has been collected only for the economically important species such as tunas and billfishes. Exploratory fishing expeditions by the U.S. Bureau of Commercial Fisheries and observations of commercial longline fisheries have provided information on species composition, distribution, abundance and behavior of sharks, tunas, and billfishes (Springer 1957; Iwamoto 1965; Bransetter and McEachran 1983; Anderson 1985, 1990; Russell 1993). Biological data (size, age, and reproductive condition) on billfishes and tunas have been gathered by researchers visiting recreational fishing tournaments held along the Gulf coast (NMFS 1999a). Recently, J. Franks and colleagues of the Gulf Coast Research Laboratory have investigated age, growth, reproduction, and stock identity in wahoo (*Acanthocybium solandri*) using specimens obtained from recreational fishing tournaments. Information on spawning of tunas and other species has been inferred from larval fish collections made in the eastern Gulf (e.g., McGowan and Richards 1989; Richards et al. 1989).

Table 10.1. Orders and families of epipelagic (0 to 200 m) fishes known from the Gulf of Mexico, arranged in phylogenetic order

- Order Orectolobiformes
    - Rhincodontidae (whale shark)
- Order Lamniformes
    - Alopidae (thresher sharks)
    - Cetorhinidae (basking shark)
    - Lamnidae (mackerel sharks)
- Order Carcharhiniformes
    - Carcharhinidae (requiem sharks)
- Order Myliobatiformes
    - Dasyatididae (stingrays)
    - Mobulidae (mantas)
- Order Lampridiformes
    - Lampridae (opah)
    - Lophotidae (crestfishes)
    - Regalecidae (oarfishes)
- Order Lophiiformes
    - Antennariidae (frogfishes)
- Order Beloniformes
    - Belonidae (needlefishes)
    - Exocoetidae (flying fishes)
    - Hemiramphidae (halfbeaks)
- Order Syngnathiformes
    - Syngnathidae (pipefishes)
- Order Perciformes
    - Echeneidae (shark suckers)
    - Carangidae (jacks)
    - Coryphaenidae (dolphins)
    - Bramidae (pomfrets)
    - Lobotidae (tripletail)
    - Kyphosidae (chubs)
    - Gempylidae (snake mackerels)
    - Istiophoridae (billfishes)
    - Xiphiidae (swordfish)
    - Scombridae (tunas and mackerels)
    - Centrolophidae (driftfishes)
    - Nomeidae (man-o-war fish)
    - Ariommatidae (ariommatids)
    - Stromateidae (driftfishes)
- Order Tetraodontiformes
    - Monacanthidae (filefishes)
    - Diodontidae (puffers)
    - Molidae (molas)

The most frequently caught tuna species during exploratory fishing trips were skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*), blackfin (*T. atlanticus*), and bluefin (*T. thynnus*). The highest catches of tunas were made along the 1,000 fm curve east of the Mississippi delta (Bullis 1955b ; Iwamoto 1965). The most common sharks in deepwater catches were silky (*Carcharhinus falciformis*), spinner (*C. brevipinna*), and sandbar (*C. plumbeus*) (Anderson 1985, 1990; Russell 1993).

The distribution and abundance of epipelagic species is influenced by several interrelated variables: water temperature, thickness of the isothermic layer, circulation patterns, and biological productivity (Parin 1968). Fishermen contend that yellowfin tuna aggregate near sea surface temperature boundaries or water mass convergence zones; however, Power and May (1991) found no correlation between longline catches of yellowfin tuna and sea surface temperature in the Gulf of Mexico. A consequence of water mass convergence zones is the surface accumulation of flotsam and Sargassum (Carr 1986). This drifting material plays an important ecological role as habitat for many fishes.

Floating seaweed (Sargassum), jellyfishes, siphonophores, and driftwood attract juvenile and adult epipelagic fishes. Larger predators forage around flotsam. As many as 54 fish species are closely associated with floating Sargassum at some point in their life cycle, but only 2 spend their entire lives there: the sargassumfish and the sargassum pipefish (Adams 1960; Dooley 1972; Bortone et al. 1977). Most fish associated with Sargassum are temporary residents, such as juveniles of species that reside in shelf or coastal waters as adults (Dooley 1972; Bortone et al. 1977). However, several larger species of recreational or commercial importance including dolphinfish, yellowfin tuna, blackfin tuna, skipjack tuna, Atlantic bonito, little tunny, and wahoo feed on the small fish and invertebrates attracted to Sargassum (Manooch et al. 1983; Manooch and Mason 1984; Morgan et al. 1985).

Some epipelagic fishes also exhibit another behavioral phenomenon related to flotsam attraction: affinity for large moored objects. This is often referred to as the FAD (fish attracting device) effect, and it has been documented in various regions of the world for tunas, dolphins, and other species (e.g., Holland et al. 1990; Higashi 1994; Relini et al. 1994). In many areas of the world, fishers have taken advantage of this behavior by deploying FADs to attract tunas and other species. Deepwater oil and gas structures in the Gulf of Mexico act as large FADs and attract epipelagic fishes of all kinds.

Information on spawning of tunas and other species has been inferred from larval fish collections made in the eastern Gulf (e.g., McGowan and Richards 1989; Richards et al. 1989, 1993). Much of the information available on spawning in epipelagic fishes points to the importance of temperature gradients and mesoscale oceanographic features. Spawning by bluefin tuna in the Gulf of Mexico appears to be associated with the Loop Current (McGowan and Richards 1989). Adult bluefin tuna migrate into the Gulf of Mexico in springtime and spawn. This appears to be the only major spawning area for the western Atlantic bluefin stock (NMFS 1999a). Yellowfin and skipjack tuna also spawn in the Gulf of Mexico (NMFS 1999a). Other, noncommercially important species such as big-eye cigarfish (*Cubiceps pauciradiatus*) also spawn along the edge of the Loop Current (Richards et al. 1993; Lampkin 1997).

### Mesopelagic Fishes

Mesopelagic fishes are generally found from 200 to 1,000 m depths in the water column. This group is phylogenetically primitive and among the most morphologically specialized of fishes (Marshall 1979). Their long evolutionary history has presumably allowed for the adaptive radiation that has occurred in response to the cold, dark midwater environment (Marshall 1979). Mesopelagic fish assemblages in the Gulf of Mexico are taxonomically diverse, consisting of eight orders comprising 30 families with 213 species (**Table 10.2**). The most specious groups are stomatiids (dragonfishes), myctophids (lanternfishes), and gonostomatids (bristlemouths). These and all other taxonomic groups listed in **Table 10.2** are entirely restricted to the midwater environment. The Stomiidae with 73 species are the most diverse family of fishes known for the Gulf of Mexico (Sutton and Hopkins 1996a; McEachran and Fechhelm 1998). The second most diverse group is the myctophids represented by 49 species in the Gulf of Mexico (Backus et al. 1977; Gartner et al. 1987).

T.L. Hopkins, his students, and colleagues have contributed most of the information on mesopelagic fish ecology in the Gulf of Mexico. This group has published data on species composition, abundance, biomass, vertical migration patterns, reproductive patterns, and trophic structure for the common families. Common families include gonostomatids, myctophids, sternoptychids (hatchetfish), and stomiids (e.g., Hopkins and Lancraft 1984; Hopkins and Baird 1985b; Gartner et al. 1987; Gartner 1993; Sutton and Hopkins 1996a).

Table 10.2. Orders and families of mesopelagic and bathypelagic fishes known from the Gulf of Mexico, arranged in phylogenetic order (following McEachran and Fechhelm 1998)

**MESOPELAGIC (200-1,000 m)**

- Order Anguilliformes
  - Nemichthyidae (snipe eels)
- Order Osmeriformes
  - Microstomatidae (microstomatids)
- Order Stomiiformes
  - Gonostomatidae (bristlemouths)
  - Sternoptychidae (marine hatchetfishes)
  - Phosichthyidae (lightfishes)
  - Astronesthidae (snaggletooths)
  - Chauliodontidae (viperfishes)
  - Idiacanthidae (black dragonfishes)
  - Malacosteidae (loosejaws)
  - Melanostomidae (scaleless dragonfishes)
  - Stomiidae (scaly dragonfishes)
- Order Aulopiformes
  - Giganturidae (giganturids)
  - Aulopidae (flagfins)
  - Scopelarchidae (pearleyes)
  - Alepisauridae (lancetfishes)
  - Evermannellidae (sabertooth fishes)
  - Paralepididae (barracudinas)
- Order Myctophiformes
  - Myctophidae (lanternfishes)
  - Neoscopelidae (neoscopelids)
- Order Lampridiformes
  - Stylephoridae (tube-eye)
  - Trachipteridae (ribbonfishes)

**MESOPELAGIC (200-1,000 m) (continued)**

- Order Stephanoberyciformes
  - Gibberichthyidae
  - Melamphaidae (bigscales)
  - Stephanoberycidae
  - Barbourisiidae
  - Cetomimidae (whalefishes)
  - Mirapinnidae
  - Rondeletiidae
- Order Beryciformes
  - Anoplogasteridae (fangtooth)
  - Diretmidae (spinyfins)

**BATHYPELAGIC (>1,000 m)**

- Order Osmeriformes
  - Argentinidae (argentines)
  - Bathylagidae (deep-sea smelts)
  - Opisthoproctidae (spookfishes)
  - Platytroctidae (tubeshoulders)
- Order Aulopiformes
  - Notosudidae
  - Omosudidae
- Order Gadiformes
  - Melanonidae (pelagic cods)
- Order Lophiiformes
  - Ceratiidae (seadevils)
  - Diceratiidae (deep-sea anglers)
  - Himatolophidae (football fishes)
  - Linophrynidae
  - Melanocetidae
  - Oneirodidae

Mesopelagic fishes tend to be small and can be extremely abundant; they are often responsible for the deep scattering layer in sonar images of the deep sea. Gonostomatids (bristlemouths) numerically dominated mesopelagic fish collections in the Gulf of Mexico (Murdy et al. 1983; Hopkins and Lancraft 1984). The genus *Cyclothone* contributed 34% of the numbers (1 to 2 fish·m$^{-2}$) of micronekton in the upper 1,000 m (Hopkins and Lancraft 1984). Another species, *Gonostoma elongatum*, exhibited a density of 0.2 fish·m$^{-2}$ and standing stock of 75.6 mg·m$^{-2}$ (dry weight) (Lancraft et al. 1988). The second most abundant group was the myctophids (lanternfishes). The most abundant myctophid species in the eastern Gulf were *Ceratoscopelus warmingii*, *Notolychnus valdiviae*, *Lepidophanes guentheri*, *Lampanyctus alatus*, *Diaphanus dumerilii*, *Benthosema suborbitale*, and *Myctophum affine* (Gartner et al. 1987). The most common sternoptychids (hatchetfishes) collected were *Argyropelecus aculeatus*, *A. hemigymnus*, *Sternoptyx diaphana*, and *S. psuedobscura* (Hopkins and Baird 1985b). These four species ranged in abundance from 0.021 to 0.053 fish·m$^{-2}$ in the upper

1,000 m (Hopkins and Baird 1985b). For the entire stomiid assemblage sampled in the upper 1,000 m of the eastern Gulf, minimum biomass and standing stock estimates were 1.86 individuals·m$^{-2}$ and 35.3 kg·km$^{-2}$ (dry weight). The most abundant stomiid species were *Photostomias guernei, Chauliodus sloani,* and *Stomias affinis.*

A common characteristic of mesopelagic fishes is the phenomenon of diel vertical migration. Many species will migrate vertically each night from depths of 400 to 800 m into epipelagic waters, often reaching the surface. This phenomenon has been studied for several of the common Gulf of Mexico species and three basic patterns have been found: synchronous migration, asynchronous migration, and no migration. Synchronous migration is when all individuals of a species undergo nocturnal vertical migration. Individuals of *Gonostoma elongatum* were found to migrate synchronously, moving from daytime depths of 425 to 725 m to 25 to 325 m depths at night (Lancraft et al. 1988). This species migrated as much as 400 m vertically, but never occurred above the 25 m layer. Myctophids, also synchronous migrators, spend the daytime in depths of 200 to 1,000 m, but migrate vertically at night into near-surface waters. Individual myctophid species migrated in patterns that formed a complex series of layers of migrating fishes that clearly separated into 5 day and 5 night groups (Gartner et al. 1987). Four stomiid species of the genus *Astronesthes* also migrated synchronously between 400 to 700 m and 0 to 200 m. There was also circumstantial evidence of bathypelagic (below 1,000 m) to epipelagic (0 to 300 m) migration by two other stomiid species, *Echiostomias barbatum* and *Leptostomias bilobatus* (Sutton and Hopkins 1996a). The most abundant stomiids (*P. guernei, C. sloani,* and *S. affinis*) were asynchronous vertical migrators; about half of the individuals migrated from 500 to 900 m depths to 20 to 300 m at night while other half of the individuals remained at daytime depths (Sutton and Hopkins 1996a). Hatchetfishes of the genus *Sternoptyx* were found not to migrate and remained in 500 to 800 m depths throughout the diel cycle (Hopkins and Baird 1985b). Two species of the genus *Argyropelecus* did migrate into the epipelagic zone at night to feed upon zooplankton.

Feeding cycles correspond closely with vertical migratory patterns in mesopelagic fishes, and hunger may be an important driving force behind diel migrations. Many midwater species depend upon the food-rich epipelagic layers to fulfill their daily energy requirements. In general, three feeding guilds are recognized for mesopelagic fishes: micronekton feeders, zooplankton feeders, and generalists (Gartner et al. 1997). Representatives from all of these groups occur in the Gulf of Mexico (Hopkins et al. 1997). Myctophids, sternoptychids, and gonostomatids were the primary zooplankton feeding taxa. They consumed 31%, 27%, and 14% of the planktonic food biomass eaten daily by the midwater assemblage (Hopkins et al. 1997). The primary fish-consuming family was the Stomiidae, accounting for 61% of all fish eaten.

Myctophids fed mostly on crustacean zooplankton (copepods) (Hopkins and Baird 1985a; Hopkins and Gartner 1992; Hopkins et al. 1997). The hatchetfish *A. aculeatus* appeared to migrate vertically into the epipelagic zone where young stages consumed ostracods and copepods and larger individuals consumed pteropods and euphausiids. All size classes of *A. hemigymnus* foraged at 300 to 500 m on ostracods and copepods. Juvenile

*S. diaphana* ate copepods, ostracods, and amphipods, and adults consumed mostly amphipods and euphausiids in water depths of 500 to 800 m. *S. hemigymnus* remained below 800 m where juveniles fed upon copepods, polychaetes, and euphausiids, and adults fed upon amphipods and fishes (Hopkins and Baird 1985b). The gonostomatid *G. elongatum* fed mainly upon copepods and ostracods as young individuals, and on euphausiids as adults mostly at night in the epipelagic zone (Lancraft et al. 1988).

Stomiids proved to be an important upper level group of predators in the pelagic food web (Sutton and Hopkins 1996a). The stomiid assemblage formed four basic categories with respect to food habits: myctophid predation, zooplankton/small micronekton predation, penaeidean shrimp predation, and copepod/micronekton predation (Sutton and Hopkins 1996b). The stomiids investigated were selective with respect to prey items ingested. Stomiids inflict the highest predation impact on myctophids in low-latitude ecosystems, and historic use of predation-avoidance arguments to explain certain mesopelagic phenomena (e.g., vertical migration, ventral photophores) appears to be substantiated. The stomiids may be important in the transport of energy from the mesopelagic to the bathypelagic and benthopelagic.

Hopkins and colleagues (Gartner et al. 1987; Hopkins and Gartner 1992; Hopkins et al. 1997; Hopkins and Sutton 1998) interpreted much of the observed interplay between vertical migration and feeding mode in the light of ecological competition among fish and invertebrate species. Considerable dietary overlap was found among the abundant myctophid species that inhabit the epipelagic zone at night (Hopkins and Gartner 1992). When both vertical distribution and diet were considered together, little inter- or intra-specific overlap occurred. This was construed as a prime example of resource partitioning that evolved in response to competition during the evolution of the midwater ecosystem. The high degree of overlap in diet allows species packing in an otherwise structureless water column (the epipelagic zone at night).

The daily consumption of the eastern Gulf midwater assemblage was estimated to be 2.5 to 4.3 kg $C \cdot km^{-2}$ in the upper 1,000 m (Hopkins et al. 1997). Most (80%) of this was provided by zooplankton and the remainder was larger prey, mostly fish. The ingestion rates accounted for only 5% to 10% of the daily production, but 95% of fish daily production. These dietary findings agree with similar studies performed in other oligotrophic regions of the oceans. In Chapter 6 of this report, Biggs and Ressler argue that for areas other than the eastern Gulf, and where productivity "hot spots" occur, the pelagic environment is more productive, or mesotrophic.

## Bathypelagic Fishes

The deeper dwelling bathypelagic fishes inhabit the water column at depths greater than 1,000 m and seldom migrate into shallower waters. This group is composed of bizarre, little-known species such as gulper eels, slickheads, deep-sea anglers, bigscales, and whalefishes (McEachran and Fechhelm 1998). There are 4 orders, 13 families, and 49 species known for the Gulf of Mexico. Many of these species also occur above 1,000 m. Like mesopelagic fishes, most species are capable of producing and emitting light (bioluminescence) to aid in communicating in an environment devoid of sunlight. Like the mesopelagic fishes, these species display some of the most interesting evolutionary adaptations to the deep-sea environment. Unfortunately, there have been no studies directed at bathypelagic fishes in the Gulf of Mexico.

## Demersal Fishes

Demersal fishes are those that are either in direct contact with the substrate or hover above it from the shelf slope transition to the abyssal plain. The taxonomic composition of the demersal ichthyofauna in the Gulf of Mexico includes 27 orders with 70 families representing 300 species (**Table 10.3**). The most diverse order is the Gadiformes (cod-like fishes) with 7 families and 44 species followed by Anguilliformes (eels) with 5 families and 35 species, Ophidiiformes (brotulas and cusk-eels) with 4 families and 33 species; and Perciformes (perch-like fishes) with 10 families and 28 species.

Representatives of these groups were collected during the MMS-sponsored demersal sampling programs summarized by Pequegnat (1983) and Gallaway et al. (1988). These two programs have provided the most comprehensive data available on the demersal assemblage. The latter program collected samples from eastern, central, and western transects which allowed some spatial comparisons to be made in species composition, density, diversity, food habits and depth-related zonation patterns.

The five most abundant species collected during Pequegnat's sampling program were *Gadomus longifilis*, *Dicrolene intronigra*, *Synaphobranchus oregoni*, *Dibranchus atlanticus*, and *Nezumia aequalis*. The top five species collected by Gallaway et al. (1988) were *Urophycis cirratus*, *S. oregoni*, *Coelorhincus caribbaeus*, *D. atlanticus*, and *Bembrops gobiodes*. **Table 10.4** shows the top species and their depth of maximum occurrence. The numbers of fish per hectare collected on the three transects were 1,222 (western), 620 (central), and 1,511 (eastern). Densities of demersal fishes were estimated from photography as 198.5 fish·ha$^{-1}$ during cruises II to V. Densities estimated by trawling were much less than those estimated by benthic photography; some were as high as 12.5 times less. Diversity (Shannon's H') declined with depth along all three transects, but did not differ significantly among the three transects. Some evidence for differing spatial patterns in species composition was provided by sampling along three (eastern, central, and western) downslope transects. A basic finding was that the eastern Gulf supported a more dense and species rich assemblage than the western Gulf (Gallaway et al. 1988).

Table 10.3. Deepwater (>200 m) demersal fishes known from the Gulf of Mexico, arranged in phylogenetic order

- Order Myxiniformes
  - Myxinidae (hagfishes)
- Order Chimaeriformes
  - Chimaeridae (ratfishes)
  - Rhinochimaeridae (longnose ratfishes)
- Order Orectolobiformes
  - Odontaspidae (sand tiger sharks)
- Order Carcharhiniformes
  - Scyliorhinidae (catsharks)
  - Carcharhinidae (requiem sharks)
  - Triakidae (smoothhound sharks)
- Order Hexanchiformes
  - Hexanchidae (sixgill and sevengill sharks)
- Order Squaliformes
  - Echinorhinidae (bramble sharks)
  - Squalidae (dogfish sharks)
- Order Squatiniformes
  - Squatinidae (angel sharks)
- Order Torpediniformes
  - Narcinidae (electric rays)
  - Torpedinidae (torpedo rays)
- Order Rajiformes
  - Rajidae (skates)
- Order Myliobatiformes
  - Dasyatididae (stingrays)
- Order Notacanthiformes
  - Halosauridae (halosaurs)
  - Notocanthidae (notacanthid eels)
- Order Anguilliformes
  - Synaphobranchidae (cutthroat eels)
  - Ophichthidae (snake eels)
  - Colocongridae
  - Congridae (conger eels)
  - Nettastomatidae (duckbill eels)
  - Serrivomeridae (sawtooth eels)
- Order Osmeriformes
  - Alepocephalidae (smoothheads)
- Order Ateleopodoiformes
  - Ateleopodidae
- Order Aulopiformes
  - Aulopidae (flagfins)
  - Ipnopinae (tripodfishes)
  - Synodontidae (lizardfishes)
- Order Polymixiiformes
  - Polymixiidae (beardfishes)
- Order Ophidiiformes
  - Carapidae (pearlfishes)
  - Ophidiidae (cusk-eels)
  - Aphyonidae
  - Bythitidae
- Order Gadiformes
  - Bregmacerotidae (codlets)
  - Phycidae (hakes)
  - Macrouridae (grenadiers)
  - Merlucciidae (offshore hakes)
  - Steindachneriidae (luminous hake)
  - Moridae (moras)
- Order Batrachoidiformes
  - Batrachoididae (toadfishes)
- Order Lophiiformes
  - Antennariidae (frogfishes)
  - Chaunacidae (gapers)
  - Ogcocephalidae (batfishes)
  - Thaumatichthyidae
- Order Beryciformes
  - Trachichthyidae (slimeheads)
  - Berycidae (alfonsinos)
  - Holocentridae (squirrelfishes)
- Order Zeiformes
  - Grammicocephalidae (diamond dories)
  - Macrurocyttidae
  - Parazenidae
  - Zeidae (dories)
  - Caproidae (boarfishes)
- Order Gasterosteiformes
  - Centriscidae (snipefishes)
  - Syngnathidae (pipefishes)
- Order Scorpaeniformes
  - Scorpaenidae (scorpionfishes)
  - Triglidae (sea robins)
- Order Perciformes
  - Acromatidae
  - Serranidae (groupers and sea basses)
  - Epigonidae
  - Apogonidae (cardinalfishes)
  - Malacanthidae (tilefishes)
  - Lutjanidae (snappers)
  - Zoarcidae (eelpouts)
  - Uranoscopidae (stargazers)
  - Percophididae (flatheads)
  - Callionymidae (dragonets)
- Order Pleuronectiformes
  - Paralichthyidae (flounders)
  - Bothidae (lefteye flounders)
  - Cynoglossidae (tonguefishes)
- Order Tetraodontiformes
  - Triacanthodidae (spikefishes)
  - Monacanthidae (filefishes)

Table 10.4. Comparison of most abundant species of fish between the Gallaway et al. (1988) and Pequegnat (1983) studies. Fish are ranked in order of decreasing abundance

| Gallaway et al. (1988) (All Transects) | | Pequegnat (1983) (All Stations) | |
|---|---|---|---|
| Species | Depth of Max. Pop. (m) | Species | Depth of Max. Pop. (m) |
| *Poecilopsetta beani* | 348 | *Poecilopsetta beani* | 250 |
| *Bembrops gobiodes* | 348 | *Bembrops gobiodes* | 400 |
| *Coelorinchus caribbaeus* | 348 | *Coelorinchus caribbaeus* | 300 |
| *Hymenocephalus italicus* | 348 | *Hymenocephalus italicus* | 450 |
| *Urophycis cirrata* | 348 | *Urophycis cirrata* | 450 |
| *Dibranchus atlanticus* | 657 | *Dibranchus atlanticus* | 650 |
| *Nezumia aequalis* | 657 | *Nezumia aequalis* | 900 |
| *Synaphobranchus* sp. | 839 | *Synaphobranchus* sp. | 1,000 |
| *Gadomus longifilis* | 1,341 | *Gadomus longifilis* | 1,050 |
| *Monomitopus* sp. | 839 | *Monomitopus sp.* | 1,050 |
| *Dicrolene* sp. | 1,341 | *Dicrolene* sp. | 1,200 |
| *Stephanoberyx monae* | 1,341 | *Stephanoberyx monae* | 1,200 |
| *Parasudis truculenta* | 348 | *Parasudis truculenta* | 250 |
| *Setarchus guentheri* | 348 | *Pontinus longispinus* | 200 |
| *Chlorophthalmus agassizii* | 348 | *Yarella blackfordi* | 650 |
| *Epigonus pandionis* | 348 | *Bathygadus melanobranchus* | 900 |
| *Malacocephalus occidentalis* | 348 | *Aldrovandia gracilis* | 1,450 |
| *Peristedion greyae* | 348 | *Halosaurus guentheri* | 900 |

Despite problems with examining stomach contents of fishes brought to the surface from great depths (i.e., stomach eversion, regurgitation, rapid decomposition of stomach contents), several investigators have examined food habits in deepsea fishes (Bright 1970; Rayburn 1975; Gallaway et al. 1988). The specimens examined consumed a wide range of organisms including fishes, epifauna, infauna, meiofauna, and planktonic invertebrates. Fishes were important in the diets of the eel *S. oregoni*, and greeneye *Chlorophthalmus agassizi*. The stomachs of three common species, *B. gobiodes, G. longifilis,* and *N. aequalis* contained mostly natant crustaceans (shrimps). The batfish *D. atlanticus* consumed pagurids (hermit crabs) and polychaete worms, whereas *Coelorhincus caribbaeus* fed mostly upon polychaetes. Rayburn (1975) found that *Nezumia hildebrandi, Halosaurus guntheri, D. intronigra*, and *Cariburus zaniophorus* fed upon infauna, predominantly polychaetes and amphipods. *Bathygadus vaillanti* consumed calanoid copepods and infauna. *Monomitopus agassizii* ate ostracods, copepods, and amphipods.

A central focus of the demersal slope studies (Pequegnat 1983; Gallaway et al. 1988) was the analysis of depth distribution of the megafaunal (larger invertebrates and demersal fishes) assemblage as a whole. Like others working in similar environments elsewhere in the world (e.g., Gage and Tyler 1996), the Gulf investigators suggested that species assemblages form discrete depth-related groups along the continental slope and upper abyssal plain (Pequegnat 1983; Gallaway and Kennicutt 1988; Pequegnat et al. 1990). Fishes figured prominently in the formation of depth-related faunal zones, and when analyzed separately, fish data seemed to agree with the overall megafaunal zonation schemes. Depth zones were objectively derived using cluster analyses of the megafaunal data sets. In the earlier study, Pequegnat (1983) recognized five depth zones, based upon the distribution of benthic megafauna:

- Shelf/Slope Transition Zone (118 to 475 m)
- Archibenthal Zone-Horizon A (500 to 775 m)
- Archibenthal Zone-Horizon B (800 to 975 m)
- Upper Abyssal Zone (1,000 to 2,275 m)
- Mesoabyssal Zone (2,300 to 3,225 m)
- Lower Abyssal Zone (3,250 to 3,850 m)

Gallaway et al. (1988) conducted further sampling both horizontally and vertically along the depth gradient seeking to test the validity of the earlier scheme. They (LGL Ecological Research Associates, Inc. and Texas A&M University 1986) initially decided that four basic zones existed: shelf/slope transition, archibenthal, upper abyssal, and mesoabyssal. Following similar analysis of their data, Gallaway et al. (1988) revised the existing scheme as follows:

- Shelf/Slope Transition Zone (300 to 500 m)
- Upper Archibenthal Zone (500 to 800 m)
- Lower Archibenthal Zone (800 to 1,650 m)
- Upper Abyssal Zone (1,650 to 2,250 m)
- Mesoabyssal Zone (2,250 to 3,000 m)

Minor differences between these two approaches include a change in terminology; a deepening of the lower limit of the Lower Archibenthal Zone; and classification of the Upper Abyssal Zone as largely transitional in nature (Gallaway 1988). Thus, the same general zonation scheme was upheld.

The fish assemblage found in each zone was characterized by one or several common species (Pequegnat et al. 1990). In the shelf/slope transition zone *B. gobioides*, *D. atlanticus*, *C. caribbaeus*, and *P. beani* were most common. The upper archibenthal zone was characterized by two grenadiers (*C. coelorhincus* and *Bathygadus macrops*), whereas the lower archibenthal zone supported high numbers of two additional grenadier species (*N. aequalis* and *B. melanobranchus*). In the upper abyssal zone, the dominant fish species was *G. longifilis*. The mesoabyssal zone supported a depauperate fish assemblage consisting of only five species including *Dicrolene kanazawai* and *Basozetus normalis*. The lower abyssal zone was depauperate, but supported a unique fish assemblage represented by *Barathronus bicolor* and *Bathytroctes macrolepis*.

That megafauna form discrete bathymetric zones is certainly appealing to managers, for good reason. Unfortunately, imposing artificial boundaries on continuous species-specific variation can present problems. Carney et al. (1983) cautioned against the use of unproven zonation schemes presented for the deep sea in general and presented an alternative and simpler scheme that described the slope assemblage as undefined and essentially continuous (**Figure 10.2**). The interpretation of multivariate data along environmental gradients can be affected by sampling adequacy, sampling scale, and analytical technique (Carney et al. 1983). The Pequegnat (1983) original zonation scheme was based upon 25 trawl hauls and 79 dredge tows made across the depth gradient at various locations along the continental slope. Fishes were collected primarily in the 25 trawl hauls, not in the dredges. Of these samples, only 12 were taken in depths greater than 1,000 m: seven from 1,000 to 2,000 m, two from 2,000 to 3,000 m, and three from 3,000 to 4,000 m. This may be too few samples, distributed in haphazard fashion, to adequately represent the structure of the existing demersal assemblage. Another possible sampling bias is that the areas selected for trawling (level bottom) may inaccurately represent the average (and untrawlable) topography of the slope (see Chapter 3, Geology). Gallaway et al. (1988) recognized some of these problems and attempted to resolve the problem by taking samples at smaller downslope intervals along their (western) transect. Nevertheless, their study added 58 trawl hauls (17 in water depths greater than 1,000 m), but used a smaller trawl (9 m opening vs. 24 m opening). Additional problems may arise when certain analytical techniques such as cluster analysis are used to form depth-related assemblages (Carney et al. 1983). Given the potential problems with the basic underpinning of the original zonation schemes, a more conservative approach for managers may be to accept the Carney et al. (1983) scheme (i.e., no true zones on the slope) until further data are available to support another proposed zonation scheme. In a similar analysis of fish depth distribution along the northeastern Atlantic continental slope, Haedrich and Merrett (1990) claimed that for benthopelagic fishes of the northeastern Atlantic slope, data do not produce repeatable patterns among adjacent stations. These authors concluded that the zonation concept, or any concept involving organized communities, was not valid for deep sea fishes.

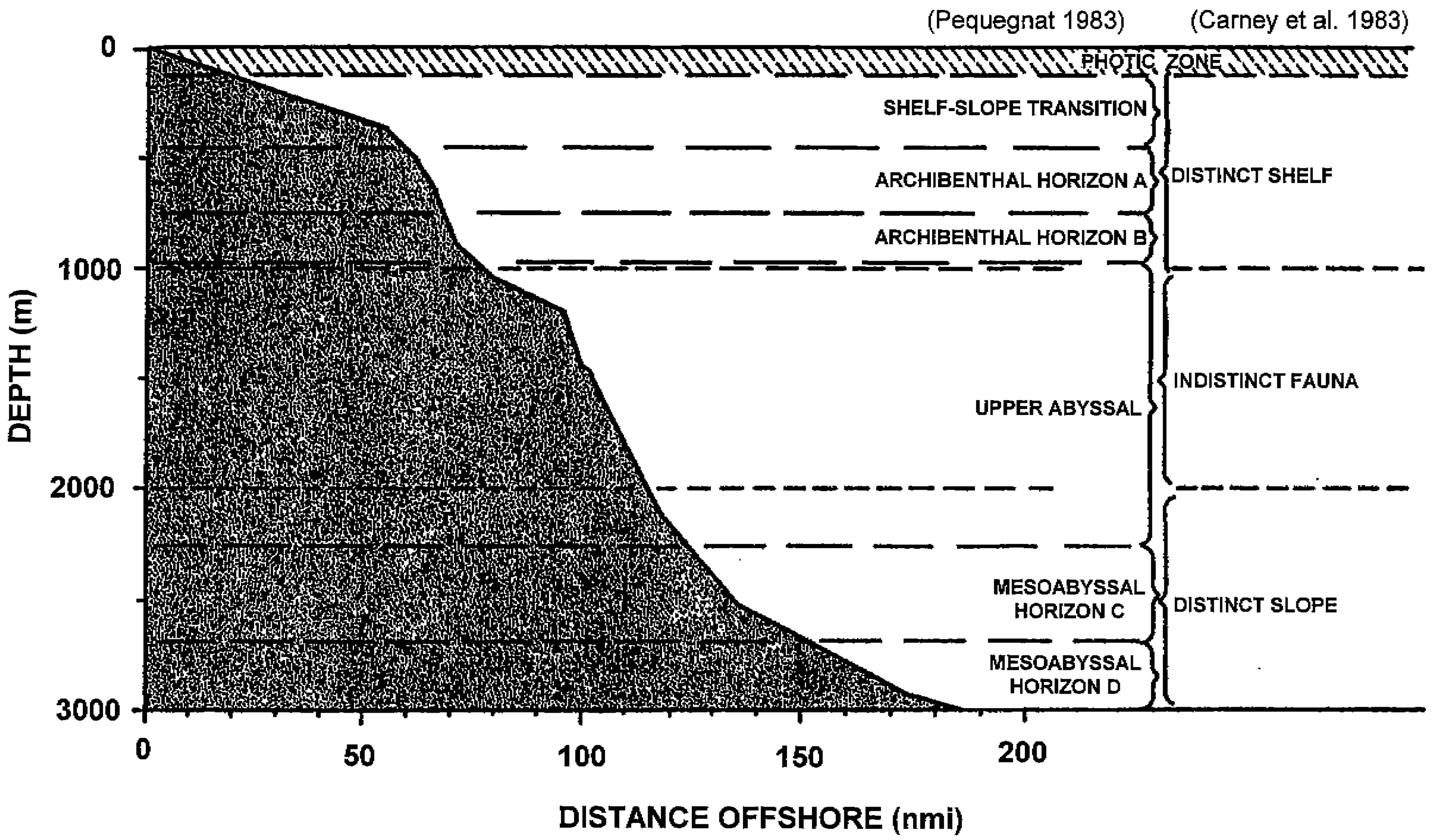

Figure 10.2. Opposing views of expected megafaunal zonation that might be observed on the Gulf of Mexico continental slope (From: Gallaway et al. 1988).

This same debate over continuous versus discrete assemblages along gradients has been waged by plant ecologists and others in the past (see summaries by McIntosh 1985, 1995; Brown 1995). In these circles, the continuum or individualistic hypothesis usually has been favored or at least considered as a null hypothesis (Price 1986).

### Interactions among Fishes of Different Assemblages

Midwater (mesopelagic and bathypelagic) fish taxocenes have most likely evolved in the deep sea, whereas demersal and epipelagic assemblages are more derived from shallow water ancestors and may be secondary invaders into the deepwater environments (Haedrich 1997). Despite this modular taxonomic nature of fish assemblages inhabiting the broad environmental subdivisions, considerable ecological interaction occurs among the groups. Most of the important ecological interactions in deepwater proximately involve trophic processes, and ultimately (presumably) reproductive success. When the feeding and ontogenetic migratory patterns are considered, there is considerable exchange among the taxonomically disparate groups of fishes. Mesopelagic fishes feed in the epipelagic zone, where they are in turn fed upon by epipelagic predators such as tunas and dolphin. Epipelagic and midwater fishes contribute organic matter in several forms to the demersal habitat where it will contribute to the productivity of the invertebrate food base that supports the demersal fish assemblage.

## Deepwater Fisheries

### Introduction

Commercial fisheries in the Gulf of Mexico are among the most productive in the world. Species such as menhaden; brown, white, and pink shrimp; oysters; blue crab; and red snapper drive the landings and dockside values. Gulf coastal states derive considerable revenues from regional commercial fisheries (Browder et al. 1991; O'Bannon 1999). In 1998, commercial fishery landings in the U.S. Gulf of Mexico, which includes western Florida, Alabama, Mississippi, Louisiana, and Texas, exceeded 1.5 billion pounds and were worth over $700 million (O'Bannon 1999). Most of these landings were generated from fish and invertebrate species caught in estuarine, coastal, and shelf waters. Species caught in the deepwater (>200 m) region contribute minimally to the overall regional landings, but are still very important to a smaller sector of the commercial fishing population (NMFS 1999a).

Deepwater fisheries of the Gulf of Mexico have not been formally reviewed, but McIlwain (1999) briefly described the deepwater fisheries and fishery practices occurring in the De Soto Canyon region of the eastern Gulf of Mexico. He listed deepwater trawling, butterfish trawling, golden crab trapping, surface longlining, and bottom longlining as the major fishing endeavors of that area. Both butterfish trawling and golden crab trapping appear to be of minimal importance in the overall deepwater fishery (Josh Bennett, 2000, NMFS, Miami, FL, personal communication). Surface longlining, shrimp trawling, and bottom longlining are the most important deepwater fisheries in terms of pounds landed. All three of these methods were initially "discovered" through the exploratory fishing efforts of the Bureau of Commercial Fisheries, which began around 1950. Species sought by deepwater commercial fishers can be divided into three basic groups: epipelagic fishes, demersal fishes, and invertebrates. The following review examines the history of deepwater commercial fisheries, key species, gear types, and landings trends associated with the three basic fisheries. Commercial fisheries are the subject of this review, not because recreational fisheries are unimportant or do not occur in deepwater, but because there has not been enough information published on them.

## History of Deepwater Fisheries in the Gulf of Mexico

The history of deepwater commercial fishing in the Gulf began in 1950 with federally funded exploratory fishing programs. The program began investigating deepwater shrimp resources and graduated to tuna fishing in the waters of the open Gulf (Bullis 1955a; Iwamoto 1965). After unsuccessful attempts to catch tunas with purse seines and live bait fishing, the Bureau's exploratory efforts shifted to longlining for tunas in 1952 (Bullis 1955a,b,c). About the same time, Japanese fishers began fishing for tunas in the Gulf, also using longline gear (Iwamoto 1965; Lopez et al. 1979). Japanese vessels fished in the Gulf of Mexico for the next 30 years from 1952 until 1982, when the longlining ceased under an international agreement (Honma et al. 1985; Prager and Browder 1992). In the early 1970's a domestic swordfish fishery became established in the Gulf (South Atlantic Fishery Management Council 1985). This was a seasonal fishery, mostly in fall and winter. By about 1983, an increasing demand for tuna caused many swordfish longliners to switch methods to target them (Taniguchi 1987). The Gulf tuna longlining fleet reached 350 to 400 vessels in 1988-1989 (Russell 1993), and continues today with a similar number of vessels (Cramer and Adams 1999). In the southern Gulf, Mexican fishers have been longlining for yellowfin tuna since about 1980 following the departure of the Japanese fleet (Prager and Browder 1992).

In the 1980's, the NMFS conducted another exploratory fishery program to examine the efficacy of trawling for gulf butterfish (*Peprilus burti*). Commercial butterfish vessels and captains from the northeastern U.S. were hired to fish in various areas of the eastern Gulf (Vecchione 1987). Although the results were promising (Vecchione 1987), no extensive butterfish fishery has developed (but see McIlwain 1999).

While the epipelagic fishery was developing, exploratory fishing with bottom trawls proved productive when in the early 1950's, exploitable quantities of royal red shrimp (*Pleoticus robustus*) were found around the Gulf of Mexico in 500 to 900 m water depths (Bullis 1956). Commercial fishers did not begin targeting royal red shrimp until the 1960's (Gulf of Mexico Fishery Management Council [GMFMC] 1996). Exploratory efforts by the Bureau of Commercial Fisheries were also the first to attempt bottom longline fishing in deepwaters of the Gulf of Mexico (Nelson and Carpenter 1968). The primary species caught by bottom longlining during this cruise was tilefish (*Lopholatilus chamaeleonticeps*), which was of no commercial importance at that time. In the late

1970's, another exploratory fishing program sought to develop a fishery for deep dwelling golden crab (Otwell et al. 1984).

## Key Species

Epipelagic fishes found in the commercial catch include dolphin, sharks (mako, silky, and thresher), snake mackerels (escolar and oilfish), swordfish, tunas (bigeye, blackfin, bluefin, and yellowfin), and wahoo. These species are widespread in the oceanic waters of the Gulf, generally in the upper 200 m of the water column. Sharks, swordfish, and tunas are the most important fishery species and are currently managed as a unit (Highly Migratory Species) by the NMFS Office of Sustainable Fisheries, Highly Migratory Species Division (NMFS 1999a). As such, these species are covered by a management plan as mandated in the Magnuson Stevens Fishery Management Act of 1976. These same species are sought by offshore or bluewater fishers.

Demersal fishes caught in deepwater include groupers (snowy, Warsaw, and yellowedge), snappers (queen and silk), and tilefishes (blueline tilefish, goldface tilefish, and tilefish). These are often referred to as reef fishes (i.e., GMFMC 1981). However, this group of deeper dwelling fishes, particularly tilefishes and yellowedge grouper, may be found on level clayey bottoms in 80 to 450 m water depths rather than on reefs or hard bottom. Other deepwater snappers and groupers associate with hard bottom outcrops in water depths ranging from 80 to 600 m.

Deepwater invertebrates important to commercial fisheries in Gulf of Mexico are royal red shrimp and, to a much lesser extent, golden crab. Royal red shrimp occur over specific substrata in different areas of the Gulf: blue-black terrigenous silt and silty clay off the Mississippi Delta and calcareous mud off the Dry Tortugas (Roe 1969; GMFMC 1996). Peak abundance of royal red shrimp in the Gulf of Mexico occurs in the depth range from 250 to 500 m (Roe 1969). Golden crab occur in a similar depth range as royal red shrimp but prefer hard bottom and outcroppings such as the Florida Escarpment (Lindberg and Lockhart 1993).

## Fishing Gear Types

Epipelagic fishes are primarily caught with drifting longlines fished in the upper water column. Longlines consist of a monofilament main line suspended in the water column by regularly spaced buoys. The buoy lines are used to adjust the fishing depth of the mainline that can range from 15 to 75 m. Leaders with baited hooks are attached along the length of the mainline as it is being deployed. Leaders range from 15 to 70 m long (Russell 1993). From 1994 to 1998 sets by permitted longline vessels in the Gulf of Mexico ranged from 3 to 103 km and averaged 60 km (NMFS 1999c). The number of sets per month ranged from 77 to 502 and averaged 322 (**Figure 10.3**). In 1998 the number of sets ranged from 77 to 391 and averaged 259. Longlines are often set near oceanographic features such as fronts or downwellings often with the aid of sophisticated onboard temperature sensors, depth finders, and positioning equipment. **Figure 10.4** depicts the spatial distribution of longline sets in the northern Gulf of Mexico for 1998.

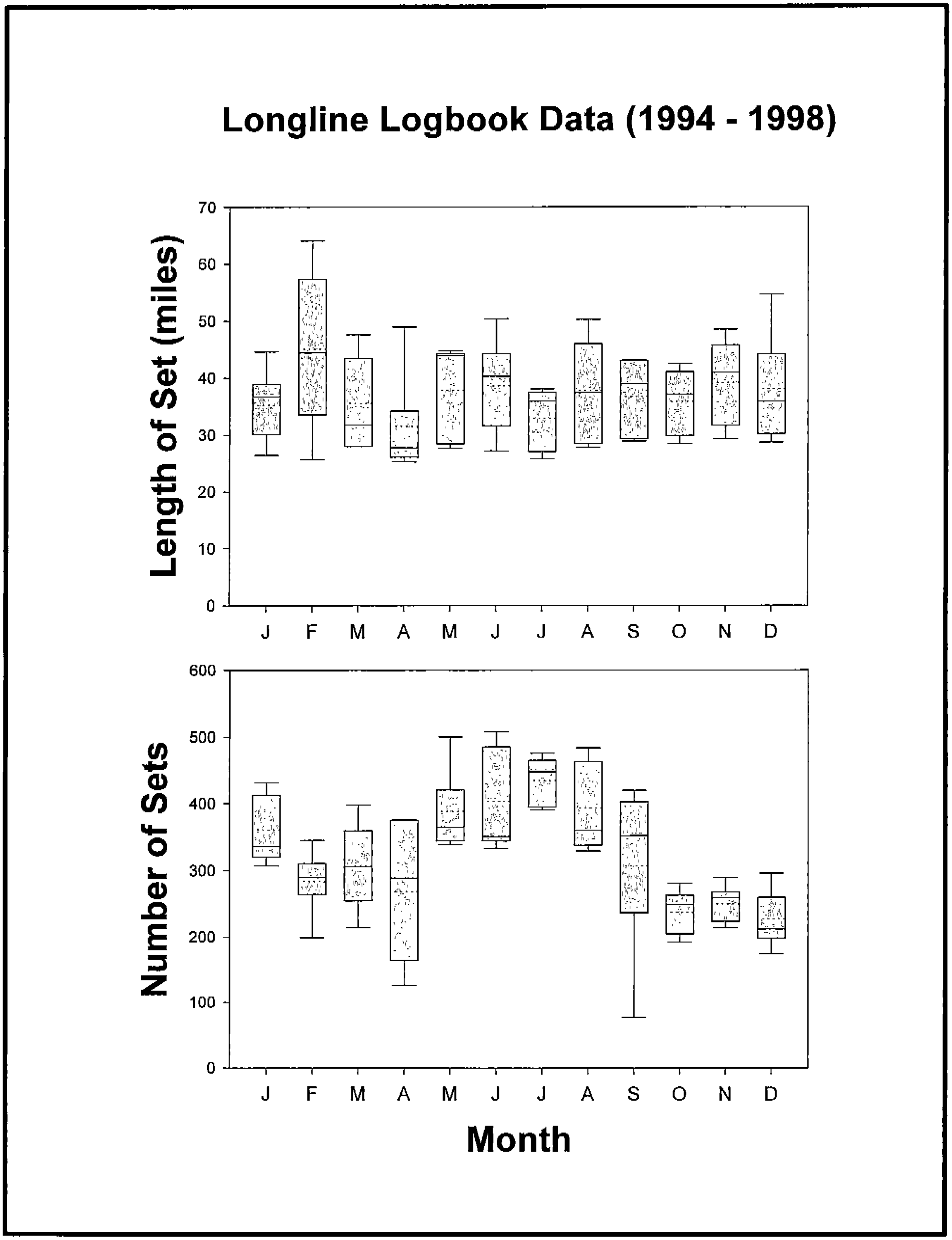

Figure 10.3. Monthly lengths (a) and numbers (b) of surface longline sets made in the Gulf of Mexico from 1994 to 1998. Values shown are mean (dotted horizontal line), median (solid horizontal line), tenth and ninetieth percentiles (error whiskers), and twenty-fifth and seventy-fifth percentiles (gray box) (From: NMFS 1999c).

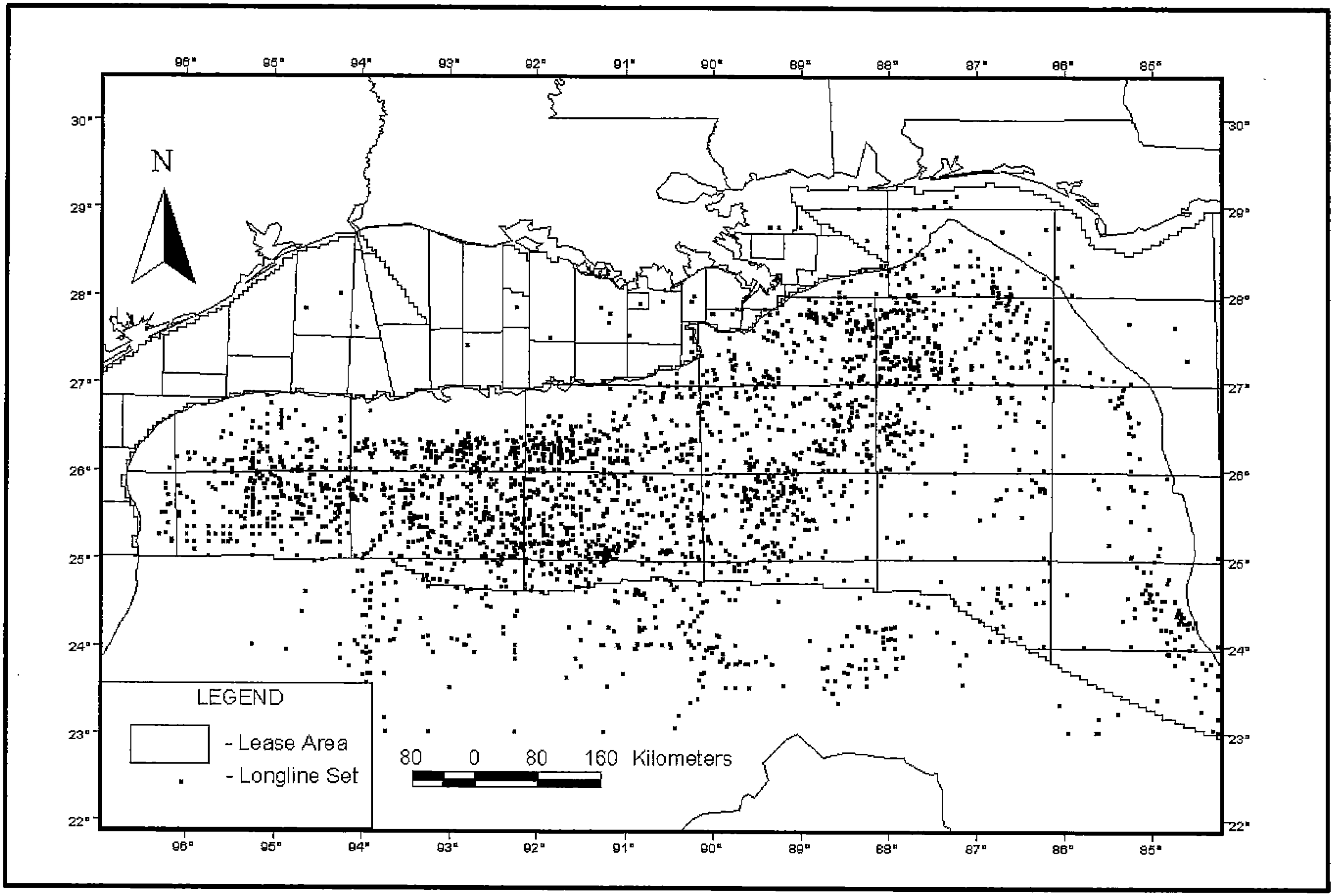

Figure 10.4. Spatial distribution of surface longline sets made in the Gulf of Mexico during 1998 (From: NMFS 1999c).

The primary homeports for longline vessels are Dulac, Louisiana; Venice, Louisiana; Destin, Florida; Madiera Beach, Florida; and Panama City, Florida (Tanaguchi 1987; NMFS 1999a).

Deepwater demersal/reef fishes are caught with bottom longlines, traps, and hook-and-line. Most of the landings are produced by bottom longlines. The longlines are similar to the surface longlines except that the lines are anchored to the bottom. Bottom longlines are much shorter than surface longlines, usually less than 3 km, but can reach 30 km (GMFMC 1981).

Shrimp trawling is one of the most important commercial endeavors in the Gulf of Mexico. However, most of the shrimp grounds lie well inshore of the 200 m isobath. Trawling for royal red shrimp occurs in water depths of 400 to 500 m offshore Florida, Alabama, and Texas (GMFMC 1996). Gear used for royal red shrimp is very similar to shallow water shrimp trawling gear, but to accommodate the greater depths involved, all components including winches, trawl doors, lines, and vessels must be heavier.

Golden crab gear consists of rectangular wire mesh traps that are attached in series along a weighted mainline. Most of the fishing for golden crab has been offshore of western Florida. Very few fishers are involved in the golden crab fishery. In fact, so few that the landings data cannot be released separately because of confidentiality (Josh Bennett, NMFS, Miami, personal communication).

## Landings Trends

Epipelagic fishes comprised most of the weight and value of deepwater landings in the Gulf of Mexico for 1998 (**Tables 10.5 and 10.6**). Yellowfin tuna represented 55% of the value and 47% of the weight of all deepwater species landed. Swordfish, dolphin, and wahoo collectively accounted for another 19% of the value and 21% of the weight. Louisiana and Florida led Gulf Coastal states in terms of value and weight of epipelagic species landed, followed by Texas. Alabama and Mississippi reported no landings of epipelagic fish in 1998.

Demersal fish landings were dominated by yellowedge grouper, which accounted for 9.7% of the value and 8.8% of the weight of deepwater species landed in 1998. Two tilefish species and snowy grouper contributed another 5% of the value and 7% of the weight reported for deepwater species in 1998. Most 1998 reef fish catches were landed in Louisiana and Florida. Alabama and Texas contributed little to the landings, and Mississippi did not report any deepwater reef fish landings in 1998.

Invertebrate landings were restricted to specific states. A majority of the royal red shrimp were landed in Alabama where 1998 landings weighed 123.5 mt and were valued at $586,575. Florida and Texas reported only small fractions of this amount during 1998. Florida was the only Gulf coastal state to report landings of golden crab in 1998 (133 mt valued at $205,000).

Table 10.5. Weight (metric tons) of deepwater species landed in Gulf coastal states in 1998 (From: National Marine Fisheries Service 1999b)

| Species | State[a] | | | | | |
|---|---|---|---|---|---|---|
| | Alabama | Florida | Louisiana | Texas | Grand Total | Percent |
| EPIPELAGIC FISHES | | | | | | |
| Tuna, yellowfin | | 237.6 | 1,341.8 | 137.4 | 1,716.8 | 47.0 |
| Swordfish | | 162.1 | 306.2 | 41.2 | 509.5 | 14.0 |
| Dolphin | | 157.8 | 30.7 | 2.4 | 190.9 | 5.2 |
| Wahoo | | 17 | 62.6 | 2 | 81.6 | 2.2 |
| Escolar | | 8.5 | 51.1 | -- | 59.6 | 1.6 |
| Shark, shortfin mako | | 6.1 | 35.8 | -- | 41.9 | 1.1 |
| Tuna, blackfin | | 12.4 | 20.9 | 2.9 | 36.2 | 1.0 |
| Oilfish | | 4.8 | 10.1 | -- | 14.9 | 0.4 |
| Tuna, bluefin | | 1.3 | 12.2 | -- | 13.5 | 0.4 |
| Tuna, bigeye | | 4.4 | 8.9 | -- | 13.3 | 0.4 |
| Tuna, unc | | -- | 5.7 | -- | 5.7 | 0.2 |
| Tuna, albacore | | -- | 2.6 | -- | 2.6 | 0.1 |
| Shark, silky | | 2.3 | -- | -- | 2.3 | 0.1 |
| Shark, longfin mako | | -- | -- | 1.4 | 1.4 | 0.0 |
| Shark, thresher | | 1 | -- | -- | 1 | 0.0 |
| Tuna, skipjack | | 0.5 | -- | -- | 0.5 | 0.0 |
| REEF FISHES | | | | | | |
| Grouper, yellowedge | | 252.7 | 46.2 | 20.8 | 319.7 | 8.8 |
| Tilefish | | 104.6 | 17.1 | 14.4 | 136.1 | 3.7 |
| Grouper, snowy | | 58.9 | 3.1 | -- | 62 | 1.7 |
| Tilefish, blueline | | 58.5 | -- | -- | 58.5 | 1.6 |
| Snapper, silk | | 46.8 | 0.7 | -- | 47.5 | 1.3 |
| Grouper, warsaw | | 13.7 | 15.1 | 9.9 | 38.7 | 1.1 |
| Speckled hind | | 22.6 | -- | -- | 22.6 | 0.6 |
| Snapper, queen | | 8.5 | 5.4 | -- | 13.9 | 0.4 |
| Brotula, bearded | | 5.9 | 4.7 | -- | 10.6 | 0.3 |
| Barrelfish | | 1.7 | -- | -- | 1.7 | 0.0 |
| Hake,Atlantic,red & white | | -- | 0.9 | -- | 0.9 | 0.0 |
| Tilefish, goldface | | -- | 0.6 | -- | 0.6 | 0.0 |
| Bass, longtail | | -- | 0.2 | -- | 0.2 | 0.0 |
| INVERTEBRATES | | | | | | |
| Shrimp, royal red | 123.5 | 9.7 | -- | 1.2 | 134.4 | 3.7 |
| Crab, deepsea golden | -- | 113 | -- | -- | 113 | 3.1 |
| **GRAND TOTAL** | **123.5** | **1,312.4** | **1,982.6** | **233.6** | **3,652.1** | |

[a] No landings of deepwater species were reported by Mississippi.

Table 10.6. Value (dollars) of deepwater species landed in Gulf coastal states in 1998 (From: National Marine Fisheries Service 1999b)

| Species | State[a] | | | | | |
|---|---|---|---|---|---|---|
| | Alabama | Florida | Louisiana | Texas | Grand Total | Percent |
| EPIPELAGIC FISHES | | | | | | |
| Tuna, yellowfin | -- | 1,233,884 | 7,338,444 | 691,142 | 9,263,470 | 55.4 |
| Swordfish | -- | 924,546 | 1,335,696 | 166,690 | 2,426,932 | 14.5 |
| Dolphin | -- | 494,432 | 71,054 | 5,595 | 571,081 | 3.4 |
| Wahoo | -- | 67,432 | 143,740 | 4,611 | 215,783 | 1.3 |
| Tuna, bluefin | -- | 7,316 | 113,605 | -- | 120,921 | 0.7 |
| Escolar | -- | 21,105 | 96,643 | -- | 117,748 | 0.7 |
| Tuna, bigeye | -- | 24,545 | 71,281 | -- | 95,826 | 0.6 |
| Tuna, blackfin | -- | 26,374 | 22,425 | 5,864 | 54,663 | 0.3 |
| Shark, shortfin mako | -- | 15,315 | 32,911 | -- | 48,226 | 0.3 |
| Oilfish | -- | 11,855 | 22,332 | -- | 34,187 | 0.2 |
| Tuna, unc | -- | -- | 23,555 | -- | 23,555 | 0.1 |
| Shark, silky | -- | 3,177 | -- | -- | 3,177 | 0.0 |
| Tuna, albacore | -- | -- | 3,079 | -- | 3,079 | 0.0 |
| Shark, longfin mako | -- | -- | -- | 2,256 | 2,256 | 0.0 |
| Shark, thresher | -- | 1,055 | -- | -- | 1,055 | 0.0 |
| Tuna, skipjack | -- | 466 | -- | -- | 466 | 0.0 |
| REEF FISHES | | | | | | |
| Grouper, yellowedge | -- | 1,277,115 | 254,121 | 93,160 | 1,624,396 | 9.7 |
| Tilefish | -- | 269,540 | 53,062 | 38,725 | 361,327 | 2.2 |
| Grouper, snowy | -- | 252,151 | 14,809 | -- | 266,960 | 1.6 |
| Snapper, silk | -- | 216,501 | 3,064 | -- | 219,565 | 1.3 |
| Grouper, warsaw | -- | 48,663 | 67,973 | 35,603 | 152,239 | 0.9 |
| Tilefish, blueline | -- | 112,586 | -- | -- | 112,586 | 0.7 |
| Speckled hind | -- | 85,537 | -- | -- | 85,537 | 0.5 |
| Snapper, queen | -- | 37,801 | 23,181 | -- | 60,982 | 0.4 |
| Brotula, bearded | 276 | 14,799 | 9,570 | -- | 24,645 | 0.1 |
| Barrelfish | -- | 6,194 | -- | -- | 6,194 | 0.0 |
| Hake,Atlantic,red & white | -- | -- | 1,715 | -- | 1,715 | 0.0 |
| Tilefish, goldface | -- | -- | 1,439 | -- | 1,439 | 0.0 |
| Bass, longtail | -- | -- | 591 | -- | 591 | 0.0 |
| INVERTEBRATES | | | | | | |
| Shrimp, royal red | 586,575 | 30,778 | -- | 5,068 | 622,421 | 3.7 |
| Crab, deepsea golden | -- | 205,440 | -- | -- | 205,440 | 1.2 |
| **GRAND TOTAL** | **586,851** | **5,388,607** | **9,704,309** | **1,048,714** | **16,728,481** | |

[a] No landings of deepwater species were reported by Mississippi.

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# Chapter 11: Socioeconomics

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## Introduction

The socioeconomic effects of oil and gas development on communities, families, and individuals in the Gulf of Mexico region are significant dimensions of the petroleum industry. For decades, increased outer continental shelf (OCS) oil and gas production has piqued the interests of researchers wanting to further their understanding of the impacts this natural resource extraction has on coastal communities. Evolving from simple land-based exploration and production platforms to technologically sophisticated offshore structures produced significant social changes and responses over the years within those regions most affected by oil and gas activities. The industry is dependent on a multitude of suppliers (McKenzie et al. 1993), creating a vast interdependent network that has consequently involved and impacted nearly every community within the region.

Recent deepwater Gulf of Mexico operations, in depths of water 300 m or greater, have prompted sociologists to question whether impacts are comparable to, or different from, those activities of more shallow offshore oil and gas operations. Determining the specific socioeconomic impacts of deepwater development is difficult, if not impossible, because many of the activities associated with deepwater exploration, drilling, and production are integrated within regular offshore operations. Therefore, this chapter will include literature on existing social, economic, and infrastructural conditions in places that are likely to be affected by deepwater development, including those port and coastal communities now impacted by offshore oil and gas activities, including deepwater. One of the disadvantages of research on socioeconomic effects of offshore development involves timing; too often research begins long after development starts and impacts occur. When researchers are able to study regions, communities, families, and individuals before these events, they have a more comprehensive framework in which to make assessments. Therefore, we believe a broad review of socioeconomic effects already identified in these regions will benefit and provide a better understanding of potential impacts of deepwater development to communities in the future.

There is a rich variety of sources from which existing literature addresses the socioeconomic impacts of oil and gas development in the Gulf of Mexico region. Social impact assessments, funded by various agencies, carried out by social scientists, and published in numerous scientific journals, serve as important sources of information. Likewise, economic and community development initiatives provide researchers with clues concerning internal and external forces of oil industry activities impacting community sustainability. Technical reports presented at industry symposiums and articles in trade publications contribute to our knowledge of offshore oil and gas activities. Lastly, regional and local media reports sifted through to gain a sense of heartfelt (and therefore sometimes biased) opinions commonly found in communities where the potential to lose may be as great as the potential to gain complete the literature review. Choosing to ignore any of this literature results in a picture a little less sharp, a little less focused, than what is necessary if we are to understand, as completely as possible, the socioeconomic impacts of oil and gas development on Gulf of Mexico communities.

## The Importance of Time and Space

Key to understanding what oil industry activity has meant to the Gulf Coast region is knowing that oil and gas activity has developed unevenly in the Gulf of Mexico region, both temporally and spatially, and with increased activity in deepwater drilling, will continue to do so. Certain communities fortuitously benefited because of their location relative to offshore activities and the acceptance by residents of such activities, while other communities in other coastal regions either consciously chose not to participate, or location prevented them from so doing. Fifty years of oil industry development in the Gulf of Mexico has seen significant changes in activities, and technological advancements and improvements. With time, diffusion and integration of oil industry networks and activities have resulted in an almost complete envelopment of numerous coastal communities and areas. This results in sometimes disparate, yet more frequently often, similar social and economic consequences for communities within the region. Thus it can be said that uneven economic development is a consequence of oil and gas industry involvement. And as national and worldwide demand for oil and gas grows, social, cultural, and economic impacts increase in those areas.

However, the market dynamics of the petroleum industry are primarily controlled by the Organization of Petroleum Exporting Countries (OPEC), a 13-nation cartel of mostly Arabian Gulf nations created in the early 1970's. At that time, the OPEC nations controlled almost 75% of the world's proven crude oil reserves (Hodel and Deitz 1993). The OPEC oil embargo of 1973 strongly encouraged U.S. oil corporations toward increased national oil exploration and production in an effort to reduce foreign oil dependency. Ironically, petroleum conservation legislation was soon to follow, and a nationwide recession in the early 1980's effectively laid the groundwork for a collapse in the industry, the severity of which had never before been seen. Socioeconomic effects were far-reaching and long-lasting nationally, but even more so along the coastal states of the Gulf of Mexico, which had gained the most economically, although not without cost, but which also stood to lose the most. State and community leaders seeking socioeconomic robustness within their areas began to realize that a strong presence of oil and gas industry-related companies in their midst also meant that they were susceptible to global forces over which they had no control. Regional economic sustainability, a goal to which all state and community leaders aspired, appeared elusive.

A brief history of oil and gas development in the coastal states along the Gulf of Mexico will provide a framework that will help us to understand how and why the industry developed unevenly. It is interesting to note the differences between states in their degree of acceptance of oil industry development and activities over the years, and the factors that played significant roles in those differences.

## History of Oil and Gas Development in the Gulf Coast States from 1900's Forward

The oil and natural gas industry has operated along the Gulf coast for nearly 100 years, beginning with the push for overwater drilling at Caddo Lake, southeast of Shreveport, Louisiana, in 1905. Several technical problems were solved at that location that had significant implications later for the move offshore into the Gulf of Mexico. First, downhole pressures encountered were beyond any previously experienced. Because of inability to deal with the pressures effectively, blowouts and fires became common. This led to the emergence of increasingly reliable blowout preventers, which would be required for the high pressure reservoirs along the Gulf coast. Second, it was necessary to be able to drill and produce without direct contact to the land. Construction engineers developed pilings that could be driven deep enough into the lake bottom to provide solid footing, on top of which platforms were constructed, while barges transported drilling equipment and supplies to the drill site. One final technological innovation occurred, an underwater pipeline connecting the producing wells to one of four gathering stations on the lake (Brantly 1971; Cicin-Sain et al. 1992). That pipeline would be a precursor to the vast network of pipelines that would later bring oil and gas from offshore production platforms to onshore facilities.

Access to coastal Louisiana drilling prospects in the early 1900's was difficult due to the marshy, swampy environment, and it was not until 1933 with the Texas Company's introduction of the submersible drilling barge that exploration of marsh and shallow coastal waters became cost efficient (Lankford 1971). The submersible barge could be towed to the drilling site and sunk, providing a stable drilling base. After drilling was completed, the barge was raised and used elsewhere. Consequently, the marine environment became more accessible to exploration companies (Gramling 1996). However, another dilemma arose as exploration and production moved into increasingly isolated areas of coastal marshes and estuaries: the labor force necessary to perform those activities found it increasingly difficult to commute on a daily basis. Two organizational responses emerged, significantly impacting the industry's organization of work. First, because these isolated areas had no housing facilities available for the work crews, companies built and provided living quarters situated near the work site. Later on, as offshore oil activities proliferated, living quarters became part of the work site, built on top of oil platforms situated over open water. Second, concentrated working periods became common, in which the division of work was frequently broken down by the week: one week at work and one week off. This type of concentrated work scheduling has become the model for offshore development and has increased in importance as offshore activities have grown. Oil companies are eager to recoup their investment expenditures, which are considerable, as quickly as possible (Gramling 1989, 1995, 1996). Therefore, as oil industry activities have progressed farther offshore, work schedules have also been extended, with today's workers commonly staying 7, 14, or 21 days, with daily shifts of 12 hours on, 12 hours off. Because of this type of concentrated work scheduling, offshore workers may not necessarily live in the Gulf Coast region, instead choosing to make infrequent long distance commutes from their homes to whatever site they leave from for offshore. Gramling and Brabant (1986), in their analysis of labor survey data conducted in East St. Mary Parish, an area heavily involved in offshore support activities, found that only 30% of the 381 offshore workers in the sample lived within 100 miles of where they met to go offshore. This phenomenon eliminated the necessity for geographic concentration of human settlement in the vicinity of this type of economic activity (Gramling 1996).

Louisiana's coastal zone incorporates all land and water bottoms within the territorial sea (about 3 miles offshore) and the adjacent shorelands, encompassing approximately 9.5 million acres in southern Louisiana, of which 5.2 million acres are water. Marshes constitute 63% of the land area in the coastal zone, while swamps, forests, and agricultural areas constitute 9% each (Lindstedt et al. 1991). The movement of oil activities into the Louisiana marsh in the 1920's and 1930's was aided by the development of the highway network along the natural levees, parallel to the waterways crossing the marsh (Kniffen 1968). Land use and other economic patterns were significantly modified by the oil and gas industry. There was a pronounced shift of population from scattered rural homesites and abandonment of more isolated areas, to more permanent structured locations and concentration in long "string town" settlements (Kniffen 1968; Davis and Place 1983). Settlement density along the highways on the crests of the levees approached that of urban row housing. Demand for land had a decisive and cumulative impact on the land use and land cover patterns as the region's rural character was being changed by phases of oil exploration and development. Towns grew on the crest of the levees while adjacent lower extremes of the levees were cleared for agriculture. Bayou Lafourche, from Donaldsonville to the Gulf of Mexico was known as the world's "longest street," referring to the importance of the bayou for communication, transportation, and the focus of economic life (Emmer et al. 1992). These growing urban areas helped provide a small, but growing local labor supply for expanding oil and gas activities. Construction and support sites for the offshore industry grew in number as the industry moved ahead. Activities built to serve oil industry development were constructed on these higher lands next to navigable waterways and as close as possible to the offshore platforms they were supporting. Most of these locations were already occupied by trade centers, agricultural enterprises, and fishing communities. The more inland parishes and municipalities were the locations for company offices, or the manufacturing and processing of the oil industry hydrocarbons (Emmer et al. 1992). Therefore, even small traditional communities were transformed into vital interconnected pieces of an increasingly global industry network.

Practical solutions often solved immediate problems: extensive networks of canals were cut through marshes to allow submersible drilling barges to operate (Cicin-Sain et al. 1992). Private landholders and the State of Louisiana allowed almost unlimited access via barge to drill sites, and later, a network of pipeline corridors was laid through those same wetlands. The Texas-Louisiana coast in the late 1940's was an ideal site for production because the proximity of vast refining capacity and pipeline availability made transportation to market easy. Chemical plants and refineries were built from Freeport, Texas to Lake Charles, Louisiana and further east (Burleson 1999). By the late 1950's an average of 100 production platforms a year were being placed offshore, in ever-deeper water (Gramling and Freudenburg 1995).

The importance of the coastal zone to the oil industry in Louisiana cannot be overstated: from 1926, when production was first recorded in Louisiana's coastal zone, until 1983, 58% of the state's oil and 47% of its gas was produced in that part of the state. More than one-half of the state's leasing activity has been in the coastal zone, and state revenues generated from oil and gas activities in that area totaled $12 billion of $28 billion during that same period. Offshore technology expanded rapidly in the late 1940's, after a movable submersible marine drilling rig was successfully used in Breton Sound. Innovations were constantly being developed, including surplus war ships that were used as floating warehouses, drilling platforms, and crew quarters (Lindstedt 1991). By the early 1950's huge inland submersibles were capable of drilling to 20,000 ft depths (Albright and McLaughlin 1952; McLaughlin 1953; Gramling 1996).

The 1950's and early 1960's were years of intensified exploration and development activity as large and small operators were continually drilling in the wetlands (Davis and Place 1983). From the mid 1960's through the early 1970's, the oil and gas fields of Louisiana's coastal zone were extended. A massive network of manmade waterways or canals, constructed to meet local needs, became a permanent landscape feature, significantly enlarging fields and intensifying canals' regional impact (Lindstedt et al.

1991). Davis and Place (1983) note that marsh or swamp drainage ditches had been used as early as the 1700's by farmers and settlers to drain potential crop and pasture land, and as transportation routes; later, the cypress found in the swamps was accessed and removed by logging companies through excavation of logging canals. The oil and gas potential of the coastal zone served as an impetus to the industry to dredge more access canals throughout the coastal lowlands. Those interconnecting canals served as transportation waterways to oil and gas activities throughout the coastal zone. Movement of oil from isolated wells to refineries also necessitated the building of extensive pipeline networks throughout the coastal zone. As oil and gas production moved further offshore, so did the pipeline, and by 1951, the first large-diameter pipeline for offshore production was laid in the Gulf (Clark 1963; Gramling 1996).

Although Davis and Place (1983) found that early exploration in offshore waters was erratic due to high development costs and legal problems, during the 1950's and 1960's large fields continued to be discovered and developed. Between 1952 and 1960, 34% of the wildcatting operations had been successful along Louisiana's coast, resulting in further expansion of activities with increased socioeconomic effects. The first fabrication yard solely for construction of fixed drilling platforms was established at Bayou Boeuf, Louisiana, in 1955. Along with 13 others, this yard has produced most of the platforms placed in leases off Texas and Louisiana. By 1955, 10 refineries, 14 petrochemical plants, and 3 carbon black firms had located in southern Louisiana. Population and employment patterns were changing in the coastal zone; for instance, between 1950 and 1960, the population in seven coastal parishes increased an average of 30% or about 7,800 people per parish (Bobo and Charlton 1974; Davis and Place 1983).

Production in many of the large fields was slowing by the 1970's, not only because new fields had become harder to find, but discoveries were smaller. The coastal zone's production peaked at 513 million barrels in 1970, and rapidly declined thereafter. Less than one-fourth of its peak production was being produced by 1983.

## A Natural Extension of Growth

Residents of the central and western Gulf have in most instances generally accepted oil industry activities in their areas. This is because offshore activity in the Gulf, particularly in Louisiana, occurred as a gradual extension of land-based gas and oil production through the coastal marshes and into ever deeper offshore waters. Growth was incremental, and focused on the solution of local problems for local use, largely isolated from mainstream economy and industrial development. It did not appear suddenly, or appear as a harm, threatening to the region, but rather as a natural evolution (Cicin-Sain et al. 1992). Texans, already accustomed to producing oil and gas fields within their state, saw the development of the offshore oil industry as another facet of a burgeoning industry.

At least in coastal Louisiana, the economy had always been traditionally based on extractive activities. At the turn of the century, the mainstay of the local economy included furs, shrimp, fish, oysters, cypress lumber, moss, waterfowl, and crawfish.

Marsh inhabitants consumed marsh products and marketed them to settlements in the region. Oil production was seen as just one more product from this rich resource-laden environment that would benefit the people. Comeaux (1972) notes that prior to World War II, most coastal Louisiana extractive activities occurred in the marsh and swamps. Not until the 1950's was the current major commercial species, shrimp, known to be available in the open Gulf. Temporally, the significance of this was that oil and gas development and fishing/shrimping grew up together. Also, during the 1930's and 1940's, there was no general environmental awareness, no conception of the marsh as a potentially vulnerable ecosystem (Gramling 1996). The canals and channels carved through the marshes that solved problems of accessibility and served as transportation routes were seen as solutions, and not as having future environmental consequences. Today most would agree that those canals and channels, while beneficial to the development of the oil industry, have also played a role in the loss of coastal wetlands.

One of the most important issues in the development of the offshore oil industry involved the dispute over subsurface land ownership, with coastal states and the Federal government vying for ownership of the petroleum-rich environment, particularly in waters beyond the 3-mile state limit. By the early 1950's, Louisiana and Texas had already sold over 300 leases in the Gulf beyond 3 miles offshore, and most of that was off the coast of Louisiana. Regardless, the 1953 Submerged Lands Act gave the states title to offshore lands that were within approximately 3 miles of their coastline, and subsurface lands beyond 3 miles fell under the ownership of the federal government. The first OCS lease sale was held in the Gulf off the coast of Louisiana in 1954, followed shortly thereafter by a lease sale off Texas, and in 1959, off the coast of Florida. The Secretary of the Interior leased through competitive bidding those offshore lands beyond the 3-mile limit to companies for the purpose of developing oil, gas, salt, and sulphur resources (Gramling 1995). Offshore development was proceeding along the western and central sections of the Gulf of Mexico, but a different story was developing in the waters of the eastern Gulf, off the beaches of Florida.

Development and acceptance of offshore oil industry activities along the eastern side of the Gulf of Mexico, has been erratic, controversial, and at least in state waters, nonexistent since 1962. Historically, opportunities for economic activities were more limited in Florida marshlands than Louisiana because the wetlands in Florida were different. Agricultural opportunities along the natural levees were constrained by the absence of rich alluvial soils common to Louisiana, and the ecosystem of the Florida marshes differed in the types of edible foods found, and building materials available (Gramling and Freudenburg 1995). Consequently, there was no natural extension of marsh activities into the Gulf because resource extraction in the region never reached the magnitude of that in Louisiana. The growth and subsequent economic importance of the Florida tourism industry, particularly along the coastal waters, was not compatible with oil industry activities. Most Floridians along the Gulf of Mexico do not welcome nor encourage those activities in their waters. Today there is some small production in federal waters in the Eastern Planning Area of the Gulf of Mexico, but that is not off the coast of Florida, rather Alabama.

The economic bases of the majority of coastal states (Louisiana, Texas, and to a lesser extent Alabama and Mississippi) have benefited from oil activities in the Gulf of Mexico. History of oil industry development has shown not only must the industry find oil offshore and move it ashore, everything required to operate the over-water facility needs to be delivered to an onshore support site, and transported to the platform (Davis and Place 1983). Therefore, a huge support system has developed over time, one that today essentially keeps all operations on schedule. Fabrication yards, refineries, terminals, boat docks, airports, helicopter bases, repair facilities, shipyards, and pipe storage areas are all essential to offshore operations. Communities along the industry's corridor became bases of operation, attracting numerous types of businesses involved in meeting the needs of the onshore and offshore operators. Expansion of these support facilities stimulated the local economies and prompted an increase in residential, commercial, industrial, and utility land uses, impacting nearly every community in the region (Applied Technology Research Corporation 1994). In fact, there are those who believed it was difficult to find one community, at least in Louisiana, that had not profited by the exploration and development of the hydrocarbon reserves off the state's coast.

However, the oil industry, not unlike other extractive industries, is cyclical in nature. This means there are oscillations in the price of oil and natural gas, and changes in demand; it is an international industry characterized by episodic fluctuations of advance and decline conditions in the market, and eventual exhaustion of the resource (McKenzie et al. 1993). Decisions that govern oil exploration and production in the Gulf of Mexico are made by companies that operate within the larger global political economy of energy. It involves high levels of risk, and has a history of domination by large integrated companies able to take on those risks, while being regulated by government (Laska et al. 1993). Therefore, economic development and social stability in oil-dependent regions of the coast depend on the continuation of profitable oil prices.

## The Past Thirty Years

The 1970's witnessed a dramatic increase in exploratory drilling in a climate of rising oil and gas prices. The 1973-1974 oil embargo by the Arab members of the OPEC served as a tremendous stimulant for further offshore development. Rapid employment growth and significant income gains were not uncommon for any community involved in oil activities; it was a time of prosperity for the region. But there were also socioeconomic problems associated with this period of time. Population expansions of many of the Gulf of Mexico communities could be traced to the growth in demand for oil and gas (McKenzie et al. 1993), but these were accompanied by strains on existing transportation networks, community infrastructures, and the delivery of social services. National publications brought news of employment opportunities in the Gulf coast region, and a transient labor force arrived en masse, problematic in itself. The high-paying jobs so often associated with oil industry activities made it difficult for Gulf coast economies to diversify, because businesses with lower profit margins could not compete for labor. Gramling and Freudenburg (1990) demonstrated that in terms of employment, 90% of the variance in Louisiana coastal parish local employment could be explained by national and international petroleum indicators, a sure sign of the dependency they had on oil and gas activities. By 1980, many offshore operators assumed that $40 per barrel of oil was a permanent reality and that large amounts of offshore acreage were desirable at nearly any price (LeBlanc 1980).

This was not to be. In the early 1980's, the economy of the Gulf coast region went into a tailspin. Falling crude oil prices and reduced demand for petroleum products created a crude oil glut in 1982 that hurt exploration both onshore and offshore. When there is a decline in oil and gas prices, oil and gas activities follow suit. Communities involved in these activities, particularly those whose economic base is primarily connected to the industry, experience economic downturns that can be difficult to overcome. Across the region, job growth slowed, and unemployment rates swelled to well above the U.S. average. Gramling (1996) noted that unemployment levels in some parishes went from a low of about 4% to a high of 20% by the mid-to-late 1980's. The national savings and loan crisis of the late 1980's gained fuel from the oil price collapse, because banks and S&Ls with outstanding loans to oil companies, and real estate developers who borrowed to build during the oil boom, were caught short by the rapidity of economic decline. Anyone involved in the housing industry was hurt by employment declines and outmigration (Laska et al. 1993). The Gulf coast was feeling the effects of a regional recession.

Since that time, the 1990's has seen the oil industry recover from its lows of 1986, and the Deepwater Royalty Relief Act of 1998, along with technological advancements has enabled oil exploration and development to become more economically feasible in waters of 300 m or greater beyond the continental shelf. In 1998, according to MMS, deepwater production was 36% of the total Gulf of Mexico OCS activity, but this is anticipated to greatly increase over the years.

In reviewing briefly the history of oil and gas development in the Gulf coast region, it is obvious that dramatic economic and social changes have occurred as oil exploration marched inextricably into the Gulf of Mexico. In some communities, as we shall see, cultural traditions have been irrevocably altered, while concurrently, new community patterns were being forged in newly created "boomtowns." The socioeconomic benefits to the Gulf coast region have been beyond the wildest dreams of most people, yet at the same time, they have levied a price on those communities. In the next pages, we shall examine more closely the impacts of oil and gas development on the coastal region of the Gulf of Mexico.

## Socioeconomic Effects of Oil and Gas Activity across Space

When we examine the activities of oil development and its socioeconomic effects across the central and western Gulf of Mexico region, we notice that the impacts within and between communities vary. Not surprisingly, they appear to be greater in rural coastal communities that were traditional settlements, and which were transformed into various types of staging areas and support sites. Of course, few communities within these coastal areas were left untouched by the development of the oil and gas industry. Louisiana, the primary location in the continental U.S. for offshore exploration, has accepted and welcomed the oil industry as playing a pivotal role in the lives of thousands of individuals and dozens of communities across the state. The value of Louisiana oil and natural gas produced in 1954 was about $5.4 million; by 1980 the value had risen to more than $11.4 billion (Manuel 1984). Like Louisiana, Texas has always actively encouraged and promoted the development of the offshore oil industry. By 1996, Texas was producing one-third of the nation's natural gas, the majority of those reserves lying offshore or along the coastal plain, and one-fourth of the nation's oil, a significant amount occurring in the coastal zone (U.S. Department of Commerce 1996).

One important point must be made when assessing the socioeconomic impacts of oil development along the Gulf of Mexico, particularly in the 1980's. McKenzie et al. (1993) found that the socioeconomic effects of non-OCS (state) activities and those of the OCS are inextricably mixed due to the high number of businesses and industries that serve both sectors of the oil and gas industry. That being argued, some of their analyses showed that non-OCS production was a better predictor of some socioeconomic change in the 1980's than was OCS production. They further argue that though there is a general perception that OCS declines severely impacted the U.S. economy in the 1980's, there was, at the same time, a general decline in the economy as a whole across the nation, suggesting that factors other than OCS activity, or oil activity in general, may have contributed to the Gulf Coast decline.

## Community Impacts

One of the primary characteristics of any resource extraction, such as oil or natural gas, is that extractive activities must locate where the resource is. These activities may or may not take place in a populated area with existing infrastructure and support sectors; if not, provisions must be made to support the primary activity. Frequently this involves the rebuilding of physical, economic, and social environments in those locations (Gramling 1996). This rebuilding was particularly evident in Louisiana's traditional communities in the coastal zone from the very early stages of oil activity. However, there are consequences associated with rebuilding efforts, and one of those consequences that has been noted over the years is loss of community flexibility. This means that human and financial capital are concentrated too narrowly on the primary extractive and support sectors, and therefore not easily transferable to new diversified activities. Economic diversification contributes to community sustainability. When capital, either human or financial, is constrained within a specific type of industrial activity, communities become vulnerable to fluctuations that occur within that industry, including the possibility of slowdowns. Other rebuilding consequences may be the creation of new support sectors that use up or destroy local resources; and finally, high-paying jobs in the extractive sector create intense labor competition, so that once again, the introduction of alternative economic activities becomes difficult. When the new extractive industry declines or ceases to exist, the community frequently finds itself inflexible and overspecialized, a condition referred to as "overadaptation" (Freudenburg and Gramling 1992).

An example of this could be seen in Morgan City, Louisiana. Located in East St. Mary Parish, Morgan City was a traditional community with an extractive economy derived from basin and marsh resources (cypress lumber, furs, alligators, crawfish, shrimp, etc). Because of its location, bounded by the Atchafalaya River, a major distributary of the Mississippi River, which intersects the Gulf Intracoastal Waterway close by, before traveling to the Gulf of Mexico 20 miles away, Morgan City was ideal for the development and support of offshore oil (Freudenburg and Gramling 1994). The first offshore activities took place just south of East St. Mary Parish, which helped to establish its importance in the industry in the coming years. It became a staging area for a multitude of offshore activities, and the demand for land increased as sites were increasingly needed for fabrication yards and support facilities. To accommodate the expansion, reclaimed swamp was chosen (Stallings et al. 1977) because it was conveniently close to water, and cheaper than agricultural land. Between 1955 and 1975, a total of 373 new businesses was added to the list of firms located in both Morgan City and Houma, Louisiana, each year (Davis and Place 1983). By 1970 the population of East St. Mary Parish had increased by 200%, from a stable number of 12,796 in 1940 to 36,227 (U.S. Department of Commerce 1940, 1970). This was attributable to the development of the oil industry.

At the time large-scale development of offshore oil began in the 1950's, Morgan City was the self-proclaimed "shrimp capital of the world." The offshore oil activities brought tremendous employment opportunities, and jobs, even those requiring few skills, paid well. If one job didn't work out, there were always others to be had. Consequently, those who had worked the shrimp boats or participated in the shrimping industry turned to the oil industry for jobs that were guaranteed to pay well, as opposed to the type of livelihood they knew so well that entailed hard work but no promise of financial security. Shrimp boats were converted to crew boats by owners wanting to get a share of the economic "good times" associated with the development of offshore oil. But by the mid 1980's, when the oil slowdown had hit the area hard, those same residents gave thought to returning to shrimping as a source of livelihood, only to discover the area no longer had a resident shrimp fleet or processing facility (Gramling and Brabant 1986). This phenomenon in Morgan City, East St. Mary Parish, was a classic case of overadaptation.

Morgan City was impacted in other ways besides increases in employment opportunities and population growth. Housing shortages were acute, public utilities services couldn't keep up with demand, and the numbers of medical facilities weren't adequate for the size of the population. By the mid 1970's, the violent crime rate in Morgan City was two or three times the average rate for U.S. cities of comparable size (Cicin-Sain et al. 1992). There could be found labor camps in Morgan City, which housed transients lured to the area by the promises of guaranteed jobs. The owners of the camps fed them, transported them to and from the work sites, and exacted exorbitant prices from them for services provided (Brabant 1993). Oil and gas extraction brought economic prosperity to many in the Morgan City area, but it was accompanied by significant social and economic changes as well.

Morgan City was just one community of many in a vast region along the Gulf coast that felt the impacts of oil industry development. A multitude of staging areas and support sites spread throughout the coastal region as the industry expanded. Gramling (1996) points out that wherever road or rail met waterways, local docks and staging areas appeared. What was important was location. Places like Intracoastal City and Venice, both located in Louisiana, had virtually no notable populations in the 1950's, but because of their proximity to the Gulf, became important staging areas without ever developing significant permanent populations. During the 1970's, one could drive down to Intracoastal City, Louisiana, and view a large number of bustling offshore support enterprises, but only a handful of permanent housing was seen. Oyster shell parking lots were filled with vehicles, a testament to the frenetic pace of the oil industry activities. According to a local business owner, when the slowdown came in the 1980's, Intracoastal City almost shut down completely, and there was little activity for a long period of time.

Lafayette, Louisiana, located in the heart of the "Oil Patch," and only about 30 miles from the Gulf, was not always tied to the oil and gas industry, but rather developed first as a railroad town, and then later functioned as a transportation center for farming communities in the area. Because of its location, the rapid development of oil activities created growth in Lafayette, particularly in administrative activities. It offered urban amenities that smaller communities could not offer, and so became headquarters location for many petroleum corporations. Between 1940 and 1980, the city of Lafayette grew from a population of 19,210 to 81,861, an increase of 327%, according to U.S. Department of Commerce (1940, 1980). The oil industry became so important to the economy of the city that Lafayette became the focus of much media attention. National publications targeted conspicuous consumer wealth brought on by oil industry development. The University of Southwestern Louisiana, in an attempt to accommodate students working offshore, offered classes that met just every other week, capitulating to the demands of students with concentrated work schedules. When the slowdown in the industry came, unemployment in Lafayette Parish rose to 9.6% in 1986. Property values dropped, business failures were not uncommon, and there was high outmigration (Gramling and Freudenburg 1990). Over the 1984-1989 period that covered the worst years of the oil bust, Lafayette Parish lost over one-third of its total revenues.

Many coastal Texas communities were significantly impacted by oil industry development as well. The discovery of onshore oil east of Houston, Texas in 1901 and subsequent discoveries closer to the city set the stage for the city to become a major oil center. By 1919, three-quarters of Gulf coast oil was coming from fields in the Houston area, and by the mid-1930's, Houstonians were proudly labeling their city the "oil capital of the world." The East Texas oil field, developed in the 1930's, had 26,000 wells on it by 1939 (Feagin 1985).

Between the 1940's and 1980's prosperity continued in the greater Houston area. There was substantial development of support industries linked to oil exploration and production, including refineries, oil tools and services, and petrochemical plants. In the early 1980's about 35% of the jobs in the area were connected directly to the oil and gas industry (Feagin 1990). Houston was chosen over Galveston, and Beaumont, as an oil and gas center by oil-related companies, according to Feagin (1990), because it was less exposed on the coast to hurricanes, and also had the necessary infrastructural support. It was a major port due to having a ship channel deep enough for large ships, and was a center for 17 railroads. By the 1960's and 1970's, Houston's role in the oil economy had become central in research and operations in exploration, production, refining, and marketing. Thirty-four of the 35 largest oil companies had major office and plant facilities in the Houston area, and at least 400 other major oil and gas companies also were located there, along with hundreds of oil-related service companies. In 1984, 60% of Texas oil industry onshore personnel reported to work at sites in the greater Houston area (Centaur Associates, Inc. 1986).

As in Louisiana, the economic benefits from the oil industry were substantial in Houston until the slowdown. Unparalleled prosperity was enjoyed until the 1980's, when the most serious economic downturn in that city's history occurred. Between 1981 and 1986 Houston lost more than 100,000 energy-related industrial jobs. The unemployment rate rose to 9.7% in 1983, recovered somewhat, and then late in 1986 the Chamber of Commerce estimated the unemployment rate had risen to nearly 11%. Besides serious job losses, Houston experienced housing foreclosures, increased office vacancy rates, and outmigration in the 1980's (Feagin 1990).

Studies of local economies like Morgan City and Lafayette, Louisiana, and Houston, Texas provide examples of oil and gas divisions of labor over space. Employment within the industrial sectors of extraction, manufacturing, or services is associated with different working conditions, opportunities, and job outcomes (McGranahan 1988; Lobao 1990). Houston, and Lafayette on a much smaller scale, developed into administrative headquarters for both major and independent oil companies. Located in different states, both cities demanded educated labor that could be assured of high wages, which is still true today. Demand for labor in Morgan City was considerably different. Highly paid jobs resulted from complex manufacturing needs of oil and gas fabrication yards. Educational attainment was not important; the ability to become skilled at one's job, was. Another community in Louisiana, Abbeville, appeared to have a strong presence of producer services, and still does. A center for oil field logistics and operations, Abbeville remained reasonably resilient throughout the industry slowdown in the 1980's. These patterns of industrial organization continue to significantly impact the socioeconomic conditions of Gulf coast local economies.

## Port Development

As the industry grew, communities wanting to attract the fabrication and construction industries associated with offshore activities and thus produce local jobs approved long-term bond issues for the construction of the marine equivalent of local industrial parks, or small ports contiguous to the waterfront near the community, committing local resources to the continuation of the offshore sector. Conversion of existing facilities, such as dock space, significantly altered the environment. Port development was and still is a major goal of most coastal communities. Texas port authorities believe the development of one or more deepwater ports along the Texas coast, at locations such as

Houston and Corpus Christi, would have a substantial impact in the area because deepwater port facilities would reduce both tanker traffic in Texas' bays and estuaries and the frequency of lightering operations in the Gulf of Mexico. This would reduce the risk of major and chronic oil spills (U.S. Department of Commerce 1996).

Studying the spatial development of the oil and gas industry across the Gulf of Mexico coastal region allows us to understand how and why the industry evolved as it did. Because of this differential spatial development, community and regional socioeconomic effects have also differed. Subsequently, among the many effects that can be observed is the impact offshore development has had on the organization of work.

## Impact of Oil and Gas Development on the Organization of Work

Because of the long-distance commuting made possible by concentrated work schedules, a widely dispersed work force in the offshore industry has been created. In a 1980 labor survey of a Louisiana parish heavily involved in offshore activities, not only was it found that only about 30% of the 381 offshore workers surveyed lived within 100 miles of where they met to go offshore, 70% of them had been commuting long distances for over 10 years, while they continued to live in communities far from the staging site (Gramling 1980; Gramling and Brabant 1986). These concentrated work schedules are believed to be particularly beneficial in geographical regions experiencing high unemployment, because they effectively spread the unemployment lowering effects of new jobs over a wider region. As has already been pointed out, from the perspective of a petroleum corporation, temporal and spatial management strategy of concentrated work scheduling made the exploitation of remote sites, or resources, more profitable (Gramling 1989, 1996). Later on, as offshore development spread globally, experienced offshore workers from the Gulf of Mexico were used in those operations, with lengthened work schedules. Initially, this relieved corporations of having to train inexperienced work crews, until those countries involved in oil and gas extraction passed legislation that among other requirements, mandated quotas for number of local residents to be used in oil and gas development.

### Labor Markets

One of the limitations on the expansion of oil industry development is the availability of a labor force. One of the characteristics of the offshore labor force observed by some in 1979 was that most of the new workers in the entry-level categories received no formal training before going offshore; rather they received on-the-job training after they had arrived on the platform. There was a high rate of turnover reported among the personnel of the drilling contractors, marine service companies, and food service firms. Workers were quickly finding out that offshore work was demanding, dangerous, and the schedules were unlike any they had known. Additionally, being away from family and friends for extended periods of time convinced some workers that offshore disadvantages overshadowed financial gains. This created a labor force composed of a high proportion of new and inexperienced workers at any given time, which was not only costly to companies, it also affected issues of safety. Personnel managers complained of labor that was unskilled and undisciplined. This rapid development of the offshore industry in the 1970's, along with high rate of employee turnover, resulted in a huge demand for workers in an industry dealing with a chronic shortage of workers (Perez 1979). By the late 1970's and early 1980's, the offshore oil industry supported dozens of small independent companies wanting to cash in on the rapidly escalating oil prices, but found it difficult to find enough qualified, experienced people available to fill the positions that were waiting (Hodel and Deitz 1993).

Interestingly, some of those same observations and complaints are being made today. In a recently concluded coastal Louisiana oil and gas labor demand study (forthcoming), on-site managers and personnel administrators recognized and expressed concern about a number of issues that are similar to those of the 1970's: the availability of skilled or certified workers, the increasing emphasis on industry safety, the need to keep turnover rates down, and a growing frustration with new employees wanting high wages for less work. On-the-job training is still recognized as an important part of the labor process in some sectors.

The rapid growth of oil industry activities required an immediate labor force. Yet from the 1970's until the early 1980's, and then again in the mid 1990's until recently, observations have been made that a shortage of available workers seems to be a chronic problem in times of increasing activity. To meet their growing needs, companies involved in the offshore oil industry had to attract potential workers from afar, rather than rely solely on local labor. This was the situation regardless of whether they were offshore workers with concentrated work schedules, or onshore laborers needed for oil industry activities working regular schedules. It was therefore necessary for a labor force to migrate to the Gulf Coast region. Historically, economic factors have been shown to overshadow social factors as the major causes of migration between different areas. Migration is a function of "push" and "pull" forces: if there is a lack of economic opportunities in the sending area, there is a push, and the pull is the presence of economic opportunities in the receiving area (Maruggi and Wartenberg 1996). Activities along the upper Texas and Louisiana coasts presented economic opportunities in the way of plentiful jobs at high wages, making that region very attractive. For example, welders were being paid $18 an hour in Morgan City's fabrication yards in the mid-1970's, and fabrication companies still couldn't hire enough to meet demand (Freudenburg and Gramling 1992).

Labor supply problems notwithstanding, by 1981 the offshore oil industry in Louisiana provided direct employment to 41,781 persons. Additionally, it was indirectly responsible for the creation of 83,500 other jobs in construction, maintenance and repair, retail and wholesale trade, business services, and 34 other economic sectors. It was estimated in this same study that for every new job created in the Louisiana oil and gas industry, two new jobs were created in other sectors of the state's economy (Scott 1981). The American Petroleum Institute (1984) estimated that in 1982 Texas employed 292,5222 persons in the oil and natural gas producing segment of the industry, of which a substantial portion worked in activities related to offshore oil production.

These types of economic advantages for labor persisted until the severe slowdown started in the 1980's, when companies associated with domestic oil development began to lay off significant numbers of workers. McKenzie et al.'s (1993) study of coastal Texas, Louisiana, Mississippi, and Alabama found that between 1982 and 1986, the number of mining industry jobs, of which oil and gas were predominant, decreased by 28.63%. Some who had migrated to the region left the area, and inmigration nearly ceased. A significant number of those who stayed in the Gulf of Mexico coastal regions eventually found new employment in other industrial sectors. This employment was to have serious consequences for the industry when it rebounded in the early 1990's.

When the industry began to turn around in the early 1990's, there was again an increasing demand for labor. This time, it was more difficult to attract workers. Many of those who had worked in the oil and gas industry previously, and experienced the slowdown of the 1980's had no desire to reenter an industry that they believed was too volatile. Respondents in a forthcoming 1997 study of the socioeconomic sustainability of a small Louisiana coastal community in a parish significantly involved in the oil and gas industry frequently reported economic or financial responses during the slowdown of the 1980's as involving diversification of economic activities, or obtaining employment in an industry other than oil and gas. Regardless of economic opportunities, there appeared to be a reluctance (at least in this study) to give up what they considered stable employment, for the roller coaster ride associated with oil and gas employment. Interestingly, the mid 1990's shortage of skilled workers in shipbuilding was so extreme that firms offered workers from outside the area temporary housing and mimicked the practice of the offshore oil and gas industry with a 7 days on/7 days off work schedule (Pulsipher et al. 1998).

## Industrial and Business Linkages

While the industry was rapidly developing, resources associated with human and social capital, skills, knowledge, experience, teamwork, and networks of supply and distribution and physical infrastructure began to interact and develop quickly as well (Gramling 1996). Adaptation occurred within oil and gas company organizations, while independent offshore supply companies quickly emerged. Oil and gas production companies did not, nor could not, operate without a multitude of suppliers. Small businesses within the oil and gas industry wanted to fill particular niches within the industry for which they felt there was a need, so there was a tendency toward specialization. Existing businesses adapted in a variety of ways, which might have included refitting their equipment to meet the needs of the industry. For example, there were mechanic shops that shifted attention to a new oil-related consumer base and spent considerable amounts of money on equipment to become marine diesel repair facilities. New specialty businesses opened to accommodate the growing industry's needs. Linked activities, upstream (those that supply the primary activity) and downstream (those that use the product produced by the primary activity) generated jobs and capital. Industry growth created a need for thousands of vendors along the Gulf coast that derived at least a portion of their income from offshore operations, and this is still true today (Applied

Technology Research Corporation 1994). In the mid 1950's in southern Louisiana, there were 1,187 principal businesses serving the oil and gas industry. An analysis of telephone directories in the early 1970's identified over 3,500 businesses in coastal Louisiana, directly serving the petroleum industry, an increase of more than 100 businesses per year (Davis and Place 1983).

During the 1970's in particular, the emphasis in the industry was on speed, not costs. The quicker a company could supply equipment, products, or labor, the faster the industry grew. A basic rule of economics states that when the demand for a product or service is high, such as skilled labor, the result is higher wages. This was certainly the case in the growth of offshore activities, where profit margins were so high companies did not need to be concerned with expenses or becoming expert business managers. It was a phenomenon remarked upon by one respondent in a 1992 study, "People made money in spite of themselves" (Freudenburg and Gramling 1992).

Today oil and gas exploration and production companies operating in the Gulf are usually classified as either major corporations or independent companies. Major corporations are integrated or engaged in all phases of the industry: exploration, production, transportation, manufacturing and refining, and retailing. They have the most money, the largest assets, revenues, and reserves, and employ the most people. Independent companies are comparatively small and vary in the degree of integration, from relatively little downstream integration activities, to a great deal. A 1995 study found that nonintegrated independent businesses were becoming more involved in the offshore Gulf, while major and integrated independent companies were maintaining a steady rate of activity or reducing their involvement in the Gulf (Seydlitz et al. 1995). Businesses' activities tended toward becoming more involved in downstream integration operations. The same study also found that there were more companies involved in Gulf activities in 1994 than 1986, but major and large integrated independent corporations reportedly had smaller workforces in 1994 as compared to the mid 1980's. About 66% of the study's respondents reported an increase in the use of outside contractors or service companies for various activities, while more joint ventures existed between companies (Seydlitz et al. 1995).

## Industrial Restructuring

Since the mid 1980's, a major restructuring of the oil and gas industry in the Gulf of Mexico has occurred. Cost cutting, along with financial and organizational restructuring, has occurred among integrated oil companies, but these same measures in varying degrees have been taken by most companies that survived the slowdown of the mid 1980's. Measures to reduce costs have included reductions in the number of management layers, and tighter control by headquarters over budgets of home offices, and field offices. Remote monitoring and control technology for offshore production platforms has made possible reductions of offshore maintenance and production staff. The proliferation of joint ventures between two or more companies, particularly in deepwater drilling, has been seen as a way for each company involved to reduce financial risks by sharing those risks and their own resources (Laska et al. 1993).

Restructuring in the oil service industry, distinct from the integrated and independent oil companies, has been consolidating since 1983 through bankruptcies, mergers, and takeovers. Much of the work offshore is performed by subcontractors, whose tasks include drilling, processing drilling mud, well service, and workover. Among others, oil service companies are engaged in transportation (vessels and helicopters), supply (mud, tubing, catering), rental, and manufacturing (metal fabrication and ship and boat building and repair). Because service company employment is dependent on the exploration and production budgets of offshore oil producers, any reductions in exploration and production budgets of oil companies contribute to further consolidation (Laska et al. 1993).

## Relationships to Physical Environment

The development of the oil and gas industry along the Gulf coast, by its very nature, has significantly impacted the natural and physical environments of the region. Any extractive activity involving a natural resource must by necessity be interconnected to its surroundings, whether earthly or manmade. The effects of this relationship are numerous and varied. Early offshore oil and gas activities required navigation channels and canals to be dredged for oil and gas extraction, dramatically altering the hydrology of the coastal area. According to the Texas Coastal Management Program in 1996, construction of oil and gas exploration and production facilities were believed to have disturbed or destroyed wetlands, seagrass communities, and oyster reefs in Texas (U.S. Department of Commerce 1996), and the Louisiana Coastal Wetlands Conservation and Restoration Task Force noted in 1998 that although dredge and fill activities for petroleum exploration, pipelines, and canal developments had by that time almost completely halted, those activities directly and indirectly contributed to marsh destruction (Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority 1998).

A growing environmental concern among coastal states of the Gulf coast region has been the high rate of coastal land loss. Within the last 50 years in Louisiana alone, coastal land loss rates have exceeded 40 square miles per year, and in the 1990's the rate has been estimated to be between 25 and 35 square miles each year, or about 80% of the coastal wetland loss in the entire continental United States (Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority 1998). Factors that cause marshes to change to open water are complex, combining natural processes like subsidence and hurricanes with human actions. Along with loss of the acres of coastal marshes, swamps, and islands, goes the loss of functions and values associated with the wetlands: commercial harvests of fisheries, furbearers and alligators; recreational fishing and hunting, and ecotourism; habitats for threatened and endangered species; water quality improvement; navigation corridors and port facilities; flood control; and the intangible value of land passed from generation to generation. These losses affect public usage, but more significantly, they are immeasurable in terms of cultural and heritage losses.

Regardless of reasons for coastal land loss, federal, state, and local community agencies along the Gulf coast not only recognize the importance of preserving and protecting coastal resource, but are taking measures to slow the erosion process. Loss of this natural habitat threatens the resilience of commercial fisheries and seafood, endangering not only that industry, but the economic sustainability of coastal communities.

## Agriculture

Oil development activities have impacted the agricultural community as well. Navigation channels and canals that were once dredged to expedite oil and gas activities have allowed saltwater intrusion into the rich alluvial land along the Louisiana coast. Today, citrus growers in Plaquemines Parish in south Louisiana are experiencing crop losses due to this saltwater intrusion, and rice growers in the central Acadiana region of Louisiana are concerned about the continued supply of fresh water for their crops (Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority 1998). Agriculture and its related activities have historically conflicted with other land uses and activities, and oil and gas development is no exception. As noted before, some farmers sold their land to oil-related companies as the industry expanded along the Gulf coast. But according to the Vermilion Historical Society of Vermilion Parish in south Louisiana, the development of the oil industry in that area was a great boon to the farmers, many of whom had heavy mortgages from depression years (Vermilion Historical Society 1983). In a recent (forthcoming) study of a small Louisiana coastal community with a strong oil industry presence, it was noted that many farmers in the area supplemented their agricultural income with royalties received from oil production. They were able to make improvements to their lands and operations, but during the slowdown of the 1980's, the funding needed for farm improvements dried up.

## Recreational Uses of the Coast and Oil

Land usage along the Gulf coast is impacted by offshore activities in yet other ways. If we look at state maps of Texas, Louisiana, Mississippi, Alabama, and Florida, we will notice that among them, only Louisiana has no coastal highway. Louisiana has an unusual coastline compared to most coastal states in the United States, in that it is lined with a broad and sometimes nearly impenetrable band of coastal marshes. Virtually none of the state's population lives on or near the coast, and it is often impossible to get within 10 miles of the coast by road; in fact, it has been estimated that only 12.26% of the Louisiana coast is accessible by roads. This contrasts sharply with the other Gulf coast states, where the opposite situation exists: most of their population lives on or near the coast because it's readily accessible by road. In Louisiana, there is no beautiful visual coastal imagery as is found in other areas like Florida and California, where the coasts are viewed as things of beauty and easily accessible for recreational pursuits of visitors and nearby residents (Freudenburg and Gramling 1994).

The importance of tourism in the economy of Florida has already been noted in this chapter, and increasingly, the central and western Gulf coast states are following Florida's lead in realizing the potential for economic growth in the tourist and recreational industries. In recent years, the states of Mississippi and Alabama have begun to emphasize tourism as a major component of their economy, and in Texas, community leaders, government officials, and parks and recreation professionals too have begun to appreciate the economic value of tourism. This emphasis began during the economic downturn of the mid 1980's, when community leaders and economic development planners began to capitalize on the potential of recreational resources in their areas, realizing recreation and tourism could create jobs, encourage a more diversified economy, and help moderate recessions (U.S. Department of Commerce 1996). However, a study by Gramling et al. (1995) found that individuals most closely associated with coastal tourism in those states believed it would be, or could be, negatively impacted by offshore oil and gas activity either due to an offshore accident that would foul the beaches or that tourists would find the presence of rigs irritating. Therefore, states along the Gulf of Mexico will have to balance the socioeconomic benefits of the oil and gas industry with the increasing socioeconomic potential of coastal tourism.

Because Louisiana's coast is inaccessible in all but a few areas, it has few beach-oriented tourist attractions, so the offshore presence of drilling platforms is a non-issue in that regard. There is some eco-tourism in the swamps and marshes, where one can take an air boat tour of the area, looking for alligators, spotting numerous types of birds, and admiring huge cypress groves, but those activities, along with duck and goose hunting and fresh and saltwater fishing, carry on it spite of the network of oil and gas pipelines and presence of other offshore infrastructures.

### Industrial Development and Infrastructure

An examination of oil industry facilities sites by Davis and Place (1983) noted two forms were evident: clustered facilities and interspersed facilities, both forms of which involved land use conflicts. In the first type, it was found that residential areas were mixed with heavy industry or commercial activities and were actually competing for the available higher ground along watercourses. In some cases, research showed this was because there was only one road along the bayou, and the community had been there first, but offshore oil facilities needed deep draft access, so they became neighbors. In the second type, family businesses were located on land already owned, which happened to also be the place of residence. Both of these two types of facilities related to oil activities can be found almost anywhere along the Gulf of Mexico. In Corpus Christi, Texas, there are some neighborhoods where oil refinery holding tanks are as close a neighbor as the house next door (Corpus Christi Caller-Times 1998). In 1993, more than 2,000 refinery-area residents united in a class-action suit with property damage claims against 11 refinery row industries. As a result of the litigation, still in the courts, little business development has occurred in those areas. Since 1985, refineries in the area have bought about 500 homes along their boundaries in order to clear a buffer zone they need, which has caused a sharp decline in the appraised home property values. A struggle over land use has resulted in this particular city, but it appears unlikely these residential areas will ever rebound from oil and gas industrialization.

The 1990's has seen a resurgence in the oil and gas industry that has resulted from the discovery of oil and gas in the deepwater fields of the central Gulf of Mexico. Subsequent deepwater royalty tax relief and continued technological improvement has brought about an increase in offshore and onshore activities in the coastal regions of the Gulf states. However, the volume of activity that is, and will be, associated with deepwater has raised concerns about infrastructural capabilities of communities involved in offshore oil industry activities. A 1998 study by the Economic Development Administration found that coastal leaders are concerned that recent economic growth due to deepwater development has exacerbated the problems of the deteriorating infrastructural network found in the region (Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority 1998).

Infrastructural networks may be both physical and cultural. Physical infrastructure usually refers to capital facilities and land assets that are necessary to support development while protecting public health, safety, and well-being. Among others, this includes water supply and wastewater disposal, transportation (ports, roads, bridges, airports, rail, navigation, highways), solid waste disposal, drainage, flood protection, industrial parks, electricity, and oil and gas structures. Social infrastructure generally refers to social services, educational facilities, hospitals, and parks.

In order to understand the concerns of today's leaders, we have to look back at the infrastructural needs of coastal zone activities as the industry developed, and consequences thereof for the Gulf coast. Communities caught up in rapid development found they were unable to keep up with the demands for adequate infrastructure. Significant population increases strained utility and sewage systems, medical facilities, social service services, and created housing shortages. The shortage of available land in the 1950's for residential sites around Morgan City, Louisiana was alleviated by creating a new community, Bayou Vista, in former sugar cane fields. By 1970 it was an incorporated community of 5,000. The education system was severely strained during periods of rapid oil and gas development; between 1950 and 1970, St. Mary Parish experienced a 115% increase in public school registration. The educational system, perpetually underfunded, experienced crowded classrooms, scarcity of supplies, and teacher shortages (Gramling and Freudenburg 1992).

At the same time, oil industry development also led to infrastructural improvements in local medical facilities, and water and sewer systems, among others. Public bonds funded new construction projects that communities hoped would draw new enterprises, but with the decline in production value and activity associated with exploration in the mid-1980's, these facilities constructed to attract new businesses became liabilities for the communities instead, as they had to continue making payments on those facilities, regardless of economic downturns. Property values declined, in some instances there was high outmigration, and businesses of all types failed (Gramling and Freudenburg 1992).

The concerns that coastal leaders have today of the physical infrastructure involve roads, highways, and bridges that are not only deteriorating with age, but are concomitantly becoming more congested as regular offshore oil and deepwater activities increase. Many of these are vital hurricane evacuation routes for coastal residents (Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority 1998).

## Port Fourchon

Located 21 miles south of Port Fourchon, Louisiana, in Lafourche Parish, is home of the Louisiana Offshore Oil Port (LOOP), the nation's only deepwater superport, providing tanker offloading and temporary storage services for crude oil transported on some of the largest tankers in the world. This port is the geographic and economic center of offshore drilling efforts along Louisiana's Gulf coast. In 1995, LOOP handled over 250 million barrels (bbl) of crude oil, or an estimated 685,000 bbls of oil per day. Louisiana Highway 1 is Port Fourchon's only land-based access, and it was estimated in 1998 that each month 30,000 trucks and over 200,000 passenger vehicles traveled that road. Traffic flow figures predict an increase of between 3% and 6% annually in the next decade with continued anticipated expansion of the port (Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority 1998). A report in *The Advocate*, a Baton Rouge, Louisiana newspaper (Guarisco 1998), estimated that 21% of Highway 1 was in poor condition and 98% was in need of some kind of improvement. Furthermore, most people agreed in the Port Fourchon area that the Leeville Bridge, on which every vehicle must cross heading south to the port, was the most critical point on the route. This 30 year old deteriorating bridge must lift to allow boats to pass below on Bayou Lafourche; when it is open, or broken, traffic backs up. There is no alternate route.

The primary worries of leaders and residents of Lafourche Parish at the time of the newspaper article dealt with both present and future concerns: there were only five deepwater rigs in operation, but another 78 were on the drawing boards (Guarisco 1998). Because deepwater activity takes place so far offshore, beyond state waters, the federal government keeps the taxes collected on production. Not much is returned to the states, so without this tax base, local and state economies find needed infrastructural improvements problematic, unless local and state economies are further burdened. Coastal states are therefore hoping to have legislation passed that would give more of the tax proceeds to the states. Besides road and bridge maintenance and repairs, infrastructural concerns included nonexistent available housing, with waiting lists for those wanting rental property to lease, and availability of fresh water; the Lafourche water company was then selling millions of gallons of fresh water to Port Fourchon and the surrounding area daily, and demand was anticipated to increase as deepwater projects continued.

## Oil Spills and Hazardous Waste

Growth of offshore oil activities in the Gulf coast has been accompanied by other environmental concerns, those of potential oil spills and hazardous waste disposal. The Louisiana Department of Transportation (1999) Internet website cites the LOOP facility in Louisiana as having had a satisfactory safety and performance record, according to the Executive Director of the facility, noting cumulative volume of spills in 1996 totaled 1.5 gallons. Furthermore, since 1980, OCS operators have produced 4.7 billion bbl of oil and spilled only 0.001% of this oil, or 1 bbl for every 81,000 bbl produced. In the last 15 years, according to MMS (1999), there have been no spills greater than 1,000 bbl from an OCS platform or drilling rig, and the spill risk related to a diesel spill from drilling operations is even less. From 1976-1985, there were 80 reported diesel spills greater than 1 bbl associated with drilling activities, compared with 11,944 wells drilled, or a 0.7% probability of occurrence. Interestingly, natural seepage of oil in the Gulf of Mexico is far more extensive. Researchers have estimated a natural seepage rate of about 120,000 bbl per year from one area of 23,000 square kilometers offshore of Louisiana.

The lead state agency in Texas for the prevention of and response to oil spills in the marine environment is the Texas General Land Office. In 1995, the program responded to approximately 1,250 reported oil spills, noting that despite the increasing amount of oil handled in Texas waters, the number of oil spill responses decreased due to the program's aggressive enforcement program, aerial surveillance activities, and increased harbor and vehicle patrols (U.S. Department of Commerce 1996).

However, as offshore activities have developed, there have been reports of oil spills in the Gulf of Mexico that have either involved ship/barge collisions, or pipeline ruptures. In 1993, three vessels collided at the entrance to Tampa Bay, Florida, resulting in the release of an estimated 328,000 gallons of oil which formed a 17-mile oil slick. High winds drove the oil to shore, impacting 2 miles of beach park and wildlife found in the area along the Gulf of Mexico. Within a month all loose oil had been recovered. This particular incident was significant as it was the first major demonstration of the U.S. Coast Guard vessel response plan requirements. The cleanup was financed by owners of the barges involved in the collision, who divided tasks and geographic sectors among several contractors. Approximately 1,800 professionals and volunteers assisted in cleaning up the oil that came ashore (Environmental Protection Agency [EPA] 1999).

In 1997, there was a 5,000 bbl oil spill in the saltwater Lake Barre, off the Louisiana coast. The spill was the result from the rupture of an offshore pipeline bringing oil onshore. A study conducted Pulsipher et al. (1998) at the time of the oil clean-up showed that the short-term social and economic consequences of the oil spill were modest. This has been attributed to three factors. The first is that there is a flexible adaptive cooperative coalition in the oil spill cleanup industry that springs into action when large spills occur along the Gulf coast. The presence of this coalition was noted during clean-up activities. Second, cleanup activities were fortunately of relatively short duration, which further limited the short-term economic and social impact. Third, because the spill site was geographically isolated, most coastal users were able to avoid the spill site.

Hazardous waste disposal has been somewhat more problematic for the Gulf coast region. Drilling and production activities generate liquid and solid wastes, including debris, drill cuttings, drilling fluids, and wastewater, particularly produced water or brine. Additionally, activities of companies directly linked to the oil industry frequently produce contaminants that are potentially environmentally harmful. Although most agree that tighter government control along with close monitoring of waste disposal has helped reduce potential environmental problems, costly federal cleanup operations of numerous sites along the Gulf coast point to problems arising from the past. Improper disposal of oil and gas activity contaminants in some areas have threatened groundwater of some communities. In Abbeville, Louisiana, for example, two adjacent sites placed oil drilling muds, salt water, and other drilling fluids into either on-site tanks, or earthen pits. EPA tests in late 1985 revealed, among other compounds, lead, arsenic, benzene, and toluene in an area where about 2,600 people obtained their drinking water, and 1,000 acres of cropland were being irrigated by private wells within 3 miles of the site. Another 9,000 acres were being irrigated with surface water, also potentially threatened by the sites (EPA 1999).

It is clear that oil and gas development in the Gulf of Mexico has significantly affected and altered land use patterns; residential, industrial, recreational, and occupational. In some coastal communities, there is ready acceptance and acquiescence of oil industry development needs and demands, in others, there is uneasy give-and-take, and in yet still other coastal communities, there is absolute rejection. The industry in effect asks of these communities to make a considerable investment in their own future, a future over which they actually have very little control.

## Impacts on Families and Individuals

Researchers have known that rapid technological development in the oil industry has been accompanied by significant impacts on individuals and their families. Some of these have taken place rather quickly, while other impacts have been spread along a continuum over the many decades of Gulf coast oil involvement. Most research has shown that communities experiencing rapid industrial development have an improvement in their economic position (Laska et al. 1993); therefore, it follows that individuals residing within those communities should benefit from increases in employment opportunities and higher wages. Offshore oil industry activities in the coastal communities of the central Gulf of Mexico are no different; they are widely believed to be connected to positive economic benefits which includes generating new jobs within the industry itself, and general economic spinoffs. Conviction that these activities are associated with positive economic benefits stemmed from either past experiences, or a general understanding that it was logical for industrial activity to stimulate job growth (Gramling et al. 1995). From 1959 to 1969 the new jobs created by the oil and gas industry increased the median income of families in urban areas of 2,500 or more inhabitants by several thousand dollars per year (Bobo and Charlton 1974; Davis and Place 1983). Another example of economic improvement of individuals within a particular community can be shown by the growth of per capita personal income in Lafayette, Louisiana from 1973-1980 when it increased at an annual rate of 8.1% during the period of rapid development in the offshore industry. This exceeded the total Louisiana rate by a factor of two and by a factor of four over the United States rate, and was the result of the widespread real growth of Lafayette (Manuel 1983). This unparalleled economic prosperity, and significant economic gains, were felt not only in Louisiana coastal communities and their residents, but as was pointed out previously, in Texas as well.

Although offshore oil extraction shares similarities with Western U.S. energy development projects, among them the cyclical nature of extraction, creation of new jobs, and the influx of immigrants into an area seeking job opportunities, there are differences: new employment opportunities associated with offshore oil development may not be located near the source of the oil, and jobs on oil rigs may be filled by non-local individuals who are able to commute long distances due to concentrated work scheduling (Gramling and Brabant 1986; Gramling 1989; Forsyth and Gauthier 1991). But Gramling and Brabant (1986) also found that in the case of East St. Mary Parish in Louisiana, there was a strong secondary and tertiary service sector that developed, employing local people working under traditional conditions and hours.

In some cases, traditional economic activities of long-term residents were replaced by the development and expansion of economic activities associated with offshore oil that appeared to be more highly paid. This was exemplified in the case of the Morgan City shrimp industry, which ceased to exist with the rapid expansion of offshore activities and subsequent growth of oil and gas related services sector.

## Oil and Louisiana Cajuns

An ethnic group in Louisiana whose traditional economic activities were greatly affected by oil industry development was the "Cajuns." These exiled Acadians from Nova Scotia, Canada, began moving into south Louisiana in the 1750's. Acadian pioneers were characterized by individualism, adaptability, pragmatism, industriousness, egalitarian principles, and an ability to pull together when threatened. They possessed extended families, distinctive language and speech patterns, and lived an agrarian way of life (Brasseaux 1992). All immigrants to Louisiana's wetland landscapes, according to Davis (1994), developed cultural practices tied to the annual-use cycle that is still linked to the region's natural resource base.

Getschow and Petzinger of the *Wall Street Journal* (1984) printed a series of articles on the oil industry's impact on Louisiana's Cajun culture, concluding that extraction had depleted that culture. Specifically, the articles focused on how the oil boom brought oil men in the 1930's to an area where life was "frozen in time," and fishing was "in the blood." These outsiders, or "Texians" as they were called, at first disparaged the Cajuns because of their quaint customs and clumsy English. The Cajun "swampers" and subsistence farmers gave up their traps and leased or sold their land to take part in the economic boom of rapid oil development. Many became the backbone of the oil industry in south Louisiana, toiling under the harsh sun to help extract a resource that was needed by an entire nation. But the price that was paid by this ethnic group was high, according to the Wall Street Journal. The concentrated work schedules pulled apart family ties, fishing grounds were despoiled by years of furious oil and gas production, and the Cajun society was no longer self-sufficient, but rather one dependent on oil.

Not everyone agrees with this depiction. Gramling (1994) did not concur with the Wall Street Journal's articles, instead remarking that people he interviewed gave the offshore industry credit for helping to hold the Cajun culture together. In times of prosperity, oil industry development may actually have helped sustain locally valued ways of life. Long extracting the region's natural resources, Cajuns viewed oil as another opportunity for employment and business development. The concentrated work scheduling allowed the offshore workers the chance to earn good wages, while continuing to enjoy a home life on days off in an area they felt comfortable with. It is well known to anyone living in south Louisiana that many of the traditional ways of life are alive and well. In our experience, when interviewing respondents who reveal they are of Cajun heritage (and they usually do), they frequently pride themselves as having a heritage that breeds stubbornness and toughness in times of turmoil and trouble. Today they continue to have a strong cultural presence in the south Louisiana region.

## Economic Impacts on Individuals and Families

Because the oil industry is cyclical, there are times of slowdown, with decreased exploration, drilling, and production activities. This impacts communities, families, and individuals negatively, and we would expect to see this reflected in certain economic measures. Tolbert (1995) examined family income inequality trends in coastal Louisiana parishes adjacent to the developed OCS, and coastal counties of the Florida panhandle where there has been no significant onshore or offshore development. A comparative inequality analysis of data from the 1970, 1980, and 1990 U.S. Censuses revealed that inequality in Louisiana exhibited a great deal of volatility from the 1970's period of rapid oil and gas expansion through the 1980's period of decline. Although Florida inequality trended downward over time, by 1990 in selected Louisiana parishes, inequality was higher in several cases than it had been in 1970. These patterns suggest a substantial impact of onshore and offshore industry activity on coastal families in the middle to upper-middle portions of the income distribution.

Increased opportunities for the types of highly paid employment frequently associated with offshore oil activities usually suggests widespread prosperity within those communities. However, there are other reasons than those previously mentioned why not all local individuals will benefit from the development; those with few skills or who are not willing to train for work in energy-related jobs will not benefit from the improved economic conditions (Manuel 1983). Those that are economically marginal at the time of rapid growth and development in the offshore oil industry are impacted in numerous ways. Brabant (1993) found that in four Louisiana parishes, those who were poor prior to development were similar in that they were local people, uneducated, and they lacked skills. With the tremendous growth in the offshore oil industry, there was a significant decline in the mean number of households receiving food stamps by the mid 1970's. Not only were those poor who wanted to work able to extricate themselves from welfare rolls, they were able to earn substantial incomes even if skills and education were deficient. Yet, not all locals benefited from the growth. Brabant found that the situation for the elderly poor worsened because the cost of living went up, which impacted them financially. Fixed incomes and low incomes meant housing could be problematic for families because of housing shortages or higher housing costs, unless they were home owners prior to the increased activities.

There are other negative economic impacts on individuals and their families during this period of rapid oil industry development. These include inflationary prices on goods purchased in the community which contributes to increased costs of living, and economic issues with regards to "amenity" uses of the coast, such as tourism, versus "consumptive" uses (Gramling 1995). This has been at the heart of the argument against offshore development by residents and communities of the Florida Gulf coast. There, tourism is not simply a dominant element in the economy; it is the economy. Offshore oil development seen as unwanted competition over limited coastal resources, and is aesthetically incompatible with the amenity utilization of the coastal areas (Gramling and Freudenburg 1995).

During times of decline in oil industry activities, impacts on individuals and their families include loss of employment or reduction in wages/number of hours worked, and increased poverty. In the 1950's and 1960's, migrants came to the Louisiana coast seeking jobs in the oil industry, and many of them had no familial or other ties to the area. The local social service agencies that provided Food Stamps and Welfare Assistance reported that many of these were hopeful and desperate to find employment, and were unaware that social service provisions in this particular part of the country were not as available as they had been in the North Central "Rustbelt" economies. The state was simply not prepared to deal with this influx of new residents needing social services, and when the slowdown came, the state retracted its expenditures at the local level (Laska et al. 1993). Brabant (1993) found that the mean number of households in Lafayette Parish receiving food stamps in 1983 increased 20.7%, and in St. Mary, 29.9%. These households consisted of previous welfare recipients, and those referred to as "new poor"; individuals who had once enjoyed high-paying jobs in the oil industry, but had subsequently lost them, and consequently found themselves unable to meet their financial obligations. These were people who had never been poor before. The number of people in Texas living below the poverty level grew by more than 500,000 in the decade of the 1980's, to 2.7 million in 1990 from 2.2 million 10 years earlier. During the same time, demands for social services increased (Hodel and Deitz 1993). In a recent study (forthcoming) of a small coastal Louisiana community, executives with oil-field related businesses frequently reported that in the late 1980's, a period of severe oil industry slowdown, in an effort to avoid letting employees go, would greatly reduce employees hours, eliminate bonuses and paid vacations, and asked employees if they were willing to take a cut in pay. Although these appear to be drastic measures, it was their attempt to delay as long as they could, laying off their employees.

## Social Problems

There has been some research investigating the relationship between rapid oil and gas development and various social problems. It is widely accepted by researchers that rapid social change is often accompanied by social disorder. Factors such as increased economic inequality and inmigration are believed to be partly responsible for breakdowns in social control that lead to increases in social problems. Seydlitz et al. (1993), using data from 1956-1990, found in her analyses of Louisiana parishes that rapid increases in oil and gas activities do disrupt social controls that serve to inhibit social problems. For instance, increases in suicide and homicide rates between periods of rapid growth of activities and severe industry retractions were found to be greater in these parishes between 1956-1990 than those in the U.S. overall. However, there appeared to be a cycle of disruptions and reequilibriums, with increases in social problems followed by decreases, and not just one large fluctuation related to rapid growth and abrupt decline. Criminal court cases, homicide rates, suicide rates, and rates of juvenile commitments were not consistently statistically significant among parishes differing in level or type of involvement in oil and gas activities. Although Seydlitz et al. (1993) did find a relationship between oil and gas development and social problems, they point out that it is not clear, consistent, nor strong.

## Concentrated Work Scheduling

Among the biggest socioeconomic impacts of offshore oil development and activities on individuals and families has been the concentrated temporal scheduling of work. There are a number of reasons. First, concentrated work scheduling (7 days on, 7 days off, etc.) attracts employees from a larger geographical area, and diminishes the potential concentration of settlement around this economic activity, oil and gas extraction (Gramling 1989). This allows families of offshore workers the flexibility of living in a traditional place of residence while the offshore worker goes where needed. Decisions concerning the site selection of oil activities can be made with less regard to existing human settlement patterns because of the large number of these long-distance commuters. Gramling and Brabant (1986) found that employment patterns in East St. Mary Parish in Louisiana prior to the offshore industry development did not emphasize this type of nontraditional work scheduling. Therefore, local residents appeared reluctant to work offshore in a concentrated work scheduling environment. Because the rapidly growing support sector offered available jobs, offshore work was often filled by commuters outside the area. For some, this pattern of concentrated work scheduling has become a way of life. By working offshore, they may be able to escape fluctuations in local or regional economies; for example, if they or their family reside in an economically depressed area, concentrated work scheduling elsewhere allows them the possibility of escaping the local economic impacts and participating in a wider labor market. In addition, there is the possibility of upward mobility without familial dislocation.

A major aspect of concentrated work scheduling is that participation in the nuclear family and its social networks is interrupted. While other family members operate on more traditional time/space schedules, the offshore worker experiences a totally different non-standardized work schedule. A 1991 study by Forsyth and Gauthier reported that families of offshore workers frequently experienced problems with integration; only through changing their basic structure and organization could they remain viable social systems. Adaptation to that type of work scheduling remains a source of stress for individuals and families.

Those individuals working offshore find transportation between work sites offshore and support bases onshore requires boats or helicopters and takes time. With deepwater drilling developing in areas hundreds of miles offshore, transportation time will increase. Concentrated work schedules may change to accommodate those longer distances and increased time in that workers' periods of "on days" and "off days" may be extended. Although offshore housing has a number of amenities, there are still problems associated with living offshore, including physical risk and strenuous labor in sometimes hostile environments, limited recreational facilities, and loneliness (Gramling 1989).

## Impacts of Oil on Education, Migration, and Population

As oil industry activities developed along the Gulf of Mexico, and residents of communities began to enjoy the positive economic benefits associated with the rapid economic growth of the industry, individuals began to make career decisions based on the expectation that the oil industry would stay at that high level of development. Becker (1971) notes that people make conscious decisions to invest in education: factors such as costs of obtaining an education, rate of return, market influences, and supply and demand conditions determine an individual's decision. Costs vs. benefits are weighed.

Furthermore, people are more likely to migrate/relocate than invest in education when higher paying jobs can be obtained simply by moving and higher education is not necessary for those jobs. There was such a growth in activities along the Gulf coast that more highly paid jobs become available without greater education, which reduced the perceived benefits of higher education. Seydlitz and Laska (1994) found that greater petroleum industry activity in Louisiana parishes from 1956-1990 was associated with higher percentages of students completing high school, but lower percentages of high school graduates enrolling in college. Trade schools, in response to industry demand, taught skills that were marketable for the offshore activity (Gramling and Reilly 1980). Because educational attainment of the residents of an area has a strong impact on future development opportunities, localities would benefit from a well-educated populace. One of the concerns of Louisiana economic development specialists is that the success and embeddedness of the oil and gas industry has actually served as a deterrent to education.

The development of the oil industry over an extended period of time has attracted people to the area because of the available work in the industry that promised financial rewards. A 49 county and parish study of the Texas, Louisiana, Mississippi, and Alabama Gulf coast showed that there was a 20.78% increase in population from 1960-1970; from 1970-1980 there was a 27.88% increase. The average annual population growth rate of 2.79% across those states was nearly twice the national average of 1.15% during the same period. Oil and gas activities are used to explain why the population in this central and western Gulf of Mexico region increased by 54.46% from 1960-1980. During this same

20 year period, the central Louisiana coast alone gained 58% (McKenzie et al. 1993). Unprecedented net inmigration of 126,007 persons to Louisiana occurred in the 1970's, which was the first and only decade since 1870 that Louisiana had experienced any substantial net inmigration, and it was clearly related to the oil boom and accelerated job growth that began in the early 1970's and extended through the early 1980's (Maruggi and Wartenberg 1996).

One impact attributed to the decline in oil and gas activities along the Gulf of Mexico coast has been population decline. In 1981, 5 of the 49 counties and parishes within the McKenzie et al. (1993) study area experienced negative net migration. In other words, there were more people moving out of the area than moving in. By 1984, the number of counties and parishes experiencing negative net migration had increased to 35. In southwest Louisiana, the 1981-1982 percent change of 3.33 in population shifted from a rate three times the national average to a net population loss within 2 years. The loss of the high-paying oilpatch jobs in the 1980's resulted in an outmigration from Louisiana of 411,099 persons, and according to Maruggi and Wartenberg (1996), the underlying cause of the net migration reversal was not so much from an increase of people moving out of Louisiana, but from the virtual cessation of people moving into the state.

With the 2000 Census on the horizon, researchers will have access to much data, including population data from the 1990's. It will be interesting to see what changes have taken place in coastal communities along the Gulf of Mexico in the past decade. At least until the slowdown of the late 1990's, the authors of the Louisiana Economic Outlook were forecasting that the Houma Metropolitan Statistical Area would add almost 6,000 jobs during the 1998-1999 fiscal year. Behind their belief in rapid growth was the oil and gas exploration and production resurgence in the Gulf, especially in the "deep water Gulf" (Pulsipher et al. 1998). Because of the recent slowdown in the oil and gas industry, forecasts such as this one may have been overly optimistic.

## Conclusions

No other industry in recent history has had more of an impact on individuals and families living along the central and western Gulf of Mexico coastal region than oil and gas. Particularly along the Louisiana Gulf coast, nearly everyone knows someone who earns a living as an employee of an oil- and gas-related company, and many people can relate a story involving some aspect of offshore development. The effects are so pervasive it would be hard for most people residing in the area to imagine what it would be like without the presence of oil industry activities.

The brief review presented here of the socioeconomic impacts of oil industry activities on the Gulf of Mexico coastal region has primarily focused on those resulting from shallow water activities, not deepwater. Because deepwater activities are fairly new along the historical continuum of oil and gas development, and therefore little socioeconomic research exists for those activities, there is a recognition among researchers that before gaps in data become too large, research efforts need to step up their pace. Ascertaining the differences and similarities of socioeconomic impacts upon individuals, families, communities, and states between shallow and deepwater oil industry activities will not be easy because of the integration of respective activities by oil- and gas- related companies. With few exceptions, those areas most likely to be affected are presumed to have already become immersed in such activities.

Some of the differences we have noted between deepwater and shallow or coastal zone operations, in terms of social and economic impacts, are derived from the need for cost-effective measures, and technological innovations. These may include lengthened concentrated work schedules for those employed offshore in deepwater; joint ventures between companies affecting labor demand; and stricter industry safety standards necessitating a greater need for skilled labor. Additionally, activities supporting deepwater development strain community infrastructures, and communities must have an adequate tax base with which to meet both public and private needs. Federal revenue from taxes levied on deepwater production must be fairly distributed to compensate for demands placed on Gulf coast communities due to OCS activities.

Information needs continue to be similar to those noted in Carney (1998). The goal of this socioeconomic research is to better understand events of the past, placing them in some theoretical perspective, and then through further use of empiricism, explain societal structures in such a way as to benefit the future. For instance, industrial labor surveys would provide information on industry behavior, and community capacity evaluations and subsequent action could help mitigate potential problems.

Deepwater development is now a technological advancement that will serve to strengthen the commitment of individuals and families within this area to the oil and gas industry. Regardless of problems brought forth by oil industry activity, and the rhetoric of needed economic diversification, it is a fact that oil and gas development along the OCS in the Gulf of Mexico has been a significant force that in many respects has benefited the entire region.

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# Chapter 12: Synthesis

*Neal W. Phillips*

*(with contributions by authors of Chapters 2-11)*

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## Introduction

The rapidly increasing level of deepwater development in the Gulf of Mexico poses a number of environmental, socioeconomic, and technological issues. Both new and old (existing) technologies are being introduced into a relatively unfamiliar environment. The effects of new technologies and deepwater development are not limited to that environment, but also have implications for onshore, coastal, and shelf environments where the existing infrastructure lies.

As noted by Carney (1998), the Minerals Management Service (MMS) is highly experienced in evaluating potential impacts of existing technologies in coastal and shelf environments. He identified two main problems posed by deepwater development:

1. " Identify those aspects of deepwater development for which the possibility of environmental or socioeconomic impact is no different than that now experienced in shallow water. Such activities may be evaluated and regulated largely within the current scope of knowledge, and MMS' needs for new information should be modest and easily met."

2. "Identify those aspects of deepwater development for which the modes of development and/or the environments subject to impact possibly pose novel threats of impact. For such activities the adequacies of current knowledge for evaluation and regulation must be seriously questioned. In many cases, the absence of management information will be the result of major gaps in scientific understanding of the deep ocean...."

Previous chapters of this report have discussed deepwater technology (Chapter 2), the physical and chemical environment (Chapters 3-5), biological communities and fisheries (Chapters 6-10), and socioeconomics (Chapter 11). This Synthesis Chapter draws together information from the preceding chapters to contrast deepwater operations and deepwater environments with their shallow water counterparts. Important differences are noted and their implications discussed. Such contrasts provide a basis for addressing the two problems cited by Carney (1998) and for identifying data gaps and future study needs. **Table 12.1** summarizes selected operational and environmental contrasts discussed in this chapter.

The chapter is organized into three main sections:

- *Operational contrasts and implications.* Based on Chapter 2 (Deepwater Technology) and other sources, this section highlights the main differences in oil and gas operations between deepwater and shelf environments, and discusses implications for assessing potential environmental and socioeconomic impacts.

- *Environmental contrasts and implications.* This section focuses on significant differences between deep and shallow ecosystems that could affect the nature of environmental and socioeconomic impacts.

- *Data gaps and information needs.* This section identifies what types of information are needed that are currently not available to support decisions regarding oil and gas operations in deepwater environments.

Table 12.1. Operational and environmental contrasts between deepwater and shelf settings, and their implications

| Contrast | Implications |
|---|---|
| **Operational** | |
| High oil and gas production rates | • Technological challenges for transportation and processing<br>• Increased volumes of produced water discharge<br>• Potential increase in spill risk (and size) |
| Shift from bottom-founded to floating production structures (tension leg platforms, spars, etc.) and subsea systems | • Epipelagic fishes should be attracted to deepwater structures (similar to shelf), but fewer structures needed<br>• Possible future reduction in explosive platform removals<br>• Benthic impacts will still occur due to mooring/anchoring systems, flowlines, etc. |
| Changes in drilling and production | • Increased use of synthetic drilling fluids (environmental impacts are being studied)<br>• Drilling impacts lessened if wells are fewer, more dispersed spatially (e.g., subsea wells tied to floating production structure), and in deeper water (enhanced dispersion)<br>• Flowline chemicals pose new spill risks |
| Transportation challenges | • Longer and heavier pipelines needed, with impacts to deepwater benthic environment<br>• Increasing cost of pipelines may favor FPSOs (environmental risks being studied) |
| Onshore activities | • Distance from shore affects work schedules, MMS inspections<br>• Sophisticated technology, stringent safety requirements increase demand for skilled labor<br>• Increasing strain on coastal infrastructure<br>• Concerns over future economic downturns |
| **Environmental** | |
| Complex, rugged topography, steep slopes, etc. | • Novel geohazards, engineering challenges |
| Energetic currents (various classes) | • Challenges for designing facilities, predicting fate of leaks and spills |
| Complex mesoscale circulation features | • Effects on productivity of biological communities in water column (and benthos?) |

Table 12.1. Operational and environmental contrasts between deepwater and shelf settings, and their implications (Continued)

| Contrast | Implications |
|---|---|
| **Environmental (continued)** | |
| Hydrocarbon seepage | • Background of hydrocarbon presence in relatively uncontaminated environment<br>• Presence of chemosynthetic communities (requiring protection/avoidance) |
| Biological "hot spots" of increased primary and secondary productivity in the water column | • Localized concentrations of plankton, fishes, cetaceans (potential for impacts) |
| Migratory pathways for epipelagic fishes present in deepwater | • Attraction of epipelagic fishes to structures may have regional impacts on migration and spawning |
| Fisheries include extensive surface and bottom longlining operations | • Potential space-use conflicts with fishing industry |
| Concentrations of fish eggs and larvae in deepwater | • Potential for impacts due to spills |
| Much larger suite of up to 28 cetacean species (vs. 2-3 species on shelf) including deep-diving and cryptic species | • Many more cetacean species may come in contact with oil and gas operations (e.g., potential for colliding with vessels) |
| Some cetaceans associated with mesoscale oceanographic features | • Cetacean preferred feeding areas are not geographically fixed. Complicates protection, but also offers possibility of avoiding some impacts by coupling project schedule/location with remote sensing |
| Lower adult turtle abundance, with leatherbacks outnumbering loggerheads | • Potential for some impacts reduced (especially those associated with structures and benthic activities) |
| Hatchlings and juveniles of all five turtle species may be present in *Sargassum* and flotsam | • Potential for impacts due to spills |
| High diversity of deepwater benthos | • Potential impacts on benthic biodiversity |
| Lack of understanding of benthic processes including benthic-pelagic linkages | • Complicates predicting impacts and recovery (e.g., do benthic hot spots occur, and if so, are they spatially predictable?) |
| Topographic complexity of benthic environment, much of which has not been explored | • Potential for unusual benthic communities (e.g., associated with canyons) |
| Widespread presence of chemosynthetic communities | • Dense assemblages require protection and avoidance |

## Operational Contrasts and Implications

Deepwater operations differ from their shelf counterparts in several key aspects, as discussed in Chapter 2. Differences are also highlighted in proceedings of the MMS Deepwater Workshop (Carney 1998) and in an MMS report by Cranswick and Regg (1997).

### High Production Rates

Large, productive reservoirs exist in the deepwater Gulf of Mexico. As discussed in Chapter 2, flow rates for wells completed in reservoirs typical of shallow water locations have generally been in the range of up to 2,500 barrels of oil per day (BOPD). In contrast, daily production rates as high as 50,000 BOPD have been reported from the deepwater Gulf of Mexico. Such rates are due to the characteristics of deepwater reservoirs and advances in well technology.

High production rates are among the characteristics that make deepwater development economically attractive. But they pose technological challenges for transporting and processing oil and gas (Chapter 2). In addition, rates of produced water discharge are expected to increase (Hays and Ray 1998). Risks of oil spills may increase, since such risks are calculated relative to the volume of oil handled (Anderson and LaBelle 1994). Spill size may increase due to the higher flow rates handled by larger pipelines (Rainey 1998). The environmental implications are well known to MMS and are a matter of degree rather than a novel problem.

### Shift in Types of Structures

With increasing water depth has come a shift from primarily bottom-founded structures (fixed platforms and compliant towers) to floating production systems (tension leg platforms [TLPs], spars, semisubmersibles), and subsea production systems (Chapter 2). It has also been suggested that the overall numbers of production structures per unit area will be lower in deepwater due to more productive reservoirs and increased use of subsea wells (Hays and Ray 1998).

Oil and gas platforms on the shelf typically develop a fouling community and attract epipelagic fishes (Gallaway and Lewbel 1982; LGL Ecological Research Associates, Inc. and Science Applications International Corporation 1998). While fouling community development is expected to decline with increasing water depth, deepwater oil and gas structures in the Gulf of Mexico will certainly attract epipelagic fishes of all kinds. The attraction of fishes to floating structures in the upper water column should be similar to what is observed on the shelf (Chapter 10).

A shift away from bottom-founded structures should tend to reduce future impacts of platform removal. On the shelf, platforms are usually removed using explosives to sever platform legs just below the seabed (MMS 1997). Explosive platform removals pose risks to marine mammals and turtles (Klima et al. 1988; Gitschlag and Herczeg 1994) that have been effectively mitigated by NMFS monitoring requirements (National

Research Council 1996). Deepwater structures that are not bottom-founded may not require explosive removal. Cranswick and Regg (1997) also mention the possibility of mid-water abandonments, in which structures might be cut off in mid-water, leaving the bottom half in place. Ecological implications have not been studied.

The shift away from bottom-founded structures will not avoid all benthic impacts of structure installation. TLPs, spars, and semisubmersibles are held in place by mooring systems that connect the floating production system to piled foundation systems or anchors on the seafloor. Subsea wells are connected to the floating production system via flowlines, which rest for some length on the seafloor. Impacts on benthos in the deepwater Gulf of Mexico have not been studied. The MMS is initiating a monitoring study (Effects of Oil and Gas Exploration and Development at Selected Continental Slope Sites in the Gulf of Mexico) that should provide relevant information.

## Changes in Drilling and Production

Deepwater drilling is expected to make increasing use of synthetic based drilling fluids (Hays and Ray 1998). In the last decade, a variety of synthetic drilling fluids have been developed in an effort to provide the oil and gas industry with "environmentally safe" alternatives to oil-based muds. While potential impacts of water-based drilling fluids have been studied extensively (National Research Council 1983; Neff 1987), impacts of synthetic drilling fluids are less well documented. The MMS has just initiated a Gulf of Mexico Comprehensive Synthetic Based Fluids Monitoring Program to provide information on the environmental distribution, fates, toxicity and ecological effects of cuttings from synthetic based drilling fluid systems near platforms in the western and central Gulf of Mexico. This information will be used by the U.S. Environmental Protection Agency and the oil industry to develop effluent limitation guidelines and other regulations for these discharges.

As noted in Chapter 2, with increasing use of subsea wells tied to a floating production system, the wells can be spread out and distributed to penetrate the reservoir where needed. This may result in simpler, shorter, more direct wells, as compared with having to drill wells from a common surface location with significant horizontal segments to reach different parts of the reservoir. Where surface locations are spread out, drilling fluid and cuttings discharges from initial spudding of a well (i.e., before the riser is set, allowing drilling fluids to be recirculated to the surface) should also tend to be more diffuse. On the other hand, Hays and Ray (1998) noted that greater total volumes of cuttings may be expected in deepwater due to multiple wells and horizontal well segments. Also, the dispersion of discharged cuttings will differ due to the increasing use of synthetic drilling fluids, which adhere strongly to cuttings particles; cuttings from synthetic based systems tend to clump and sink rapidly to the seafloor. The aforementioned MMS monitoring study of selected exploration and development sites is expected to provide relevant information.

A major technological challenge is ensuring continuous flow of unprocessed oil and gas from subsea wells through the flowlines on the seafloor (Chapter 2). Technology is not presently available for subsea processing of oil and gas produced from subsea wells.

Thus, the oil and gas must flow unprocessed through the flowlines to the manifold and the host. Due to cold temperatures at the deep ocean bottom, waxes in oils and gas hydrates can cause flow restrictions or complete plugging of flowlines and pipelines. Both chemical and mechanical techniques are used to assure flow. With increasing use of flowline chemicals, potential impacts of spills or leaks in the deepwater environment will need to be evaluated.

### Transportation Challenges

In deepwater, pipelines tend to be larger to handle the high production rates, and thicker walled pipe is necessary to resist the higher water pressures and operating pressures (Chapter 2). Thus, the pipelines have become very heavy, and different installation methods have been developed so that the laying process can be carefully controlled. Environmental impacts of pipeline installation in the deepwater Gulf of Mexico have not been studied.

Deepwater pipelines are expensive (e.g., $1 million per mile), and pipeline costs can be a significant factor in the overall cost of a deepwater development (Chapter 2). As new discoveries are made that are farther and farther from the existing pipeline infrastructure, floating production storage and offloading facilities (FPSOs) can be an attractive option for the Gulf. Oil can be produced to an FPSO, stored, and then offloaded onto a shuttle and shipped to shore. This transportation option can save the cost of expensive deepwater oil pipelines. The MMS is conducting a study to prepare an Environmental Impact Statement for the use of tanker-based FPSOs in the Gulf (George et al. 1999). The MMS is also sponsoring a comparative risk analysis that will compare the risks of an FPSO operating in the Gulf against the risks of other deepwater production systems currently operating in the Gulf (Gilbert and Ward 2000). Both studies should be completed in late 2000, and will be used by the MMS in their permitting decisions.

### Socioeconomic Implications

As development moves farther offshore, the increasing distance results in increased travel time for everything from crew changes to MMS inspections (Oynes 1998). As noted in Chapter 11, concentrated work scheduling (e.g., seven days on, and seven days off) is among the biggest socioeconomic impacts of OCS development and activities on individuals and families. With increasing deepwater development, concentrated work schedules may change to accommodate longer travel distances. Although offshore housing has a number of amenities, there are still problems associated with living offshore, including physical risk, strenuous labor, and limited recreational facilities.

The increasingly sophisticated technology used in deepwater development and increasingly stringent industry safety requirements are expected to increase the already strong demand for skilled labor. It has also been noted that the number of joint ventures between companies is expected to affect labor demand (Chapter 11).

Activities supporting deepwater development strain the infrastructure of coastal communities, which are concerned about receiving their fair share of proceeds from deepwater development. Coastal communities are particularly concerned about roads, highways, and bridges that are not only deteriorating with age, but are becoming more congested as deepwater activities increase. These concerns are exemplified by the discussion of Port Fourchon, Louisiana in Chapter 11. Besides road and bridge maintenance and repairs, infrastructural concerns include housing shortages and availability of fresh water.

Historically, the social and economic effects of offshore oil and gas development, as reviewed in Chapter 11, have included dramatic economic and social changes. No other industry in recent history has had a more pervasive impact on individuals and families living along the central and western Gulf of Mexico. While deepwater development is currently booming, history shows that there are times when the oil industry is in a slowdown, with significant negative impacts on communities, families, and individuals.

## Environmental Contrasts and Implications

### Physical/Chemical Environment

#### Geology

Roberts (1998) noted that, "twenty-five years ago our knowledge of processes on the continental slope in the northern Gulf of Mexico was so limited that it was viewed simply as an accreting sedimentary structure." In contrast, the synthesis in Chapter 3 reinforces the contemporary view that this is an extremely complex and dynamic environment.

The Gulf of Mexico is unique in the construction and evolution of its northwestern continental margin and in particular the continental slope off Texas and Louisiana (Chapter 3). The processes that determined the physiography of the continental slope are almost completely dominated by the halokinesis of allochthonous salt. Bathymetric maps reveal the presence of over 90 intraslope basins with relief in excess of 150 m. Intraslope-interlobal and intraslope-supralobal basins occupy the upper/middle and lower continental slope, respectively. In addition to the many structural effects discussed in Chapter 3, salt movement creates subsurface conduits that allow liquids and gases to seep into near-surface sediments and the overlying water column. The extent of seepage on the slope as compared with the shelf is important from the standpoint of both chemistry (Chapter 5) and the chemosynthetic communities associated with seeps (Chapter 8).

The engineering and geological constraints on the continental slope off Texas and Louisiana related to hydrocarbon recovery will require both novel geological and geophysical surveys and engineering methods. Significant seafloor engineering problems in deep water include slope instabilities, both short-term (slump) and long-term (creep); pipeline spanning problems; mass transport from unknown causes; and unusual stiffness and strength conditions. The geohazards (engineering and geologic constraints) present in and on the central and western continental slope are many in number and are mainly due to the activity of salt and rapid sedimentation. Specific examples cited in Chapter 3 include: faults (sediment tectonics, halokinesis); slope stability (slope steepening, slumps, creep, debris flow); gassy sediments (sediment strength reduction, hydrates, sediment liquefaction); fluid and gas expulsion features; diapiric structures (salt, mud, hydrates); seafloor depressions (blowouts, pockmarks, seeps); seafloor features (sediment waves, differential channel fill, brine-low channels, seabed furrows); shallow waterflow; and deep water high-velocity currents (mega-furrows, seabed erosion).

## Physical Oceanography

Physical oceanographic characteristics of the deepwater Gulf may be of concern to the MMS from three perspectives: (1) facilities design; (2) pollutant transport; and (3) biological consequences, such as intensified primary and secondary production associated with cyclonic eddies and confluence zones between Loop Current eddies (LCEs).

Chapter 4 discusses five classes of energetic currents in the deepwater portion of the Gulf of Mexico of potential concern from a design perspective to those involved with offshore oil and gas production and transportation. The first class is a familiar one that has long been of interest to the MMS and oil industry operators on the continental shelf. The others are specific to, or more associated with, the deepwater environment.

(1) currents resulting from energetic, episodic atmospheric events, including cold air outbreaks, extratropical cyclones, and tropical cyclones such as hurricanes;
(2) surface-intensified currents arising from the major surface circulation features (the Loop Current, the anticyclonic LCEs derived therefrom, and both cyclonic and anticyclonic eddies spun up in the Gulf);
(3) currents extending from about 1,000 m through the deeper water column with little depth variation (e.g., those believed to be associated with topographic Rossby waves), sometimes with bottom intensification;
(4) high-speed, subsurface-intensified currents or jets; and
(5) currents responsible for large, linear mega-furrows discovered along the base of the continental slope in some locations of the northwestern Gulf.

From the standpoint of pollutant transport, numerical modeling discussed in Chapter 4 offers the possibility of increasingly accurate predictions. Predicting the fate of spills or leaks from subsea pipelines, flowlines, and/or wellheads will require an understanding of currents throughout the water column.

Oceanographic studies such as the Louisiana-Texas Shelf Physical Oceanography Program (LATEX), the Northeastern Gulf of Mexico Physical Oceanography Program (NEGOM), and GulfCet I and II have produced an understanding of the circulation dynamics of the deepwater Gulf and its relationship to biological productivity. This research has shown that the continental slope is characterized by a complex array of cyclonic and anticyclonic eddies of varying time and length scales. These features have substantial impacts on nutrient concentrations, plankton and micronekton communities, and cetacean distribution (Davis et al. 2000).

### Chemical Oceanography

In general, the chemistry of the deepwater Gulf of Mexico is not well studied (Chapter 5). In many ways, the deep Gulf is buffered from the direct influence of coastal waters and processes. This is reflected in the low levels of anthropogenic contaminants present in the dissolved and particulate phases of the water column. However, oceanographic mechanisms can transport low-salinity, nutrient-rich waters across the shelf and into the deepwater environment. This has been shown to occur off the Mississippi River mouth, for example, when a seaward-moving surface flow confluence is created by deepwater cyclone-anticyclone circulation pairs (Chapter 6). Riverine input of dissolved and particulate materials is important to the chemistry of the deepwater basin. Secondary movement of materials downslope is an important process as well. The sparse information on sediments in the area suggests that the benthic environment is mostly unaffected by anthropogenic impacts. One important feature of the study area is the widespread occurrence of natural seepage of oil, gas, and brines in near-surface sediments and up through the water column. This unusual "natural background" of hydrocarbons and other disturbances is important to consider when attempting to detect impacts related to oil and gas exploration and production activities in the area.

## Water Column Ecosystems

### Plankton

It has been known for years that both standing stocks and productivity of plankton are low seaward of the shelf-slope break in the Gulf of Mexico. Chapter 6 supports this description of the mean condition but also shows that "hot spots" in primary production occur when/where nutrient availability is locally enhanced, even in deepwater. The available evidence from the Gulf of Mexico indicates that deepwater "hot spots" that are temporally persistent (even if spatially variable) have higher stocks of zooplankton and micronekton.

The occurrence of "hot spots" in the deepwater Gulf of Mexico is relevant not only to plankton, but to fisheries and apex predators like marine mammals. The presence of sizeable populations of apex predators in the deepwater Gulf of Mexico implies a reliable supply of lower trophic level prey resources and suggests that underlying physical processes allow "oases" of biological productivity to develop in the mostly oligotrophic deepwater environment.

Chapter 6 shows that when/where they occur over deepwater in the Gulf, anticyclonic and cyclonic hydrographic features play an important role in determining biogeographic patterns of and controlling secondary productivity. The potential enhancement of fisheries productivity associated with the cyclones and the frontal zones of both types of eddies is becoming better understood, now that these have been identified as deepwater concentrating mechanisms for higher trophic levels and apex predators. Continued study and assessment of zooplankton and nekton abundance within these mesoscale circulation features is warranted, since these organisms ultimately serve as food stocks for higher trophic levels.

## Fishes and Fisheries

Taxonomically, the epipelagic and demersal fish assemblages are similar at the familial and higher levels between shelf and deepwater environments (Chapter 10). Deepwater mesopelagic and bathypelagic assemblages consist of phylogenetically older taxa that have proliferated in the deep pelagic waters that are cold and devoid of light. Also the species composition of the shelf fauna tends to be more geographically restricted than deepwater faunas, which include many cosmopolitan species. One particular difference in feeding mode between shelf and deepwater environments is the prevalence of filter feeding in shelf species. In shelf waters, plankton filtering is an important feeding mode that supports extremely productive stocks such as gulf menhaden. This mode of feeding is not common in the deepwater environment.

An obvious difference in fish habitat types is the extensive occurrence of hard bottom/reef habitat on the shelf. In contrast, structured hard bottom habitats are rare in the deepwater demersal environment. However, most sampling of the deepwater demersal environment has been on featureless sedimentary bottoms amenable to trawl gear.

The fishing and offshore energy industries have coexisted and developed amicably for many years in shelf waters of the northern Gulf of Mexico. However, now that interest has extended beyond the shelf and into deep waters (>300 m), the potential for conflicts between differing technologies and fishing practices exists. All phases of the deepwater offshore energy industry—geophysical surveys, exploratory drilling, development/production, and abandonment—could conflict with current deepwater fishing practices. Current deepwater fishing practices in the northern Gulf of Mexico include trapping for golden crab, trawling for royal red shrimp, bottom longlining for groupers and tilefishes, and surface longlining for sharks and tunas. Of these gear types, the pelagic longline presents the greatest possibility for interactions or space-use conflicts.

Another concern with oil and gas activities in deepwater is the potential for interference with migratory routes. Such interference could occur because surface structures and attendant mooring lines will act as a fish attracting devices (FADs). The FAD effect would be most pronounced for epipelagic fishes such as tunas, dolphin, billfishes, and jacks (Chapter 10). The concern is that these highly migratory species would be diverted from their normal migratory routes and, consequently, from traditional spawning or feeding areas. Because of the highly migratory nature of many epipelagic species, these effects could extend to the regional scale (hundreds of kilometers). At present, spawning areas have been identified for the eastern Gulf of Mexico, but likely exist in the central and western Gulf as well.

Eggs and larvae of many epipelagic and mesopelagic fishes are commonly found in the surface waters of the deepwater Gulf. These ichthyoplankton could be exposed to contaminants discharged from surface facilities, such as produced water and domestic discharges. The potential for impacts from discharges or spills could be higher where eggs and larvae are unusually concentrated, as may occur in association with certain oceanographic features.

## Cetaceans and Turtles

Cetacean species inhabiting continental shelf waters of the Gulf of Mexico are relatively few in number (primarily bottlenose dolphins, Atlantic spotted dolphins, and perhaps Bryde's whales within certain areas of the outer shelf and shelf edge). In comparison, the deepwater environment is inhabited by a relatively rich assemblage of up to 28 cetacean species (Chapter 9). The assemblage includes resident population(s) of endangered sperm whales and several "cryptic" species (beaked whales, dwarf and pygmy sperm whales) whose habits are poorly known due to their avoidance of aircraft and ships. Therefore, a much greater number of cetacean species may come in contact with routine oil and gas operations in deepwater.

Conversely, the majority of historical sea turtle sightings, in terms of both numbers of species and numbers of individuals, have been recorded on the continental shelf. Historically, deepwater sea turtle sightings have consisted primarily of adult leatherbacks, with few loggerheads and Kemp's ridleys (to the shelf edge only) (Chapter 9). Offshore waters of the Gulf (which may include outer continental shelf, slope, and abyssal waters) may also serve as developmental habitat for hatchling and juvenile sea turtles of the five Atlantic species, and may be used by all species as a transitory habitat.

The oceanographic processes of the continental shelf of the Gulf of Mexico are dominated by shallow water, wind-driven circulation and riverine outflow influences. In comparison, the waters of the continental slope and abyss are enriched by the presence or passage of dynamic mesoscale oceanographic features such as cold-core and warm-core rings and eddies which originate from the Loop Current (Chapter 4). In addition, the slope waters south of the Mississippi River mouth appear to be primarily influenced by the volume of river outflow. The presence and persistence of these deepwater mesoscale features may strongly influence the distributions of protected species (Davis et al. 2000). In some respects, the spatial variability of these features makes a geographical designation of cetacean habitat (e.g., preferred feeding areas) difficult because it may move. On the other hand, knowledge of the position and persistence of these mesoscale features, as well as the ability to detect and track them through remote sensing, may provide a tool for mitigating some impacts of oil and gas operations in the deepwater Gulf.

Potential impacts to protected species may change due to differences in operational or logistical requirements for oil and gas operations in deepwater environments (Chapter 2). For example, in cases where oil will be transported to shore by vessel, the increased volume of vessel traffic may increase the chances for vessel collision with cetaceans (especially deep-diving species which may spend greater periods of time resting on the surface) or sea turtles. It is assumed that explosive structure removals, a concern for both turtles and mammals, will not be needed in most deepwater operations. And in the event of a deepwater oil spill, there is a much lower probability of the spilled oil reaching land or sensitive coastal, or nearshore waters when compared to such operations on the continental shelf.

## Benthic Ecosystems

Compared with continental shelf benthos, the continental slope has lower abundance and biomass and higher diversity of soft bottom macrofauna and megafauna (Chapter 7). As is the case on the shelf, the Eastern and Western Gulf differ in species composition due to a difference in substrate (carbonate vs. terrigenous). Faunal diversity of the macrofauna is high but it is not characterized by a mid-depth maximum (unlike some other ocean basins). The low biomass of the macrofauna and megafauna suggest that the biota is food limited. Budgets of carbon cycling on the slope suggest that most of the organic matter is cycled through the smaller organisms of the communities (i.e., meiofauna and bacteria).

The state of knowledge concerning the deepwater benthos (other than seep communities) has not kept up with understanding of processes in the water column ecosystem. In part, this reflects the enormous expense of collecting and processing benthic samples from the deep sea. Most benthic studies have been descriptive, focusing on abundance, biomass, species composition, and zonation. While the GulfCet program has shown that oceanographic mesoscale features strongly affect water column primary and secondary productivity ("hot spots"), this understanding has not been extended to the benthos. It is reasonable to suspect that where such "hot spots" persist spatially, benthic enrichment may occur. Studies during GulfCet II showed these features can be persistent but spatially variable. The implications for the deepwater benthos have not yet been investigated. The MMS recently initiated the Northern Gulf of Mexico Continental Slope Habitats and Benthic Ecology Study. One of the hypotheses being tested by the study is whether benthic communities underlying persistent "hot spots" are different from those in other areas.

On the continental shelf, topographic features have been of much interest to the MMS from the standpoint of environmental protection due to the unusual biological communities associated with some of these features (e.g., East and West Flower Garden Banks). Compared with the continental shelf, the northern Gulf of Mexico continental slope offers complex and rugged morphology including numerous submarine canyons and salt structures. Due to the water depth, true reef communities such as those seen at the Flower Garden Banks will not be present. However, there are some physiographic features whose benthic communities are practically unknown, including the Sigsbee and Campeche Escarpments. As additional information is obtained through MMS studies or other research on the continental slope, new habitats and resources may be encountered, and the MMS will need to evaluate their need for protection from oil and gas operations.

Chemosynthetic communities are a distinctive and widespread feature of the deepwater environment (Chapter 8). They are not found on the continental shelf. Dependence upon seeping hydrocarbons places Gulf of Mexico chemosynthetic fauna in a locality that may be affected by human activities. The amount of seafloor influenced by seepage is quite small compared to the extent of the subbottom hydrocarbon system, and industry engineers generally strive to avoid the unstable substrate at seeps. In addition, through a Notice-to-Lessees (NTL 88-11), the MMS requires site-specific surveys for proposed bottom disturbing activities in water depths greater than 400 m to evaluate the potential for chemosynthetic communities. When such areas are identified, they are subsequently protected from physical disturbance from anchors, pipelines, chains, and templates (MMS 1997). Current interest lies in improving the capacity to predict where seep communities will occur and in understanding processes that contribute to either stability or change in this environment so that anthropogenic changes could be distinguished from natural processes.

## Data Gaps and Information Needs

### Deepwater Technology

Many technical challenges have been discussed in Chapter 2. These include extending the depth range of floating production systems; improving subsea production systems including subsea pressure boosting and flow assurance; ensuring continuous flow of unprocessed oil and gas from subsea wells through flowlines on the seafloor; and constructing and maintaining increasingly long and heavy deepwater pipelines across the rugged terrain of the continental slope.

Among the other technical challenges and needs, some of the more significant topics include drilling wells in areas prone to shallow water flows, deepwater risers and moorings, and geotechnical properties of the deep ocean bottom. Research and development activities are underway, and future needs will continue to be addressed through projects conducted and/or sponsored by individual companies, through joint industry funded projects, and through broad industry sponsored programs such as DeepStar and the Offshore Technology Research Center. Technology assessment and research and development in support of deepwater development and regulations are also being sponsored by the MMS through their Technology Assessment and Research Program.

### Geology

Previous geological studies and surveys of the continental slope and rise off Texas and Louisiana were limited to regional scales. Detailed bathymetric maps cover diversified geological areas and offer a blueprint for further studies. However, the spatial resolution of present bathymetric maps is still limited to 25 m, 50 m, and 300 m, depending on the data source. We need to fill the resolution gap as well as using other instruments, like deep-towed seismic systems or Autonomous Underwater Vehicle (AUV) platforms and 3-D seismic systems, to detail geological structures. There is also a need to incorporate the old and new data into a database for intra-disciplinary and inter-disciplinary studies.

The recent discovery of mega-furrows at the base of the Sigsbee Escarpment (described in Chapter 3) is the first such observation for the Gulf of Mexico. It shows that, working in very complex geological environments such as the continental slope and rise off Texas and Louisiana, any increase in resolution of geophysical, geological and geotechnical tools will increase the possibility of finding something new and totally unexpected. The existence of mega-furrows in deepsea settings suggests that bottom currents exist in the range of 1 to 100 $cm{\cdot}s^{-1}$ and higher, and they are inferred to be formed due to helical secondary circulation. The significance of these features is the high water velocities necessary for their formation and the large amount of erosion occurring at the base of the Sigsbee Escarpment. There are indications that a single massive abyssal storm *may have* created the vast furrow field south of Green Knoll. The possible impact of such an event on seafloor structures is beyond imagination. More detailed high resolution geophysical deep-tow or AUV surveys and water current studies are needed to determine the nature, timing, and magnitude of the forces that created the mega-furrows.

## Physical Oceanography

Critical information is lacking regarding several topical areas of the physical oceanography of the deepwater regions of the Gulf of Mexico. From the view of basic science, we lack hard estimates for all terms in the salt (or freshwater) and heat budgets for the Gulf of Mexico with error estimates. A closely related unknown is the renewal rate (or residence time) of waters below the depths of sills connecting the Gulf with the Caribbean Sea and open Atlantic. Recent model studies have addressed the latter issue, but results must be confirmed with observations. Closure of these information gaps is not being addressed by known ongoing or planned studies.

Statistical information regarding energetic currents in the deep water Gulf is needed to improve the safety, economy, and environmental integrity of deepwater petroleum exploration and production. This will require a long-term program coupling sustained observations with modeling. The information gaps remain large. During the past decade, three new classes of deepwater Gulf currents have been described from direct observations or from their effects: (1) topographic barotropic Rossby waves, (2) upper ocean subsurface transient jets, and (3) bottom currents along the base of the Sigsbee Escarpment. Some observational work is ongoing to address knowledge of the first of these, and there is ongoing analysis of the second class based on existing observations. The physics responsible for currents of classes (2) and (3) are not yet known. In fact, it is not known if deep currents responsible for the mega-furrows along the Sigsbee Escarpment occur at present or if the furrows result from an energetic current event in the geologic past. It seems likely that oil and gas companies will explore the causes of these mega-furrows. The MMS has plans to support a measurement program to better describe and understand currents of the first two classes as well as surface-intensified currents (e.g., those due to Loop Current Eddies or cyclonic eddies). However, it is unlikely that these programs will be of sufficient duration to characterize statistically the energetic currents of the deep water Gulf of Mexico.

Although the currents and water properties have been studied in the vicinity of the broad De Soto Canyon, there have been no detailed studies of the effect of the narrower Mississippi Canyon on the circulation over the upper slope and outer shelf; modeling studies, however, suggest that Mississippi Canyon may generate eddies and upwelling in the region and may cause a branching of flows.

## Chemical Oceanography

The input of non-photosynthetic carbon (i.e., from seeps) is an unknown in any ecological model of the deepsea Gulf of Mexico. The exact areal extent and amount of seepage are not well known. A better understanding of the distribution of this potential nutrient and toxin in the deep sea is needed.

The vertical transport of contaminants through long water columns is not well understood and should be studied to determine if the contaminants would ever make it to the seafloor. Obviously, there is also concern about subsea oil spills and their fate and effects. The presence of gas hydrates may affect how hydrocarbons from a blowout at the seafloor would be distributed in the deepsea environment, including enhancing their persistence by sequestration. (At many sites on the slope where thermogenic gas hydrate exists, it releases globules of oil on decomposition.) The innate ability of benthos to cope with hydrocarbon exposure is not known, and the rate of microbial oxidation would be expected to be retarded in the high-pressure and cold environment. In pristine areas, populations of indigenous hydrocarbon-oxidizing bacteria would be expected to be low.

Although most studies of contaminants in the Gulf of Mexico have been restricted to shelf and coastal areas, no appreciable levels of hydrocarbons or metals have so far been detected in the water column or sediments of the deepwater environment (with the obvious exception of seep areas). While there is always a need for broad surveys of contaminant loadings in relatively unknown environments, such a survey in the deepwater Gulf would probably produce mostly zeros and not be very rewarding.

## Water Column Biology

More is known about the biology of the water column of the continental shelf than of the biology of the water overlying the deeper regions of the northern Gulf of Mexico. Because oil and gas exploration and production activity has been in place over the shelf for some time, there have been many environmental impact studies and ecological assessments of biological systems on the shelf. Now that oil and gas exploration and production is moving into increasingly deeper water, it seems timely to consider how deepwater and shelf regimes interact.

As emphasized in Chapter 6, the interaction of freshwater on the shelf with circulation regimes over the outer shelf and slope is a key mechanism that can produce "hot spots" of biological production in the deepwater Gulf of Mexico. Another key mechanism, also mentioned in Chapter 6, is the doming of nutrients within the cyclonic slope eddies and within the high current velocity shear zones that surround these cyclones and the anticyclonic eddies. An improved understanding is required of the influence of these mesoscale oceanographic features on deepwater zooplankton, micronekton, and ichthyoplankton. Finally, Chapter 6 provides an extensive list of taxonomic studies, which we believe are important to the interpretation of biological standing stock and productivity data (see Cady and Wormuth 2000). Further taxonomic analysis of recent GulfCet II Multiple Opening/Closing Net Environmental Sensing System (MOCNESS) and Isaacs-Kidd midwater trawl data, for example, would lead to an improved understanding of the biomass patterns revealed by net and acoustic sampling of mesoscale cyclones and anticyclones in the northeastern Gulf of Mexico.

Future studies should use a combination of acoustical, optical, and net sampling for biological surveys (for example, see Ressler 2000 and Remson and Hopkins 2000), in order to understand the scales of variability in zooplankton/micronekton/ ichthyoplankton biomass. Post-cruise work should include the analysis of archival data (SEAMAP) as well as of data gathered using newer time series monitoring techniques (i.e., volume backscattering data from Acoustic Doppler Current Profiler moorings; see Scott et al. 2000).

We still have more "biomass" than "productivity" data. It would be useful to explore whether the "hot spots" we describe are always areas of higher than average primary production as well as elevated standing stock biomass (which would improve our functional understanding of these systems). We certainly need additional primary production measurements within these features, especially in the central and eastern deepwater Gulf of Mexico (see Chapter 6, Figure 6.1).

## Benthic Communities

Oceanographic programs such as LATEX, NEGOM, and GulfCet I and II have produced an abundance of information about the deepwater circulation in Gulf and its relationship to primary and secondary productivity in the water column. This level of understanding has not been extended to the benthic environment. Information on deepwater benthic communities consists primarily of descriptive studies focusing on abundance, biomass, and zonation. Process-oriented studies and linkages to water column are have not been emphasized.

This situation is currently being addressed by the MMS through its recently initiated Northern Gulf of Mexico Continental Slope Habitats and Benthic Ecology Study. In addition to standard sampling for community structure, the study includes process measurements of community metabolism, meiofaunal feeding rate, sediment community oxygen demand, and foodweb studies using stable isotopes. One of the hypotheses being tested by the study is whether or not benthic communities underlying persistent water column "hot spots" are different from those in otherwise similar areas.

## Protected Species

The GulfCet I and II programs represent the most current research for marine mammals and sea turtles in the oceanic Gulf of Mexico. Future research needs are discussed in some detail in Davis et al. (2000). These include collecting additional information on environmental variables that influence the distributions of continental shelf and shelf edge cetacean species, such as bottlenose dolphins, Atlantic spotted dolphins, and possibly Bryde's whales; collecting additional data on daily movement patterns and feeding behavior of cetaceans in association with mesoscale hydrographic features to determine relationships between physical and biological processes and their influences on the distributions of cetaceans. Also recommended were additional studies on the population structure, seasonal movements, and behavior of sperm whales in the Gulf of Mexico to ascertain the importance of lower slope water habitat south of the Mississippi River mouth. A survey of the entire Gulf was recommended to improve the level of understanding of the seasonal and annual distribution, abundance, and habitat associations of cetaceans utilizing simultaneous satellite and conventional radio tracking methods, and photo-identification of predominant species (e.g., pantropical spotted dolphins and sperm whales).

Effects of noise from oil and gas operations are a prime subject for future research. To date, concern has centered on geophysical surveys, which are widespread in the Gulf and employ a variety of technologies. Davis et al. (2000) recommended conducting a systematic study of human acoustic perturbations on the large-scale distribution of local cetacean populations, including small-scale behavioral changes in addition to distribution. This would include behavioral monitoring and *in situ* behavioral experiments on the short-term and long-term effects of seismic and other loud industrial sounds on the behavior and distribution of Gulf cetaceans.

### Fishes and Fisheries

One of the important issues raised during the Deepwater Workshop (Carney 1998) was the potential for space-use conflicts between deepwater fisheries and oil and gas operations. The pelagic longline presents the greatest possibility for interactions or space-use conflicts. There have been interactions reported that involved pelagic longlines and drilling rigs in the Gulf. Recognizing this problem, MMS recently (October 1999) initiated a contract study to investigate the potential problems between the deepwater fishing and energy industries. Mappable and descriptive information on the fishing and energy industries from the Gulf of Mexico is being gathered and synthesized in order to develop proactive management approach that will allow MMS to avoid or lessen the severity of space-use problems (Snyder et al. 1999). To further support the findings for the Gulf of Mexico records of conflicts from other U.S. and international waters where the two industries overlap are being analyzed.

### Socioeconomics

Increasing deepwater development poses social and economic challenges for individuals and communities along the Gulf of Mexico. Socioeconomic research needs continue to be similar to those noted in the Deepwater Workshop (Carney 1998). The top priority identified in that workshop was a large scale industry and labor force analysis, which would include collection of data on infrastructure and community capacity. Industrial labor surveys would provide information on industry strategies and behavior. Research on vertical and horizontal integration among oil and gas operations would be instrumental in assessing labor demand, an important issue associated with socioeconomic implications of deepwater development. Community capacity evaluations and resource assessments are necessary to mitigate potential problems that will come with expanded deepwater oil and gas activities. Determining infrastructural capabilities of communities and their subsequent potential for growth and sustainability would benefit not only communities, but industry as well.

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MARCH 3, 1849

## The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

## The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Royalty Management Program** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.