DISTRIBUTION AND SIGNIFICANCE OF COARSE BIOGENIC AND CLASTIC DEPOSITS ON THE TEXAS INNER SHELF

by

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CONTENTS

FIGURES

TABLES

DISTRIBUTION AND SIGNIFICANCE OF COARSE BIOGENIC AND CLASTIC DEPOSITS ON THE TEXAS INNER SHELF[1]

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ABSTRACT

Sediments of the Texas inner shelf are generally fine grained; coarse clasts (>0.5 mm) are uncommon (<1%) over much of the area. Higher concentrations of coarse material, however, occur in discrete areas that apparently represent positions of former deltas. Coarsest constituents are predominantly whole shells and shell fragments with subordinate amounts of lithic clasts. The calcareous skeletal debris represents a mixture of extant shelf fauna and relict brackish-water molluscs including Rangia spp. and Crassostrea virginica. Rounded sandstone, limestone, and mudstone clasts up to 7 cm long and caliche nodules are common in some areas. Maps showing (1) coarse fraction percent, (2) distribution of brackish-water molluscs, and (3) rock fragments show similar trends outlining ancestral Rio Grande, Brazos-Colorado, and Trinity deltas; a patchy, arcuate trend between Pass Cavallo and Aransas Pass is enigmatic. Criteria used to determine post-depositional history and possible sources of shell debris for each of the four trends are degree of abrasion, fragmentation, etching, boring, and discoloration.

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Possible explanations for concentration of coarse material include high biological productivity, low rates of terrigenous clastic sedimentation, selective deposition by modern shelf processes, and reworking of locally shelly relict deposits exposed on the seafloor during the Holocene transgression. Of these possibilities, no single explanation adequately accounts for areal variations in coarse material. Reworking of delta-plain and estuarine deposits during and after sea-level rise is characteristic of areas that are now receiving insignificant amounts of coarse-sediment. The Sabine-Bolivar trend is interpreted as a transgressive lag derived from erosion of a late Pleistocene Trinity delta. In contrast, Brazos-Colorado and Rio Grande trends are interpreted as compound strandline features associated with subsidence, erosion, and retreat of Holocene deltas.

INTRODUCTION

Surface sediments of the Texas inner shelf are principally unconsolidated terrigenous clastics with minor calcareous components. Both relict sediment which was reworked during the Holocene transgression and modern sediment which is in equilibrium with present-day shelf processes are represented. Similar conditions have been documented for many shelf areas of the world; however, the Texas shelf differs in the (1) predominance of fine-grained sediments, (2) relatively low physical energy (except during storms), and (3) small tidal ranges that characterize the northwestern Gulf of Mexico.

The present study is based on the coarse fraction washed and retained from surface samples collected for biological studies of the Texas submerged lands (McGowen and Morton, 1979; Morton et al., 1977). During sampling operations local high concentrations of shells, including brackish-water species and rock fragments, appeared in striking contrast to the normal shelf sediments. Unfortunately, the biogenic components are frequently omitted from studies of clastic shelf sediment (Emery and Uchupi, 1972) even though they contain a wealth of time-averaged information. Pilkey et al., (1969), recognized the potential sedimentological importance of the coarse, predominantly carbonate fraction in noncarbonate shelf areas. As in previous studies, our study also demonstrates that the coarse fraction contains information valuable to interpreting the geologic history of continental shelves.

Previous Work

In contrast to the present study, previous studies of surface sediments from the Texas inner shelf were based on widely spaced transects and sample sites. Regional reconnaissance work for this area was reported by Stetson (1953). Several other studies followed, but the most complete investigation heretofore was API Project 51, conducted in the 1950's and summarized by Shepard et al. (1960).

Notable among this excellent collection of papers was the study by Curray (1960) who described sea-floor topography, physical processes, surface sediment characteristics and distribution, and interpreted Holocene development of the continental shelf between the Rio Grande and Mississippi River. Curray's study included the entire shelf, but fewer than 100 samples were obtained from the Texas inner shelf, and those were mainly concentrated offshore from Matagorda and San Jose Islands. In spite of the small number of samples, Curray was able to delineate (1) sand grading to mud with increasing water depths in the area between Pass Cavallo and Mansfield Channel, (2) greater abundance of shell and sand between the Rio Grande and Mansfield Channel, and (3) widespread occurrences of mud along the upper coast. Shell percentages for the inner shelf estimated by Curray (1960, p. 242) are generally low; moreover, he recognized the close association of abundant shell and sand which he interpreted as relict nearshore deposits.

More recent studies of the inner shelf with high sample density but limited areal extent were published by Nelson and Bray (1970) for the Sabine-High Island area, by Bernard et al. (1962) for Galveston Island, by Nienaber (1963) for the Brazos delta area, and by Shideler and Berryhill (1977) for the Corpus Christi area. All of these studies reported that the coarse fraction was minor and comprised primarily of shells. According to Shideler (1976) relict molluscan shells comprise the gravel fraction of the South Texas outer continental shelf as well.

Shelf Sediment Characteristics

Sediments found on the Texas inner shelf are typically multicyclic sands and muds. Fine to very fine grained sands are widespread and parallel to the coast south of the Brazos delta; elsewhere, mud is substantially greater than sand (figs. 1-4).

Sources for terrigenous shelf sediments have been traced to individual rivers by diagnostic heavy mineral suites (Bullard, 1942; Goldstein, 1942; Hsu, 1960; and Van Andel and Poole, 1960). These suites in turn have been used to establish lateral extent of petrologic provinces and to infer directions of sediment transport. Much of the previous work was summarized by Curray (1960), Van Andel (1960), and Van Andel and Curray (1960), who concluded that large-scale sediment transport on the Texas shelf was negligible except in the zone of net littoral drift convergence. A minor difference in their interpretations concerned the present influence of the Rio Grande. Van Andel (1960) suggested that terrigenous sand is being deposited as far basinward as the shelf break, whereas Curray (1960) concluded that middle and outer shelf sediments were deposited when sea level was lower. More recent sedimentological and oceanographic data support Curray's interpretation and show that the present influence of the Rio Grande is generally restricted to the inner shelf near the river mouth.

Differences of opinion still exist as to the direction of net sediment movement near midshelf off the Rio Grande and these differences bear, to some degree, on the inner shelf because the sharp sand-mud contacts in the vicinity of the Rio Grande are critical for any interpretation. Shideler (1976) implied that the mud reentrant represented an advancing front of southward migrating mud. In contrast, Curray (1960) attributed the same pattern to northward movement of sand during a brief sea-level rise.

Perhaps both interpretations are partly correct. Northward transport was probably more important when sea level was lower and the Rio Grande delta extended to the middle and outer shelf. After transgression of the delta and subsequent reorientation of the shoreline, the influence of southerly drift may have begun to penetrate into areas where northerly drift formerly dominated.

METHODS OF STUDY

Sample Collection, Location, and Description

Surface sediments were collected from the State submerged lands extending from the shoreline to the three-league boundary, or approximately 10.3 miles (16 km) offshore. Smith-McIntyre samplers were used to obtain approximately 4,000 samples at sites determined by a rectangular grid with a spacing of about one mile (1.6 km). The sample sites were located in the field with portable radio-navigation equipment and shipboard radar. Samples contained up to 0.45 ft^3 (0.001 m^3) depending on depth of penetration (4-18 cm) which was controlled by sediment properties. Penetration was usually greatest in soft mud and least in clean sand and stiff mud.

Sample descriptions were based on visual estimates of three principal components--sand, mud, and shell (McGowen and Morton, 1979). Also noted were sediment color, worm-tube abundance, degree of bioturbation, presence of plant material, and anomalous constituents including brackish-water fauna, caliche nodules, rock fragments, and other suspected relict sediments. In all, twelve sediment types were recognized and mapped using the three end-members and associated mixtures (McGowen and Morton, 1979). The surface sediment distributions presented in this study (figs. 1-4, part A) were simplified from the original data.

Sample Preparation, Identification, and Quantification

Approximately half (2,000) of the sediment samples were processed for biological studies. Those samples were wet-sieved through a 0.5 mm screen so that only the coarsest materials (whole valves, comminuted shell, and lithic clasts) were retained.

An important aspect of this study was the identification of molluscs (Abbott, 1974; Andrews, 1977) typical of restricted salinities or bioherms that are not representative of modern shelf environments but are indicative of relict shore zone sediments now submerged on the inner shelf (Curray, 1960; Nelson and Bray, 1970). The most abundant and consequently most useful shallow-water molluscs were *Rangia* spp. and *Crassostrea virginica* (Table 1, fig. 5). Equally important was the identification of rock fragments.

The coarse fraction (>0.5 mm) was estimated as a percentage of total volume for each sample according to the following procedure. First the volume occupied by each sieved sample was measured using calibration marks on the sample jars. It was then determined by volumetric displacements that these volumes contained on the average 70% solid material and 30% liquid. Therefore, measured volumes for the coarse fraction were multiplied by 0.7 in order to adjust for the intergranular space.

Original sediment sample volumes were estimated by measuring penetration depth of the sampler at each station; these depths were converted to volumes by using a rating curve calculated from the semicylindrical shape of the sampler. Finally, adjusted coarse fraction volumes were divided by total sample volumes to give the percentages mapped in figures 1-4, part B. The mapped data actually depict percent coarse sand and gravel (sizes), but because nonskeletal detritus comprises only a small part of the coarse fraction, the data also portray relative shell abundance.

ABUNDANCE OF COARSE FRACTION

High concentrations of coarse sediment, consisting of shells, shell fragments, and rock fragments, are the exception rather than the rule for sediments of the Texas inner shelf. For more than half of the area, the coarse fraction comprises less than one percent of the sediment (fig. 6). Concentrations greater than eight percent are rare and local.

Four regions with abundant coarse material were recognized, each with distinctive patterns of distribution and composition. The four map areas (figs. 1-4) correspond to those regions. The Sabine-Bolivar Area (fig. 1B) shows a lobate pattern of abundant coarse material. At the offshore limit of the study area is a linear trend that corresponds to a minor bathymetric high. This high is parallel to the larger Sabine and Heald banks located farther offshore (Nelson and Bray, 1970). In the Brazos-Colorado Area (fig. 2B) the main pattern is roughly arcuate rather than lobate. The arc extends from western Galveston Island to about 10 miles offshore and then to the present mouth of the Colorado River. In the Matagorda-San Jose Area (fig. 3B) high concentrations of coarse material are rare and show a patchy distribution. In the Rio Grande Area (fig. 4B) the overall distribution is lobate. Superimposed on this pattern is a linear grain, oriented north-northeast, which corresponds to the trend of the bathymetric ridges (McGowen and Morton, 1979).

NEARSHORE OCEANOGRAPHY

Insights into the physical and biological factors that may control the high concentrations of coarse material can be obtained by examining the nearshore oceanography. General circulation patterns in the Gulf of Mexico have been described by Emery and Uchupi (1972) and by Leipper (1954), among others. Several specific studies have documented movement of nearshore water masses along and across the Texas inner shelf. From these studies it is clear that regional circulation patterns and the nearshore movement in particular are largely dependent on meteorological conditions. Wind is the primary force that generates movement in the surface layers. Below the mixed surface layer, flow can be generated either by wind-driven currents, by density contrasts (mainly temperature and salinity differences), or by tidal motion. Tidal influence in the northwestern Gulf of Mexico is probably minimal (Smith, 1978) because of low amplitude and diurnal period of the tides. Of these potential mechanisms, wind stress is responsible for the strongest currents affecting the seafloor.

Fair Weather Conditions

Inner shelf circulation patterns are generally seasonal with onshore surface transport and offshore bottom flow dominant in summer months, and offshore surface transport and onshore bottom flow occurring at least temporarily in winter months (Hunter et al., 1974). Current drifters and current meter studies, however, have shown spatial and temporal variations in current directions that result from fluctuations in wind direction regardless of the season (Smith, 1977).

For the purposes of this study, the ability of bottom currents to erode and transport near-surface sediments is of more interest than short-term direction of water movement. Sparse field data (Smith, 1975; 1977; 1978) suggest that under fair weather conditions, near-bottom currents beyond the breaker zone are usually less than 10 cm/sec. Recently Young and Southard (1978) found that fine-grained marine sediments can be eroded by current velocities exceeding 6 cm/sec. They also found that erosion is affected by organic content and bioturbation of the sediment.

Fine-grained sediments eroded from the inner shelf are most likely transported in suspension; furthermore, shear velocities during fair weather would be insufficient to erode and transport the coarse fraction described in this study.

Storms

Current velocity measurements (Smith, 1975; 1977; 1978) and theoretical calculations (Curray, 1960) indicate that significant sediment transport on the seafloor below wave base is periodic, infrequent, and chiefly the result of strong currents produced by storms in the Gulf of Mexico. During storms, high-velocity winds drive surface water ashore. This landward movement is confined by physical barriers at the coast and, through conservation of mass, the landward transport is balanced by bottom-return flow in the nearshore lower boundary layer. This strong bottom-return flow may parallel the coast as in fair weather (Murray, 1975) or it may be directed offshore at a high angle to the coast like a large-scale rip current.

Maximum storm-generated current velocities of 1.5 and 2.0 m/sec were reported respectively for the Florida and Texas inner shelves by Murray (1970) and Forristall et al. (1977). Considering the location of study sites and storm characteristics, the recorded velocities were probably lower than the maximum velocities on the seafloor near landfall of major hurricanes. Theoretical computations of bottom orbital velocities for storm waves by Herbich and Brahme (1977) lead to similar conclusions.

Direct observations of coarse sediment transport on the Texas inner shelf have not been made; however, the present water depth and the intrastratal position of the shell and rock fragments with finer sediments suggest the coarse fraction is eroded and transported only during extreme storm conditions.

Temperature, Salinity, and Nutrients

The concentrations of shells on the inner shelf might also reflect hydrographic variations since nearshore areas where water masses mix are often sites of high biological productivity. Water masses issuing from rivers and tidal inlets within the coastal zone are generally warmer and fresher than open Gulf waters. The fresher nearshore water is transported along the coast by littoral processes and trapped or dispersed (mixed) depending on available energy. Temperatures and salinities as well as stratification and mixing vary seasonally, and in winter months the Gulf is characterized by cooler, fresher water nearshore (Jones et al., 1965). The steep gradients in surface temperatures and salinities during winter months are attributed to high rainfall and to strong northerly winds that drive fresher bay waters into the Gulf.

Discharge from the Atchfalaya and Mississippi Rivers may influence the physical and chemical characteristics of shelf waters along the upper Texas coast, but nutrient and freshwater supplies to the inner shelf are controlled mainly by locations of coastal rivers and inlets and the climatic gradient that extends from Louisiana to Mexico (Thornthwaite, 1948).

According to recent seasonal studies of plankton, hydrography, and nutrients for the South Texas shelf (Berryhill, 1977), the inner shelf is more productive than the outer shelf, and the most productive area borders the Rio Grande delta. Nutrients are supplied directly to the inner shelf by freshwater runoff and, therefore, nutrients tend to decrease offshore except near upwelling water masses. Upwelling of deeper shelf waters may be enhanced partly by runoff in conjunction with wind stress.

FOSSIL ASSEMBLAGES

In order to make a reasonable interpretation of fossil assemblages, basic distinctions must be made between _in situ_ accumulations and transported assemblages.

Methods for distinguishing life from death assemblages were listed by Imbrie (1955); later Johnson (1960) described the most likely histories of faunal assemblages. Although Johnson's models were developed for exposed fossil assemblages, the criteria are applicable to samples from modern marine environments. Considering the high physical energy, abundance of shell debris, low number of living individuals, and mixed faunal assemblages, the areas of high shell concentrations on the Texas inner shelf fall somewhere between Johnson's models I and III which respectively represent conditions of gradual accumulation and transportation.

As previously noted, bottom currents can play an important role in forming death assemblages, especially in transgressive marine sequences or in areas of low sediment influx. Menard and Boucot (1951) and Johnson (1957) conducted experiments of shell transportation and burial for different current velocities, shell orientations, and substrates. More recently Kranz (1974a, 1974b) simulated catastrophic local burial of molluscs; this type of burial is apt to occur on storm-dominated shelves such as the northwestern Gulf of Mexico. These studies clearly show why fossil assemblages can be vastly different from living assemblages.

Some of the criteria used to distinguish allochthonous and autochthonous assemblages could not be used in our study. For example, sampling methods prevented documentation of preferred orientation and distribution of shell within each sample. Shipboard observations, however, indicate that some shell occurs in distinct layers (fig. 7) and some occurs throughout the sediment column. Boucot (1953) and Boucot et al. (1958) developed statistical methods for distinguishing living and transported assemblages by using valve sorting, shell sizes, and valve disassociation. Neither shell fragmentation nor valve disassociation was useful in this study because there are no obvious trends where broken or whole shells predominate and nearly all shells are disarticulated. Furthermore, counts of Rangia valves resulted in nearly equal numbers of right and left valves within each area.

POSSIBLE CAUSES OF SHELL DEPOSITS

Storm Processes

Shell layers in shelf sediments are commonly attributed to storm processes although the mechanics of sediment transport are seldom mentioned. High waves and strong currents are appealing explanations, but these mechanisms only apply if the shell beds are in equilibrium with the present-day hydraulic regime and are not relict deposits.

Powers and Kinsman (1953) proposed that pressure fluctuations attendant with storm swell were capable of _in situ_ sorting of shell beds. Hayes (1967) and Reineck and Singh (1972) also used modern examples of storm processes to explain graded shelf deposits. These interpretations have been widely accepted and applied to ancient strata despite the fact that the adverse conditions posed by storms have precluded field observation of shell transport. Even without this confirmation we can safely conclude that storms are responsible for some shell deposits, such as graded beds with sharp basal contacts (fig. 7), but storms are not necessarily responsible for all shell deposits.

Beach-Strandline Deposition

Some shell concentrations could be beach-strandline deposits that became submerged and buried following sea-level rise (Curray, 1960). Modern shell beaches, which are common along the Texas coast, are formed by landward and longshore transport and winnowing of modern shells and relict molluscs eroded from shell-rich estuarine and deltaic sediments (fig. 7). Similar shell beaches and submerged shell deposits derived locally in response to shoreline retreat have been described elsewhere by Greensmith and Tucker (1969).

Shells concentrated along beaches should be highly abraded and rounded, rather than bored by organisms or etched by solution. Highly abraded valves of *Noetia ponderosa* are characteristic of Big Shell Beach on Central Padre Island, for example. Relict shell beaches should leave linear or curvilinear trends of concentrated coarse material in plan view.

Low Clastic Sedimentation

Carbonate abundance can also be controlled by rates of clastic sedimentation. Van Andel (1960) presented a regional picture of the relative rates of sedimentation for the Texas coast. When considered with directions of net sediment transport suggested by Curray (1960), the patterns of nondeposition along the upper coast and off the Rio Grande delta and deposition within the zone of convergence provide an excellent portrayal of shelf conditions as they are presently known. The areas of nondeposition (Van Andel, 1960, fig. 14) generally coincide with the areas of high shell abundance (figs. 1-4) and vice versa.

Prolonged accumulation of shell in areas of low sediment influx could account for the greater shell volumes, but it would not explain the close correlation among relict fauna, rock fragments, and shell deposits.

High Productivity

Enrichment of organics and nutrients suspended in shelf waters by continental runoff and upwelling of deeper basin waters is well known from other coastal settings even though synoptic data for the Texas coast are sparse. Nutrient influx from coastal runoff is probably a major factor determining the large areal variations in shell production. At present, the numbers of molluscs living on the inner shelf indicate low productivity for most areas except in the vicinity of the Rio Grande.

The quantity and quality of nutrients supplied by coastal runoff and upwelling and their subsequent influence on the shelf benthos are not well documented. Furthermore, increased nutrient supply by upwelling may have been more important several thousand years ago when freshwater discharges were probably greater and the inner shelf was closer to the shelf break because the Rio Grande delta was in a more seaward position.

COMPOSITION OF THE COARSE FRACTION

Shells and Shell Fragments

In most samples from the inner shelf, the coarse fraction is dominated by mollusc shells and shell fragments. The number of live mollusc individuals is typically very small relative to the total number of shells. Unless otherwise indicated, this discussion will refer to skeletal remains rather than to live individuals.

Interpretation of shell deposits requires that endemic shelf species be distinguished from those which may have been transported from other environments or exhumed during erosion of underlying deposits. Unfortunately, the live molluscan communities of the shelf are still inadequately known. Preliminary results from detailed biological examination, still in progress, of the same samples used in this study indicate that molluscan assemblages of the Texas shelf are substantially different from those reported by Parker (1960), whose work is the standard to date. The following discussion is based on the more recent work.

No single species is a reliable indicator of the inner shelf environment. Virtually all common live species that we have observed occur to some extent in the bays and lagoons (Parker, 1959, 1960; Harry, 1976) or farther offshore (Parker, 1960; Berryhill, 1977). For the most part, assemblages of the inner shelf represent a mixture of (1) species that are most common on the shelf, but occur locally in the bays, and (2) wideranging bay species. The first category is dominated by the pelecypods *Abra aequalis*, *Anadara* spp., *Corbula* spp., and *Chione clenchi* and the gastropods *Natica pusilla*, *Terebra protexta*, and *Vitrinella floridana*. All of these, particularly *Abra*, have been found live in shelf sediment samples.

The second category, species that are common in bays but also occur on the shelf, is dominated by the pelecypod *Mulinia lateralis*. *Mulinia* shells are the most abundant species in many shelf samples although live individuals are uncommon. Other common species in this category are the pelecypods *Nuculana concentrica*, *N. acuta*, *Linga amiantus*, *Parvilucina multilineata*, *Ostrea equestris*, *Anomia simplex*, *Chione cancellata*, and the gastropods *Polinices duplicatus* and *Nassarius acutus*. Of these, *Nuculana*, *Linga*, *Parvilucina*, *Polinices*, and *Nassarius* have been found live on the inner shelf. *Ostrea* and *Anomia*, according to Parker (1960), live on high-salinity reefs in the bays, whereas *Chione cancellata* is typical of open-bay margins. The frequent and widespread occurrence of these three species in shelf sediments is enigmatic.

Restricted Species

Some of the common molluscs are known to be restricted, when living, to low-salinity environments. Their presence in shelf sediment is, therefore, a good indicator that brackish-water sediments have been reworked.

Rangia cuneata is characteristic of river-influenced environments where salinity usually ranges from 0 to 15 ‰ (Hopkins, et al. 1973). *R. cuneata* prefers lower salinities and dominates the river-influenced assemblage, particularly the distributary mouths of bayhead deltas. *R. flexuosa* prefers slightly higher salinity and shallow water, and thus is more common in interdistributary bays (Parker, 1960).

Crassostrea virginica is the dominant species of low-salinity oyster reefs, where salinities usually range between 15 and 25 ‰. It is abundant in the upper bays of the Texas coast and in interdistributary bays of the Mississippi delta (Parker, 1959, 1960).

Mercenaria campechiensis is more typical of high-salinity bay margins (Parker, 1959). In shelf sediments, it occurs in the same general area as Crassostrea.

Shells of these pelecypods are large and durable (fig. 5), which makes them easy to recognize even after extensive abrasion, dissolution, and boring by sponges. Rangia spp. can usually be recognized by fragments of the hinge area alone. In many cases, Rangia shells were damaged to the point that species could not be distinguished, so the two species were grouped for the purpose of mapping. Crassostrea fragments were sometimes difficult to distinguish from Ostrea equestris fragments. The true distribution of Crassostrea may therefore be wider than indicated on the basis of positive identifications.

In parts C and D of figures 1-4, the shaded areas represent the combined distribution of rock fragments, Rangia, Crassostrea, and Mercenaria. In general, the combined distributions of these relict sediment indicators correspond closely to the areas of high shell concentration. Differences in coarse-fraction composition of the four areas (Table 1) suggest different origins for these concentrations.

State of Shell Preservation

Several processes can affect the state of shell preservation. Mechanical processes, such as abrasion, act mainly during transport, whereas biological processes, such as boring and encrustation, are probably related to the duration of exposure on the sea floor. Fragmentation can be either a mechanical or a biological process (Pilkey et al., 1969). Chemical processes, including etching, leaching, and darkening, appear to be primarily a function of burial. For this study, the main purpose in examining state of preservation was to generalize about the age and history of Rangia and Crassostrea where only a small number of radiocarbon dates were available.

On the basis of visual estimates, shell fragments comprise 30-70 % of shell material in most samples; however, the percentage of shell fragments did not appear to define any significant geographic trends. Abrasion is recognized by rounding of edges, destruction of ornamentation and dentition, and polishing. An extreme example of shell abrasion is on Big Shell Beach on Central Padre Island, where virtually every shell is heavily abraded (Watson, 1971). In the shelf samples, abrasion is common on individual shells, but it is never characteristic of all shells in a sample.

Borings and encrustations are also common on individual shells (fig. 5), particularly in samples with abundant shell material. Biological modification appears to be largely independent of other processes. For example, shells that are otherwise well preserved can be extensively bored, whereas heavily abraded or deeply etched shells can be free of borings or encrustations.

Pilkey et al. (1969) observed darkened shells in Atlantic shelf sediments. They also demonstrated experimentally that darkening can be produced by short-term burial in anoxic mud. The time required for darkening was only three weeks. In Texas shelf sediments, darkening is typical of Crassostrea shells in general, but is greatest for shells in the Matagorda-San Jose trend (Table 1; fig. 5).

Etching and bleaching are apparently the most useful characteristics for distinguishing Holocene from Pleistocene shells. Bleaching, or loss of color, is typical of shells in Pleistocene sediment. This has been illustrated in the literature (Pampe, 1971) and observed by the authors; however, some shells, particularly Crassostrea, may retain some color. Etching is by no means characteristic of Pleistocene shells (Pampe, 1971), but has been observed on Rangia shells in offshore cores of the Pleistocene Beaumont clay. Etching generally increases the relief on the shell surface, particularly the growth lines, and removes the inner gloss. Moderate etching occurs on some Rangia cuneata shells of the Brazos-Colorado trend, but the deepest etching occurs in Rangia shells of the Sabine-Bolivar trend (fig. 5), where Pleistocene radiocarbon dates have been reported (Stevens et al., 1956; Nelson and Bray, 1970; U.S. Geological Survey, 1978, personal communication).

Rock Fragments

Three basic types of rock fragments occur in sediments of the inner shelf: cemented terrigenous clastics, limestone, and caliche nodules (Table 1). Each of the four regions of concentrated coarse material is characterized by a particular association of rock fragments. The absence of mixing between adjacent regions suggests that coarse material is not transported long distances (> 100 km) parallel to the shore.

Calcite-cemented sandstone and mudstone (fig. 5) are the most common types of rock fragments on the shelf. They are widely distributed in the Sabine-Bolivar, Brazos-Colorado, and Rio Grande areas. Most are small (< 2 cm) and are colored a wide range of grays and browns. Sandstones are more common in the Rio Grande trend whereas mudstones predominate in the Sabine-Bolivar trend. Large fragments of similar lithologies occur locally on beaches of the Texas coast. Their sources, however, are not precisely known.

Indurated sandstone is fairly common in Pleistocene sediments. Winker (1979) encountered calcite-cemented horizons in shallow (< 100 feet) Pleistocene marine sands in Brazoria County. Similar indurated sands are occasionally reported in water-well driller's logs. Cemented sediments also crop out locally on the shelf where they form bathymetric prominences. Two of these outcrops have been studied in detail. Thayer et al. (1974) collected rock samples from an indurated ridge on the inner shelf off central Padre Island. They concluded that the sand was deposited in a lacustrine environment during the last period of lowered sea level and cemented with calcite in the same environment. Winchester (1971) studied Freeport Rocks, which consist of calcite-cemented quartz sand and shell hash with reworked caliche nodules. He inferred a barrier-island or offshore-bar origin of Holocene age. Like Thayer et al., he attributed the calcite cement to fresh-water diagenesis. Rusnak (1960) described similar cemented sandstone fragments reworked from the Pleistocene Rio Grande delta and from late Quaternary beach rock.

Fragments of micritic limestone occur in all four trends, but are most common in the Matagorda-San Jose trend. Shells have been recognized in a few limestone fragments, but most appear to be unfossiliferous. Rusnak (1960) described Pleistocene beach rock cropping out on the mainland shore of Laguna Madre as dense, calcite-cemented shell hash. He reported that recrystallization commonly made the shells indistinguishable from the cement. Holocene beach rock, in contrast, is light-colored shell hash loosely cemented by aragonite. On the basis of Rusnak's descriptions, it appears that limestone fragments on the shelf are derived from Pleistocene sediments.

Caliche nodules (fig. 5) occur in shelf sediments in the Sabine-Bolivar, Brazos-Colorado, and Rio Grande regions (Table 1). They are readily distinguished from the limestone fragments by their white color and low density. On the lower coastal plain, caliche nodules occur in soils as far east as southwestern Louisiana (Jones et al., 1956) and are found in Holocene fluvial sediments (Bernard et al., 1970). Caliche becomes more abundant to the south (Price, 1933), a result of the climatic gradient with increasing aridity toward the southwest (Thornthwaite, 1948).

COMPARISON OF TRENDS

Sabine-Bolivar Area

In this area, dominant constituents of the coarse fraction are large valves of Rangia cuneata and Anadara spp. Pleistocene Beaumont clay which crops out on the shelf in this area (Nelson and Bray, 1970; McGowen and Morton, 1979) is probably the source of these shells. Deeply etched Rangia shells have been encountered in offshore cores of Beaumont clay obtained by the U.S. Army Corps of Engineers Coastal Engineering Research Center. These shells yielded radiocarbon dates of more than 30,000 years (U.S. Geological Survey, personal communication). Stevens et al. (1956)

also obtained a date of more than 30,000 B. P. from shells in a core of Beaumont clay offshore from High Island.

Nelson and Bray (1970) reported numerous radiocarbon dates for various species of shell recovered from surface sediment samples and shallow cores from the Sabine-High Island area. Most species, including Crassostrea virginica, gave mostly Holocene dates, but Rangia cuneata, with a few exceptions, gave Pleistocene dates. Shells of Anadara transversa gave Holocene dates, but these were collected farther offshore than the limits of the present study. Deep etching and bleaching of Anadara shells on the inner shelf suggest that they are the same age as the Rangia shells. Crassostrea shells are not as common or widespread as Rangia in this area and are probably mostly Holocene.

The onshore extensions of abundant shell, restricted molluscs, and rock fragments (fig. 1) generally coincide with high concentrations of these same constituents on beaches extending from eastern Bolivar Peninsula to east of High Island (Table 2). Winchester (1971) reported that Crassostrea shells from the High Island beach consistently yielded Holocene dates whereas Rangia shells gave both Holocene and Pleistocene dates. The dates presented by Winchester tend to confirm a Holocene age for Crassostrea and a Pleistocene age for Rangia (Table 2).

The absence of Holocene Rangia shells within this trend can be explained by the present shoreline configuration. The modern Trinity delta is located at the head of Trinity Bay, far from the coastline. Thus, recent river-influenced sediments are not available for marine reworking. The Rangia shells and rock fragments were apparently exhumed by submarine erosion of the late Pleistocene Trinity delta. Perhaps the strongest evidence for this interpretation is the close correlation between occurrences of the coarse fraction (fig. 1) and outcrops of Pleistocene deltaic sediments (Nelson and Bray, 1970; McGowen and Morton, 1979).

Brazos-Colorado Area

This trend is dominated by shells of typical shelf species, but Rangia and Crassostrea are significant components. In contrast with the Sabine-Bolivar area, both Rangia cuneata and R. flexosa are common, and are typically well preserved (Table 1). A minority of R. cuneata shells are etched and bleached, but not to the extent that is characteristic of the Sabine-Bolivar area. Crassostrea shells are well preserved, except for breakage. The only radiocarbon dates in this area are from Freeport Rocks, pinnacles of indurated sediment that occur slightly landward of the shell trend. Crassostrea shells from Freeport Rocks date as Pleistocene (Curray, 1960), but these may not be representative of the main shell trend. Crassostrea shells of the main trend are indistinguishable from those of the Sabine-Bolivar and Rio Grande trends where Holocene dates have been reported.

The arcuate shape of the trend is similar to a postulated former shoreline position estimated by extrapolating present rates of shoreline erosion (Morton, 1977). Evidently the Brazos-Colorado deltaic headland was more prominent at stillstand and has since been retreating at a rapid rate; thus, the shell trend may have originally formed along the delta margin at stillstand. An alternate explanation suggests that the trend was originally lobate, like the Sabine-Bolivar and Rio Grande trends, but the inner portion has been covered by recent mud introduced by the Brazos and Colorado Rivers. If the second explanation were true, then above-average concentrations of shell should be encountered in cores near the base of Holocene mud. From the few core logs we have examined, such is apparently not the case.

In places the shell trend corresponds to bathymetric ridges parallel to the coastline. Similar shell concentrations occur on Sabine and Heald Banks (Nelson and Bray, 1970). The ridges are erosional remnants that have been interpreted as shoreline (Curray, 1960) or barrier island-offshore bar deposits (Winchester, 1971). The arcuate trend (Table 2) indicates a possible beach-shoreface origin that is further corroborated by the coincidence of (1) shell beaches east of the Colorado River and on Galveston

Island with (2) the landward termini of the coarse-fraction trend in those same areas (fig. 2).

Matagorda-San Jose Area

This is generally an area low in coarse material (fig. 6). High concentrations of shell occur only in small patches, including areas adjacent to Aransas Pass and Pass Cavallo. Other patches may be related to former inlet positions.

A more interesting distribution is that of rock fragments and Crassostrea shells, which define a more-or-less arcuate trend (fig. 3). Since this is mainly an area of low shell concentration, the occurrence of large fragments of dark limestone and Crassostrea shells is particularly striking. The occurrence of Crassostrea shells is easily explained because they are preserved in Holocene lagoonal mud that underlies the shelf sediment (fig. 7) and have probably been exhumed during storms. Crassostrea shells from the seafloor in this area give Holocene dates (Curray, 1960). They are generally darker colored than Crassostrea shells in adjacent areas, possibly an effect of burial under reducing conditions (Pilkey et al., 1969), but are otherwise well preserved.

The presence of limestone fragments is more difficult to explain. As previously discussed, they were probably derived from Pleistocene rocks. However, indurated Pleistocene sediments are not known to crop out on the shelf in this area; in fact, Holocene sediments are believed to be thicker than 20 feet (Curray, 1960). This thickness is generally corroborated by sparker data and by Wilkinson's (1975) interpretation of Holocene thickness under Matagorda Island. In cores, rock fragments occur along with shells at the base of graded beds (fig. 7) indicating that they are storm deposits. The clasts possibly were transported from Pleistocene outcrops, through the inlets to the shelf, but this seems unlikely; alternatively they may have been exhumed from underlying Pleistocene sediments.

Rio Grande Area

This area, which has the highest overall concentration of shell material on the inner shelf (fig. 6), is dominated by shells of shelf species. Crassostrea and Rangia are uncommon (Table 1), and Rangia is limited to within 20 miles of the mouth of the Rio Grande.

The paucity of low-salinity species may be an effect of the high salinities in Laguna Madre (Rusnak, 1960) which severely restrict the distribution of Crassostrea and Rangia. However, Anomalocardia auberiana, which is diagnostic of faunal assemblages in Laguna Madre (Rusnak, 1960) is similarly uncommon on the shelf. Therefore, the shelf sediments probably contain reworked lagoon fauna only as a minor component. Crassostrea shells in this area give Holocene dates (Curray, 1960). The only indicators of reworked Pleistocene sediments are the widespread fragments of calcite-cemented sandstone.

The high shell concentration probably represents the accumulation of endemic species deposited in an area of very slow clastic sedimentation and possibly augmented by high biologic productivity.

The shoreline in this area, as in the Brazos-Colorado area, is characterized by rapid erosion of a formerly more prominent deltaic headland (Morton, 1977). In addition, the northern flank of the lobate trend (Table 2, fig. 4) is contiguous with Big Shell Beach. Together these lines of evidence suggest that the shell deposits were formed by beach-shoreface processes and were subsequently submerged and partly buried. Even though the onshore and offshore shell trends are contiguous, they are dominated by different shell species with markedly different surficial features. Highly abraded fragments and valves of Noetia ponderosa, Mercenaria campechiensis, and Echinochama arcinella are typically found on Big Shell (Watson, 1971) at its juncture with the offshore trend. Anadara spp. and Chione spp. are common to both trends, whereas unabraded Corbula sp., Linga amiantus, and Parvilucina multilineata characterize the nearshore samples adjacent to Big Shell Beach.

The degree of shell abrasion is probably a function of the age and stability of Big Shell Beach. The Holocene radiocarbon dates for Mercenaria shells (Watson, 1971) and the general stability of this beach segment (Morton, 1977) suggest that continual reworking of these shells by waves for prolonged periods has led to the high degree of abrasion. The differences in species between samples from Big Shell and the inner shelf are not as easily explained.

DISCUSSION

Relative rates of sedimentation and biological productivity continue to be important factors in determining the availability of shell material. Low rates of modern sedimentation (Van Andel, 1960) together with the ready availability of modern and reworked relict molluscs provided optimum conditions for the concentration of skeletal debris off the Rio Grande and Brazos deltas. Low rates of modern sedimentation also characterize the upper coast (Nelson and Bray, 1970), but here modern shell production is low and shell deposits are supplied mainly from the fossiliferous Pleistocene sediments (Richards, 1939). In contrast to the preceding conditions, relatively high rates of modern sedimentation together with moderate rates of shell production and negligible availability of relict molluscs have resulted in less abundant shell in interdeltaic areas.

Although rates of sedimentation and biological productivity are responsible for the availability of shell material, the distinct trends with mixed relict and modern faunal assemblages and their coincidence with shell beaches point toward physical mechanisms of concentration. Apparently waves and nearshore currents preferentially concentrated the coarsest sediment as local promontories were transgressed (Morton, 1977).

Movement of these deposits has probably decreased as water depths increased during their submergence. The large caliber of the coarse fraction, substantial depths at which it occurs, muddy texture of surrounding sediment, and low velocities of near-bottom currents suggest that cross-shelf transportation is presently negligible. Further evidences of deposit stability are provided by the (1) relatively sharp boundaries and steep gradients of mapped trends, (2) surface encrustations, and (3) minor abrasion of the shell material.

Because of their common transgressive histories during the Holocene, most shelf sediments contain relict shallow water faunas (Emery, 1968). Thus, it is not surprising that the Texas shelf is similar in many respects to other shelves with minor carbonate fractions. For example, the inverse relationship of shell abundance to sedimentation rates, the presence of rock fragments, the patchy distribution of molluscs, the common mollusc species, their surface appearance, and their physical concentration are comparable to most of the same attributes reported for the Atlantic shelf off North and South Carolina (Pilkey, 1964; Milliman et al., 1968; Pilkey et al., 1969) and Georgia (Frey and Pinet, 1978).

Shell beds associated with shelf deposits of the modern Mississippi delta were also attributed to low sedimentation rates and reworking by Coleman and Gagliano (1965). The similarities of shell beds described from the Mississippi delta with those described herein suggest that comparable processes are responsible for shell deposits associated with local delta abandonment or regional marine transgression of deltaic sediments.

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Table 1. Constituents of coarse fraction which indicate reworking of relict sediments. Maximum sizes for rock fragments are for intermediate diameter; maximum length for shells.

		Sabine-Bolivar	Brazos-Colorado	Matagorda-San Jose	Rio Grande
Rock fragments	Calcareous Sandstone	Uncommon, 1.5 cm maximum	Uncommon, 2 cm maximum	Uncommon, grades into sandy micrite 2 cm maximum	Common, 3 cm maximum
	Calcareous Claystone	Common, 2 cm maximum	Rare, 0.8 cm maximum	Absent	Rare, 1 cm maximum
	Limestone	Locally common, medium-to light-gray argillaceous micrite 3 cm maximum	Uncommon, medium gray micrite. rarely fossiliferous 2.5 cm maximum	Common, Dark gray micrite. rarely fossiliferous 4 cm maximum	Rare, dark gray micrite 1.5 cm maximum
	Caliche	Locally common but not widespread, 2.5 cm maximum	Locally common, but not widespread, 1.2 cm maximum	Absent	Locally common but not widespread, 3 cm maximum
Restricted species	<u>Rangia</u> <u>cuneata</u>	Abundant, deeply etched and bleached, 4.5 cm maximum	Common, a few etched, many with well-preserved color and gloss 5 cm maximum	Absent	Absent
	<u>Rangia</u> <u>flexuosa</u>	Rare, etched and bleached 2 cm maximum	Common, consistently fresh, color and gloss preserved 3 cm maximum	Absent	Locally common, but not widespread moderately worn to fresh 4 cm maximum
	<u>Crassostrea</u> <u>virginica</u>	Locally common, many broken and bored otherwise fresh, color preserved 7.5 cm maximum	Common, Preservation similar to Sabine-Bolivar area 7.5 cm maximum	Common, Darker than adjacent areas (burial effect?) otherwise similar 6.5 cm maximum	Locally common but not widespread Preservation similar to Sabine-Bolivar area 6 cm maximum

Table 2. Characteristics of the four main trends of abundant coarse fraction.

	Sabine-Bolivar	Brazos-Colorado	Matagorda-San Jose	Rio Grande
Shape of main trend	Lobate	Arcuate	Arcuate (?)	Lobate
Associated shell beach	High Island	Eastern Matagorda Peninsula, Western Galveston Island	None	Big Shell Beach (Central Padre Island)
Relative contribution to coarse fraction from Pleistocene	Major, Shells and rock fragments	Moderate, shells and rock fragments	Moderate, rock fragments only	Minor, rock fragments only
Radiocarbon dates	Pleistocene for _Rangia cuneata_ Holocene for _Crassostrea virginica_	Holocene and Pleistocene for _Crassostrea virginica_	Holocene for _Crassostrea virginica_	Holocene for _Crassostrea virginica_
Inferred cause of shell concentration	Reworking of Pleistocene Trinity delta	Former margin of the Holocene Brazos-Colorado delta, some reworked Pleistocene	Reworking of Holocene lagoonal deposits, possibly concentration around inlet mouths	Accumulation of shells on reworked Rio Grande delta, possibly enhanced by high productivity
Remarks	Beaumont clay (Pleistocene) crops out on shelf	Shell concentrations on bathymetric highs, active mud deposition landward of trend	Holocene > 20 feet thick	Shell concentrations on bathymetric highs

Figure Captions

Figure 1. Maps of the Sabine-Bolivar area showing A) surface sediment distribution, B) coarse fraction percent by volume, C) rock fragments, and D) restricted mollusc species.

Figure 2. Maps of the Brazos-Colorado area showing A) surface sediment distribution, B) coarse fraction percent by volume, C) rock fragments, and D) restricted mollusc species. Symbols explained on Figure 1.

Figure 3. Maps of the Matagorda-San Jose area showing A) surface sediment distribution, B) coarse fraction percent by volume, C) rock fragments, and D) restricted mollusc species. Symbols explained on Figure 1.

Figure 4. Maps of the Rio Grande area showing A) surface sediment distribution, B) coarse fraction percent by volume, C) rock fragments, and D) restricted mollusc species. Symbols explained on Fig. 1.

Figure 5. Surficial features, relative abundance, and distribution of restricted mollusc species, rock fragments, and caliche nodules in each of the four trends.

Figure 6. Frequency distribution of percent coarse fraction in each of the four trends and for all samples studied. Total number of samples shown in parentheses.

Figure 7. Cores from the Matagorda-San Jose trend showing 1) shelf deposits overlying estuarine sediments with abundant oyster shells, and 2) graded bedding interpreted as a storm deposit.