ORIGIN OF SHELL BEACHES,

PADRE ISLAND, TEXAS

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by

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Richard L. Watson

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A B S T R A C T

Shell-rich beaches on central Padre Island correlate with a convergence of longshore drift. Wind data collected at Corpus Christi from 1951 to 1960 and sedimentation at inlets to the north and to the south of the study area both suggest a similar convergence of longshore drift. Local highs in shell content of beach sands correspond to areas of high and continuous foredunes, whereas the position of lows correspond with small dunes and numerous hurricane channels.

Waves which approach the beach obliquely, sort pelecypod valves such that if the waves approach from the right as the observer faces the sea, there is an abundance of right valves at the top of the foreshore and an abundance of left valves in the shell step at the base of the foreshore. If the waves approach obliquely from the left, the opposite sorting occurs.

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I N T R O D U C T O R Y   R E M A R K S

INTRODUCTION

The purpose of this study is to determine the relationships between the sediments of Padre Island, the longshore drift system operating along the shoreline, and the wind system. Because the longshore drift convergence postulated by several workers coincides with the shell accumulations known as Little Shell and Big Shell, I decided to make a detailed study of the quantity and faunal composition of the shell material in this area. For this purpose the shells are considered primarily as recognizable clastic particles. In order to check the validity of longshore drift predictions based on sedimentologic studies, measurements of the actual longshore current were made in the surf zone. Nearshore currents out to a distance corresponding to a depth of 8 fathoms are now being measured through the monthly release of drift bottles along the length of Mustang and Padre Islands. Finally, a vector analysis of hourly winds for more than 10 years of wind data from Corpus Christi and several years of data from Brownsville is used to predict the resultant, long term, longshore drift.

Shell orientation and sorting of opposite valves as a function of longshore drift direction, shell concentration normal to the shoreline, and other related problems have also been studied.

Correlation of shell distribution on Padre Island with the processes effecting the distribution provides criteria for environmental reconstructions of Recent, Pleistocene, and Tertiary sediments of the Gulf coast.

On many barrier islands there is more than one foredune chain. On Padre Island trenches behind the presently active foredune chain, and in front of the older dune chain further inland reveal beds containing up to 80 percent shell material. These beds must represent shell concentrations of an old beach that probably was active at the same time as the foredunes behind it. It might be possible to study this old beach by trenches and interpret the longshore drift system acting at the time of deposition using knowledge of the behavior of presently active shell beaches and the present longshore drift system.

Similarly, the Pleistocene Ingleside - barrier - island complex (80,000? year old barrier island and lagoon) on the mainland shore of Laguna Madre has many outcrops of lithified shell-rich beach rock. A study of the shell percent and assemblage distribution of this beachrock outcrop might shed light on the longshore drift system and thus the wind system during the last interglacial stage when the beachrock sediment was probably deposited. Similarity to the present shell beaches of Padre Island suggests a similar history.

Offshore from Padre Island are numerous outcrops of a carbonate cemented rock, which may also represent beachrock of other older barrier islands. The beaches of southern and south-central Padre Island are littered with chunks of similar rock of varying shell content. I suspect that the source for this rock is the offshore outcrops, but the only evidence to support this idea is the lack of any other probable source nearby. There seems to be no beachrock forming at the present time on Padre Island with the exception of a few pieces I have found that are carbonate and iron carbonate concretions around an iron pipe and a piece of steel plate.

There are some carbonate-rich zones in Tertiary barrier island oil sands, which might indicate similar shelly beach zones. This shell material is, of course, a likely source of carbonate cement which could destroy the sand's porosity and its value as a reservoir (Scott, personal communication, 1967).

Finally and perhaps most important, this study sheds a bit more light on the longshore drift system operating on the south Texas coast. Longshore drift is a major problem in coastal engineering, because unwanted sediment is deposited in inlets or eroded from beaches where it is needed. In order to adequately plan inlet, harbor, and beach protection structures it is of paramount importance to have accurate data on the longshore drift system. It is especially important to know the net direction of drift and also the volume of drift past a given point in a year. At present, the only reliable method of determining the volume of drift has been to measure the amount trapped behind a catchment structure, such as a groin or a jetty. It is possible to determine the direction of drift by indirect studies, but not the volume.

GEOGRAPHIC SETTING

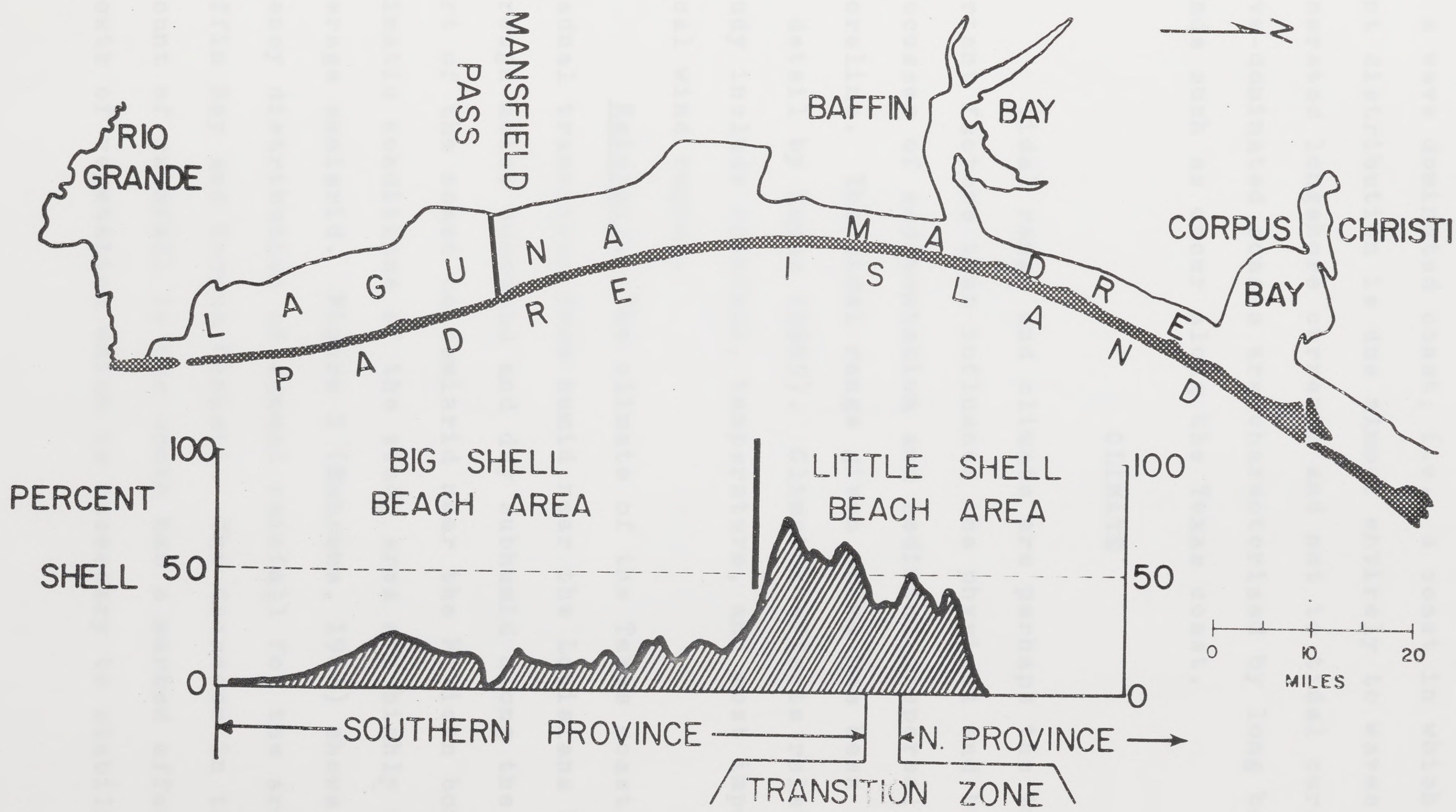
The study area consists of Mustang and Padre Islands, two connected barrier islands which compose the southernmost 125 miles of the Texas shoreline (fig. 1). Only Mansfield Pass, a dredged and jettied channel 90 miles south of Aransas Pass and 35 Miles north of Brazos Santiago Pass, interrupts this stretch of barrier island. In the vicinity of lat 27° N. there is a pronounced concave curvature of the shoreline called the Coastal Bend Area. In this investigation beach sediments have been studied for the entire length of the barrier from Aransas Pass to Brazos Santiago Pass, but detailed study was made of only the 60 miles of beach in the center of the Coastal Bend Area. The southern limit of the detailed study area is Mansfield Pass.

COASTAL CLASSIFICATION

The tidal range along this portion of the coast ranges from less than 1 foot to about 18 inches. Waves are small,

Figure 1.

Geographic location map showing shell percent distribution. To find the shell percent of the beach sediment at any location on the map, read straight down to find the value on the percent shell graph.



PERCENT SHELL IN PADRE ISLAND BEACHES

R.L. WATSON 1967

averaging 2-6 feet in height. According to Hayes (1965) this is a wave dominated coast, i.e., a coast in which the sediment distribution is due almost entirely to waves and wave-generated longshore currents and not to tidal currents. Wave-dominated coasts are characterized by long barrier islands such as occur along the Texas coast.

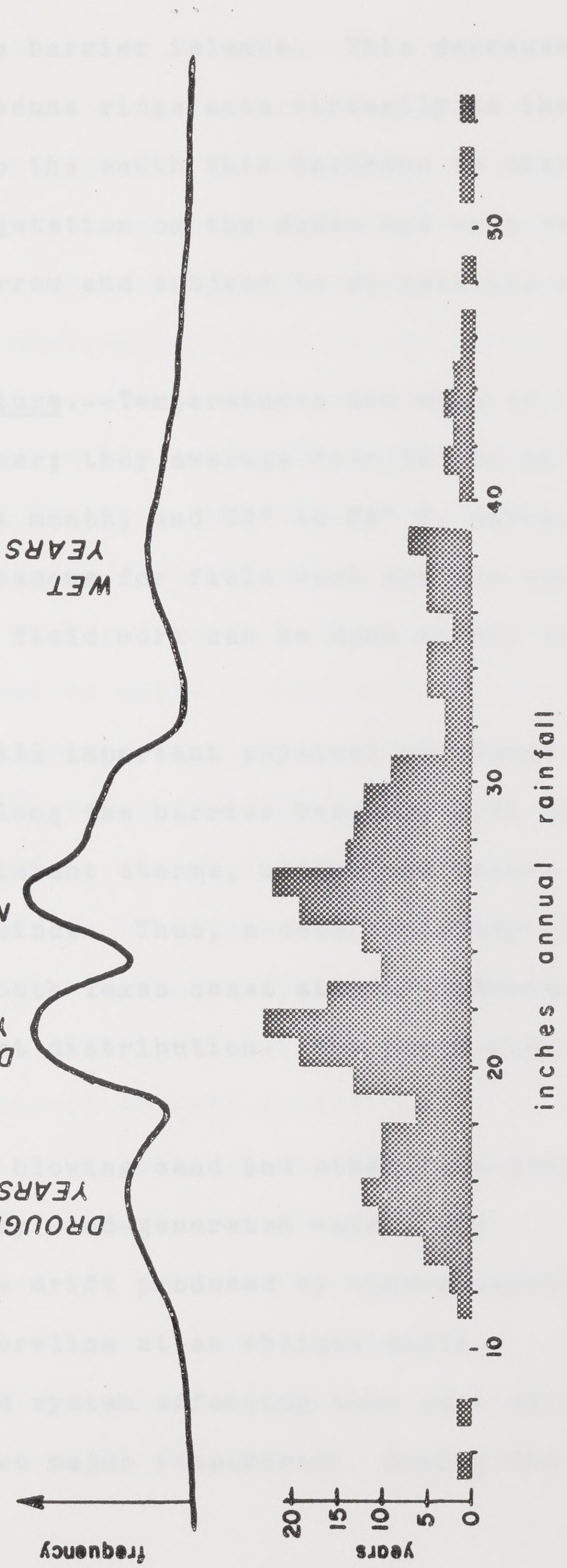
CLIMATE

Tidal range and climate are perhaps the two most important factors that influence the physical and biologic processes of sedimentation and sediment dispersal along a shoreline. The tidal range given above has been considered in detail by Hayes (1965). Climatic effects relative to this study include rainfall, temperature, and most important, the local wind regime.

Rainfall.--The climate of the Texas coast shows a gradual transition from humid near the Louisiana border through moist subhumid and dry subhumid along the central part of the coast to semiarid near the Mexican border. The climatic conditions of the study area are highly variable but average semiarid. Figure 2 (Behrens, 1966) shows the frequency distribution of annual rainfall for the area between Baffin Bay and Corpus Christi. The decrease in the average amount of rainfall to the south has a marked effect on the growth of vegetation which is necessary to stabilize the

Figure 2.

Frequency distribution of annual rainfall for 290 record years for the Texas coast between Corpus Christi and Baffin Bay (Behrens, 1966, p. 170).



DROUGHT YEARS
DRY YEARS
NORMAL YEARS
WET YEARS
frequency
years
0
5
10
15
20
10
20
30
40
50
inches annual rainfall

foredunes of the barrier islands. This decrease is important because the foredune ridge acts virtually as the backbone of the barrier. To the south this backbone is missing due to insufficient vegetation on the dunes and as a result the island is low, narrow and subject to devastating wave attack during storms.

Temperature.--Temperatures are mild in the winter and warm in the summer; they average from 56° to 62° F. for January, the coldest month, and 82° to 86° F. during July. The most pleasant seasons for field work are the early spring and early fall, but field work can be done at any time of the year.

Wind.--All important physical processes affecting sedimentation along the barrier beaches, with the exception of waves from distant storms, ultimately derive their energy from the local winds. Thus, a detailed study of the wind regime of the south Texas coast aids in understanding the regional sediment distribution. The local wind acts to transport sediment:

1. directly by blowing sand and other fine-grained sediment,
2. indirectly by wind-generated waves, and
3. by longshore drift produced by wind-generated waves that approach the shoreline at an oblique angle.

The wind system affecting this part of the Texas coast is made up of two major components. During the summer months and early fall, the wind blows almost continuously from the southeast. During the winter months storms with north and northeast winds called "northers" move from the arctic and the Pacific Northwest across the plains states to the Texas coast. These frequent winter storms and accompanying northerly winds play an important part in the distribution of sediments by producing waves and longshore currents which oppose the prevailing waves and currents produced by the southeast winds. Finally, tropical cyclones or hurricanes with wind velocities in excess of 75 miles per hour cross some part of the Texas coast with a frequency of about one storm every two years. The effect of these storms is tremendous. Hurricanes are usually accompanied by a storm surge or exceptionally high tide caused by the lowered atmospheric pressure associated with the storm and by the stress of the storm winds in piling up water shoreward as the storm approaches. High surges are, of course, accompanied by devastatingly large waves driven by the strong winds. The result is that the barrier is often inundated and subject to wave attack. The storm waves breach low and discontinuous parts of the foredune ridge and carry large amounts of sediment from the foreshore, the beach, and the foredune ridge and dump it on the vegetated flats, tidal flats and inland into the lagoons behind the barrier islands. Thus, even though the storm may appear to be highly destructive to the barrier, it actually aids the growth of the island by building it lagoonward through the intermittent construction of washover fans and tidal deltas (Andrews, 1967). Most of the apparent destruction caused by the storm is rapidly healed by the normal processes of longshore drift and by rebuilding of the foredune ridge by wind-deposited sand. Due to the frequency of occurrence of these storms, or to the absence of stabilizing vegetation, many hurricane channels heal only across the beach. If the foredunes do not rebuild across these hurricane channels, they remain as weak places where additional deposition may occur by washover during the next hurricane.

The resultant winds for each month and the resultant or vector sum of the winds for each year based on weather data collected at Corpus Christi from 1951 to 1960 show two opposing wind direction modes: one from the northeast and one from the southeast (fig. 3). These winds are of greatest importance in generating longshore drift and longshore currents which transport sediments parallel to shore. Hurricanes are most important in the transportation of sediment perpendicular to the trend of the shoreline, and thus will not greatly influence the distribution of sediments by longshore drift. For this reason the effect of hurricanes will not be considered in further detail. I refer the reader to Hayes (1965) for an excellent discussion of the effect of major hurricanes on sedimentation along the Texas coast and to Andrews (1967) for a

Figure 3.

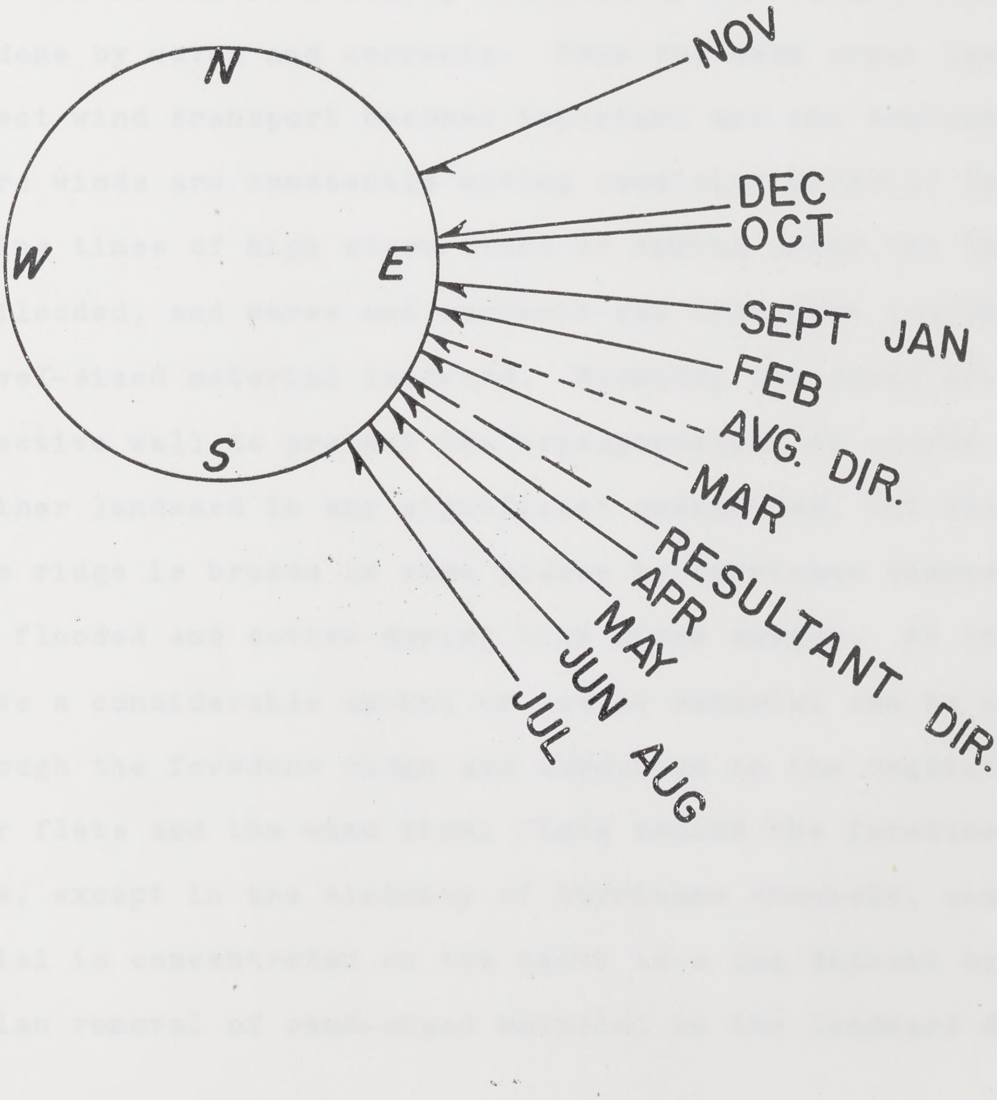
Mean monthly wind directions for Corpus Christi
1951 - 1960.

Directions shown represent the average of the monthly vector resultants determined for 10 years of wind data collected at Corpus Christi. The RESULTANT DIR. shown is the vector resultant for the entire 10 year period. The AVG. DIR. is the average of all of the monthly vector resultant directions for the 10 year period. Note that the resultant direction and the average direction separate the winter regime of northers from the summer regime of strong southerlies if March is taken to be a transitional month.

MEAN MONTHLY WIND DIRECTIONS

1951 – 1960

CORPUS CHRISTI



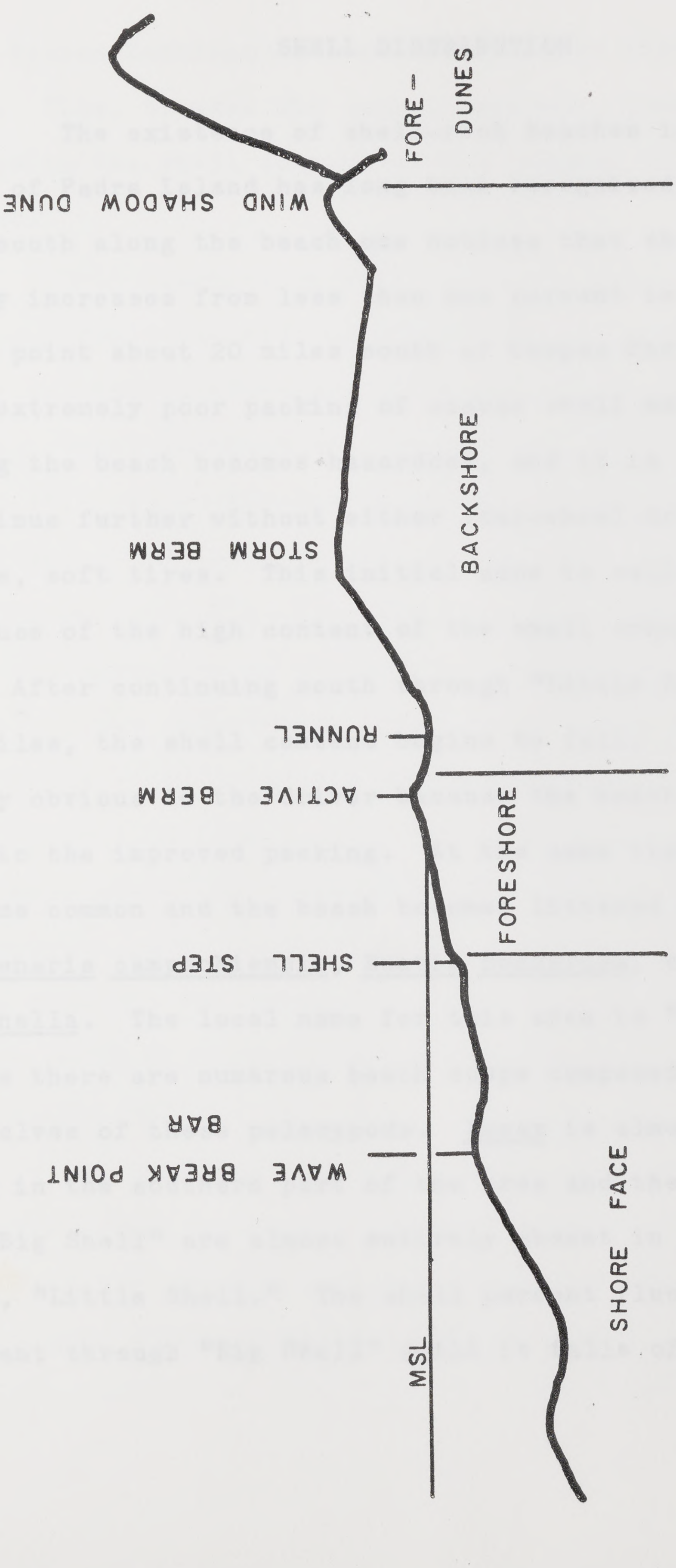
detailed description of the growth of washover fans by deposition during hurricanes.

DEPOSITIONAL ENVIRONMENTS

Distribution of shell is affected by processes operating in the shoreface, foreshore, backshore, foredune ridge, and hurricane channels (fig. 4). It is important to consider the transportational media in each of these environments. From the foreshore seaward, essentially all sediment movement is done by waves and currents. From the berm crest landward direct wind transport becomes important and the dominantly onshore winds are constantly moving sand-size material landward. During times of high storm tides or spring tides the backshore is flooded, and waves and currents can transport coarser gravel-sized material landward. Normally the dunes act as an effective wall to prevent the transportation of coarse material further landward in any significant quantities, but the foredune ridge is broken in some places by hurricane channels that are flooded and active during high storm surges. At these times a considerable amount of coarse material can be carried through the foredune ridge and deposited on the vegetated barrier flats and the wind tidal flats behind the foredunes. Thus, except in the vicinity of hurricane channels, coarse material is concentrated on the beach as a lag deposit by the eolian removal of sand-sized material in the landward direction.

Figure 4.

Generalized Gulf beach profile for Padre Island. At any one location along Padre Island one or more of the features shown on this profile may be absent.



GENERALIZED BEACH PROFILE
PADRE ISLAND, TEXAS

SHELL DISTRIBUTION

The existence of shell-rich beaches in the central part of Padre Island has long been recognized. When traveling south along the beach one notices that shell content suddenly increases from less than one percent to over 50 percent at a point about 20 miles south of Corpus Christi. Due to the extremely poor packing of coarse shell material, driving along the beach becomes hazardous, and it is impossible to continue further without either four-wheel drive or extremely large, soft tires. This initial zone is called "Little Shell" because of the high content of the small coquina clam Donax sp. After continuing south through "Little Shell" for about 20 miles, the shell content begins to fall. This is immediately obvious to the driver because the beach becomes firmer due to the improved packing. At the same time large shells become common and the beach becomes littered with valves of Mercenaria campechiensis, Eontia ponderosa, and Echinochama arcinella. The local name for this area is "Big Shell." At times there are numerous beach cusps composed almost entirely of valves of these pelecypods. Donax is almost entirely absent in the southern part of the area and the species common to "Big Shell" are almost entirely absent in the northern area, "Little Shell." The shell percent fluctuates around 20 percent through "Big Shell" until it falls off toward zero near Brazos Santiago Pass at the southern limit of the study area. Thus, to even the casual observer, there are distinct trends in the shell content of the beaches of central Padre Island.

P R E V I O U S   G E O L O G I C
I N V E S T I G A T I O N S

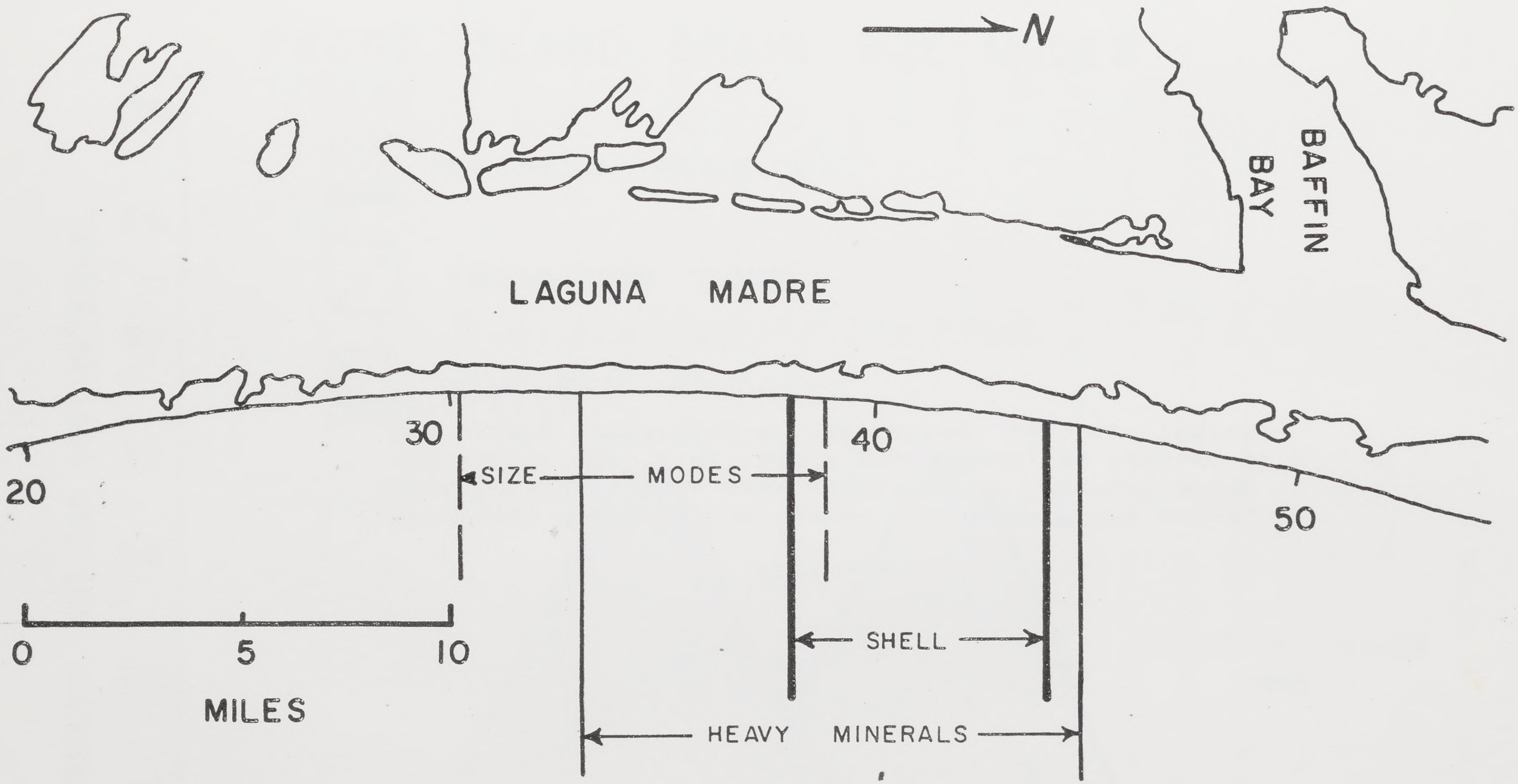
SEDIMENT DISTRIBUTION

Most previous work on sediments along Padre Island has been concerned with heavy mineral distribution (Bullard, 1942; Van Andel, 1960) and grain size distribution (Hayes, 1965). Heavy minerals such as basaltic hornblende are characteristic of the Rio Grande source area and are carried northward along Padre Island as far as the heavy mineral transition zone (fig. 5). The rivers further to the north with the exception of the Colorado River derive their heavy minerals from sedimentary rocks and are thus characterized by relatively stable minerals such as garnet, tourmaline, rutile, staurolite, and zircon. The Colorado River supplies a considerable amount of green hornblende from the igneous and metamorphic rocks north of Austin, Texas, in the Llano uplift. These minerals are carried to the south to mix with the Rio Grande heavy minerals at the transition zone (Bullard, 1942; Van Andel, 1960).

Hayes (1965) found that he could trace a finer grain size mode from the northern province and a coarser grain size mode from the southern Rio Grande province to a central transition zone where they mix (figs. 5 and 6). It can be seen that the transition zone based on heavy minerals corresponds

Figure 5.

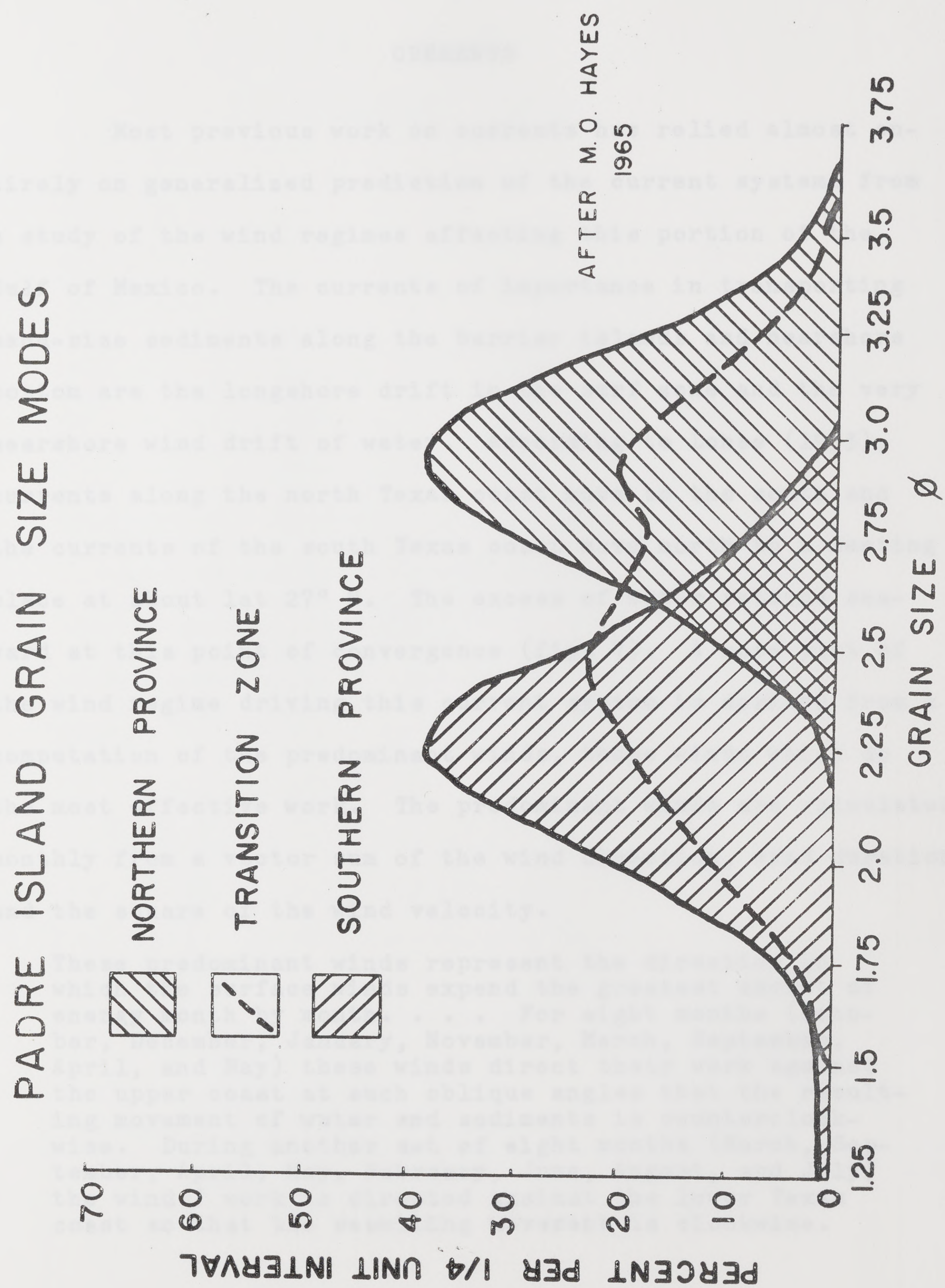
Transition zones shown by grain size, heavy minerals, and shell content. The transition zones for heavy minerals (Bullard, 1942, and Van Andel, 1960), grain size modes (Hayes, 1965), and for shell percent and assemblage distribution (this study). The numbers along the shore of Padre Island indicate the distance in miles north of Mansfield Pass.



TRANSITION ZONES

Figure 6.

Frequency distribution curves for three Padre Island dune samples. Note near normality of "coarse" south end-member and "fine" north end-member, as opposed to the strong bimodality of the central sample. (Hayes, 1965, p. 234).


PADRE ISLAND GRAIN SIZE MODES
NORTHERN PROVINCE
TRANSITION ZONE
SOUTHERN PROVINCE
AFTER M.O. HAYES
1965
PERCENT PER 1/4 UNIT INTERVAL
0
10
20
30
40
50
60
70
GRAIN SIZE ø
1.25
1.5
1.75
2.0
2.25
2.5
2.75
3.0
3.25
3.5
3.75

closely with the transition zone based on grain size modes.

CURRENTS

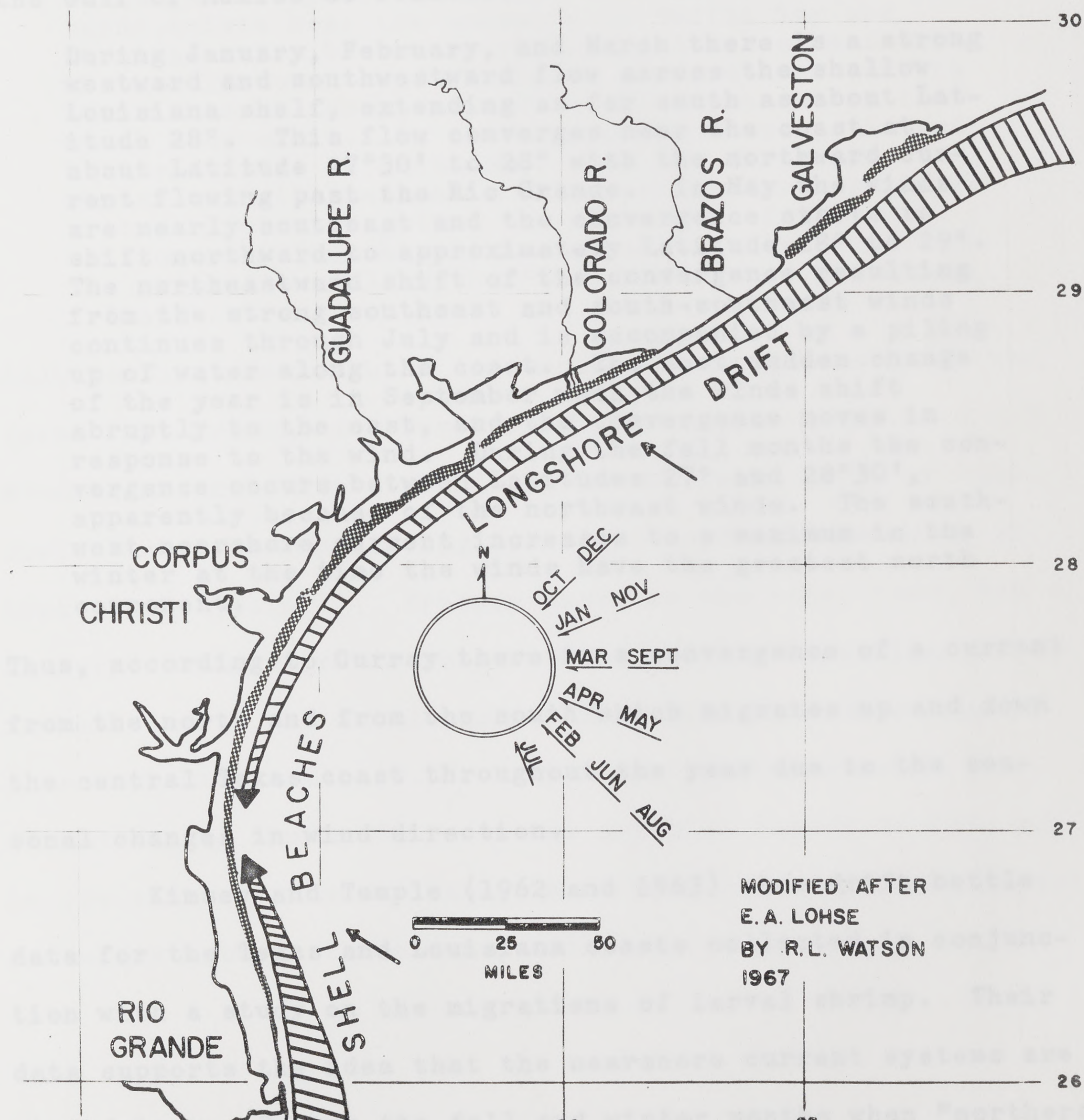
Most previous work on currents has relied almost entirely on generalized prediction of the current systems from a study of the wind regimes affecting this portion of the Gulf of Mexico. The currents of importance in transporting sand-size sediments along the barrier islands and nearshore bottom are the longshore drift in the surf zone and the very nearshore wind drift of water. According to Lohse (1955), currents along the north Texas coast move to the south and the currents of the south Texas coast move north to a meeting place at about lat 27° N. The excess of water returns seaward at this point of convergence (fig. 7). A rose plot of the wind regime driving this current system is derived from a computation of the predominant winds, those winds which do the most effective work. The predominant winds are calculated monthly from a vector sum of the wind direction, wind duration, and the square of the wind velocity.

> These predominant winds represent the direction in which the surface winds expend the greatest amount of energy month by month. . . . For eight months (October, December, January, November, March, September, April, and May) these winds direct their work against the upper coast at such oblique angles that the resulting movement of water and sediments is counterclockwise. During another set of eight months (March, September, April, May, February, June, August, and July) the winds' work is directed against the lower Texas coast so that the resulting movement is clockwise.

Figure 7.

Net annual longshore drift directions. Net annual longshore drift for the south Texas coast and the monthly predominant winds as determined by Lohse (1955, fig. 4). These winds represent the vector sum of the wind direction, duration, and square of the wind velocity. They are not in agreement with vector resultants for the wind data collected at Corpus Christi for the period 1951-1960 (fig. 3).

NET ANNUAL
LONGSHORE DRIFT



> Thus 16 wind-months, analogous to man hours, eight upon the upper coast and eight upon the lower coast, act yearly to transport beach and shallow marine sediments into the vicinity of 27° N. Lat. (Lohse, 1955, p. 101).

Curray (1960, p. 231) summarizes the current system of the Gulf of Mexico as follows:

> During January, February, and March there is a strong westward and southwestward flow across the shallow Louisiana shelf, extending as far south as about Latitude 28°. This flow converges near the coast at about Latitude 27°30' to 28° with the northward current flowing past the Rio Grande. In May the winds are nearly southeast and the convergence starts to shift northward to approximately Latitude 28° to 29°. The northeastward shift of the convergence resulting from the strong southeast and south-southeast winds continues through July and is accompanied by a piling up of water along the coast. The most sudden change of the year is in September when the winds shift abruptly to the east, and the convergence moves in response to the wind. During the fall months the convergence occurs between Latitudes 27° and 28°30', apparently because of the northeast winds. The southwest nearshore current increases to a maximum in the winter at the time the winds have the greatest north component.

Thus, according to Curray there is a convergence of a current from the north and from the south which migrates up and down the central Texas coast throughout the year due to the seasonal changes in wind direction.

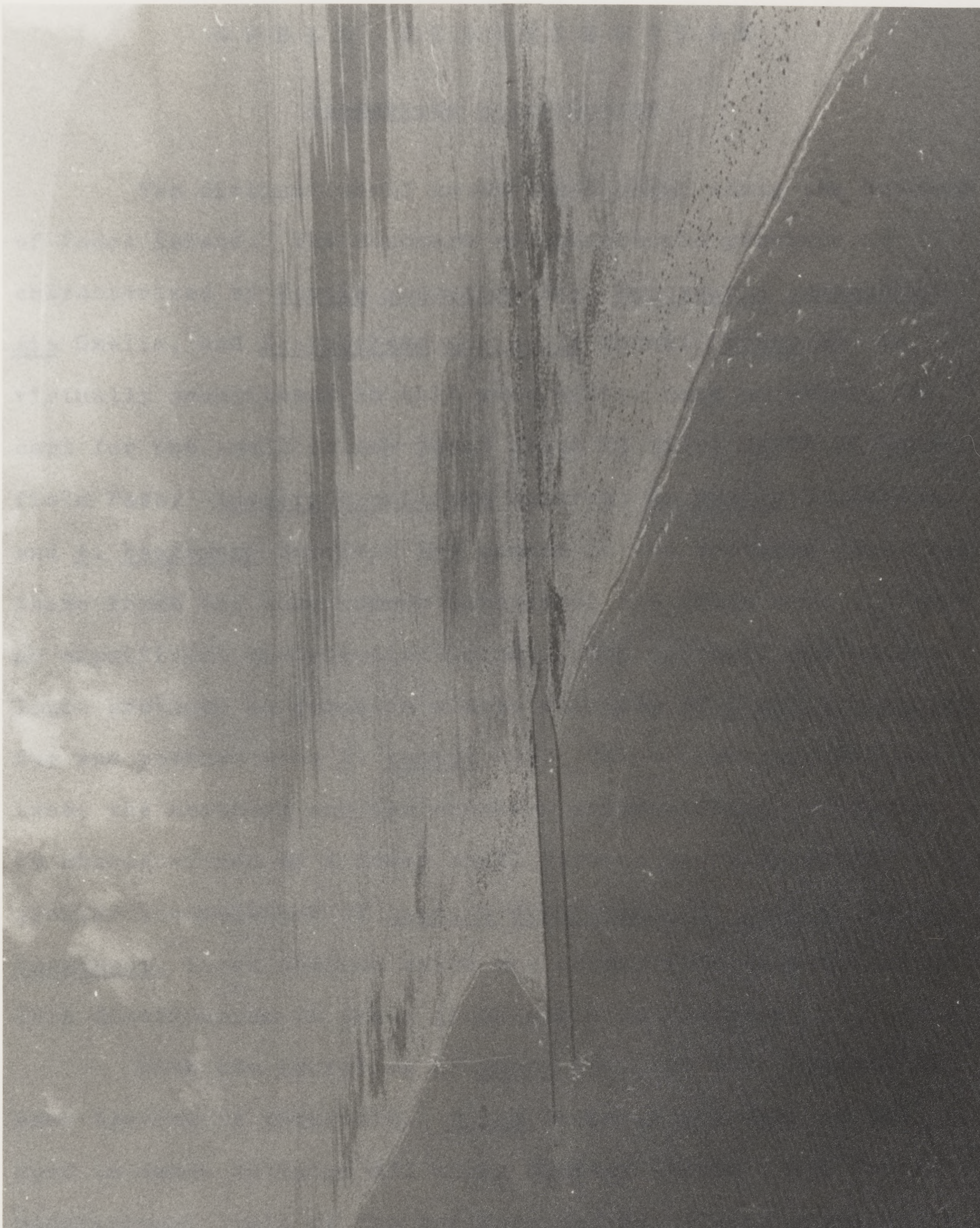
Kimsey and Temple (1962 and 1963) show drift bottle data for the Texas and Louisiana coasts collected in conjunction with a study on the migrations of larval shrimp. Their data supports the idea that the nearshore current systems are wind driven. During the fall and winter months when "northers" are common the currents move to the south. In the late spring and summer months, dominated by the strong southeasterly winds, the nearshore currents and longshore drift move primarily to the northeast.

> It is generally believed that a littoral drift nodal point exists near the entrance to Baffin Bay and about 45 miles to the southwest of Aransas Pass with the net littoral drift being to the southwest on the north side of the point and to the northeast on the south side of it. In the Aransas Pass area, the net littoral drift is quite small and its direction varies with the seasons. This fact is further illustrated by observing that the direction of the prevailing wind (southeast) is almost exactly normal to the general shoreline (U. S. Army Corps of Engineers, ? a).

Additional evidence for a convergence of longshore drift between Port Aransas and Mansfield Pass is that there is a tremendous accumulation of sediment on the south jetty of Mansfield Pass, thus indicating longshore drift to the north at that point (plate 1). Aransas Pass, on the other hand, has a history of migration to the south before stabilization which indicates that the net longshore drift in the Aransas Pass area is to the south (U. S. Army Corps of Engineers, ? a). Therefore, if the drift is to the north at Mansfield Pass and to the south at Aransas Pass, there must be a net convergence somewhere between these two points.

Plate 1.

Mansfield Pass, Padre Island, Texas. The observer is looking southwest. Note the large sediment accumulation behind the south jetty deposited by the northward net annual longshore drift. A slight erosional indentation of the shoreline can be seen on the north side of the pass where the beach is starved for sediment due to the entrapment behind the south jetty.



SHELL DISTRIBUTION

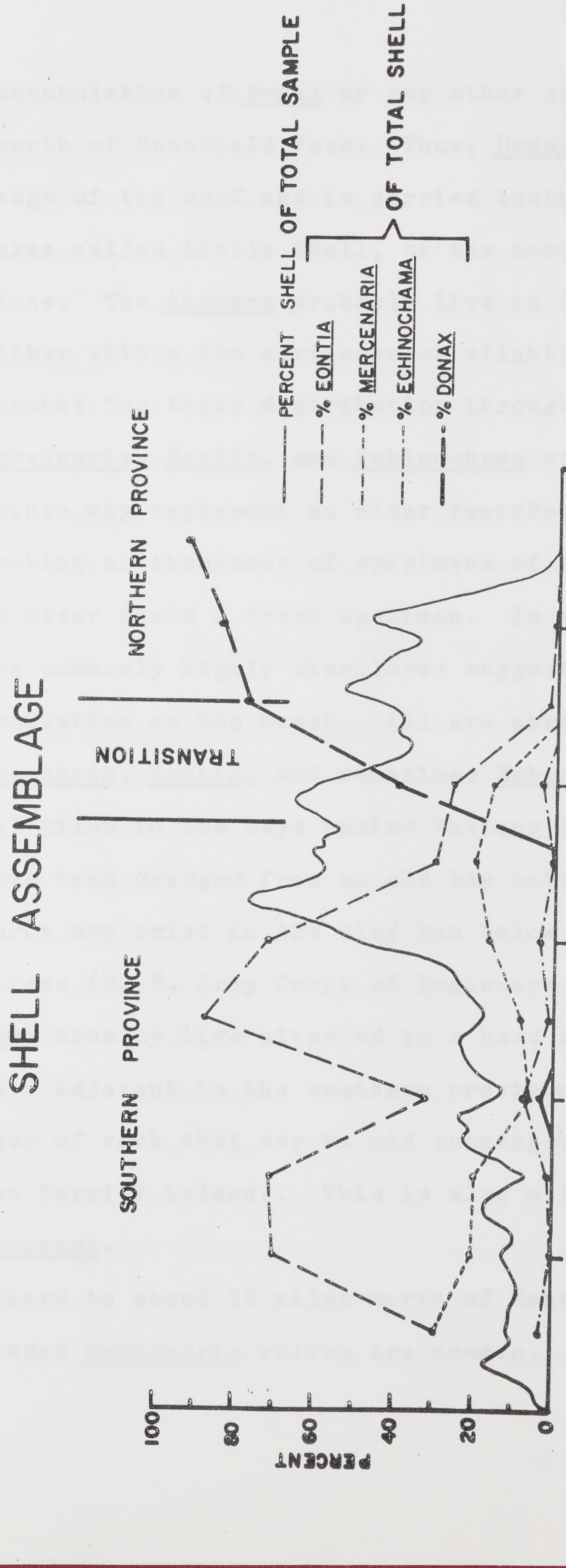
ASSEMBLAGE DISTRIBUTION

Two distinct shell assemblages occur along the beaches of Padre Island. The southern sedimentologic province is characterized by Eontia ponderosa Say, Mercenaria campechiensis Gmelin, and Echinochama arcinella Linné. Donax sp. is virtually nonexistent in this zone either dead or alive, except for one small colony found about 20 miles north of Mansfield Pass. Anadara braziliana Lamarck, A. ovalis Bruguiére, and A. baughmani Hertlein are common in the southern zone, but these forms are also common throughout the study area and show no significant distribution trends. The northern sedimentologic province is composed almost entirely of Donax variabilis Say and perhaps some D. tumida Say. The transition zone between the northern and the southern sedimentologic provinces is characterized by a lower shell percent and a somewhat greater accumulation of Anadara braziliana, A. ovalis, and A. baughmani, three species which are common to both provinces. This distribution is shown graphically in Figure 8.

With the exception of Donax sp., the exact source of each species is uncertain. Donax lives in the edge of the surf in dense colonies all along Mustang Island south to the southernmost limit of the northern sedimentologic province on Padre Island. As can be seen from the shell percent graph

Figure 8.

Shell assemblage distribution. Note that the abundance of the species of the southern province decline in the transition zone and are virtually nonexistent in the northern province. <u>Donax</u> makes up most of the northern province but declines in abundance in the transition zone and is not found in the southern province except in one small colony about 20 miles north of Mansfield Pass. The transition zone based on shell assemblage corresponds with a low in shell percent.


SHELL ASSEMBLAGE
SOUTHERN PROVINCE
TRANSITION
NORTHERN PROVINCE
PERCENT SHELL OF TOTAL SAMPLE
% EONTIA
% MERCENARIA
% ECHINOCHAMA
% DONAX
OF TOTAL SHELL
PERCENT
0
20
40
60
80
100
MILES NORTH OF MANSFIELD PASS
0
10
20
30
40
50
60

there is no accumulation of Donax or any other species north of 55 miles north of Mansfield Pass. Thus, Donax lives and dies in the edge of the surf and is carried south to accumulate in the area called Little Shell, or the northern sedimentologic province. The Anadara probably live in the shallow shelf zone either within the surf zone or slightly beyond it. This would account for their distribution throughout the study area. The Mercenaria, Eontia, and Echinochama common to the southern province may represent an older reworked shell assemblage. In looking at thousands of specimens of each in the field, I have never found a fresh specimen. In addition the Mercenaria are commonly highly discolored suggesting burial prior to accumulation on the beach. All are abraded. Furthermore, Mercenaria, Eontia, and sometimes Echinochama are found in spoil piles in the bays behind Mustang Island, where they could have been dredged from an old bay bottom deposit. A similar source may exist in the clay bed below the jetties of Mansfield Pass (U. S. Army Corps of Engineers, ? b). The Echinochama usually live attached to a hard substrate when in youth. Adjacent to the southern province offshore are many ridges of rock that may be old submerged beachrock of Pleistocene barrier islands. This is also a likely source for the Echinochama.

Northward to about 25 miles north of Mansfield Pass, whole but abraded Mercenaria valves are common. The percentage of whole Mercenaria decreases to the north. Proceeding to the north, whole Mercenaria gradually disappear and only abraded plates remain. Eventually, as one passes through the transition zone into the northern province, it becomes impossible to find even plates. Thus, the assemblage distribution suggests that the Mercenaria, Eontia, and Echinochama assemblage has a source to the south and is being transported north, the Donax assemblage has a source to the north and is being transported south, and the Anadara group has a wide source and is being introduced into both the northern and southern provinces.

PERCENT SHELL DISTRIBUTION NORMAL TO SHORELINE

Processes of sediment transport.--The swash and backwash of waves on the foreshore are responsible for almost all of the original deposition of shell material. For the purpose of analyzing the concentration of shell by the physical transportation processes acting on it, the shell can be considered as a coarse mode analogous to the presence of gravel. We can then look on the shell distribution simply as a phenomenon of competence required to transport and deposit the fine mode (terrigenous sand) in contrast to the coarse mode (shell). If we consider a typical beach profile (fig. 4), it is possible to analyze the relative transport capacity of waves and currents acting on each segment of this profile. The waves break at the toe of the foreshore creating a great amount of turbulence that enables them to pick up pebbles, cobbles, or shells of large diameter and roll them up the foreshore in the resulting swash. As the competence of the swash is reduced due to loss in velocity by moving upward against the acceleration of gravity and by loss in water volume by percolation into the sand, the capacity to transport large particles is reduced. The water stops momentarily as it reaches its upper limit, then accelerates due to gravity down toward the step at the base of the swash zone. Due to the stop and then the reversal of flow the competence of the current is highly weakened at the top of its travel and any coarse particles dropped there are not picked up by the returning backwash. As the backwash picks up speed and volume and thus increases in competence further down on the foreshore, large shells are picked up again and rolled back down into the shell step at the base of the swash zone. Thus, in the foreshore there are concentrations of shell at the top and at the base of the swash zone with relatively little shell in the central part. This simple system is modified by the fluctuation of sea level with the daily tides. As the tide rises and falls the above described swash zone features migrate up and down the foreshore. In addition, certain parts of the tidal cycle are characterized by erosion and others are characterized by deposition. Strahler has described this process operating on the beaches of Sandy Hook, N. J.

> As tide rises a short phase of initial deposition of about 0.02 foot of medium sand takes place near the inner limit of swash. There follows a scour phase in which about 0.2 foot of sand is removed in a period of 1½ to 2 hours. Scour is followed by deposition, representing advance of a wedge of mixed sand and pebbles, terminating in the well-sorted pebble and gravel step formed under the breaker point. As step phase deposition continues, median diameter increases, and sorting becomes poorer. During falling tide, changes at a given survey point are repeated but in reverse order. Thus, under equilibrium conditions, the beach is restored to its original elevation, slope and composition. About 0.2 foot of sand is completely removed and redeposited during each cycle at points in the mid-tide region of the zone of swash and backwash under characteristic summer wave conditions (Strahler, 1966, p. 247).

The result of this migration of microfacies containing fine sand and coarser shell material is the formation of alternating thin beds of sand and shell in the foreshore (plates 2 and 3). In addition the upper part of the foreshore is characterized by an intricate system of beach cusps. Due to their position these cusps are usually active only at or near the time of high tide. The coarse shell material is concentrated on the horns of the cusp (fig. 9, plates 4 and 5). The swash strikes the horns of the cusp, loses energy and drops the largest particles; the current then continues in toward the center of the cusp dropping successively finer material until all of the kinetic energy is expended. The water then returns seaward through the center or bay of the cusp (Fleming, 1964).

The crest of the active berm at any time is near the maximum height of the tides and represents the maximum height

Plate 2.

Alternating thin beds of shell and sand in the lower foreshore 30.5 miles north of Mansfield Pass. The arrow points seaward.


PD →
TR 1

Plate 3.

Alternating thin beds of shell and sand in the upper foreshore 30.5 miles north of Mansfield Pass. The arrow points seaward.


PD →
TR3

Figure 9.

Diagrammatic beach cusp. Note that the coarse shell material is deposited at the horns of the beach cusp. The large arrows indicate water movement on the cusp.

BEACH CUSP

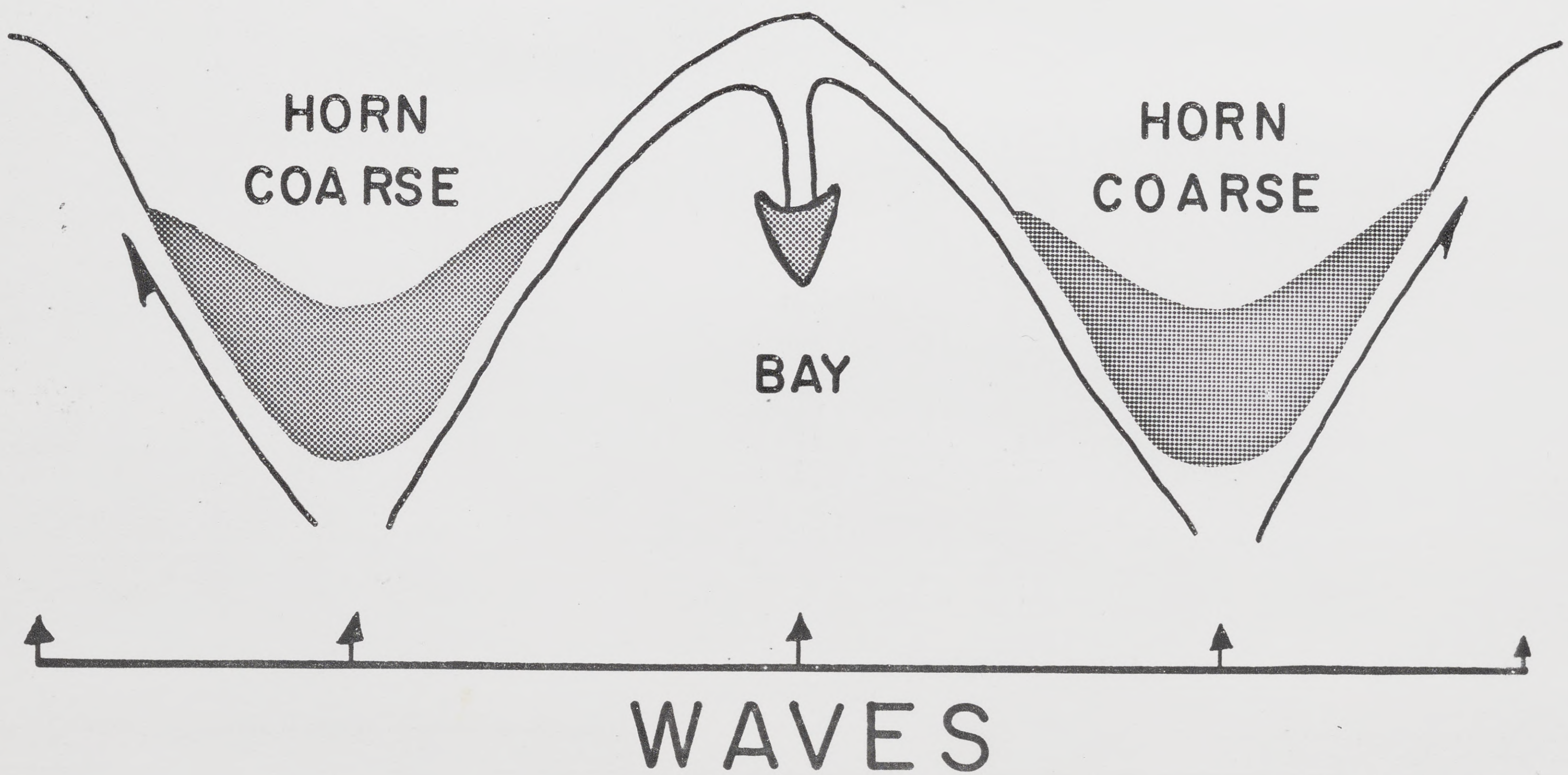


Plate 4.

Shell concentration in horn of active cusp 15 to
30 miles north of Mansfield Pass.

Plate 5.

Close-up of shell concentration in the cusp shown in Plate 4. The accumulation is composed almost entirely of _Eontia ponderosa_, _Echinochama arcinella_, and _Mercenaria campechiensis_. Scale is a 45 mm diameter lens cap.

to which the swash can reach. The swash moves rapidly up the face of the berm and nearly stops at the top dropping the last of its sediment load and thus building the berm still higher. The small amount of water that goes over the crest of the berm collects in a runnel behind the berm until it flows parallel with the berm for a while and back out through a break in the berm crest. Thus, the crest of the berm is the shoreward limit to which coarse shell can be transported by waves. Only fine material such as terrigenous sand and sand-sized shell can be carried further shoreward by the wind.

Shell percent.--The foregoing discussion concerned processes that operate during "normal" times of small waves and "normal" tides. During storms, waves are considerably larger, because they are driven by strong onshore winds. Also water level is often higher due to the low pressure associated with the storm and the piling up of water along the coast by the onshore wind and waves. This increases the magnitude of the processes acting on the foreshore and moves the respective locations of parts of the foreshore further shoreward, or higher up on the beach, to be in equilibrium with the higher sea level. This produces a storm berm considerably higher on the beach. The shell which had been collecting in the lower cusps and berms since the last storm is redistributed. A considerable amount of shell accumulates in the new high storm berm. A small amount is washed over this storm berm into the large backshore runnel resulting in a decrease in shell percent from the storm berm toward the dunes. This produces an irregular shell distribution seaward of the storm berm. Nearly pure shell deposits occur in parts of the active berm crest and in the horns of active cusps, and nearly pure sand deposits occur in the central part of the foreshore. The storm berm represents either the maximum or close to the maximum shell percent in a profile across the beach. The shell percent then diminishes toward the dunes (fig. 10). After initial deposition, wind deflation produces a surface lag concentrate of coarse shell that represents the period of time between storms of sufficient magnitude to flood the backshore and deposit a new layer of shell and sand. These lag deposits can be readily recognized in trenches cut through the backshore (plate 6).

SHELL DISTRIBUTION PARALLEL TO SHORELINE

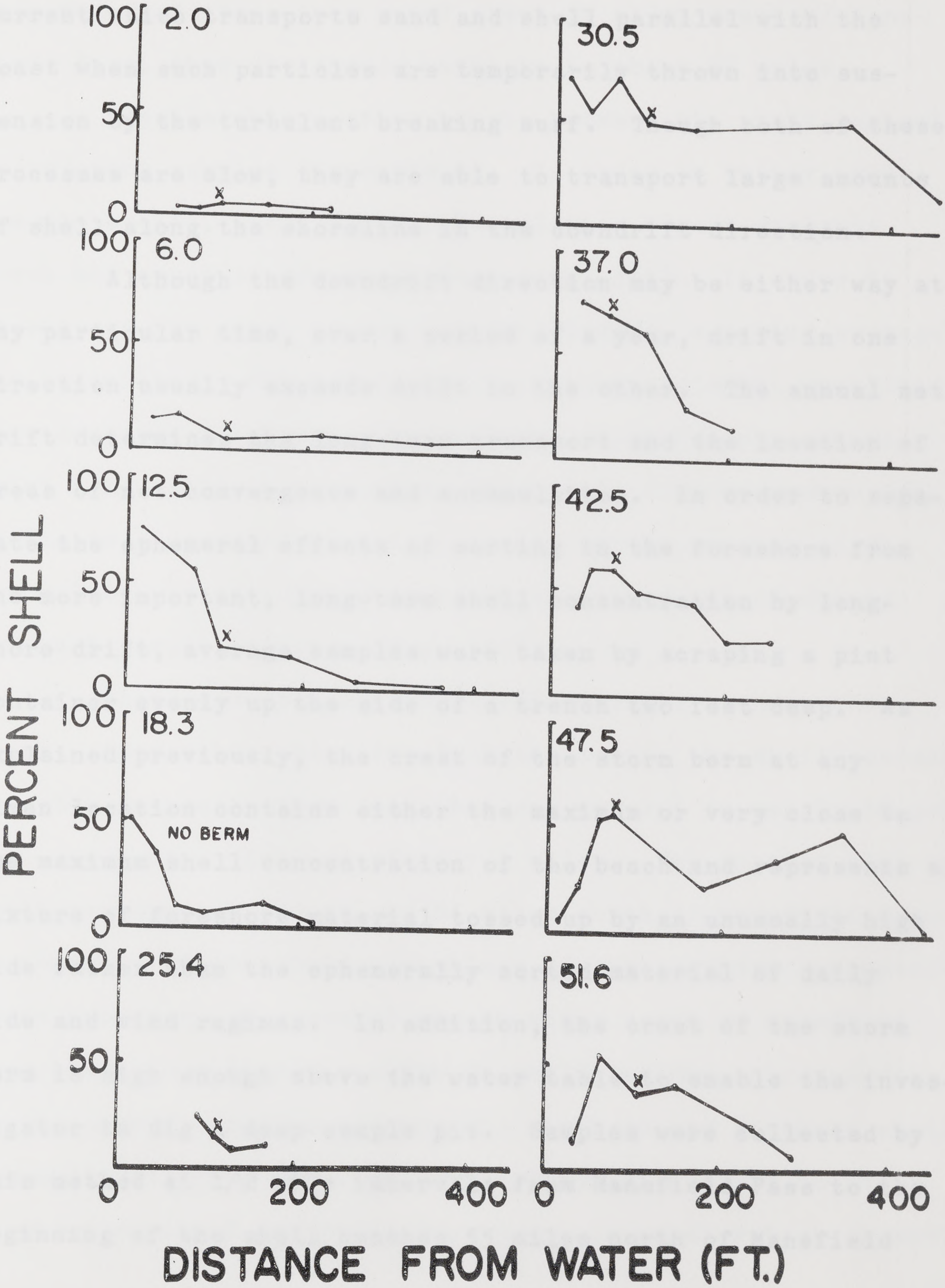
Storm berm samples.--In order for whole pelecypod valves to be transported along the coast, they must be carried by waves and currents of high competence. The greatest accumulation of pelecypod valves in the surf zone is at the base of the swash zone in a shell step at the final break point of the waves. Here the turbulence is high and valves can be transported parallel with the shore by being carried up the foreshore by an oblique swash and then returned to the toe by

Plate 6.

Vertical wall of backshore gully showing wind lag deposits, Padre Island, Texas. Coarse shell is concentrated by aeolian removal of finer material between storms of sufficient magnitude to flood the backshore. Note the similar lag deposit now forming on the surface of the backshore.

Figure 10.

Shell distribution along traverses perpendicular to the shoreline. The shell concentration versus distance landward from the edge of the water is plotted for a series of 12 traverses across the width of the beach throughout the study area. The number in the upper left-hand corner of each graph is the distance in miles that the traverse is north of Mansfield Pass. The small x by the trace of the graph denotes the approximate location of the storm berm on each traverse. Note the irregularity in shell percent seaward of the storm berm and the decrease in shell percent landward from it.



PERCENT SHELL
DISTANCE FROM WATER (FT.)
2.0
6.0
12.5
18.3
25.4
30.5
37.0
42.5
47.5
51.6
NO BERM
100
50
0
200
400

a normal backwash. Oblique waves also generate a longshore current which transports sand and shell parallel with the coast when such particles are temporarily thrown into suspension by the turbulent breaking surf. Though both of these processes are slow, they are able to transport large amounts of shell along the shoreline in the downdrift direction.

Although the downdrift direction may be either way at any particular time, over a period of a year, drift in one direction usually exceeds drift in the other. The annual net drift determines the long-term transport and the location of areas of net convergence and accumulation. In order to separate the ephemeral effects of sorting in the foreshore from the more important, long-term shell concentration by longshore drift, average samples were taken by scraping a pint container evenly up the side of a trench two feet deep. As explained previously, the crest of the storm berm at any given location contains either the maximum or very close to the maximum shell concentration of the beach and represents a mixture of foreshore material tossed up by an unusually high tide rather than the ephemerally sorted material of daily tide and wind regimes. In addition, the crest of the storm berm is high enough above the water table to enable the investigator to dig a deep sample pit. Samples were collected by this method at 1/2 mile intervals from Mansfield Pass to the beginning of the shell beaches 55 miles north of Mansfield

Pass. Samples were also collected at intervals of 3 miles from Mansfield Pass to a point about 30 miles south of Mansfield Pass, thus the sample coverage is about 85 miles.

Considerable scatter exists between the shell content in adjacent samples (Appendix A). In order to better evaluate the trends, shell content was plotted versus distance north and south of Mansfield Pass (fig. 11A). In order to smooth out the curve to see regional trends, a moving average was calculated. The values for each three adjacent localities were averaged to give a new corrected value for the central point (fig. 11B). Inasmuch as this still did not reduce the static to a desirable level, a second moving average of the new values was calculated to produce a third set of values for each sample location (fig. 11C).

There are obvious trends which can be seen on this graph. Approaching the area from the north, the shell content abruptly increases from less than one percent to nearly 50 percent shell in a distance of only 4 miles. The initial high in shell percent between 55 and 45 miles north of Mansfield Pass is composed of the shell assemblage of the northern sedimentologic province. Between 45 and 40 miles north of Mansfield Pass there is a pronounced low in shell content corresponding to the transition zone between the northern and southern shell assemblages. From 40 miles north of Mansfield Pass to about 30 miles north of Mansfield Pass there is another high in shell

Figure 11A.

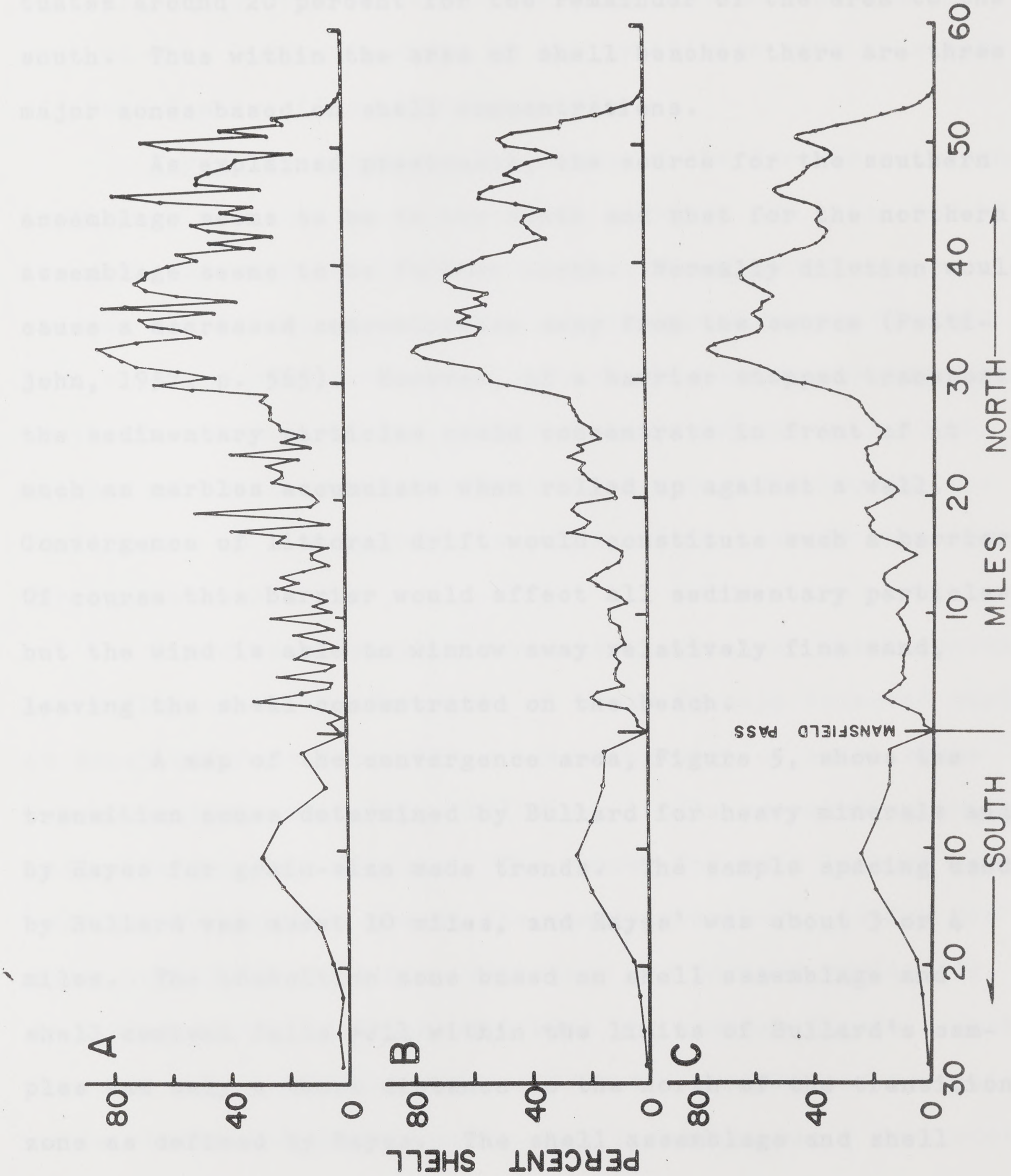
Shell abundance, storm berm samples. Raw data is plotted for percent shell every $\frac{1}{2}$ mile interval to the north and every 3 mile interval to the south of Mansfield Pass.

Figure 11B.

Raw data plotted in Figure 11A is smoothed by a moving average. Each three adjacent points are averaged to obtain a new value for the central point.

Figure 11C.

The moving average plotted in Figure 11B is further smoothed by a second moving average. Due to the wide sample spacing south of Mansfield Pass, the data south of Mansfield Pass is plotted with only a single moving average similar to Figure 11B.


A
B
C
80
40
0
PERCENT SHELL
30
20
10
0
10
20
30
40
50
60
SOUTH
NORTH
MILES
MANSFIELD PASS

percent corresponding to an accumulation of the species common to the southern sedimentologic province. Except for a low concentration at Mansfield Pass, the shell content fluctuates around 20 percent for the remainder of the area to the south. Thus within the area of shell beaches there are three major zones based on shell concentrations.

As explained previously, the source for the southern assemblage seems to be to the south and that for the northern assemblage seems to be further north. Normally dilution would cause a decreased concentration away from the source (Pettijohn, 1957, p. 565). However, if a barrier stopped transport, the sedimentary particles could concentrate in front of it much as marbles accumulate when rolled up against a wall. Convergence of littoral drift would constitute such a barrier. Of course this barrier would affect all sedimentary particles, but the wind is able to winnow away relatively fine sand, leaving the shell concentrated on the beach.

A map of the convergence area, Figure 5, shows the transition zones determined by Bullard for heavy minerals and by Hayes for grain-size mode trends. The sample spacing used by Bullard was about 10 miles, and Hayes' was about 3 or 4 miles. The transition zone based on shell assemblage and shell content falls well within the limits of Bullard's samples and only a short distance to the north of the transition zone as defined by Hayes. The shell assemblage and shell percent transition zone is probably more accurately determined because a sample spacing of $\frac{1}{2}$ mile was used. All of these data suggest that there is a transition zone in the central part of Padre Island. The shell assemblage and shell content data limit the width of the transition zone to a zone of about 8 miles (fig. 5 and fig. 8).

Foreshore samples.--The slope of the foreshore is controlled by the size of the waves breaking on the beach and by the grain size of the sediment: coarser sediment forms a steeper beach. It was expected, therefore, that there would be a distinct relationship between shell content and the slope of the foreshore. On Padre Island shell content is a rough measure of the coarseness of the beach material, because the shell makes up a mode which is considerably coarser than the terrigenous sand.

A series of samples for determination of shell content was collected on the foreshore at every $1\frac{1}{2}$ mile interval north of Mansfield Pass (fig. 12). A scatter plot of beach slope versus shell percent (fig. 13) shows little correlation between the two sets of data. The reason for this lack of correlation is probably due to the sampling method. As for the storm berm samples, a pint container was scraped vertically up a trench wall to sample all beds and laminae in the trench. This, of course, mixes sediment from the various sedimentation units of the trench. Commonly, the foreshore has a very steep

Figure 12.

Shell content, foreshore samples. The percent shell for samples collected on the foreshore is plotted against the distance north of Mansfield Pass. Samples were collected at intervals of $1\frac{1}{2}$ miles. No moving average is plotted due to the wide sample spacing.

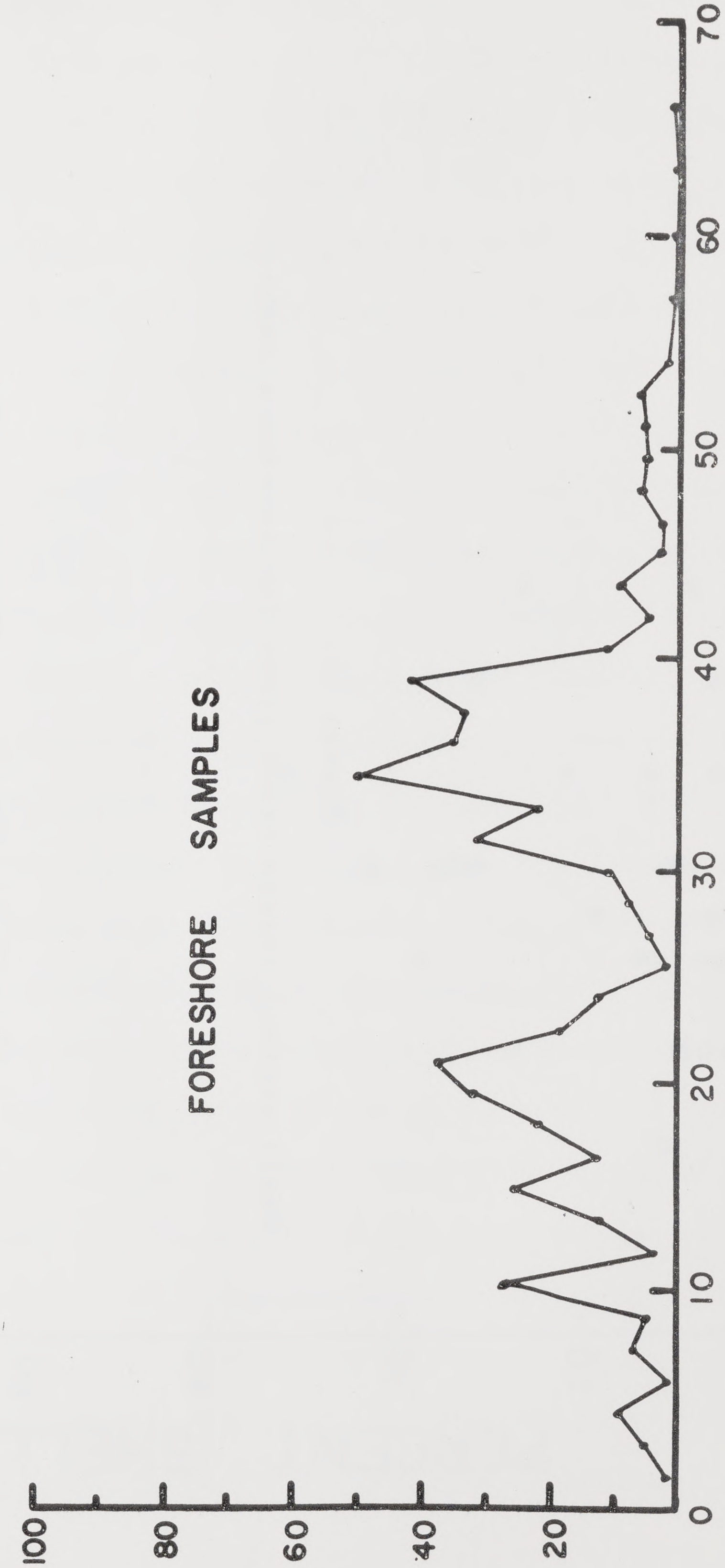
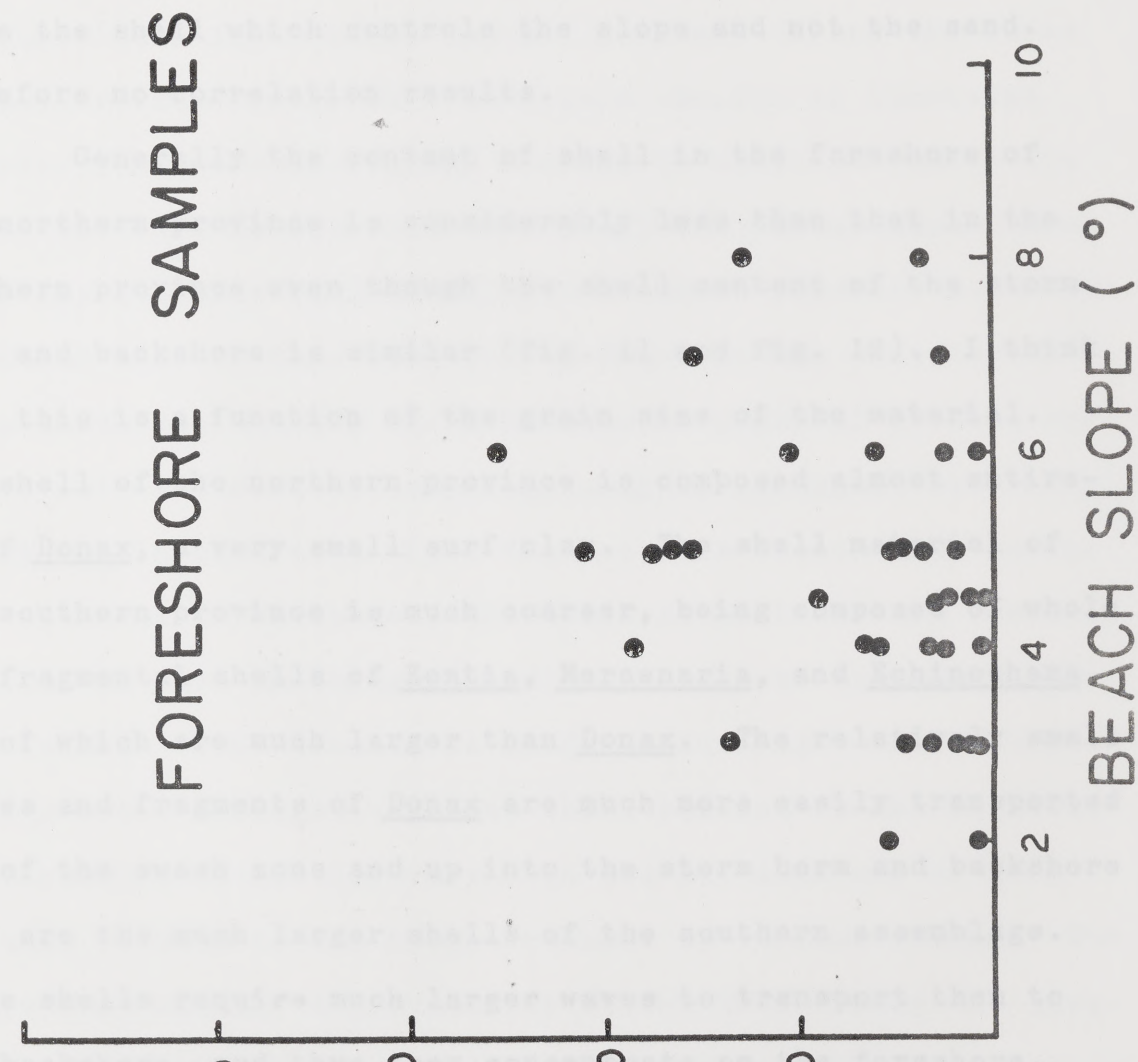

FORESHORE SAMPLES
PERCENT SHELL
100
80
60
40
20
0
10
20
30
40
50
60
70
MILES NORTH OF MANSFIELD PASS

Figure 13.

Shell content versus beach slope for foreshore samples.


FORESHORE SAMPLES
PERCENT SHELL
BEACH SLOPE (°)
0
20
40
60
80
100
2
4
6
8
10

slope and yet is covered with fine sand. In each of the trenches that I have examined under such conditions, there is a thick bed of shell only a few inches below the surface. This shell bed is probably responsible for the steep beach slope. Thus, in trench wall samples of such locations, sand and shell are mixed during sampling, diluting the shell, yet it is the shell which controls the slope and not the sand. Therefore no correlation results.

Generally the content of shell in the foreshore of the northern province is considerably less than that in the southern province even though the shell content of the storm berm and backshore is similar (fig. 11 and fig. 12). I think that this is a function of the grain size of the material. The shell of the northern province is composed almost entirely of *Donax*, a very small surf clam. The shell material of the southern province is much coarser, being composed of whole and fragmental shells of *Eontia*, *Mercenaria*, and *Echinochama* all of which are much larger than *Donax*. The relatively small valves and fragments of *Donax* are much more easily transported out of the swash zone and up into the storm berm and backshore than are the much larger shells of the southern assemblage. These shells require much larger waves to transport them to the backshore, and thus they concentrate on the foreshore.

Effect of dunes and hurricane channels.--A study of the topographic maps of Padre Island (see Appendix G for list) shows a central belt of high dunes which roughly corresponds to the zone of maximum shell percent. A careful study of the location of the many local maxima on the shell content graph (fig. 11C) and the location of high and continuous portions of the foredune ridge of Padre Island shows a nearly perfect correlation. That is, where the dunes are high and continuous there is a local shell content maximum. Where the dunes are low or where there is a hurricane channel or hurricane washover fan there is a local minimum in shell percent. The reason for this is obvious. The high, continuous dunes serve as an impenetrable wall to all but the most powerful storms. All shell that is deposited on the beach in the vicinity of these dunes must remain there because no physical process can remove it. The wind is competent only to transport the finer material. In contrast, where this wall is breached by hurricane channels or washovers, the shell is periodically removed at least in part by being washed into the interior of the barrier island. This process is self-reenforcing. Where the dunes are the strongest and the shell content is the highest, the backshore is usually very high and may show one or more terraces related to the height reached by various storms. Due to the high backshore produced by strong dunes, only the largest storms with very high tides reach the foot of the dunes. Dunes thus protected can build still higher and become still stronger and better able to resist future wave attack.

S H E L L   S O R T I N G   D U E   T O   S Y M M E T R Y

PREVIOUS STUDIES

It has been noted in the past and during this study that valves of pelecypods are often differentially sorted by wave action on the foreshore such that beach deposits consist largely of either right or left valves. Of the six papers which describe this right-left sorting on recent beaches, only two present a likely theory to explain the phenomenon. Muelen (1947) and Martin-Kaye (1951) suggest that the sorting is due to the mirror symmetry because there are no other obvious differences between the sorted valves, but they propose no specific process. Kornicker and his co-workers (1959 and 1963) tested whether the sorting of <u>Dinocardium robustum</u> and <u>Anadara braziliana</u> correlated with other factors such as weight, shape, and size but they found only negative results. Lever (1958) and Nagle (1964) explain the sorting by the effect of longshore current and the oblique approach of waves. According to Nagle, the valves are transported and rotated until the beaks point seaward by the backwash. When the next wave approaches obliquely, the beak of one valve points into it and this valve is easily moved away. The beak of the other valve points away from the uprush and it is stable. By this process, one valve remains in place while the other is carried away, resulting in a concentration of one type of valve. By this reasoning the sorting is effected by oblique swash on shells oriented by the previous backwash. The valve being carried away is carried up the beach by the swash.

In studies of the right and left sorting of Donax, Lever (1958) found that the valves turn in opposite directions with each wave. Lever suggests that the valves are oriented by the swash and then selectively removed by the backwash if the waves approach the beach obliquely. He also considers the possibility that flood and ebb currents acting in deeper water may play a part in the sorting mechanism. Because the tide range and tidal currents in the surf zone on the Texas beaches are negligible and because the right and left effect operates on the Texas beaches as well as in the Netherlands where Lever worked, it is more likely that his first interpretation of a differential sorting due to oblique wave approach is correct. Tidal currents are not necessary to effect the sorting.

SIGNIFICANCE OF SORTING

Because this sorting process may be of some value in determining the longshore drift history of an area, Dr. E. William Behrens and I decided to further develop the theory behind this shell sorting phenomenon. First, to determine the extent of this phenomenon, we made more than 200 counts of 15 or more each of right and left valves on Mustang and

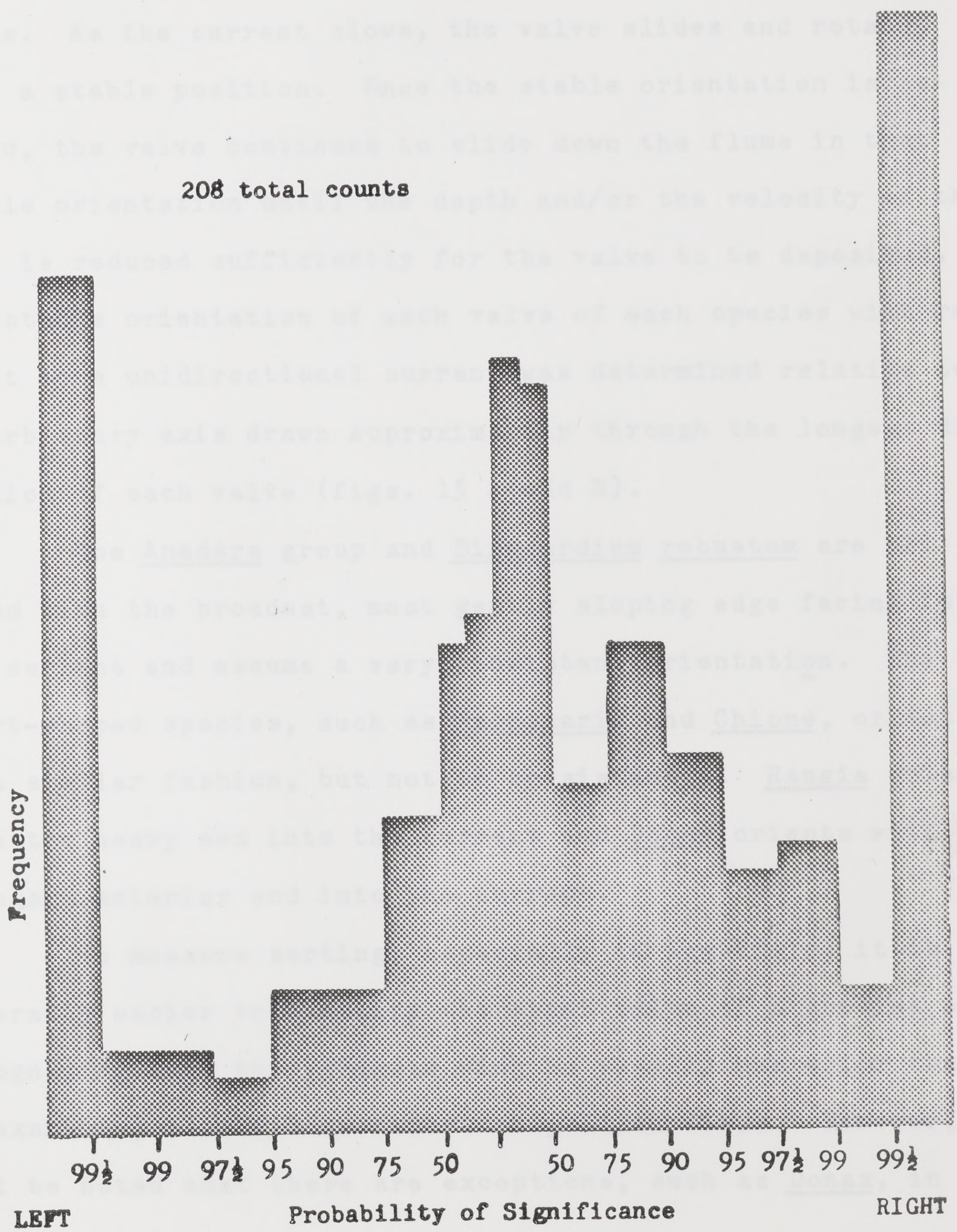
Padre Islands and applied a X^2 Test to each count (fig. 14). The X^2 Test assumes a normally distributed population and tests the probability that this assumption is false, that is, that the valves of each count are really sorted. If they were not sorted most samples should have very low probabilities, and there should be a bell-shaped curve in the center of the histogram (fig. 14). We can conclude from these data that, although the valves are randomly distributed in numerous samples, they are very well sorted in many other samples. The species counted in this study show no differences between right and left valves such as weight, strength, size, or ornamentation. The only difference that we can determine between the valves is their symmetry.

CURRENT ORIENTATION

In order to be able to evaluate the action of the complex system of currents acting to produce the sorting effect in the swash zone, Dr. Behrens and I performed a series of tests on the species studied in a 20 foot long flume at the Department of Geology of The University of Texas at Austin. The valves were placed on the sand bed of the flume in either random or oriented positions. The pump was operated for about 10 seconds and then turned off. This caused a "wave" very similar to a single wave on the beach to move down the flume. However, there was no reverse current like the backwash of a

Figure 14.

Frequency histogram of the individual probabilities by the X^2 Test of all 208 counts for right-left sorting of pelecypod valves on Texas beaches.


208 total counts
Frequency
99½ 99 97½ 95 90 75 50 50 75 90 95 97½ 99 99½
LEFT
Probability of Significance
RIGHT

normal wave. Numerous tests on each species showed that they tend to align themselves quickly and uniformly in a hydrodynamically stable position relative to the unidirectional current. If the current is initially very fast, the valve rolls. As the current slows, the valve slides and rotates into a stable position. Once the stable orientation is assumed, the valve continues to slide down the flume in that stable orientation until the depth and/or the velocity of the flow is reduced sufficiently for the valve to be deposited. The stable orientation of each valve of each species with respect to a unidirectional current was determined relative to an arbitrary axis drawn approximately through the longest dimension of each valve (figs. 15 A and B).

The _Anadara_ group and _Dinocardium_ _robustum_ are oriented with the broadest, most gently sloping edge facing into the current and assume a very consistent orientation. The heart-shaped species, such as _Mercenaria_ and _Chione_, orient in a similar fashion, but not so consistently. _Rangia_ orients with the heavy end into the current and _Donax_ orients with the elongate anterior end into the current.

To measure sorting, especially in the field, it is generally easier to identify the right valve of a species by recognizing that the elongate wing is usually posterior than by examining the beak curvature or pallial sinus. However, it must be noted that there are exceptions, such as _Donax_, in

Figure 15 A.

Orientation of valves in unidirectional flow. The line painted on each shell is the arbitrary orientation axis that we used. In the figure the valves are oriented in the stable position relative to a unidirectional current coming from the top of the figure as shown by the large arrow. Adjacent to the picture of each valve is a diagram showing the vector sum of all measured orientations for each valve in the unidirectional current. Size X 1/2.

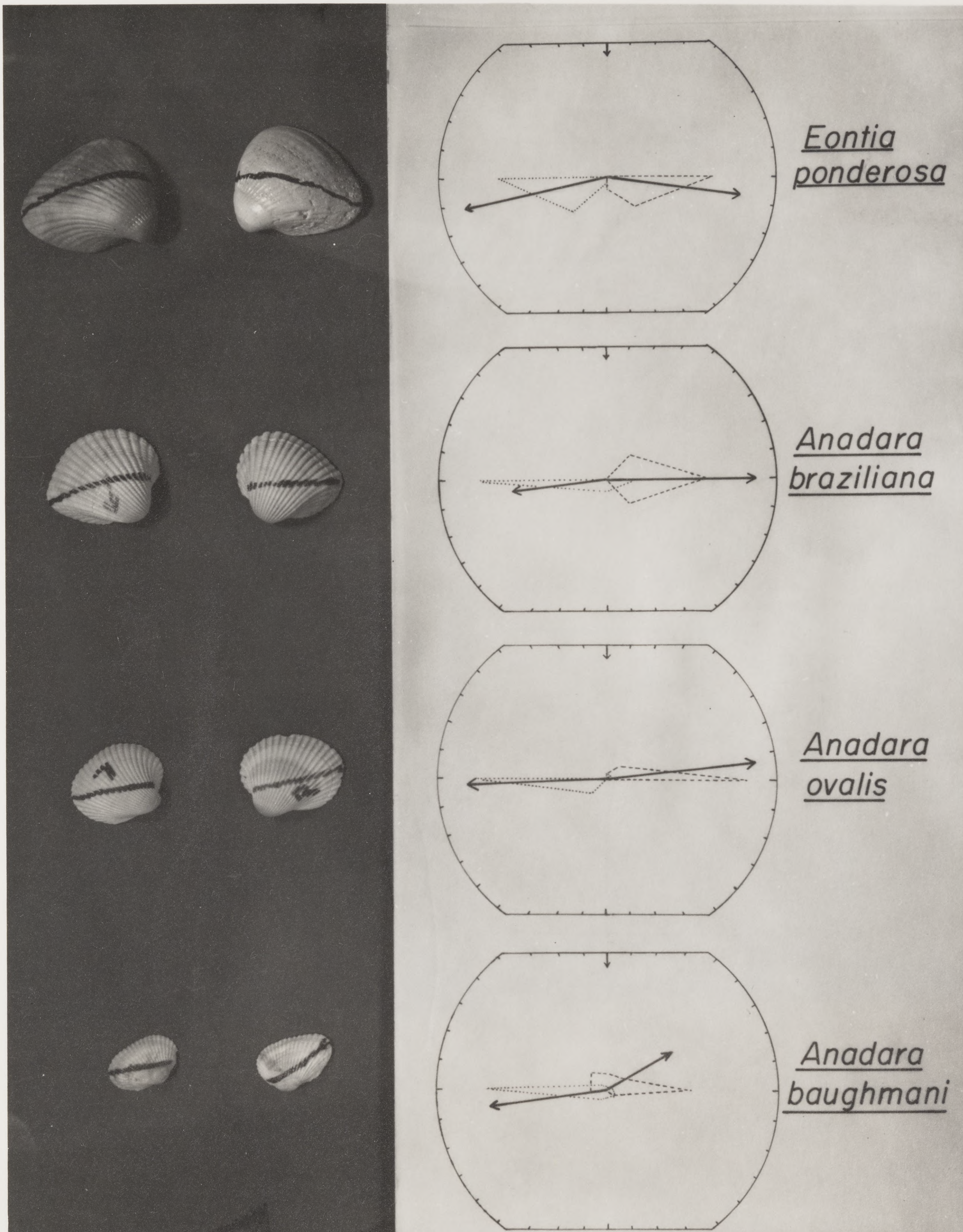
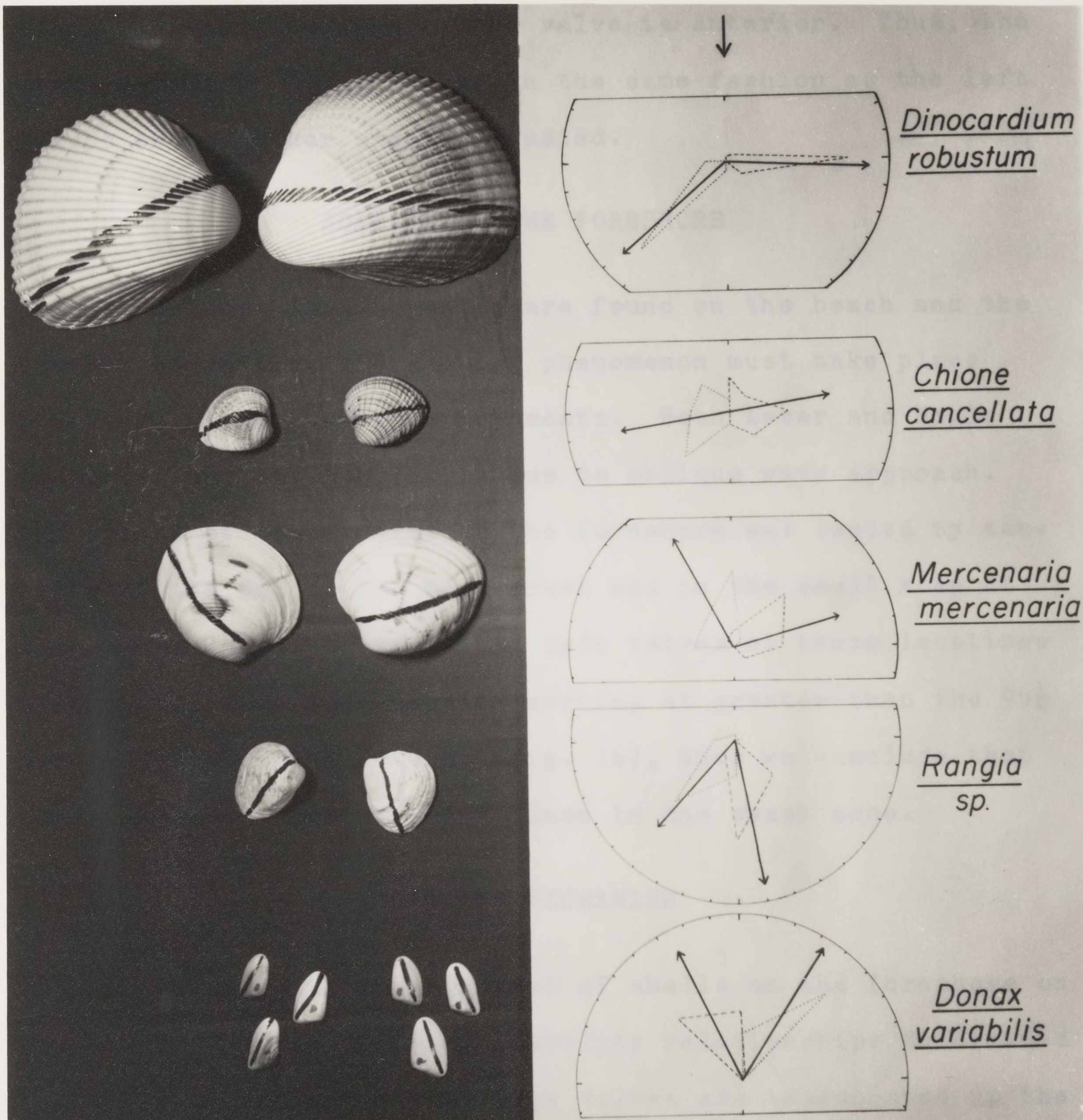

Eontia ponderosa
Anadara braziliana
Anadara ovalis
Anadara baughmani

Figure 15 B.

Orientation of valves in unidirectional flow - continued.


Dinocardium
robustum
Chione
cancellata
Mercenaria
mercenaria
Rangia
sp.
Donax
variabilis

which the elongate wing of the valve is anterior. Thus, the right valves of Donax behave in the same fashion as the left valves of the other species studied.

SORTING IN THE FORESHORE

Because these species are found on the beach and the barrier shoreface, the sorting phenomenon must take place somewhere within these environments. Both Lever and Nagle proposed that the sorting is due to oblique wave approach. The effect of these waves on the foreshore was tested by sampling at the top of the berm crest and in the shell step at its base. Counts of right and left valves at these locations show significant and opposite sorting at greater than the 99½ percent level of confidence (fig. 16), thus we conclude that the right-left sorting takes place in the swash zone.

SORTING MECHANISM

Analysis of the movement of shells on the foreshore on the basis of unidirectional stability relationships determined in the flume indicates that both valves are transported up the foreshore by an oblique swash that first tumbles the shells and then slides them so that they should orient in a stable position with respect to it (fig. 17). The next current acting on the shells is either a lateral swing in the direction of longshore current or the backwash from the wave. As a

Figure 16.

Foreshore sorting zone. Due to the oblique approach of waves from the right as the observer faces the sea (part B), the valves are sorted such that we observed a L/R ratio of 2.85 in the shell step at the toe of the foreshore and a R/L ratio of 2.17 at the active berm crest at the top of the foreshore (part A).

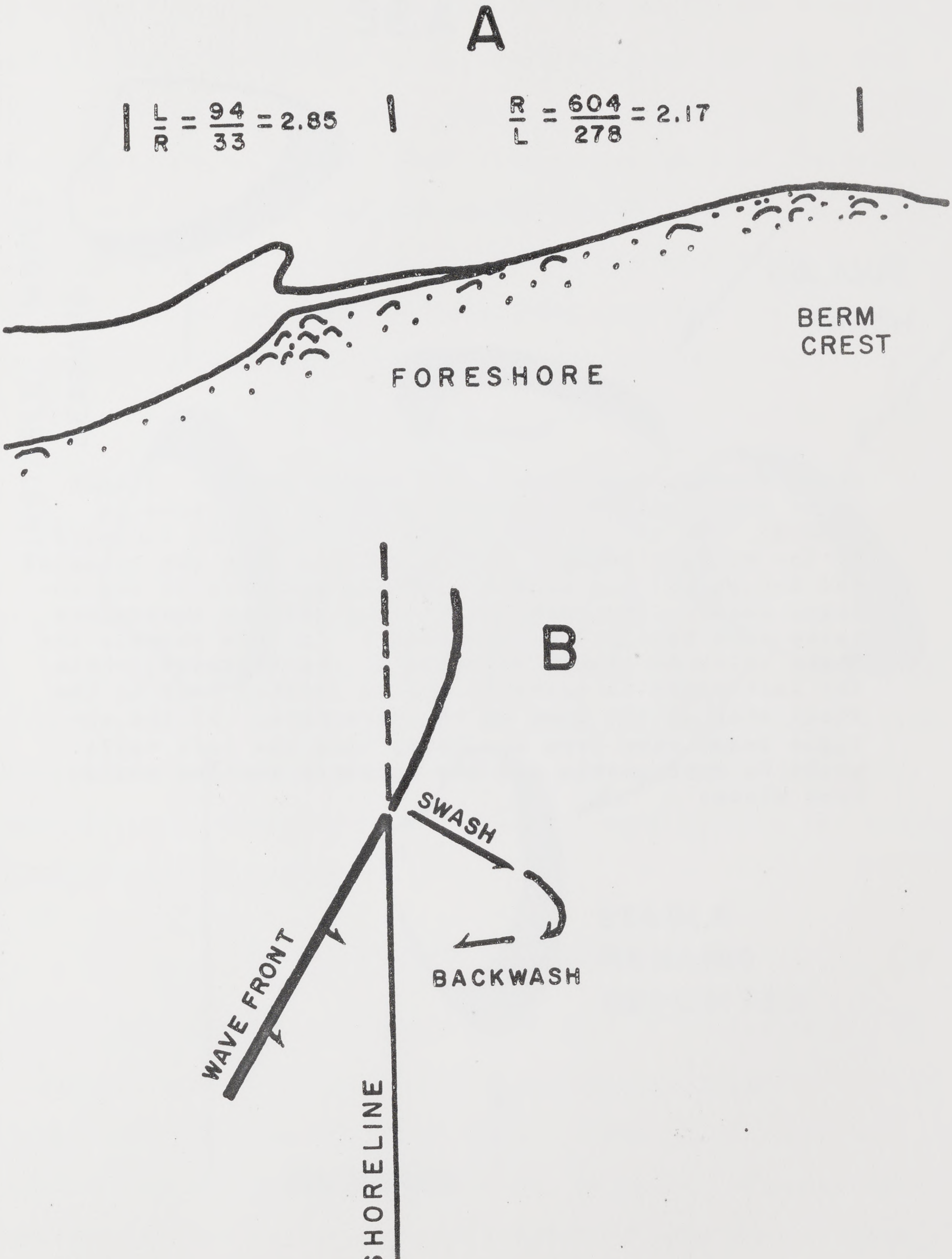
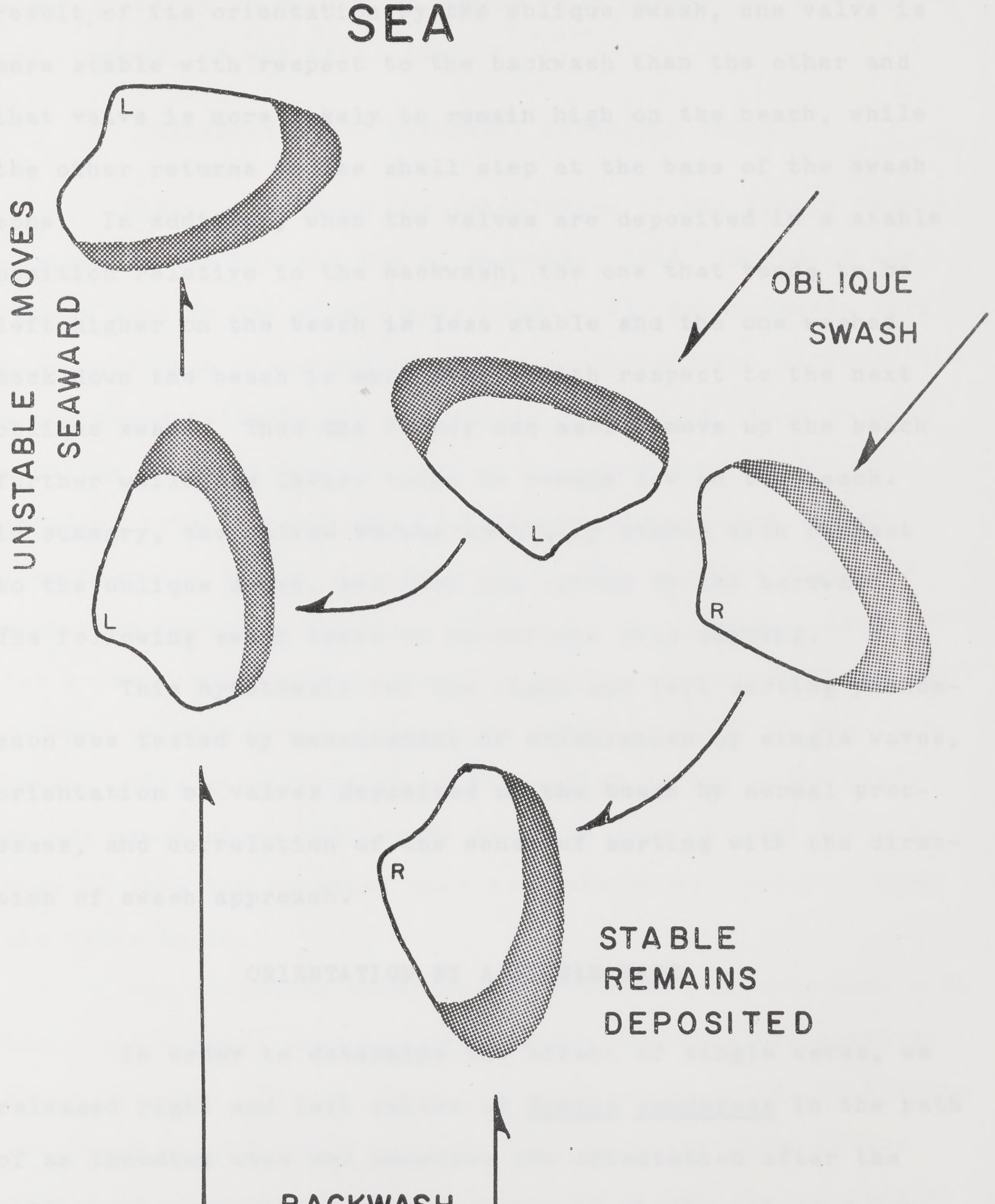

A
L/R = 94/33 = 2.85
R/L = 604/278 = 2.17
FORESHORE
BERM
CREST
B
SWASH
BACKWASH
WAVE FRONT
SHORELINE

Figure 17.

Shell sorting mechanism. The shaded portion of each valve faces into the current in which the valve is stable. The valves are rolled and then slid landward by the oblique swash. During sliding they are oriented and deposited in a stable position relative to the oblique swash. The backwash is then able to remove one valve more easily than the other. In this example the right valve is stable relative to the backwash, while the left valve is unstable and is carried back to the shell step at the base of the foreshore. If the oblique swash came from the left, then the left valve would be more stable and the opposite sorting would take place.


SEA
L
UNSTABLE MOVES
SEAWARD
OBLIQUE
SWASH
L
L
R
R
STABLE
REMAINS
DEPOSITED
BACKWASH

result of its orientation by the oblique swash, one valve is more stable with respect to the backwash than the other and that valve is more likely to remain high on the beach, while the other returns to the shell step at the base of the swash zone. In addition, when the valves are deposited in a stable position relative to the backwash, the one that tends to be left higher on the beach is less stable and the one washed back down the beach is more stable with respect to the next oblique swash. Thus the former can easily move up the beach further while the latter tends to remain low on the beach. In summary, the valves become initially stable with respect to the oblique swash, and then are sorted by the backwash. The following swash tends to re-enforce this sorting.

This hypothesis for the right and left sorting phenomenon was tested by measurement of orientation by single waves, orientation of valves deposited on the beach by normal processes, and correlation of the sense of sorting with the direction of swash approach.

ORIENTATION BY A SINGLE WAVE

In order to determine the effect of single waves, we released right and left valves of <u>Eontia</u> <u>ponderosa</u> in the path of an incoming wave and measured the orientation after the valves were deposited. The majority of shells released were transported by both swash and backwash in that order. Thus, their orientation should be stable with respect to the latter; and, indeed, it was (fig. 18A).

ORIENTATION OF NATURALLY DEPOSITED VALVES

Figure 18B shows the orientation of all *Eontia* valves counted on the 7th and 8th of December, 1966, excluding the valves used in the single wave tests. All measurements were made on valves deposited on the upper foreshore. Although the orientation patterns for the valves counted in their resting position on the beach are not as well developed as the orientation patterns developed by single waves, these valves generally are stable with respect to the incoming swash and thus were deposited by it. This is to be expected. In order for a valve to be semipermanently deposited, rather than just dropped between waves, it must be deposited high on the foreshore. This requires that it be carried to the upper limit of the swash where sufficient water is lost through percolation so that the backwash does not have enough power to move the valve again.

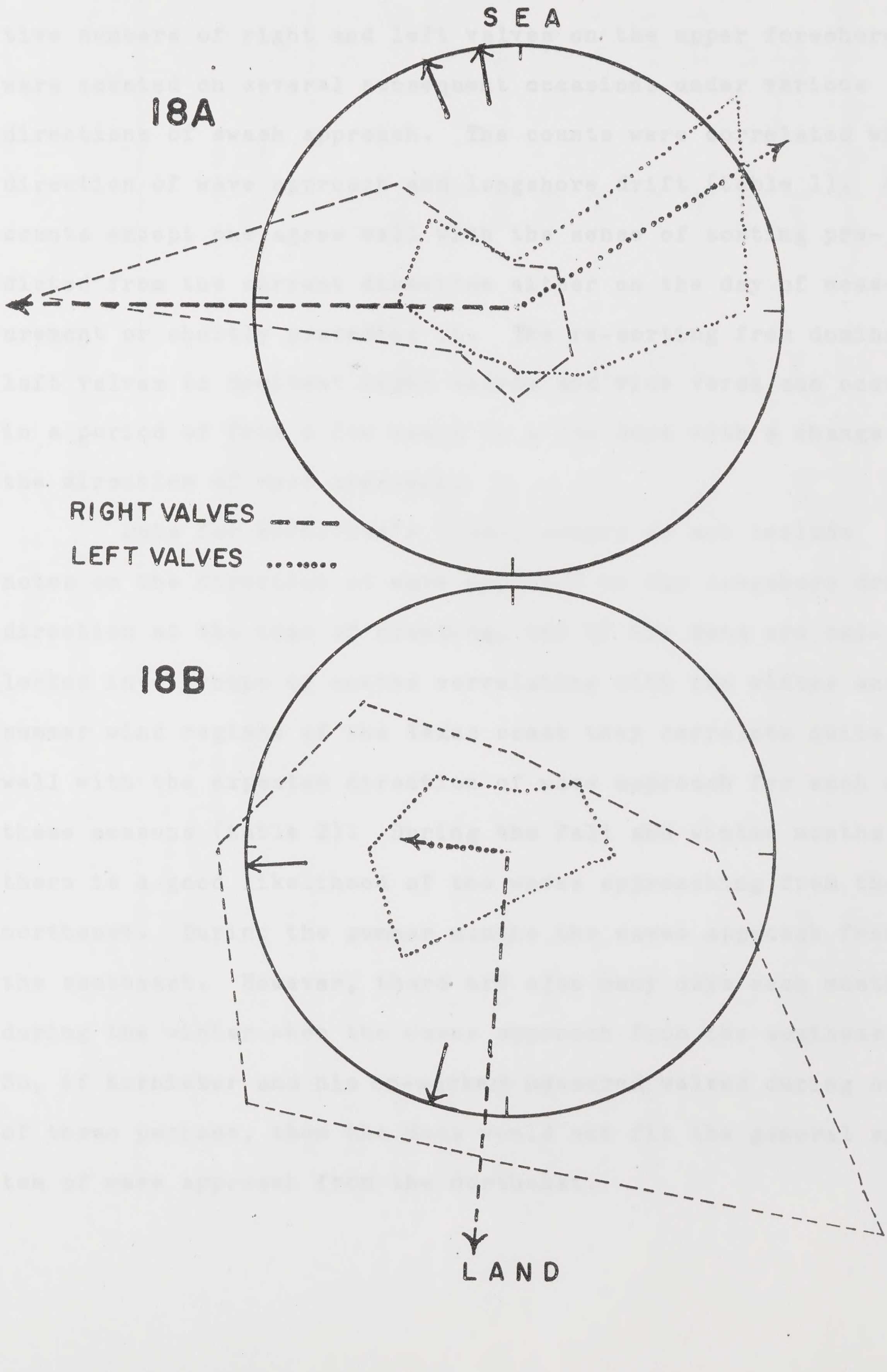
All preceding examples and measurements were made with the oblique waves approaching from the right as the observer faces the sea. This is from the south or southeast on Mustang and Padre Island beaches. With this approach right valves should be carried to the berm crest while left valves remain at the toe of the foreshore (fig. 17). An oblique approach

Figure 18A.

Rose diagram of valves oriented by one wave. The resultant orientation of the longest axis of both right and left valves is shown for a single wave. The solid black arrows show the current direction in which the valves are stable. Because the arrows indicate a seaward moving current, it is obvious that the valves were deposited in a stable position relative to the backwash.

Figure 18B.

Rose diagram of the orientation of valves naturally deposited near the top of the foreshore. The solid black arrows indicate the current direction in which the valves are stable. Preceding and at the time of measurement the swash approached the beach obliquely from the right as the observer faces the sea. It can be seen that these valves deposited high on the beach are stable with respect to this swash.


SEA
18A
RIGHT VALVES
LEFT VALVES
18B
LAND

from the left should produce the opposite sorting. The relative numbers of right and left valves on the upper foreshore were counted on several subsequent occasions under various directions of swash approach. The counts were correlated with direction of wave approach and longshore drift (table 1). All counts except one agree well with the sense of sorting predicted from the current direction either on the day of measurement or shortly preceding it. The re-sorting from dominant left valves to dominant right valves and vice versa can occur in a period of from a few hours to a few days with a change in the direction of wave approach.

Data for Kornicker's (1963) counts do not include notes on the direction of wave approach or the longshore drift direction at the time of counting, but if his data are collected into groups of months correlating with the winter and summer wind regimes of the Texas coast they correlate quite well with the expected direction of wave approach for each of these seasons (table 2). During the fall and winter months there is a good likelihood of the waves approaching from the northeast. During the summer months the waves approach from the southeast. However, there are also many days each month during the winter when the waves approach from the southeast. So, if Kornicker and his co-workers measured valves during one of these periods, then the data would not fit the general system of wave approach from the northeast.

Table 1

R - L SORTING OF PELECYPOD VALVES

Date	Direction from which the current comes as the observer faces seaward: Preceding four days	Direction from which the current comes as the observer faces seaward: Immediate current	Number of counts	Number of valves: L	Number of valves: R	Confidence level	X^2
9/11/66	L L L L	L	37	660	1144	99½	130
9/20/66	R L L L	L	1	22	6	99½	9.1
10/2/66	L R R L	L	5	120	84	97½-99	6.3
10/11/66	L L L L	L	8	133	29	99½	67
10/15/66	R R R R	L	18	237	303	99½	8.1
10/16/66	R R R L	L	12	336	126	99½	9.5
10/17/66	R R L L	R	3	32	78	99½	19.3
	R R L L	L	6	125	70	99½	15.5
10/21/66	L L L L	R	23	551	346	99½	47
	high beach		13	331	109	99½	112
	low beach		10	220	237	50-75	0.63

Table 1 - Cont.

Date	Direction from which the current comes as the observer faces seaward		Number of counts	Number of valves		Confidence level	X^2
	Preceding four days	Immediate current		L	R		
10/22/66	L L L R	R high	2	64	20	99½	23
		low	2	45	51	25-50	0.38
10/23/66	L L R R	L	6	155	124	90-95	3.45
10/24/66	L R R L	L	32	339	617	99½	81
12/7/66	L R R R	R	16	318	757	99½	187
12/8/66	R R R R	R	3	121	313	99½	81
	R R R R	L high	18	318	480	99½	33
		low	10	220	338	99½	25
1/12/67	L L L L	L	2	40	14	99½	12.5

For this portion of the Texas coast, a current from the right, as the observer faces seaward, should result in an excess of right valves on the upper foreshore where most of the counts were made. A current from the left will result in an excess of left valves. On some days, counts were made both high and low on the foreshore as indicated in the table.

Table 2

SUMMARY OF KORNICKER'S COUNTS

The sense of sorting observed by Kornicker and his co-workers (1963) for each month. The monthly data is collected into a summer regime of southerly winds from April through early September and into a winter regime of northerly winds as well as southerlies from September through March. March and September are transitional months between the winter and the summer wind regimes.

SUMMARY OF KORNICKER'S COUNTS

Year	Month	Sense of Sorting
1959	Apr.	R
"	Apr.	R
"	May	R
"	Jun.	R
"	Jun.	R
"	Jul.	L
"	Aug.	-
"	Aug.	R
"	Aug.	L
"	Sept.	R
1960	May	L
"	Jun.	R
"	Jul.	R
"	Aug.	R

Summer Regime

Right	Left	Neither	X^2	Confidence Level
10	3	1	3.5	90-95%

Year	Month	Sense of Sorting
1959	Sept.	L
"	Sept.	L
"	Oct.	L
"	Nov.	L
"	Dec.	L
"	Dec.	L
1958	Dec.	L
1960	Jan.	L
"	Jan.	L
"	Feb.	R
"	Mar.	-
1959	Jan.	L
"	Feb.	R
"	Feb.	L
"	Mar.	L

Winter Regime

Right	Left	Neither	X^2	Confidence Level
2	12	1	7.7	99-99½%

CONCLUSIONS

Although our evidence is by no means proof of the theory presented, both the data and the theory are consistent with each other. Additional testing with recent and ancient assemblages may lend further support. At the present time there is probably little use of this right and left sorting effect in the study of ancient rocks. Because the sorting is ephemeral and changes rapidly from right- to left-dominated and because the two sets of sorted valves are concentrated so close together at opposite ends of the swash zone, it would be necessary to make a great many counts in ancient rocks in order to determine the net direction of longshore drift when those ancient rocks were deposited. In addition, it would be necessary to determine the exact location on the foreshore. Perhaps the right and left sorting effect may be of some use if restricted as an aid to identifying ancient beaches and to determine if there was a longshore drift system operating. That is, if a sorting of right and left valves has occurred, then it must have been by the oblique approach of waves. Because this is likely to occur only on beaches, this sorting phenomenon may serve as a good beach indicator.

REGIONAL WIND PATTERNS

Because the wind system of the south Texas area is the dominant force affecting sediment movement, a considerable effort was spent in interpreting U. S. Weather Bureau data collected at Corpus Christi and at Brownsville, Texas. These stations at the northern and southern limits of the study area are the only Weather Bureau stations in the study area which record and publish wind data.

VECTORS

Geologists often consider the effect of the prevailing winds, that is, the direction from which the winds blow the greatest amount of the time. Somewhat more important is the predominant wind, which is the vector resultant of the wind velocity, duration and direction for all winds during a given period. This in effect gives the path of every air particle in motion during that period. It is directly proportional to the resultant kinetic energy of the wind. Sediment transport is effected by direct transfer of this kinetic energy to sediment particles or by indirect transfer to the particles through waves. From the expression for kinetic energy ($\frac{1}{2}mv^2$) we see that the amount of energy is proportional to the square of the velocity and not to the velocity. Thus, a vector sum of the winds in terms of v^2 rather than v is more meaningful to the transfer of energy from wind to water during wave generation. Furthermore, as waves become larger, they present a larger and larger surface for the wind to press against, and the frictional coupling between the wind and the water becomes more effective. Thus, the energy of wind-generated waves is proportional to an even higher power of the wind velocity ($E=0.242(v/10)^5$, Williams, 1962, p. 193).

For this area, however, the winds blow with about the same speed regardless of their direction. This makes the resultant directions for winds calculated with v^2 or v^5 about the same as the wind directions calculated with v and eliminates the need for a consideration of a higher power of the velocity in a study of the direction of energy flow. It is necessary to consider v^2 or v^5 in order to determine the magnitude of energy flow.

Beginning in 1965 the Weather Bureau published wind data in the form of monthly and annual vector resultants as well as average directions and velocities (prevailing winds). However, prior to 1965, the Weather Bureau published only average directions and velocities that are virtually useless in considerations of energy transfer. Monthly data for Corpus Christi for the years 1951-1960 give the average velocity and duration for each of 16 compass directions. With the aid of the 6600 computer, I determined monthly, annual, and a 10 year resultant for both v and v^2 vectors for the Corpus Christi data (fig. 3 and Appendix E). The annual resultant for the 10 year period ranges between 111° and 135° with a 10 year resultant of 121°. The resultant for v^2 ranges between 110° and 135° with a 10 year resultant of 123°. Note that the direction for v and v^2 is identical within the limits of the accuracy of the measurements. Data for 1965 and for 1966 fall within the limits of the 10 year data described above.

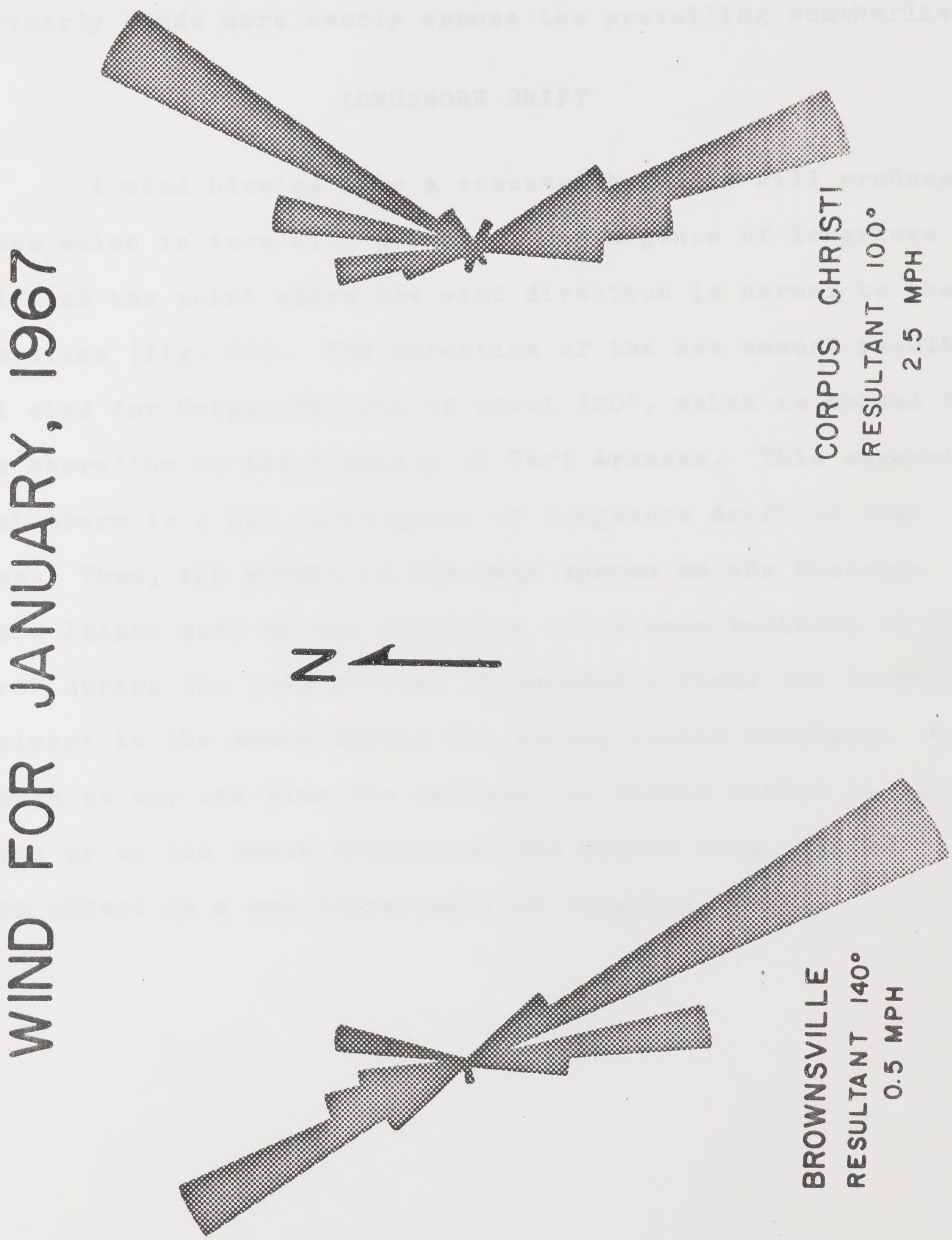
Price (1933) determined a vector diagram of the wind direction, duration and square of the velocity for the period 1923 to 1930. The annual vector sum derived from this diagram is 120°. Thus, several different computations of the vector sum of the winds for the Corpus Christi area both for velocity and for the square of the velocity all provide an annual vector sum of about 120°.

LOCAL DIFFERENCES

There is a major difference between the wind systems at Corpus Christi and at Brownsville. At both places the southerly winds blow from about the same direction and resultants from months dominated by southerly winds are about identical for both Brownsville and Corpus Christi. However, the northerly winds are considerably more easterly at Corpus Christi than at Brownsville (fig. 19). At both places they blow nearly parallel with the coastline. This may aid in the transport of sediment to the south by the northers. Although

Figure 19.

Wind roses for Corpus Christi and Brownsville, Texas for the month of January 1967. The daily vector resultants for each 10 degrees of azimuth are plotted for each city. Note that although the southerlies blow from about the same direction at each city, the northerly winds blow from a more easterly direction at Corpus Christi. In both cities, the northerly winds blow approximately parallel to the shoreline. This is typical of the winter regime in these two cities.


WIND FOR JANUARY, 1967
N
CORPUS CHRISTI
RESULTANT 100°
2.5 MPH
BROWNSVILLE
RESULTANT 140°
0.5 MPH

the average wind velocities are similar for each city, the resultant velocity is much lower at Brownsville, because the northerly winds more nearly oppose the prevailing southerlies.

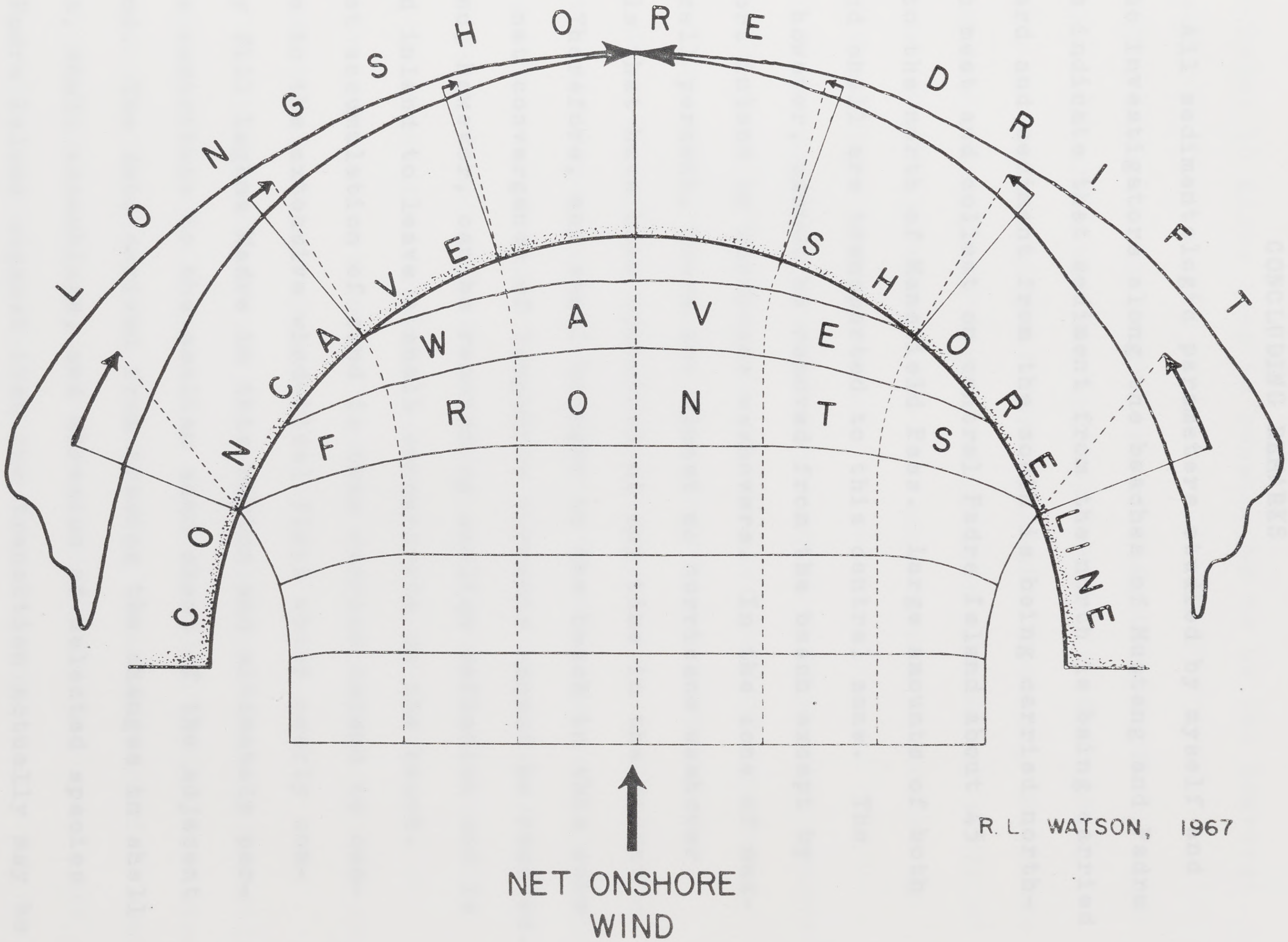
LONGSHORE DRIFT

A wind blowing into a concave shoreline will produce waves which in turn will produce a convergence of longshore drift at the point where the wind direction is normal to the shoreline (fig. 20). The direction of the net annual resultant wind for Corpus Christi is about 120°, which is normal to the shoreline in the vicinity of Port Aransas. This suggests that there is a net convergence of longshore drift in that area. Thus, the effect of the wind system on the Mustang-Padre Island part of the coastline is to move sediment to the north during the long periods of southerly winds and to move sediment to the south during the strong winter northers. Although at any one time the sediment is moving either to the north or to the south throughout the entire area, the long term effect is a net convergence of longshore drift.

Figure 20.

Idealized net drift relationships. An onshore wind blowing onto a concave shoreline will produce wave fronts normal to the wind direction. These wave fronts move shoreward and are incompletely refracted. As they break, the waves generate a longshore current due to their oblique approach to the shoreline. This current is strongest at the greatest distance from the central point where the waves approach the shore at the greatest angle. The current decreases in magnitude toward the center where it diminishes to zero because the waves approach parallel to the shoreline at the point where the wind direction is normal to the shoreline and no current is generated.

IDEALIZED NET DRIFT RELATIONSHIPS



C O N C L U S I O N S

CONCLUDING REMARKS

All sedimentologic parameters studied by myself and previous investigators along the beaches of Mustang and Padre Islands indicate that sediment from the north is being carried southward and sediment from the south is being carried northward to meet and collect on central Padre Island about 45 miles to the north of Mansfield Pass. Large amounts of both sand and shell are transported to this central zone. The shell, however, cannot be removed from the beach except by transport inland by hurricane washovers. In the zone of maximum shell percent, there are almost no hurricane washover channels that have been operative at any time in the recent past. Therefore, any shell brought to the beach in this zone by the net convergence of longshore currents cannot be removed. The sand, however, can be removed by aeolian deflation and is carried inland to leave a shell concentrate on the beach. This net accumulation of sand is thus carried inland to contribute to the extensive wind-tidal flats which nearly completely fill Laguna Madre in this region and ultimately perhaps to contribute to the aeolian sand sheet of the adjacent mainland. The data derived from tracing the changes in shell percent, shell assemblage, and abrasion of selected species along Padre Island suggest that the transition actually may be a short distance further to the north than it was previously considered. All sedimentologic data are in agreement if a zone of about 10 miles long is considered to be the convergence area.

The theoretical prediction of longshore drift by wind analysis would place the convergence further to the north, somewhere in the vicinity of Port Aransas. However, the proximity of the convergence suggested by this elementary study of the winds is strong support for the convergence indicated by the sedimentologic studies.

It is probable that analyses of wind data will be used more and more in the future in the prediction of longshore drift relationships in other areas. If these studies use higher order wave prediction theories and make use of the computer to calculate and sum the direction and magnitude of longshore drift several times daily for a period of several years of wind data, then accurate predictions may be possible. Of course, such predictions will have the greatest chance of accuracy if the wind system and the coastal configuration are as simple as on the Texas coast.

The existence of shell beaches similar to the presently active beaches at least as old as the beachrock of the Pleistocene Ingleside Barrier Complex indicates that the climatic conditions and especially the wind circulation of this area must have been about the same during the last interglacial. If similar accumulations are found in the Tertiary barriers, perhaps we can extend interpretations of the wind circulation back that far.

The right and left sorting of pelecypod valves on beaches by the oblique approach of waves may serve as a useful beach indicator. Due to the ephemeral nature of the sorting and to the proximity of the deposits of opposing valves this phenomenon is of little use in interpreting ancient longshore drift directions.

Finally, we must note that it is possible to have a tremendous accumulation of carbonate shell material in a terrigenous province which is not lacking in sediment supply. In addition this accumulation is due entirely to differential sorting by waves and wind and not due to a massive population of the species involved. Additional evidence for accumulation due to a size sorting phenomenon is the extreme abrasion of most of the species present, and the almost complete lack of fresh, unabraded specimens. If the accumulation were due to a locally rich population, one would expect to see a greater number of fresh specimens.

FUTURE STUDIES

This investigation has solved perhaps only a few problems and has uncovered a great many more problems of interest. Below is a discussion of further work to be done.

Qualitative changes in shell size and roundness can be seen by casual observation through the study area. Quantitative measurements of sorting and roundness might correlate directly with abrasion as a function of direction and distance of transport.

Old shell beaches behind the foredunes of central Padre Island suggest a seaward accretional history for the island. Detailed trench study in that area may be used to determine the rate of seaward accretion.

The distribution of shell assemblage and shell percent in the beachrock of the Pleistocene Ingleside Complex and in the offshore rock outcrops should be studied in detail and compared with the Recent. This might answer the question whether or not the convergence was to the north, to the south, or at the same location that it is today.

Environmental analysis of the clay that underlies the Mansfield Pass jetty area at shallow depth may shed light on the source of the Mercenaria, Eontia and Echinochama of the southern sedimentologic province and may aid in understanding the complex sedimentologic history of Padre Island.

Perhaps the most interesting and rewarding problem would be to undertake a detailed theoretical analysis of the longshore drift system by a prediction of wind generated waves in deep water. These waves can then be brought into shallow water mathematically, broken, and the resulting longshore current and rate of sediment transport calculated. This method of prediction of longshore drift would be extremely useful to coastal engineers in the design of coastal structures. Similar approaches have been tried in other localities and have usually failed. These have often been areas with complicated coastlines still further complicated with manmade structures. The reason for studies in such locations has been the economic need for the data. No such studies have been made of the south Texas coast, because there has been relatively little need for the data. The length of Mustang and Padre Islands is broken only by one manmade structure, Mansfield Pass. The wind system here is simple; it is composed of only two major components and the coastline is smooth and curving, with evenly sloping offshore profiles which would lend themselves to easy calculation of wave refraction. Finally, there is good sedimentologic and engineering data which indicate the net longshore drift system of this portion of the coastline. This is an ideal location to test the existing methods of longshore drift prediction and to develop better methods.

APPENDICES

APPENDIX A

PERCENT SHELL FOR STORM BERM SAMPLES

Miles North of Mansfield Pass	Percent Shell	1st Moving Average	2nd Moving Average
0.5	3.3	3.3	3.3
1.0	6.0	3.6	3.8
1.5	1.7	4.5	4.9
2.0	5.8	6.5	9.0
2.5	12.0	16.1	13.9
3.0	30.6	19.0	17.3
3.5	14.4	16.8	14.6
4.0	5.4	8.0	11.9
4.5	4.1	10.8	10.0
5.0	22.9	11.2	11.0
5.5	6.7	10.9	10.4
6.0	3.2	9.1	10.4
6.5	17.3	11.2	10.4
7.0	13.0	10.8	9.7
7.5	2.0	7.2	8.9
8.0	6.5	8.7	8.4
8.5	17.5	9.3	9.3
9.0	3.9	9.9	10.6
9.5	8.3	12.5	11.7
10.0	25.2	12.6	12.7
10.5	4.2	13.1	10.8
11.0	10.0	6.6	9.5
11.5	5.7	8.8	9.5
12.0	10.8	13.2	12.8
12.5	23.0	16.4	16.5
13.0	15.5	20.0	17.8
13.5	21.6	16.9	16.7
14.0	13.5	13.3	13.3
14.5	4.9	9.8	10.7
15.0	11.0	8.9	6.5
15.5	10.8	8.9	10.2
16.0	4.9	12.7	12.5
16.5	22.5	15.8	18.4
17.0	19.9	26.8	21.1
17.5	38.0	20.8	22.2

Appendix A - Cont.

Miles North of Mansfield Pass	Percent Shell	1st Moving Average	2nd Moving Average
18.0	4.4	19.0	20.9
18.5	14.6	23.0	22.4
19.0	50.0	25.1	23.7
19.5	10.8	23.1	19.4
20.0	8.6	10.0	14.7
20.5	10.5	11.1	12.3
21.0	14.2	15.8	15.3
21.5	22.7	19.1	18.7
22.0	20.3	21.3	20.9
22.5	20.8	22.4	21.4
23.0	26.0	20.6	23.1
23.5	15.0	26.3	22.7
24.0	38.0	21.1	23.4
24.5	10.2	22.9	19.6
25.0	20.4	14.7	18.6
25.5	13.4	18.2	17.2
26.0	20.9	18.6	19.7
26.5	21.5	22.3	21.4
27.0	24.6	23.4	23.4
27.5	24.2	24.5	24.5
28.0	24.8	25.6	25.4
28.5	27.7	26.0	28.8
29.0	25.5	34.7	35.8
29.5	50.8	46.6	44.5
30.0	63.5	52.3	50.9
30.5	42.6	53.9	54.0
31.0	55.5	55.9	58.8
31.5	69.5	66.5	65.6
32.0	74.6	74.3	73.2
32.5	78.7	78.7	76.6
33.0	82.9	76.9	74.1
33.5	69.2	66.6	66.8
34.0	47.8	56.8	59.7
34.5	53.5	55.6	58.3
35.0	65.6	62.6	59.0

Appendix A - Cont.

Miles North of Mansfield Pass	Percent Shell	1st Moving Average	2nd Moving Average
35.5	68.0	58.8	61.8
36.0	42.9	63.9	58.6
36.5	80.7	53.1	58.1
37.0	35.9	57.2	54.2
37.5	55.0	52.3	57.7
38.0	66.1	63.5	61.0
38.5	69.4	67.3	66.0
39.0	66.4	67.1	65.9
39.5	65.4	63.3	62.6
40.0	58.2	57.4	58.2
40.5	48.5	54.0	52.0
41.0	55.4	44.5	47.2
41.5	29.6	43.2	40.1
42.0	44.6	32.5	37.7
42.5	23.4	37.5	36.5
43.0	44.6	39.4	39.4
43.5	50.2	41.4	40.3
44.0	29.2	40.0	38.1
44.5	40.5	33.0	38.9
45.0	29.4	43.6	44.1
45.5	61.0	55.8	51.6
46.0	77.1	55.3	54.1
46.5	27.7	51.3	49.3
47.0	49.2	41.7	46.8
47.5	48.3	47.3	44.1
48.0	44.5	43.3	43.2
48.5	37.1	39.0	37.3
49.0	35.5	29.6	35.0
49.5	16.2	36.4	37.7
50.0	57.6	47.2	42.8
50.5	67.8	49.9	47.1
51.0	24.4	44.2	40.7
51.5	40.5	28.1	33.2
52.0	19.3	27.4	23.8
52.5	22.3	16.0	18.1

Appendix A - Cont.

Miles North of Mansfield Pass	Percent Shell	1st Moving Average	2nd Moving Average
53.0	6.5	10.9	10.3
53.5	3.8	3.9	5.6
54.0	1.3	1.9	2.1
54.5	0.6	0.6	0.6

Miles South of Mansfield Pass	Percent Shell	Moving Average
1.5	15.3	15.3
4.5	7.1	15.2
7.5	23.2	19.5
10.5	28.2	24.5
13.5	22.0	19.8
16.5	9.2	12.0
19.5	4.7	5.2
22.5	1.7	3.3
25.5	3.5	2.2
28.5	1.4	1.4

APPENDIX B

PERCENT SHELL FOR PROFILE SAMPLES

Pro-file	Miles North of Mansfield Pass	Distance from Water (Ft.)	Location	Percent Shell
A	2.0	46	top foreshore	3.7
		72	storm berm	3.6
		96	storm berm	5.5
		148	mid backshore	5.5
		218	base dunes	5.0
B	6.0	23	mid foreshore	15.2
		50	top foreshore	16.7
		105	storm berm	5.1
		211	mid backshore	7.1
		334	mid backshore	4.0
		463	small dunes	6.1
		660	hurricane flat	2.7
		860	hurricane flat	5.6
		1020	edge " "	4.9
C	12.5	13	active berm	73.5
		74	runnel	54.8
		105	storm berm	19.0
		185	mid backshore	15.8
		261	gully	4.7
		360	base dunes	2.9
D	18.3	9.9	toe foreshore	50.5
		40	mid foreshore	34.2
		63		9.9
		96	top foreshore	7.0
		162	mid backshore	11.3
		218	base dunes	2.1
E	25.4	92	runnel	24.0
		109		14.5
		129		9.4
		168	base dunes	10.3
F	30.5	10	toe foreshore	70.2
		36	mid foreshore	54.6
		66	top foreshore	71.0
		102	storm berm	49.2
		155	mid backshore	46.5

Appendix B - Cont.

Pro- file	Miles North of Mansfield Pass	Distance from Water (Ft.)	Location	Percent Shell
F (Cont.)		340	high backshore	52.2
		446	base dunes	16.1
G	37.0	27	mid foreshore	75.6
		59	storm berm	73.1
		102	backshore	61.0
		151	mid backshore	24.3
		204	base dunes	15.2
H	42.5	26	mid foreshore	41.0
		40	top foreshore	58.9
		66	storm berm	58.7
		96	storm berm	48.0
		158	mid backshore	43.8
		198	gully	26.5
		250	base dunes	27.6
I	47.5	13	toe foreshore	70.2
		33		22.2
		53	top foreshore	53.2
		69	storm berm	55.6
		175	mid backshore	21.1
		260	gully	34.5
		334	backshore	47.9
		429	base dunes	2.5
J	51.6	33	runnel	14.3
		60	storm berm	55.2
		102	storm berm	36.8
		148	mid backshore	40.4
		240	gully	20.2
		284	base dunes	7.7

APPENDIX C

PERCENT SHELL FOR FORESHORE SAMPLES

Miles North of Mansfield Pass	Percent Shell	Miles North of Mansfield Pass	Percent Shell
1.5	1.9	31.5	31.3
3.0	5.1	33.0	21.2
4.5	9.3	34.5	50.6
6.0	1.8	36.0	35.0
7.5	6.9	37.5	33.1
9.0	4.5	39.0	42.0
10.5	26.9	40.5	10.8
12.0	3.8	42.0	4.6
13.5	12.0	43.5	9.5
15.0	25.9	45.0	2.9
16.5	12.2	46.5	2.5
18.0	21.6	48.0	6.0
19.5	31.6	49.5	4.9
21.0	37.0	51.0	5.4
22.5	18.2	52.5	6.2
24.0	12.7	54.0	1.9
25.5	1.5	57.0	1.0
27.0	4.6	60.0	0.8
28.5	7.3	63.0	0.7
30.0	10.5	66.0	1.1

APPENDIX D

FORESHORE SLOPE FOR SEPTEMBER 10, 1966

Miles North of Mansfield Pass	Slope (Degrees)	Miles North of Mansfield Pass	Slope (Degrees)
1.5	4.5	31.5	7.0
3.0	7.0	33.0	6.0
4.5	5.0	34.5	6.0
6.0	3.0	36.0	5.0
7.5	8.0	37.5	5.0
9.0	6.0	39.0	5.0
10.5	3.0	40.5	2.0
12.0	5.0	42.0	4.5
13.5	4.0	43.5	3.0
15.0	8.0	45.0	3.0
16.5	6.0	46.5	4.0
18.0	6.0	48.0	4.0
19.5	5.0	49.5	4.5
21.0	4.0	51.0	3.0
22.5	4.5	52.5	3.0
24.0	4.0	54.0	2.0
25.5	6.0	57.0	3.0
27.0	4.5	60.0	4.0
28.5	4.5	63.0	4.5
30.0	5.0	66.0	4.5

APPENDIX E

CORPUS CHRISTI AVERAGE MONTHLY WIND DIRECTION FOR 1951-1960 VECTOR RESULTANTS

Month	Direction (°)
January	94.9
February	102.3
March	112.9
April	125.1
May	130.0
June	136.6
July	143.6
August	136.9
September	94.7
October	85.4
November	65.8
December	83.9

CORPUS CHRISTI ANNUAL RESULTANT WIND VECTOR DIRECTION

Year	(V) vector	(V^2) vector
1951	135°	135°
1952	119°	121°
1953	123°	125°
1954	124°	126°
1955	113°	117°
1956	122°	125°
1957	119°	122°
1958	111°	110°
1959	124°	126°
1960	114°	115°
10 year total	121°	123°

APPENDIX F

Plate 7. Abundant pelecypods of Padre Island shell beaches.

1. *Dinocardium robustum* Solander

2. *Mercenaria campecheiensis* Gmelin

3. *Anadara braziliana* Lamarck

4. *Anadara baughmani* Hertlein

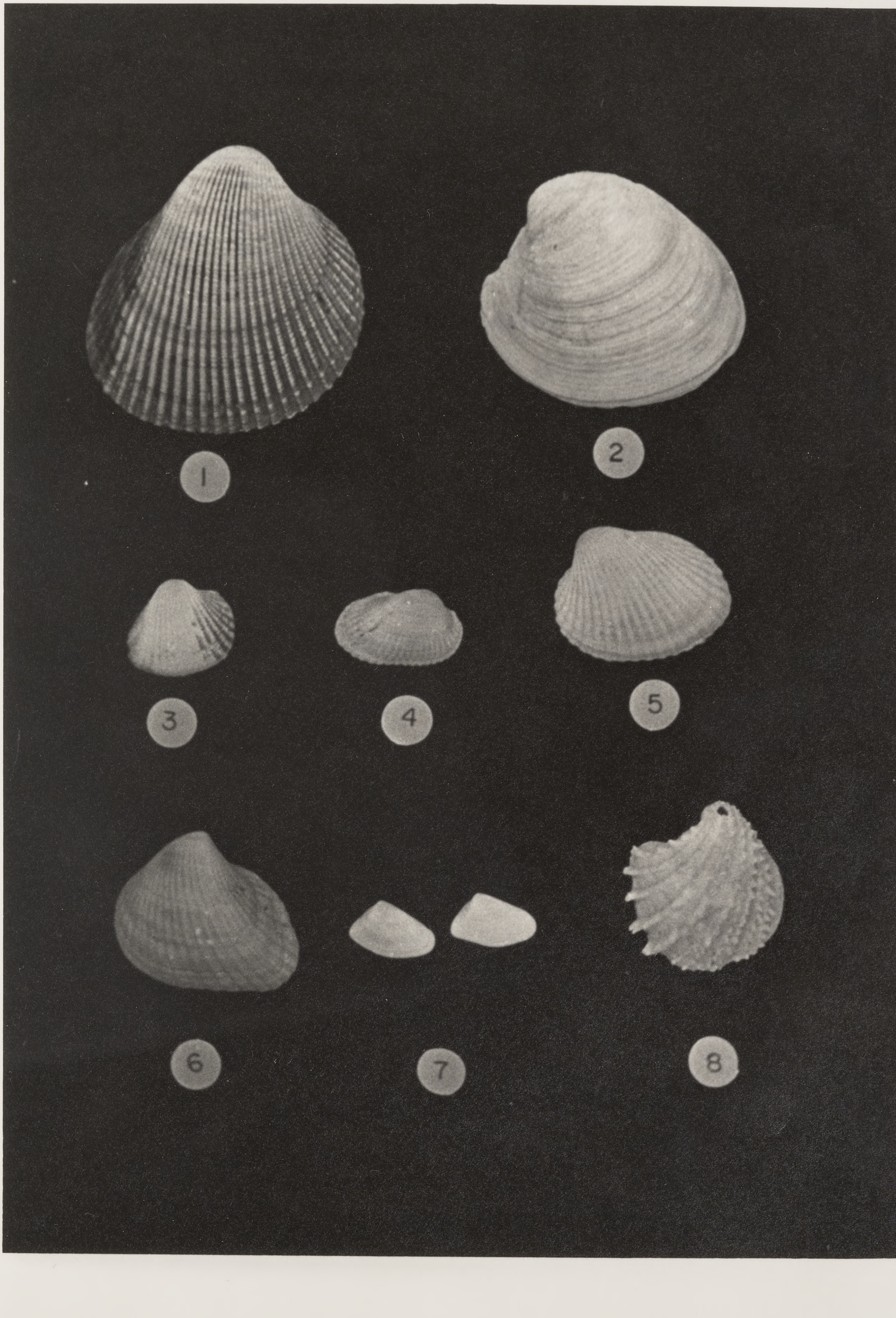
5. *Anadara ovalis* Bruguiere

6. *Eontia ponderosa* Say

7. *Donax* sp.

8. *Echinochama arcinella* Linne

The diameter of the white number circles is 1.5 cm.


1
2
3
4
5
6
7
8

APPENDIX G

TOPOGRAPHIC MAPS* OF PADRE ISLAND

<u>30' Quadrangles</u>

Los Fresnos

Port Isabel

North of Port Isabel

La Leona

South of Potrero Lopeno

Potrero Lopeno

Potrero Cortado

South Bird Island

Oso Creek

Crane Islands

Aransas Pass

Corpus Christi

<u>1/250,000 Series</u>

Corpus Christi

Brownsville

*All maps are Texas maps.

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