The Geomorphology of Beach Ridges in Tabasco, Mexico.

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by
Norbert Phillip Psuty
B.A., Wayne State University, 1959
M.A., Miami University, 1960
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The largest coastal alluvial-plain in Mexico lies along the southern Gulf Coast, almost entirely within the state of Tabasco. This plain is principally of fluvial origin, associated with the Mezcalapa and Usumacinta river systems. These two rivers, whose previous channel migrations have directly or indirectly produced most of the lowland landforms, currently share the major outlet to the Gulf, the Grijalva River.

Skirting the gulfward edge of the Tabasco Plain is a narrow zone of coastal landforms comprised primarily of beach ridges plus a few groups of sand dunes.

Systematic investigation of beach ridges includes profiles noting general configuration and dimension. Beaches are profiled to record sediment removal, migration, and accumulation over various time periods. Trenches and pits dug in accretionary portions of the beach profile reveal stratification sequences of inland-dipping foreset-units. These deposits correlate with frequent winter-season storms, nortes, which raise Gulf levels and wave heights to construct a beach crest upon the winter beach. Intermittent washover deposition contributes sediment to
the upper surface and lee side of the ridge to heighten and broaden it while producing a slow migration inland. Subsequent calm-weather accretion gradually widens the beach and eventually strands the beach ridge.

Beach ridges are most numerous and the coastal zone widest where river channels course through the coastal topography and discharge into the Gulf. Adjacent to these channels, the ridge trends collectively arch seaward, fan-like, to produce a cuspatc delta projecting into the Gulf.
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during part of the field work, aided in the compilation of data, and furnished both encouragement and understanding. Numerous individuals in Mexico contributed to this project. Dr. Otto Wolter, M.D., deserves special recognition, as does his entire family, for the provision of housing in Comalcalco, Tabasco. Dr. Wolter, in many cases, was instrumental in securing important introductions and often incurred personal inconvenience in order to aid my project. Acknowledgement is also accorded to Dr. Wolter's son, Sr. Otto Wolter P.; to Ing. Mustacho, Seismic Division of Petroleos Mexicanos at Cárdenas; Ing. Múñoz, Seismic Division of Petroleos Mexicanos at Jonuta; Ing. Gutiérrez Gil, Chief Geologist, Southeastern Region, Petroleos Mexicanos; Ing. Palacio, Head, Comisión del Grijalva, Secretaría de Recursos Hidráulicos; Ing. Echeagaray, Head, Comisión del Papaloapan, Secretaría de Recursos Hidráulicos; Ing. Carrera, Chief, Comisión de Limites de Tabasco, Villahermosa; Christiani and Nielsen, S.A., Mexico City, marine contractors; Sr. de la Fuente, local recorder of weather data in Comalcalco; and the Servicio Meteorológico Mexicano.
1579 map of Tabasco
Source: Melchor de Alfaro Sánchez (1898)
INTRODUCTION

Along the Gulf coast of southern Mexico, a little-studied belt of beach ridges fringes the alluvial plain of Tabasco. Prior to my investigation, only one brief report was published specifically discussing the distribution or genesis of Tabascan beach ridges (Flint, 1956). Other references to coastal landforms in Tabasco were normally included in studies of the much larger Tabascan alluvial plain, a geomorphologic lowland incorporating an interior Pleistocene fluvial surface and a Recent deltaic plain in addition to the seaward fringe of coastal features. Most of the previous reports describing the alluvial plain of Tabasco, dating from the first account written in 1579 by Melchor de Alfaro Sánchez (1898, pp. 318-374, and including the frontispiece reproduced in this paper), have contributed either general physiographic descriptions or have considered some fluvial aspect of the deltaic plain (Galinda, 1833; Masters, 1845; Díaz, 1850; Heller, 1856; Rovirosa, 1893; González, 1906; Santamaría, 1916, Muñoz, 1941; Ordóñez, 1941; González, 1943; Christiani and Nielsen, S.A., 1950; Echeagaray, Cravioto, and Díaz, 1956; Echeagaray, 1956, 1957). Zeevaert (1956) completed the only intensive, localized investigation when he studied the sedimentary load of the lower Grijalva River (Fig. 2) and the subsequent deposition of these sediments in the coastal zone.

Field work for the present report was conducted during a two-year span of time that included the following eleven
months in the study area: June - August, 1962; November, 1962 - April, 1963; and January, 1964. Available historic and topographic maps, hydrographic charts, and aerial photographs were examined and utilized to construct base maps and to select specific items for study. Field investigation was directed toward the general geomorphology of the Tabascan alluvial plain but concentrated on the multiple beach-ridge topography fringing the coastward margin. This paper presents the results of the beach-ridge investigation and it is divided into three parts. The first part describes the regional setting of the alluvial plain of Tabasco, emphasizing those background factors that are significant to the study of beach ridges. The second part describes the processes leading to the development of Tabascan beach ridges. The third part deals with the distribution of multiple beach ridges as they are related to the developmental processes and to specific sites of sediment surplus.

\footnote{The aerial photographs consisted principally of controlled mosaics compiled by Compañía Mexicana Aereofoto, S.A. at scales of 1:10,000 and 1:20,000 (dating from 1937 to 1944) plus trimetrogon photographic flights (1:20,000 scale on vertical photos) taken by the U.S. Army in 1943.}
Part I: REGIONAL SETTING

The Quaternary plain bordering the Mexican Gulf coast generally consists of a narrow zone of unconsolidated sediments which locally widens at only three positions (Fig. 1). In each case, the broadened zone is associated with a depositional lowland at the mouth of a major drainage basin. The largest of these Quaternary plains on the Gulf coast is nearly coincident with the state of Tabasco and is the alluvial product of the Mezcalapa and Usumacinta river systems. Extending northward from the foothills of the Chiapas highlands, the Tabascan alluvial plain is a rectangularly-shaped lowland covering an area of 34,500 square kilometers\(^1\). The general study area, however, includes only the westernmost 20,700 square kilometers\(^2\) and the coastal zone is further restricted to 1700 square kilometers extending along the 291 kilometers of shoreline bordering the state of Tabasco (Fig. 2).

The coastal landforms are but the products of the latest sedimentary additions to the depositional lowland and are genetically associated with aspects of the general climatology and geomorphology in the area. Specifically, the

\(^1\)In comparison, the Rio Grande plain has an area of 9000 square kilometers and the Papaloapan plain covers 13,500 square kilometers.

\(^2\)In this paper, subsequent discussion will refer to these 20,700 square kilometers as the "study area", "alluvial plain of Tabasco", or "Tabasco Plain". Whenever it becomes necessary to consider the political unit, "state of Tabasco" will be used or, when the reference is obviously to the entire state, "Tabasco".
Figure 1. Major Quaternary alluvial plains on Mexican Gulf coast.
Figure 2. Location of pertinent place names in study area; inset map at lower right provides general situation of study area within state.
Figure 3. Selected climatic graphs on and near the Tabascan alluvial plain. Source: adapted from "Datos Climatologicos," Boletin Hidrológico #18, Región del Sureste, 1962. Depicted stations are underlined. The distinction between short and long term records is relative and arbitrarily set at 15 years.
range from a minimum of 23°C. normally recorded in January to a maximum of 30°C. generally occurring in May. Mean annual precipitation over the map area varies from 1425 millimeters at the coastal station of Frontera, Tabasco, to 4100 millimeters at the interior station of Pichucalco, Chiapas, located in the highland foothills. In the annual precipitation regime, April is commonly the driest month (62 mm.), followed by an initial rainfall peak in June (262 mm.), a slightly drier July and August (237 mm.), and finally by the major maximum in September (400 mm.).

A particular weather phenomenon that is significant in influencing the geomorphological processes along coastal Tabasco is the cold front, or norte, of the winter season. Generated by mid-latitude anticyclones, nortes penetrate southward over the Gulf of Mexico and noticeably affect Tabascan weather. Riehl (1954, pp. 270-273) describes the cold air penetration of the nortes as waves in the westerlies which dip southward over the Gulf, introduce their attendant characteristics, and then either stagnate or veer northeastward. According to the U.S. Navy Sailing Directions (1952, pp. 36-37), approximately 35 cold air masses migrate southward over the Gulf of Mexico during the winter period and some 15 to 20 are characterized by strong winds. Nortes often occur as early as October and continue intermittently through April. Their frequency and strength are highly variable but 15-year means have been determined for the southern Gulf of Mexico; an average of 11.5 "severe" nortes may be anticipated annually with winds of at least Beaufort
force 7 (28-33 knots).

**Nortes** considerably influence the climatological characteristics of Tabasco, for these invasions of cool air are responsible for all "winter" minimum temperatures and the cyclonically-produced precipitation of the cool season. Furthermore, the strong northerly winds affect waves and currents along the coast. The Gulf is slightly elevated as storm-tide conditions prevail and increased eolian and wave activity remodel the beach. Therefore, in view of their frequency and accompanying temperature, precipitation, and wind, nortes constitute both an important seasonal aspect of Tabascan weather and climate and a significant morphologic factor generating changes on the Tabascan beach.

**Fluvial Systems**

Runoff from the abundant precipitation in the Chiapas highlands and the Tabascan lowlands drains through several of the largest rivers in Mexico. In terms of average annual discharge, the Usumacinta River carries more water (52,400 million cubic meters) than any other drainage network in the entire country. The Mezcalapa-Grijalva River is third in this category (44,000 million cubic meters\(^1\)), channeling only slightly less than the Papaloapan River (47,000 million cubic meters).

Draining almost 60,000 square kilometers, the Usumacinta River and its tributaries lead from the Chiapas-Guatemalan

\(^1\)Exclusive of Usumacinta discharge.
highlands, through the foothills, and onto the alluvial plain (Fig. 4). Although Usumacinta discharge exits primarily through the lower Grijalva River into the Gulf, the Usumacinta also has two other distributaries, the Palizada River which leads away from the main channel above Jonuta (Figs. 4 and 2)\(^1\) and the San Pedro y San Pablo River which branches seaward a short distance below Jonuta. Neither of these two channels is a major distributary; a narrowing of the San Pedro y San Pablo River channel by sediment accumulation and vegetation within its well-developed natural levees emphasizes the diminished function of this river.

The other large river system, Mezcalapa-Grijalva, drains approximately 50,000 square kilometers. There is some confusion in designating this particular stream, for although this major river is termed Grijalva in the mountains, after reaching the foothills it is called Mezcalapa and farther downstream, at Villahermosa, the name Grijalva is used once more. In this paper, Mezcalapa will be applied to the river in general, from the headwaters to the mouth, and particularly to the major channel above the town of Cárdenas. Grijalva, in turn, will only refer to that downstream portion of the river from Villahermosa to the Gulf. The connecting channel between the cities of Cárdenas and Villahermosa is the Carrizal River.

\(^1\)Figure 4 principally depicts the drainage basins of the major stream networks and includes the position of the Palizada River; all other distributary river channels and place names are shown on Figure 2, the general location map.
beach-ridge topography is the consequence of the rainy climate, the well-developed drainage systems leading to the coast, fluvial migrations in the Recent deltaic plain, a particular weather phenomenon - the norte, and the seasonal contrast of geomorphological processes on the Tabascan beach.

Climatic Characteristics

A paucity of reliable meteorological observations long restricted the description of Tabascan climate to "hot and wet". However, over the past several years, vast strides have been accomplished by the Secretaría de Recursos Hidráulicos and the Dirección de Geografía y Meteorología in securing essential quantitative climatological data for the southeastern part of Mexico\(^1\) (Secretaría de Recursos Hidráulicos, 1962). Twenty-five stations, sixteen in Tabasco and nine in neighboring states, provide basic precipitation and temperature data pertaining to the climatic characteristics of the study area. These stations are shown in Figure 3 and five climatic graphs have been included to depict the regional climatic regimes.

Mean monthly temperatures remain high throughout the year at each of the stations; these monthly temperatures\(^2\)

---

\(^1\)Tabasco currently contains 25 meteorological stations, of which 18 have been initiated since 1947. These stations commonly record temperature and precipitation, a few also measure atmospheric pressure, winds, relative humidity, and evaporation.

\(^2\)Monthly temperature and precipitation maxima and minima refer to averages derived from the 25 weather stations associated with the study area.
Figure 4. Major drainage basins leading to the alluvial plain of Tabasco.
Several large streams join the lower Mezcalapa, contribute to the total discharge, and enlarge the drainage basin. The Sierra River, after collecting waters from the foothills of the Chiapas highlands, merges with the Grijalva at Villahermosa with an average annual discharge of 5,711 million cubic meters (Boletín Hidrológico #17, Región del Sureste, 1962, p. 15). A short distance downstream from Villahermosa, the Chilapa River becomes tributary to the Grijalva and contributes an average annual discharge of 11,091 million cubic meters (loc. cit.). Although generally considered a separate drainage basin, the Usumacinta also discharges into the Grijalva, at Tres Brazos, causing the Grijalva channel to substantially widen and deepen immediately downstream from this confluence.

Approximately 10 kilometers east of Cárdenas (Fig. 2), the Mezcalapa River bifurcates, extending one channel toward the Gulf and the other, the Carrizal River, toward Villahermosa. At the bifurcation, the northeastward flowing water is initially channeled through the Samaria River, led into a large marsh, and finally discharged through the González River into the Gulf of Mexico at Chiltepec. Historic maps and reports indicate that the Samaria distributary has functioned intermittently during the past several centuries, the latest breach at the Samaria crevasse occurring in 1932 and remaining open to the present.

At the extreme western side of the alluvial plain, drainage leads to the Tonalá River. This is a separate
drainage basin, approximately 6,000 square kilometers, which has an estimated annual discharge of 5,875 million cubic meters (Tamayo, vol. II, 1962, p. 328).

River stages throughout much of interior and central Tabasco closely reflect the general precipitation regime (Fig. 5), an association first discussed by Rovirosa (1897, pp. 111-147). Normally, the rivers crest during the late summer, at the end of September or start of October, and then recede toward a low-water stage which occurs in May. A minor high-water stage begins in June and extends into July, only to fall once again toward the end of July and into August. September marks the beginning of the principal river crest and completes the annual cycle.

Christiani and Nielsen, S.A. (1950, vol. II, Plate 32) conducted a harbor study at Frontera on the lower Grijalva and correlated volumetric discharge in the river with sediment transportation. They concluded that the high river stages of August-September-October coincided with maximum sediment transport of very fine-to-coarse sand (0.05 - 1.0mm.) in the lower Grijalva and out the river mouth. Zeevaert (1956, pp. 24-26) further suggested that the sand-sized particles which are discharged into the Gulf primarily during high river stages are eventually deposited in the coastal zone and incorporated within the coastal landforms.

Landform-Areas

Three areas of morpho-genetically related landforms comprise the Tabasco Plain. The innermost landform-area
Figure 5. Mezcalapa river stages recorded at Las Peñitas, Chiapas, 1954. Source: Boletín Hidrológico #17, Región del Sureste, 1952.
(Fig. 6) is a fluvial surface deposited during the Pleistocene which presently forms broad, gently-seaward-sloping inter-fluves between the following sequence of rivers: Tonalá, Mezcalapa, Pichucalco-Sierra, Macuspana, and Usumacinta.

The second landform-area is the product of Recent fluvial deposition beyond the margin of the Pleistocene surface by the Usumacinta and Mezcalapa river systems. Each major river has constructed an arcuate delta containing the usual associations of active and abandoned channels, natural levees, and backswamps. Toward the center of the Recent plain the two large deltas coalesce, together covering an area of 12,850 square kilometers.

Only the western part of the Usumacinta delta falls within the study area. This portion of the delta, however, contains two of the three active Usumacinta distributaries. From the bifurcation which creates these two channels, the minor stream, the San Pedro y San Pablo, flows north-northwestward directly into the Gulf of Mexico whereas the major channel of the Usumacinta travels west-northwestward and discharges into the Grijalva River at Tres Brazos.

The Mezcalapa delta is outlined by the numerous abandoned and active channels which fan out toward the coast from the vicinity of Huimanguillo (Fig. 6). Channel characteristics of most of the abandoned distributaries are distinctly those of a meandering stream whereas the Mezcalapa above its delta head is braided, as is one of the more recently abandoned channels, the Seco River (Fig. 2). The Cañas
Figure 6. Geomorphologic divisions of the Tabasco Plain.
River (Fig. 2) can only be loosely described as a braided stream for the channel is ill-defined where it flows through the vast eastern delta-flank marsh. Sands, silts, and clays deposited by the Cañas are slowly alluviating the marsh and producing an anastomotic stream pattern.

Rising slightly above the general level of the Mezcalapa deltaic plain, natural levees contribute a local relief of three to five meters and provide narrow strips of dry land between the backswamps and river channels. Toward the coast, low-lying interdistributary basins are commonly the sites of elongate marshlands. At the coastal margins of the Mezcalapa delta, several shallow lagoon are positioned in the interdistributary lowlands (Fig. 6) and are, in turn, segmented by the slightly-elevated natural levees.

The third landform-area is the zone of coastal features (Fig. 6) bordering the leading edge of the deltaic plain. Several isolated groups of sand dunes occupy a minor portion of the coastal area but the principal surface configuration is produced by multiple beach ridges. In general, beach-ridge topography consists of low-relief ridges and swales whose amplitude ordinarily approaches one meter and whose spacing approximates 45 to 50 meters. There is considerable variety of beach-ridge dimensions, however, for extreme ridge heights range from 0.3 to 3.9 meters and spacing varies from almost nil to 90 meters.

The distribution of beach-ridge topography is closely associated with the fluvial history of the deltaic plain.
Coastal outlets of the active distributaries have been the sites of deposition and coastal progradation, but rather than forming an extension of fluvial floodplain characteristics, the fluvially-transported sediments have been debouched into the Gulf to be subsequently deposited onshore by marine processes. So long as an active distributary discharged through the coastal outlet, sediments were accumulated along the coast to produce local progradation, in the form of multiple beach ridges, flanking the coastal outlet. Shifts in stream flow on the deltaic plain, however, eventually cause a coastal outlet to be abandoned, terminate sediment accumulation at that site, and lead to local coastal erosion and retreat.

Tabascan beach-ridge topography is widest, approximately 40 kilometers, adjacent to the Grijalva River where the ridges have been constructed during three different periods of distributary activity and progradation of the coast (Fig. 6). Eastward from the Grijalva, the beach-ridge topography narrows to 16 kilometers along the San Pedro y San Pablo River. The area of coastal ridges also narrows westward, finally terminating near the seasonally active outlet at Barra de Tupilco. In the next 43 kilometers west of Tupilco, the coastal zone includes neither an active river mouth nor beach ridges. However, at the westernmost extent of the coastal landform-area, there is a narrow band of beach ridges adjacent to the Tonalá River.

Although there is evidence for the development of
beach-ridge topography at different locations along the coast, and even several periods of development in a specific area, comprehension of the distribution and form of this topography is based on an understanding of the formation of a single beach ridge and its subsequent abandonment. The succeeding section of this paper considers those factors which may cause an accumulation of sediment at a particular site and then strand it to create another seaward ridge.
Part II: ORIGIN OF BEACH RIDGES

Previous studies of beach ridges indicate that the development of a ridged-plain may be attributed to several geomorphic agents and that the ridges may reflect a variety of morpho-genetic conditions. The Tabascan ridges were studied by observing the local agents that shaped beach ridges and the stratification of sediments produced by both accretionary and erosional activities. This section of the paper presents a detailed account of the sedimentary accumulations formed during norte conditions, the stratification revealed in the beach and beach ridges, the relation of stratification-units to morphologic process, and an interpretation of the sequential development of a beach ridge.

Review of Literature

Beach-ridge development has been investigated and discussed by numerous geomorphologists. Douglas Johnson (1919) summarized the opinions of his time and arrived at three general methods of beach-ridge formation. Initially, he presumed that an offshore shoaling must occur to provide the necessary sediment to produce coastal progradation and lead to renewed development of a beach profile of equilibrium (op. cit., pp. 407-408). He surmised that part of the excess sediment would be transported to a subaerial position where it would accumulate as a ridge within the beach profile. Johnson cited three processes through which shoals and resultant beach ridges could be produced: 1) a diverging longshore
current would cause deposition along the beach face and pro-
grade the coast; exceptional storm waves would then trans-
port some of this recently-deposited sediment inland to pro-
vide a ridge (after Gilbert, 1890, pp. 56-57); 2) upon a
normal profile of a shoaling area, the waves produce a small
beach crest; under storm conditions, waves break farther off-
shore and place additional material in suspension; deposition
of this excess sediment upon the upper beach then constructs
another ridge seaward of the previous beach crest (after
Davis, 1909, p. 473); and 3) continuous development of a
recurved spit would produce a ridged-plain (after Davis,
1896, pp. 710-715). The major distinction pertaining to the
last suggestion is continuous extension of a particular ridge
rather than simultaneous development along the length of the
feature.

Johnson discussed studies in which beach ridges have
been described as exposed longshore bars or dune-ridges
(1919, pp. 404-413) and he also considered articles correlat-
ing ridge-formation with lunar or annual fluctuations in water
levels. He was, however, inclined to favor the storm-wave
proposal but suggested that it is unwise to correlate partic-
ular beach ridges with specific storms. He further stated
(p. 413):

*It is even possible to suppose that on a given
beach plain none of the exceptional storms of the
past are recorded by any of the ridge crests, but
only the more prolonged activities of less violent
wave action.*

Subsequent to Johnson's treatment of the beach-ridge
problem, several other investigators published conclusions pertaining to the development of these sub-parallel ridges. The results of their studies may be broadly summarized in a series of dichotomies, each grouping including a representative citation.

A basic genetic separation distinguished ridges of eolian origin (McLaughlin, 1939) from those of marine origin (Cooper, 1958). Among the marine conditions responsible for the development of multiple beach ridges, both calm water levels (Davies, 1957) and storm water levels (Brouwer, 1935) have been suggested. Furthermore, ridges composed of shingle or coarse shell fragments (Ting, 1936) have been differentiated from sand ridges (Shepard, 1963). And finally, there has been the distinction between beach-ridge formation along a continuously accreting beach (Davies, 1957) and ridge-formation accompanying intermittent retreat on an accreting beach (Geijskes, 1952).

Quite obviously, the numerous views cannot be totally reconciled. Each case may represent specific combinations of events. Beyond all controversy, however, is the necessity for sediment sufficient to produce net progradation of the coast and an intermittent, localized accumulation of sediment in the form of a ridge by some morphologic agent.

**Nortes and Sediment Accumulations**

Investigation of the Tabascan beach ridges proceeded with the assumption that the fundamental causative factor of
beach-ridge development was a repetitive morphologic agent. The ridges were therefore studied to determine which of the morphologic agents present were capable of molding the landform. Information pertaining to beach-ridge development was derived by observing and measuring beach changes over an annual cycle. Deposition and erosion were noted during both calm water and storm conditions. Numerous beach and beach-ridge profiles were surveyed to determine their general configuration and areal similarities or contrasts. Finally, those geomorphological agents actively shaping and reshaping the coastal landforms were closely studied.

Of the two agents, wind and waves, which affected or could affect the active beach, eolian activity was commonly noticed on the seaward portion of the beach ridge. Where vegetation was sparse, sand grains could be detected moving inland. In areas of high foredunes, blowouts within the seaward ridge were encountered and in places small migrating sandsheets were seen to penetrate into the foredune vegetation.

Wave action was the major morphologic agent and it was especially capable of causing beach and beach-ridge modifications during norte storms. One important change that is associated with norte conditions along the coast is the elevation of sea level in the southern Gulf, a phenomenon that can be interpreted from tidal records taken at the mouth of the Grijalva River. In the marigram for 1949 (Fig. 7), the obvious elevation of water level in September and October is a reflection of increased fluvial discharge, but not so
Figure 7. Marigram taken near mouth of Grijalva River, 1949.
obvious are the other minor peaks that occur in the middle of January, end of January, middle of February, and middle of March. These particular fluctuations become more apparent when the diurnal water oscillations are deleted (Fig. 8). In Figure 8, the mean diurnal water levels are plotted and the variations become evident. These minor peaks correlate with the occurrence of nortes as interpreted from climatic data (Fig. 9). An individual peak on the marigram may or may not represent a single norte. More often it connotes a culmination of storms within a short time period. It is particularly significant that the peaks do not occur in the rainy summer months but only during the winter, norte, storm season. The smooth summer water-level, as depicted in Figure 8, discourages the correlation of high Gulf levels merely with heavy rains.

Propelled by norte winds, the Gulf water-level rises along the coast and spreads inland. On this higher sea level (Fig. 10), higher-than-normal waves operate upon the new foreshore and produce morphological changes. Norte water-levels and associated waves, on occasion, reach the foreslope of the active beach ridge and sometimes spill over the crest.

With the exception of infrequent hurricanes which send waters plunging over the seaward beach ridge or foredune, only local winds and norte storm-waters affect the development of the beach ridges. Winds, including norte winds, augment the existing ridge by depositing sediments near the crest. On the other hand, winds also tend to disrupt the
Figure 8. Mean diurnal water levels as determined from marigram on Grijalva River, 1947, 1948, and 1949.
Figure 9. Correlation of rising Gulf water levels and incursion of nortes. Nortes represented by shading across the three scales.
Figure 10. Tabascan beach profile: summer level develops during calm water conditions; Norte beach forms during higher gulf levels and increased wave activity accompanying passage of a Norte.
general trend of the ridge by causing blowouts or transporting isolated waves of sand through breaks in the ridge (Fig. 11). During a norte, one such migratory sand mass penetrated three meters beyond the ridge crest; it measured five meters wide and 45 centimeters thick.

Although partial destruction of the seaward beach ridge may accompany the elevated water-levels, termination of a norte often leaves a well-defined ridge or a bermcrest on the beach. Whether the former or the latter condition prevails is dependent upon relative rise of the Gulf as well as width of the pre-storm beach. Ridge development is best exemplified and most uniform where net accretion characterizes the annual beach cycle.

A series of profiles were taken along the Tabascan coast to depict relative changes of the beach during the norte season. The most complete set of profiles was established at Playa Azul where on 37 separate occasions, the beach was measured and changes were noted (Fig. 12a and 12b). The first series of profiles on Figure 12 presents the totality of changes for 15 selected beach surveys whereas the second figure depicts extreme seasonal alterations. The latter three profile lines are particularly instructive for they relate the constructional and erosional potential associated with norte activity. On January 10, the winter beach platform was well developed and incorporated a marked ridge on its seaward edge. Shortly thereafter, a series of strong nortes pushed the ridge inland to the position of the
Figure 11. Tongue of eolian sand moving inland through break in foredune.
Figure 12. Beach profile at Playa Azul, Tabasco:
a) changing beach profile through ten months of surveys, 1962-1963;
b) storm and calm water extreme conditions.
foredune and, in so doing, removed the entire beach platform. Subsiding water levels later formed a steeply-sloping beach extending seaward from the foredune (Jan. 25 profile). Subsequent nortes produced additional storm berms which migrated up the steep beach slope during rising seas. The accumulation of storm berms is represented as a well-defined ridge on the April 23 profile situated atop the Jan. 23 beach slope. Immediately seaward of the norte-produced ridge is the summer beach surface.

The foredune crest at Playa Azul, which was washed by waves only once during the 1962-1963 storm season, never advanced seaward through eolian sedimentation although the flat sand beach provided an ample source of sediment. Instead, the foredune retreated as sand was blown into the vegetation to the lee of the ridge. Quite obviously, the entire foredune is migrating and has been moving back over the inland topography. Exposures of dead vegetation emerging from upper portion of the foredune as the entire ridge retreats attests to the retrogradational tendencies.

Retreat would certainly accelerate were it not for the stabilizing effect of vegetation growing upon the foredune. In several localities, man has cleared the vegetation for one reason or another, and the dune-ridge has been appreciably altered. At Playa Azul, a breach 20 meters wide was cleared through the protective vegetation. In less than two years, the foredune retreated at least seven meters, and the bare sand ridge measured nearly half again as broad as its
neighboring vegetated counterparts. Coconut palms previously located safely behind this cleared foredune are now being overwhelmed by wind-driven sands.

Investigation of the Playa Azul beach during the 1963-1964 norte season initially suggested that it was abnormally wide at that location while adjoining sections of beach were apparently very narrow. Further study revealed that the extreme width was primarily brought about by rapid retreat of the foredune and that the widening occurred not as a result of unusual beach accretion but was relative to the foredune position.

Several specific changes on the beach profile accompany norte water conditions. Many of the modifications are well known and have been subjected to past studies of beach changes accompanying higher waves (summarized by Johnson, 1956, pp. 2214-2217). The foreshore steepens, sediment is taken from the beach and put into suspension, and the beach retreats toward the foredune. In Tabasco, the narrow norte beach is partially the result of the higher water levels which extend farther inland than mean sea level regardless of profile adaptation. A second factor leading to inland penetration of the Gulf is the combination of increased wave heights and greater thrusts of the uprush.

Beach surveys made over the duration of a norte season suggest that a winter beach level, frequently possessing a small ridge, develops in response to norte water conditions (Fig. 10). The winter beach level is constructional,
composed of sediment deposited at the peak of wave uprush during both storm periods and subsiding water levels. Although storm waters erode and steepen the foreshore, sediment are deposited in the upper swash zone. Often a berm is built and migrates inland as the foreshore retreats. Trenching of this berm upon abatement of the storm displays near-surface stratification which is either horizontal or dipping slightly inland (Fig. 13). Seaward of the berm, sediment deposited during falling water levels and calmer waters widens the winter beach. Apparently, soon after peak storm waves have abated, turbulence is lessened and deposition replaces erosion. Stratification of sediments below the berm crest suggests that the steepest dip represents the storm foreshore and that subsequent deposition during abatement of storm conditions is at slightly lower inclinations. Part of this deposition is at sufficient elevation to contribute to the winter beach. Continuing deposition during the falling water level constructs and widens the calm-water beach surface. Virtually every profile surveyed on the Tabascan coast displayed these two beach levels (Fig. 14).

Stratification of Sediments

After any major beach or beach-ridge change, trenches or pits were dug to bare the stratified sediments in the zone of alterations. Observations of this type were undertaken to study the kind and degree of change and also to determine if any correlations could be discerned between types of changes and resultant stratification.
Figure 13. Stratified deposits within berm on winter beach; strata toward right are nearly horizontal or dipping inland, strata to left are dipping seaward.

Figure 14. Storm level and calm water level along coastal Tabasco. During nortes, seas operate upon upper level.
Trenches in the beach and beach ridges revealed several characteristic types of sediment stratification. Numerous variations from any particular slope or direction were observed, of course, but a few general patterns stood out. These dominant patterns are depicted in a diagrammatic representation of the stratification sequence within a generalized cross-section through the beach and adjoining beach ridge (Fig. 15). All measurements are derived from field observations in trenches, pits, and quarries. In only one case was the entire sequence revealed at any one time, but in two other instances, trenches were carried through the beach and into the beach ridge to reveal the relationship of stratification units. Only the general stratification was recorded and sketched and, therefore, most micro-patterns are knowingly neglected.

Three principal groups of general stratification are identified: 1) beach; 2) beach-ridge; 3) swales between the ridges. Each unit contains a particular pattern of laminae that is readily observable and whose characteristics were detected in various locations.

Beach laminae are relatively uniform and generally slope seaward less than 10°, most often between 2-5°. A few groupings of horizontal or landward-dipping strata, less than 3° dip, are also evidenced and invariably underlie beach berms (Fig. 15). Below the berm stratification in Figure 15, laminations display typical beach slopes of less than 5° seaward dip. Immediately gulfward of the berm, the gently-
Figure 15. Diagrammatic representation of stratification within a beach ridge: a) berm on foreshore; b) landward-dipping foreset-stratification with gently-inclined components I and III, and more-steeply-inclined component II; c) swale stratification with complex near-surface component III overlying seaward-dipping stratification common to the beach.
inclined laminae are abruptly truncated and succeeded by steeper strata overlying the erosional contact. The steepest stratification, approximately 9°, was measured immediately above the line of truncation whereas there was a transition to gentler inclinations both above (vertically) and seaward (horizontally) of the contact. Similar sequences of truncated strata were noted several times within the beach laminae between the gulf and the foredune.

Occurrences of steep laminae in the beach are localized whereas the general beach-stratification consistently dips seaward 2-5°. The calm-water foreshore zone also maintains a similar dip and most probably is a function of the fine-to-very fine sands of the accretionary beach rather than specific wave energies (Shepard, 1963, p. 171). In addition to the low inclinations within the dynamic beach, strata of similar dips are encountered at interior portions of the beach profile and, moreover, are seen to underlie the active and inactive beach ridges (Figs. 15 and 10).

Stratification within the beach ridges contrasted sharply with those patterns uncovered in the beach. In general, beach ridges contained units of foreset-stratification. The gross form of each foreset-unit consisted of three components (Fig. 15): (I) a series of laminae either horizontal or dipping slightly inland which graded into (II) more-steeply-sloping laminae that dipped inland at various inclinations and then (III) minutely cross-bedded laminae that appeared quasi-horizontal.
The three-fold division of cross-laminated\textsuperscript{1} sands is reminiscent of the deltaic stratification suggested by Gilbert in his Lake Bonneville study (1890, pp. 68-70). Initial differences, however, are: 1) the direction of dip is landward in the beach ridges whereas it slopes seaward in the classic delta profile; and 2) the beach ridge often contains several, partially-preserved foreset-units instead of the single, continuous foreset-stratification suggested for a delta. Each of the foreset-units in the beach ridge is perched on another unit and apparently dips inland after passing over the older unit. It would be next to impossible to generalize as to the number of foreset-units involved within a beach ridge for exposures only reveal those units which are locally preserved and readily distinguishable.

The scale of Figure 15 indicates that the inland penetration of a foreset-unit may extend for several meters. In general, the longest and best preserved of the stratification components are the nearly horizontal laminae (I) which continue inland from the frontal portion of the beach ridge. Inclinations of this initial component (I) vary slightly but are always close to the horizontal. In most instances, component I lies above an erosional surface which truncates the laminae below it.

The inland-sloping component (II) of the foreset-unit contains steep inclinations, ranging from 7\textdegree{} to 28\textdegree{}.

\textsuperscript{1}Cross-laminated is an all-inclusive term covering grouped laminae of assorted dips (Shrock, 1948, p. 243).
Inclinations may be consistent for short distances providing the appearance of parallel layers stacked one against another (Fig. 16), or this component may contain a transition of inclinations (Fig. 17). Wherever these transitions occur, the steepest layer is overlapped by more gently-sloping laminae.

The remaining horizontal component (III) extends inland from the steeply-inclined laminae and is highly irregular. Although the general impression is one of nearly-horizontal strata, close examination reveals considerable cross-lamination. Individual lamina continue for short distances whereas the overall component can sometimes be detected to continue into the swales behind the beach ridge. Moreover, beneath this lowest component of foreset-stratification, seaward-dipping laminae characteristically comprising the beach appear and underly all of the stratification within the beach ridge.

Near-surface stratification in the beach ridge is ill-defined. Plant growth disturbs and masks whatever stratification was formerly present. The depth of disturbance varies locally and may extend from only a few centimeters to approximately 75 centimeters. Burrowing animals and normal weathering processes also complicate and destroy the near-surface stratification.

The seaward face of the beach ridge contains lenticular cross-bedding that generally dips seaward. Individual lenses measure only a few inches across and are tightly inter-bedded.
Figure 16. Inland-dipping component II exposed in quarry along coastal Campeche. Gulf is to left of photo.

Figure 17. Varying inclinations of inland-dipping component II, near mouth of Grijalva River. Inked lines accentuate foreset-stratification within the ridge.
This entire unit may be as deep (vertically) as the beach-ridge stratification and generally extends horizontally into the beach ridge about one meter. Inland of the complex cross-bedded zone, foreset-stratification of the beach ridge begins.

Swale stratification contains a highly-disturbed near-surface zone plus apparent continuations of component III of the ridge foreset-unit. Displaying various inclinations, a thin zone of stratification, 10 to 30 centimeters, overlies the ubiquitous seaward-dipping laminae characteristic in beach deposits.

Interpretation of Stratification

The significance of stratification within beach deposits as an aid to interpretation of past events has been pointed out by several writers (Thompson, 1937; Shrock, 1948; and McKee, 1957). If contemporary stratification within the dynamic beach environment could be revealed and its development understood, this information could be transposed to static coastal features where stratification-units, when disclosed, might suggest morphogenetic processes.

Tabascan calm-water conditions produce accretion on the beach foreshore that includes laminae dipping gently seaward 2-5°. Norte conditions, on the other hand,
raise both wave heights and level of the Gulf, push the seas inland, modify the summer profile, and rearrange the sediments. Accompanying the higher water levels along the coast of Tabasco, the berm is moved back and heightened approximately one meter above summer water-levels. Laminae within the berm, which are nearly horizontal or dipping slightly landward, develop and contribute to the formation of the norte, or winter, beach. Immediately seaward of the berm crest, the steeply-dipping truncation of laminae included within the winter beach is succeeded by strata positioned upon the steep surface. The truncation of winter-beach laminae is erosional and correlates with the steepening shore in front of the berm cited by Bascom (1951, 866-874), but the overlying, steeply-dipping stratification presumes subsequent deposition. Investigation disclosed that upon abatement of storm conditions, the upper swash zone was a major area of deposition. Strata deposited on the erosional surface of 10-12° invariably dip less steeply, 6-9°, than the contact and also grade toward gentler inclinations as deposition progresses.

There are, therefore, two major phases of deposition on the high water beach. Rising water conditions produce retreat of the foreshore but deposition inland of the berm crest causes substantial heightening of this inland zone. Furthermore, upon subsidence of the storm waters, considerable deposition occurs along the berm face and contributes to the winter-beach level. Much of this deposition
apparently occurs at the peak of wave uprush and may even entail a reworking of sands derived from the crumbling berm-face. Thompson (1937, 735-736, Plate IV, Fig. 1) recognized the aforementioned sequence of erosion and deposition within beach stratification and appropriately termed the blanketed berm-face a "buried scarp".

Creation of a ridge 1.2 meters high and 11 meters wide was traced through a series of beach profiles at Playa Azul (Fig. 12). Furthermore, waves and high waters during the 1962-1963 norte season built a ridge on the terminus of the Tupilco Spit that was two meters above calm-water level. The ridge was about 55 meters wide and its crest was only 11 meters inland from the Gulf. This ridge was breached at the end of the norte season by the rising lagoon level and a clear cross-section was observed that exposed stratification along the entire width of the feature (Fig. 18a). Except for 10 to 15 centimeters on the seaward face, the entire ridge was composed of landward-dipping laminae, the product of washover deposition.

Where the Tupilco River eroded the sand dune before turning into the Gulf, another excellent vertical section was exposed (Fig. 18b). Beach stratification consisting of alternating bands of light and dark strata encroached upon the slightly-oxidized dune sands. The beach strata, of course, represented marine deposition but were most remarkable because they extended to 3.5 meters above the level of
Figure 18. Vertical sections exposed at Barra de Tupilco: a) cross-section through Tupilco beach crest; b) laminated beach sands against dune sands, coconut palm growing at contact.
the Tupilco River.

Although the beach stratification against the dune sands may record an extraordinary condition of deposition accompanying storm waters, the ridge on the Tupilco Spit indicates substantial storm deposition. The two-meter ridge was a product of a single norte season, ample evidence that frequent stormy periods, totally distinct from hurricane conditions, elevate the Gulf along the Tabascan coast, produce sedimentation at these high elevations, and intermittently move the beach crest inland.

Teichmüller and Teichmüller (1957, p. 423), working in Corsica, commented on beach-ridge stratification that was revealed when a stream channel cut through a series of ridges and bared their internal structure. They observed that a narrow section on the seaward side of a ridge was comprised of seaward-dipping laminae whereas the remainder of the ridge displayed inland-dipping strata of varying inclinations. The strata were occasionally paralleled by bits of plant remains which were regarded as material washed over the crest by wave surges and deposited along with the washed-over sands.

Stratification within the single crest at Barra de Tupilco and in the beach ridges observed by Teichmüller show strong developmental similarities. Both are considered

1According to a wave-tank study made by Bagnold (1940, p. 30) "the height of the ridge crest coincided with the surge height." Thus the spit crest at Tupilco implies only that the wave swash reached the crest and not that the Gulf level or wave heights were two meters above summer levels.
to be phenomena produced by washover deposits whose internal laminae invariably dip inland. Both are thought to develop under storm situations when the water levels are raised slightly and greater wave upthrusts sometimes carry sediments onto the ridge crest and beyond.

Along a section of the beach near the mouth of the Grijalva, a trench through an active ridge exposed landward-dipping foreset-laminae developed by water washing over a ridge. Thompson made a similar observation of foreset-stratification within a spit which he attributed to washover or "anticlines of deposition" (1937, pp. 746-747). He provided a photograph and description of the feature (op. cit., Plate VII, Fig. 2).

The writer's investigations of bars and spits in California indicate that the structure of the seaward side of a marine bar, or of a spit, is the same as that of a foreshore beach. The structure of the bayward side of an offshore bar, bar, or spit, which resembles that of a backshore beach, consists of short, steeply inclined foreset laminae dipping bayward, inter-stratified with layers of long gently inclined topset laminae, which also dip bayward.

Obviously, to paraphrase Shrock (1948, pp. 244-245), foreset-stratification represents deposition by wind or water that builds forward by the successive additions of sediment on the down-current side. Each of the foreset-units included within a beach ridge may, therefore, be viewed as a product of deposition by water as it washes over an initial ridge. In sand ridges, separate foreset-units
may be distinguished and several periods of washover detected. However, the entire foreset-unit is not always preserved. Shrock (1948, p. 243) provides a description of foreset-stratification and one of its modifications thusly:

A complete cross-laminated bed with topset (Ts), foreset (Fs), and bottomset (Bs) laminae (referring to Figure 19). The curve ABCD is a complete profile of the front of an advancing layer that is internally cross-laminated. The upper part of the curve at B is concave downward; that at C concave upward. The complete form, therefore, does not have top and bottom significance. Fortunately, however, the upper part of cross-laminated units is usually removed by penecontemporaneous erosion, producing truncation, together with the upward concavity and basal asymptotic relation of the laminae, provides an almost unfailing top and bottom criterion.

This description corresponds well with those ridges in which the stratification contains a high proportion of shell, or are entirely shell, and include steep foreset-inclinations (Fig. 16).

The several units of foreset-stratification included within the beach ridge apparently record ridge development through repeated washover by norte-elevated waters. Sediment held in suspension in the turbulent storm-waters presumably settles upon being carried over the crest and contributes to the foreset-stratification. Multiplicity of foreset-units suggests that several episodes of deposition are necessary to produce the ridge and that each washover adds to the height and breadth of the ridge.

As intermittent high waters wash over the crest, the
seaward face of the ridge is eroded and the ridge actually retreats during its constructive period. Therefore, lower-most foreset-units are towards the seaward part of the ridge and are least preserved. Younger foreset-units, accordingly, extend toward the interior, with the youngest member forming the uppermost unit.

The very complex cross-bedded unit at the seaward face of the beach ridge is apparently deposited after the latest washover contribution. This particular member generally lies against an erosional surface truncating the foreset-units. Its complex make-up is probably the result of the combined agencies of wind, water, and gravity.

Swale-stratification is also extremely complex. Some of the sediment swept over the ridge continues to be transported for a short distance inland and contributes a relatively thin, generally less than 30 centimeters, surface-unit of cross-stratification. Presence of the beach stratification-unit close to the swale surface indicates that swales remain as portions of the accreting beach which have not been covered by the constructional ridges.

Sequences of Deposition

The sequence of beach-ridge development is assumed to be based almost entirely upon the action of water-laid washover deposits. Despite the difficulty of distinguishing
beach sands from dune sands, there can be no doubt that shell particles, 10 to 20 mm. across, and pieces of pumice and driftwood incorporated within the ridges are water-deposited. Likewise, it is tacitly assumed that those ridges composed primarily of shell particles and containing the same sequences of stratification are entirely a product of deposition by water and reflect the same processes which produce neighboring sand ridges.

Proceeding on the basis that water provides the necessary transportative agent for the sand grains, the remainder of the beach-ridge problem centers on the source of sand and the intermittent deposition of the sediment. The necessity for fluctuating wave heights or sea levels is appreciated from results obtained in a wave-tank study by Bagnold (1940, p. 40) in which he states:

a further study was made by adding a small but continuous supply of fresh material to the shelf after a mature beach had been thrown up. This was intended to imitate the accumulation of material by coastwise drift. The effect was that the whole beach advanced seawards, but its profile remained entirely unchanged. The topmost surface, previously a narrow ridge, became a flat horizontal table as the beach top moved forward.

Quite obviously, therefore, a mechanism responsible for intermittent sediment deposition is inherent in constructing the undulatory beach-ridge surface.

Given a sediment supply sufficient to produce coastal progradation, the following sequence of events, as
interpreted from beach and beach-ridge stratification, transform a berm crest into a beach ridge and eventually isolate the constructed ridge from the active beach (Fig. 20):

a) Arbitrarily selecting the summer beach profile, calm-water accretion widens the subaerial portion of the profile through an accumulation of gently-inclined laminae on the foreshore.

b) Accompanying the strong *norte* winds of the winter season, slightly-elevated water levels and higher waves redistribute some of the recently-accumulated deposits. Most of the sediments are held in suspension and moved slightly seaward, only to return to the beach after the storm waters recede. However, a small portion of the sediment is carried inland and deposited on the berm surface. As the berm moves inland and the foreshore is eroded, the berm constantly increases in height through a series of washover deposits.

c) Upon abatement of storm conditions, sediments are deposited on the berm face and the winter-beach level widens slightly. Throughout the subsiding water conditions, sediments which had moved offshore return to the foreshore and build the lower level seaward.

d) During succeeding *nortes*, the preceding steps are repeated and the berm is heightened and broadened into a well-defined ridge. Accretion of the lower beach continues between individual *nortes* as well as between *norte* seasons.
Figure 20. Intermittent accretion and retreat leading to the development and abandonment of a beach ridge.
Foreset-stratification develops within the ridge and records episodes of sediment accumulation.

e) Spread over an indeterminable number of storms and seasons, the contributory higher waters continue to deposit sediments; each contribution adds to the foreset-stratification, heightens and broadens the ridge, moves the crest inland, and increasingly places it beyond the reach of subsequent storm waters.

f) The combination of inland migration of the ridge plus continued beach accretion eventually separates the ridge from the active beach profile and consequently a berm is formed which does not penetrate inland to the older ridge and thus becomes the site of a succeeding beach ridge.

Certainly, numerous positive and negative modifications occur to disrupt this idealized sequence. Particular storms are mild and do not reach the position of the ridge so that they do not contribute to its development. Other high waters only erode the face of the ridge and do not spill over the crest. They, therefore, narrow the ridge. Still another storm may be so severe so as to destroy the beach ridge and thus cause the entire sequence to be initiated once again. There is no end to the complications or adjustments that may affect the ridge but the final product remains a washover feature produced by recurrent accumulations of sediment that are transported inland by storm waters. It is a ridge formed during intermittent retreat on an accreting beach.
Although beach-ridge genesis has long been a topic of study, identification of stratification within the Tabascan ridges offers another "dimension" to the understanding of beach-ridge development. The comparison of dynamic and static environments permits the reconstruction of sequential formation and interpretation of morphological processes.
Part III: TABASCAN BEACH-RIDGE TOPOGRAPHY

Variable rates of sediment accumulation and construction of a single beach ridge contribute to a variety of ridge dimensions in the Tabascan coastal landform-area. Size and shape of the ridge-form may differ both from one coastal location to another and from a coastward to an inland position. Rapid accumulation of sediment at river mouths causes a greater number of ridges to be constructed adjacent to the channel than at coastwise locations and, therefore, produces diagnostic areal patterns in the beach-ridge topography. Within the zone of beach ridges, profiles measured normal to the ridge trends commonly include both gradual and abrupt elevational changes of ridge crests. These changes may be correlated with periods of distributary activity and the sequential depositional and erosional episodes at a particular coastal location.

Size and Shape of Beach Ridges

Contrary to the initial visual impression of Tabascan beach-ridge topography and previous reports on similar features, the ridges are not a series of symmetrical undulations. These beach ridges have a highly irregular configuration in terms of their transverse profile. On the other hand, Tabascan ridges are quite uniform along their longitudinal axes. The crestline forms a slightly-arching curve generally concave inland. Were eolian deposition significant in their formation, greater irregularity would certainly
characterize the crestlines. This condition has been appreciated previously and suggested as a basis for discarding eolian origins for particular areas of beach-ridge topography (Brouwer, 1953, p. 233). Davies (1957, p. 108) suggests that crestline regularity reflects lack of eolian deposition whereas a more irregular crest-plan signifies increasing proportions of wind-blown sediments.

Variations of beach-ridge dimensions are apparently a product of the variable rate of formation. Given a supply of sediment sufficient to cause coastal build-out, it is suggested that rapid progradation produces smaller and more closely-spaced beach ridges. Assuming that progradation causes the abandonment of a particular ridge, then the rate of progradation also limits the number of storms which contribute to development of the ridge. On a rapidly prograding coast, the newly-formed ridge will soon be placed beyond the reach of ordinary storm waters and a succeeding storm berm (incipient beach ridge) will be initiated.

Conversely, where progradation is slowed, a greater number of storms contribute washover deposits to the ridge and the landform becomes correspondingly higher and broader. Variable progradation rates especially characterize the alongshore positions of the developing ridge. Ridges in downdrift locations generally attain greater dimensions than those forming nearer the river mouth. Furthermore, it is also likely that the more distant ridges incorporate a greater proportion of wind-driven sediments than their
lower counterparts and might, therefore, be slightly more asymmetrical.

Presuming that Tabascan beach ridges are accumulations of sediments transported to the Gulf by rivers and then swept onto the beach by waves and currents, progradation should be greatest in areas adjacent to the river mouth and subsequently lessen at increasing distances from the source of sediment. It would appear that the net effect of storms and sediment supply would evolve a cuspat e delta composed of beach ridges which are low and closely-spaced adjacent to the river mouth but higher and more widely-spaced toward the delta extremities, with a gradual transition of dimensions between these contrasting forms.

Furthermore, the absolute number of ridges would lessen toward the terminal positions. Ridge crests would continually merge downdrift to the ultimate configuration of a single, high ridge. The Grijalva cuspat e delta exemplifies the particular combination of variable ridge dimensions and a "fan-like" beach-ridge pattern. Beach ridges near the river mouth are one to two meters above the water level and spaced 24 meters apart. Ridges at Miramar, 13 kilometers down the coast, rise two meters high with spacing of 38 to 30 meters. Still farther from the mouth, beach ridges at Guerrero are 2.5 meters high and spaced 33 to 36 meters apart.

A further substantiation of the correlation between ridge heights and rates of progradation is found within the present-day foredune. Near the Grijalva mouth, (Fig. 2) the
foredune is only 1.5 to 1.8 meters above the Gulf; it rises to two meters at Miramar, 2.8 meters near Guerrero, three meters near Barra de Dos Bocas, and 4 meters at Playa Azul. Shortly beyond Playa Azul, dunes replace the beach-ridge topography. Of course, the previously mentioned foredune-sequence proceeds from a coastal zone of slow progradation to a zone of retreat. However, the characterization of height and progradation remains axiomatic since the spatial sequence is maintained. It must also be recognized that eolian deposits are contributing to the foredune height and, were the entire coast to prograde, the foredune would be preserved in place. This high dune-ridge would then tower above both the inland beach-ridge topography and subsequent beach ridges. It is likely that the high inner ridges in the present beach-ridge systems developed in this manner, a result of renewed accretion and the construction of a gently-dipping series of beach ridges seaward of the foredune.

Dimensions of the newly-formed beach-ridge system would then develop in accord with the sediment supply (rate of progradation) in addition to frequency and severity of storm water-conditions. The dimension of time is constantly implied in both of these qualifying factors and could, conceivably, be termed the relevant element determining size and spacing of beach ridges.

Wind-deposited sediments are relatively unimportant in the construction of Tabascan beach ridges. There is no doubt that eolian transported sands contribute to the development
of the beach ridge. However, these sediments are viewed herein as secondary and as accumulating on the marine-developed ridge. Wind-transported sediments build the ridge above the general beach-ridge topography and provide either a dune or a high foredune. In this regard, vegetation is not seen to be the all-important stable element about which eolian-driven sediments accumulate to form a beach ridge as suggested by Davies (1957, 1961), Bird (1960), and McKenzie (1958). In particular, Bird's theory of vegetation colonizing the seaward ridge and not the swale so as to produce a selective site of deposition is not substantiated in Tabasco. Rather, in accord with views presented by Cooper (1958), vegetation colonizes the beach ridge and preserves its form. Were it not for the pioneer vegetation, the coastal winds would probably dissect the storm ridge and produce a complex of low sand hummocks.

An example of beach ridge destruction is selected from an area immediately east of the Grijalva river-mouth groin. Upon the completion of this groin on the right bank of the Grijalva in 1956, sediment accumulations on the eastern side prograded the coast (Fig. 21). Several beach ridges developed in this accretionary zone but are poorly preserved today because vegetation was slow to colonize and fix the ridge deposits. Although ridges remain broadly discernible within the landscape, they are highly irregular and are identified primarily through the linear pattern of the remaining sand hummocks. Parts of these ridges are so indefinite that it
Figure 21: Completion of the Grijalva River groin, 1956; sedimentary accumulations subsequently prograded the shoreline to the outer edge of the groin. (photo courtesy of Cia. Mexicana Aerofoto)
is easier to follow the troughs of the swales by the vegetational patterns developed therein. Thus, the rapidity of ridge formation, brought on by attempts at control of longshore-drift, produced ridges which were unstable in their environment after formation. The process responsible for ridge-development remained constant but the landform was ill-preserved for lack of concomitant stabilization by coastal vegetation.

Beach-Ridge Systems

The prograding Tabascan coast has stranded consecutive beach ridges which, in turn, record past coastal trends. Each ridge, of course, implies a previous shoreline parallel to the ridge crest. Through an interpretation of ridge sequences, changing configuration of the shoreline can be detected and areas of maximum progradation can be identified. The most rapid progradation is located adjacent to the site of sediment discharge. At the river mouth, the coast projects slightly into the sea, producing a "cape", best described as a cuspate delta composed of a flaring system of beach ridges. It is here suggested that the series of ridges closely associated with a particular river be termed a "beach-ridge system". Use of this term in further discussion implies a primary site of sediment supply as well as a flaring beach-ridge pattern widening toward the discharge outlet.

Shifting distributary discharge within the Mezcalapa delta was often accompanied by significant coastal changes
in the vicinity of the affected mouths. Active coastal outlets which were sites of surplus sediment soon developed the typical cuspate delta. However, upon abandonment of the distributary outlet, coastal erosion invariably straightened the shoreline and truncated the cuspate projection and its flaring beach ridges. Along several sections of existing beach-ridge topography, the depositional and erosional sequence briefly outlined above is preserved through subsequent beach-ridge development prograding the coast parallel to the erosion-straightened shoreline. The junction of two beach-ridge systems at an oblique angle emphasizes the sequence of development as well as the erosional time-gap separating the two constructional periods.

Numerous examples of the aforementioned sequence of coastal development and destruction could be cited from Tabascan ridge-morphology. Two slightly different cases are presented to convey both the general pattern and the minor variations and complications.

Near the coastal location of Playa Azul, the Corche River channel cuts through a high dune ridge and leads to the Gulf (Fig. 22). This river, prior to historic accounts, was a major site of sediment deposition; local progradation ensued and a flaring system of beach ridges formed a small cuspate delta. Apparently the river was not fixed in its channel but shifted both east and west, eroding portions of the flaring beach-ridge system. Accretionary point-bar deposits on the left bank suggest that the latest shift was
Fig. 22. Corche River Breach through dunes, Corche River beach-ridge system, Seco River beach-ridge system; location of profiles for Figure 23.
eastward and occurred prior to the abandonment of the channel.¹

Upon diversion of Mezcalapa discharge from the Corche distributary, the small cape projecting into the sea was a zone of sediment deficit. Marine action concentrated on the cape through the well-known focusing of orthogonals (King, 1959, pp. 17-18), eroded the point, and truncated both the river course and the flaring beach ridges. Once the shoreline was straightened, this stretch of coast probably continued to undergo slow retreat. Based upon similar contemporary conditions accompanying retreat at Playa Azul, a high foredune probably developed within the beach profile near the abandoned outlet and the entire form actively migrated inland over the Corche River channel and adjoining beach ridges (Fig. 23). Later, the Seco River became the principal site of discharge and coastal progradation began anew. Part of the sediment was transported as far as the Corche River channel and was sufficient to produce coastal progradation. This sequence is illustrated by a profile taken across the contact of the two beach-ridge systems (Fig. 23b). The Corche River system is subdued and has very low relief. The contact is a high ridge, seaward of which the Seco beach-ridge system slopes gradually downward and seaward. Approximately 800 meters north of the contact,

¹Quite obviously the shifting characteristic would only accompany an active river.
Fig. 23. Beach-ridge profiles; seaward at right margin:
 a) profile at Playa Azul where high foredune is moving inland over beach-ridge topography; b) profile at contact of Seco River beach-ridge system and Corche River system.
swales within the Seco system are near ground water and are seasonally inundated.

Thus, the western flank of Seco River beach-ridge development terminated coastal retreat in the vicinity of Corche River and preserved the remaining features. Subsequent to Seco build-out, Mezcalapa River discharge shifted and resulted in partial erosion of the Seco beach-ridge system.

A second major example of stream diversion and coastal change is associated with the Usumacinta and Grijalva rivers. Among the vast complex of beach ridges along the Grijalva (Fig. 24), the innermost ridges (A) which are identified display a sharp inland curvature characteristically associated with progradation adjacent to a river mouth. Obviously the shoreline once occupied this interior position and these ridges denote coastal progradation. Not so obvious is the particular river transporting the sediment supply. It may have been Sierra-Pichucalco drainage or possibly a distributary of the Mezcalapa. Its source of sediment is of interest but is not of immediate concern. It is sufficient that the system exists and is the oldest identifiable beach-ridge system along the Grijalva River.

The next beach-ridge system along the Grijalva developed in association with the San Pedro y San Pablo River (B). Prior to the earliest historic accounts, Usumacinta discharge flowed principally through the San Pedro y San Pablo channel. In accord with its previous eminence, a flaring system of
Fig. 24. Diagrammatic representation of three beach-ridge systems along lower Grijalva River channel. Ridge lineations only convey trends and do not outline specific ridges.
beach ridges originated at its coastal outlet. It is not certain whether the outlet was of long duration or the site of especially abundant sediment discharge, but an extremely large flaring beach-ridge system, more than 1350 square kilometers, bears witness to significant coastal progradation. The Usumacinta was by no means the only outlet to the Gulf during the development of its beach-ridge system. Several other river channels are discernable within the ridge system and probably contributed some sediment. These channels are thought to be contemporaneous with the San Pedro y San Pablo beach-ridge system rather than subsequently breaching the ridge pattern. Arching of the ridges near the river channel suggest that they recurved into an active river outlet during their formation, whereas subsequent breaching by the river would truncate the ridge pattern without recurving the ridges (see modified oxbow on González River at Barra de Chiltepec, Fig. 25). The recurved ridge-pattern is also partially preserved along the Grijalva Channel and thus the González and Grijalva are thought to be active rivers discharging into the Gulf simultaneously with the San Pedro y San Pablo.

Within the beach-ridge system of the San Pedro y San Pablo, there are several abandoned river channels penetrating the general ridge pattern. One of these channels extends northeastward off Remate Lagoon-Popal Grande and eventually terminates within the ridges (Fig. 25b). Similar to previous suggestions, adjacent arching ridges along the river channel imply a distributary which was eventually
Fig. 25. Comparison of beach-ridge trends at: a) lower González River; b) Popal Grande. The general location map depicts the dominant beach-ridge lineations whereas the larger-scale inset maps present actual ridge crests.
blocked by coastal progradation. There is remarkable 'mirror-image' similarity between the terminal positions of Popal Grande and the González River. Were Barra de Chiltepec sealed off and the channel filled, the general sequence of forms would almost duplicate the Popal Grande channel and adjacent ridge pattern.

The third and final series of ridges (C, Fig. 24) along the Grijalva is associated with the Grijalva mouth itself. Upon abandonment of the San Pedro y San Pablo channel, Usumacinta discharge led to the Grijalva at the confluence of Tres Brazos. The Grijalva mouth became the next site of multiple beach-ridge development and coastal progradation. More than 90 square kilometers of ridges have developed since this channel migration.

Upon diversion of the principal distributary course from San Pedro y San Pablo to the Grijalva, marine agencies eroded the cuspat e delta of the former and straightened the shoreline. In addition to shoreline modification, local subsidence surrounding the decaying river channel lowered the immediate beach-ridge topography. Accompanying lowering of the undulating surface, mangrove vegetation spread from along the river onto the adjacent beach ridges. Those ridges and swales near the river became blanketed by the invading vegetation while at increasing distances from the river, mangrove was restricted to the swales. Deposits of clay and silt-sized particles also accumulated upon the subsiding topography. Much of these fine-grained sediments
were probably fluvially-transported into the swales during river flood stages. In addition to the direct fluvial source, high Gulf levels also contributed fine-grained washover deposits to the swales. Trenches and pits in the beach near the San Pedro y San Pablo River mouth disclosed intercalated sand, silt, and clay continuing inland toward the beach-ridge topography. Similar deposits were also uncovered in three large washover fans which protruded inland over beach ridges and into swales. Often, the fine-grained sediments were so abundant that upon drying they formed an indurated clay crust over coarser beach and washover deposits. A further source of fine sediments was the eroded swamp deposits from along the shore face which contributed numerous clay balls to the swash. It was noted that two zones of clay balls were seen on the beach at most times. One zone marked the position of high-tide swash, whereas the other zone of clay balls was in transit within the then active swash zone (Fig. 26).

Straightening of the shoreline in the vicinity of the San Pedro y San Pablo mouth has produced a beach-ridge pattern which is currently oblique to the shore. Retreat, in turn, has caused exposure of clays, mangrove stumps, and other organic materials along sections of the beach. Where the beach-ridge topography was totally overwhelmed by the invasion of mangrove vegetation, the beach crest is slowly moving inland through the forest and exposing a solid stand of decaying mangrove in the foreshore (Fig. 27). Where
Figure 26. Clay balls in-active swash zone and at high-tide level.

Figure 27. Mangrove stumps studding rapidly retreating beach near the San Pedro y San Pablo river mouth.
fine-grained sediments and mangrove accumulated only in the swales, isolated exposures of organic matter, clays, and mangrove remains outcrop on the beach (Fig. 28). By means of borings, the beach exposures were traced through the beach sands and shown to connect with similar clays and organics presently in the swales (Fig. 29).

Beach-ridge systems may also be identified at numerous other locations fringing the Recent deltaic plain where they, in various stages of construction and destruction, combine to form most of the coastal landform-area. Additional information supplied by borings completed by the Seismic Division of Petroleos Mexicanos and Zeevaert (1956), supplemented by borings made by the writer, suggests that the coastal zone is a sandy layer, 10 to 13 meters in thickness, locally extending seaward accompanying coastal progradation. Sediments comprising the sand layer are quite uniform, Figure 30 compares surface samples collected during the 1962-1964 field investigation with subsurface samples collected by Zeevaert (1956), and are described as overlying deposits of silts and clays. It is probable that, as first stated by Zeevaert (op. cit., pp. 24-25), the sediment discharged at the river mouths is sorted and distributed by marine processes, the sands are deposited along the coast whereas the finer sediments are carried farther seaward and later covered by the advancing layer of sand. Apparently, the coarsest sediments are transported within the surf zone by the combination of beach-drifting and longshore currents.
Figure 28. Exposures of organic clay and mangrove stumps on sandy beach.
Figure 29. Cross-section through beach crest tracing swale sediments and beach exposure.
Figure 30. Grain-size distribution, comparison of field samples and Zeevaert's collection.
The depth to which this sand transport occurs remains somewhat uniform and accounts for the similarity of bore-hole records. Possibly, the depth of sand represents the 'surf-base' of Dietz (1963, p. 976) and the sand layer underlying the surface beach-ridge topography, represents his prograding 'active surf lens' (op. cit., p. 978).
SUMMARY

The spatial arrangement of landforms within Tabasco represents the sequential development of the lowland plain and the morphologic agents which distributed the sediments. Fluvial activity produced the interior Pleistocene surface and the intermediate zone of Recent deltaic plain. However, the narrow Recent coastal fringe was a product of marine morphologic agents. Most of the coastal landforms are beach ridges which are grouped around river mouths and were formed during periods of sediment debouchment. Abundant sediment caused coastal progradation but the production of a series of abandoned beach crests was the result of intermittently-raised Gulf levels which concentrated sedimentary deposition on higher portions of the beach profile.

Profiles measured across the beach and trenches dug through the sedimentary accumulations revealed that the upper level berm is transformed into a sizeable ridge and is composed of washover deposits, the strata within the ridge dipping consistently landward. Trenches and other exposures disclosed beach-ridge stratification to be composed of inland-dipping foreset-stratification. Each foreset-unit had three components. The seaward component (I) was essentially horizontal or dipping slightly inland. Component I graded into a steeply-dipping component (II), dips measured up to 28°, and then flattened out to a near-horizontal component (III). Several foreset-units composed each ridge and indicated that each sequence of deposition has
moved back over older deposits.

Accumulations of sediment on the upper beach occur primarily during raised water levels accompanying the seasonal intrusion of nortes. Although erosion characterizes lower portions of the beach profile, the upper beach, or berm, continues to gain in height and breadth through the intermittent addition of washover deposition. In the process of construction, the ridge actually retreats slightly, the seaward foreset-units are partially destroyed while the ridge accretes both upward and landward. During calm conditions, coastal progradation widens the beach seaward of the ridge and thus hinders succeeding storm waters from adding washover deposition and further molding the ridge. After sufficient progradation, norte storm waters do not penetrate inland to the ridge but initiate a new crest, stranding the previously-developed beach ridge.

Although beach-ridge genesis has long been a topic of study, identification of stratification within the ridge offers another "dimension" leading to an understanding of beach-ridge development. In this case, comparison of static and dynamic conditions has produced the conclusion that whether transported and deposited by waves or wind, the landward-dipping foreset-units definitely illustrate washover laminae comprising the ridges in contrast to beach-stratification underlying the swales.

Ridge dimensions and beach-ridge systems are products of the genetic process as well as the localized sources of
sediment. The beach-ridge system is widest adjacent to a river channel, where the ridges are most numerous, lowest, and most closely spaced; whereas at greater distances from the river mouth, the ridges correspondingly decrease in number, increase in height, and are more widely spaced.
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