DEPOSITION AND STRATIFICATION OF OBLIQUE DUNES

SOUTH PADRE ISLAND, TEXAS

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DEPOSITION AND STRATIFICATION OF OBLIQUE DUNES
SOUTH PADRE ISLAND, TEXAS

by

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Stpehen Paul Weiner

ABSTRACT

Oblique dunes have orientations that are intermediate between those of transverse and longitudinal dunes. The oblique dunes studied are reversing dunes which undergo no net annual migration when associated with normal meteorological patterns.

From April 1980 through September 1980, the dunes migrated up to 65 feet (19.8 m) northwestward under the influence of prevailing onshore winds. High velocity northerly winds (November 1980 through February 1981), associated with the passage of winter frontal systems, caused the dunes to rapidly migrate 65 feet (19.8 m) southward. Volumes of sand transported by these strong winds were commonly reduced by accompanying rainfall. In October 1980 and March 1981 neither wind direction was dominant, and frequent changes in wind direction caused many of the dunes to become flattened. Hurricanes, which strike the area in late summer, have had no lasting effects on the dunes.

Three major stratification types were observed in trenches and on etched surfaces. Translatent strata were deposited by wind ripples; grainfall deposits accumulated when saltating grains settled on leeward slopes of the dunes, and grainflow cross-strata were developed by

avalanching on leeward slopes. Preservation of these stratification types occurred in zones of net deposition, predominantly leeward of the dune crests.

Strata deposited during the summer wind regime dip northeast, whereas the winter strata dip in a southerly direction. The winter deposits are best preserved in the central cores of the dunes. This suggests that either the high velocity winds of the initial winter frontal systems destroy large volumes of the summer deposits, or that the dunes migrate southward, under the influence of dry northerly winds, during droughts.

Oblique dune deposits should be difficult to discern in the rock record, because they may contain aspects of either transverse or longitudinal dunes. It is likely that some ancient oblique dunes have been mistakenly described as other dune types in the literature.

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INTRODUCTION

Purpose of Study

The aim of this study was to relate the morphology and stratification of oblique dunes on South Padre Island, Texas, to eolian processes. In order to accomplish this goal it was first necessary to determine that these were indeed oblique dunes according to the classical definition of oblique dune.

The next objective was to substantiate the existence of meteorological patterns by examining available wind data, and by directly observing changes that occur during each wind regime. Changes in dune morphology should be concurrent with changes in wind regime. It was therefore necessary to determine how the dunes changed during a given one year period.

The final purpose of this study was to examine eolian stratification types in the oblique dunes, and relate recurring stratification packages to dune movements, and ultimately wind regime. This analysis of stratification types should provide a tool for examining ancient eolian deposits.

Methods

Long-term changes in the dunes were studied by examining sequences of aerial photographs dating from January 1954 through August 1980 (Appendix I), and meteorological data dating from January 1958 through June 1981. Long-term meteorological data were obtained from the National Weather Service station at Brownsville, Texas, 40 miles (64.4 km) southwest of the study area (24 miles inland).

Short-term changes in dune morphology and migration patterns were monitored by profiling the dunes during each seasonal wind regime of the year. Monitoring began with the summer wind regime in June 1980, and concluded with the initiation of the following summer wind regime, in March 1981. Changes in profiles were observed on a daily basis, whereas wind direction and speed were recorded continuously, but analyzed as hourly readings. These observations permitted the construction of a detailed chronology of dune response to eolian processes.

The stratigraphic history of the dunes was studied by digging trenches at different times during the year. By relating the distribution and associations of small-scale stratification types: wind ripple deposits (translatent strata), grainfall deposits, and avalanche deposits (grainflow cross-strata), sedimentary processes were related to the morphological history of the dunes.

The passage of Hurricane Allen (August 1980) across the study area provided an exceptional opportunity to study the effects of this catastrophic event on the dunes. Pre- and post-hurricane profiles across the dune field, as well as aerial photographs, revealed the magnitude of the changes in the dunes as a result of Hurricane Allen.

Previous Work

Many studies have examined coastal sand dunes, but few have centered on oblique dunes and the stratification types contained there-in. Important studies on oblique dunes are limited to Cooper's (1958) geomorphic analysis, and Hunter and others' (in preparation) study on morphodynamic processes, of Coos Bay, Oregon dunes. The oblique dunes of Padre Island were briefly discussed by Price (1958), Hunter and others (1972), and Brown and others (1980).

The formation and distribution of small-scale eolian stratification types is best discussed in Hunter's (1977a) landmark study. Other major works on the subject are by Kocurek and Dott (1981), Hunter (1977b, 1981), McKee (1966), McKee and Tibbitts (1964), and Bigarella and others (1969).

Location and Description of Study Area

South Padre Island is a barrier island in which the shoreline, east of the dune field studied, is undergoing 9.7 feet (3.0 m) of net lateral erosion per year (Morton and Pieper, 1975). General facies tracts across the island are discussed in detail by McGowen and others (1977).

The southern part of Padre Island is influenced by a longshore current which carries sand from the mouth of the Rio Grande River northward along the island (Fig. 1). This sand accumulates on the shoreface, beach and foredune ridges, and is reworked into washover fan deposits during hurricanes. These washover fans, along with the foredune ridges, are the source areas for eolian sand which is deposited onto the oblique dunes (Brown and others, 1980; Weise and White, 1980).

The dune field studied in this thesis is located on South Padre Island, Texas. It is on the Cameron and Willacy County line,

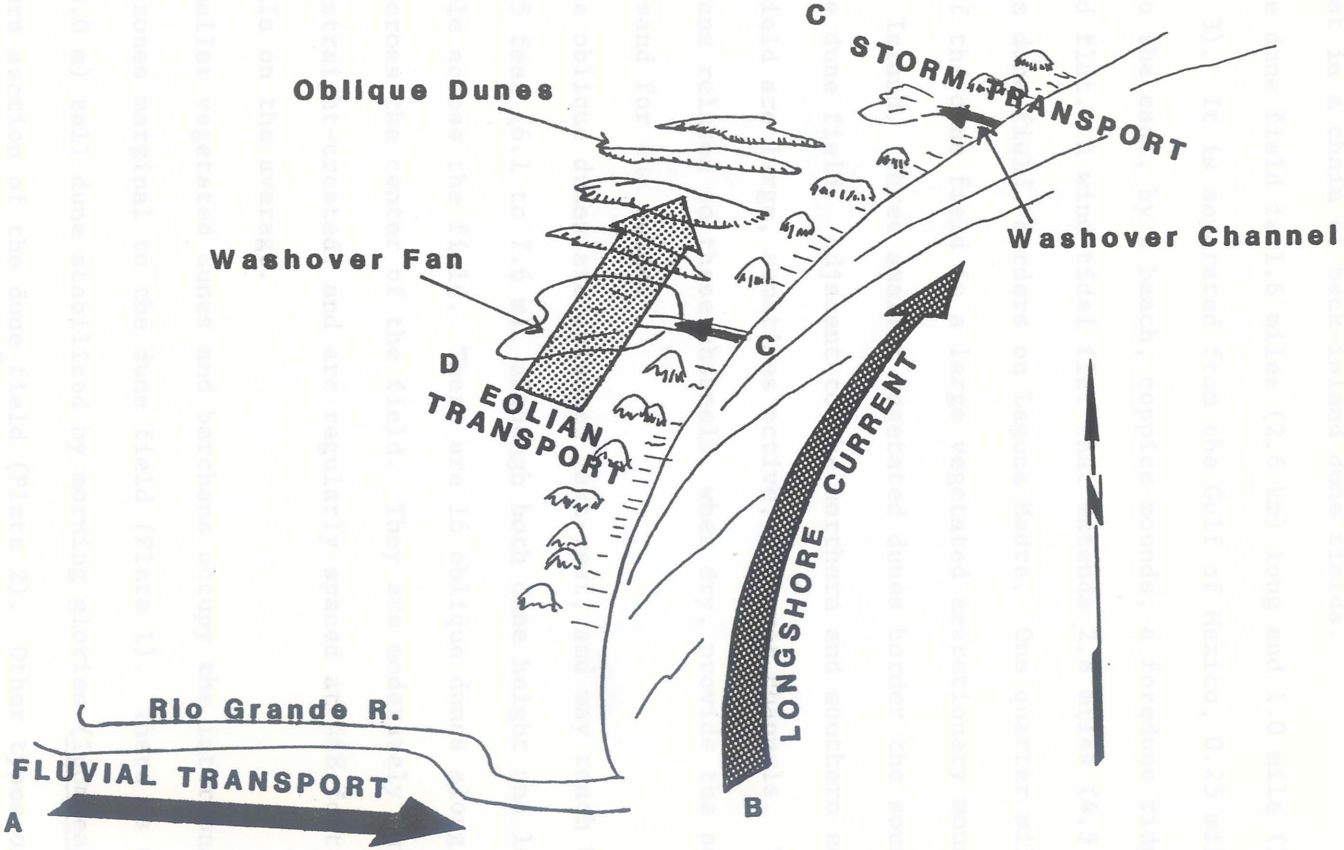


Figure 1. Sediment dispersal system of South Padre Island. Primary source area is the Rio Grande province. Longshore current, storm transport and finally eolian transport carries the sand to the back-island dunes.

28 miles (45.1 km) north of Port Isabel, Texas (Fig. 2), and is the southernmost in a chain of back-island dune fields.

The dune field is 1.6 miles (2.6 km) long and 1.0 mile (1.6 km) wide (Fig. 3). It is separated from the Gulf of Mexico, 0.25 mile (0.4 km) to the east, by a beach, coppice mounds, a foredune ridge, and a vegetated flat. A wind tidal flat that extends 2.8 miles (4.5 km) west of the dune field, borders on Laguna Madre. One quarter mile (0.4 km) west of the dune field is a large vegetated accretionary mound named Deer Island. Three smaller vegetated dunes border the southern edge of the dune field. Adjacent to the northern and southern edges of the dune field are large, sometimes active, washover channels. The washover fans related to these channels, when dry, provide the source of eolian sand for the dunes.

The oblique dunes are oriented east-west, and may reach heights of 20 to 25 feet (6.1 to 7.6 m), although both dune height and length are variable across the field. There are 16 oblique dunes along a transect across the center of the field. They are moderately curvilinear to straight-crested, and are regularly spaced at 488-foot (149.0 m) intervals on the average.

Smaller vegetated dunes and barchans occupy the interdunal areas and zones marginal to the dune field (Plate 1). There is one 10-foot (3.0 m) tall dune stabilized by morning glories (Ipomoea) in the northern section of the dune field (Plate 2). Other types of vegetation that were observed include sea oats (Uniola paniculata), bitter panicum (Panicum amarum), and sea purslane (Sesuvium portulacastrum). These plants are restricted to the foredunes, vegetated flat,

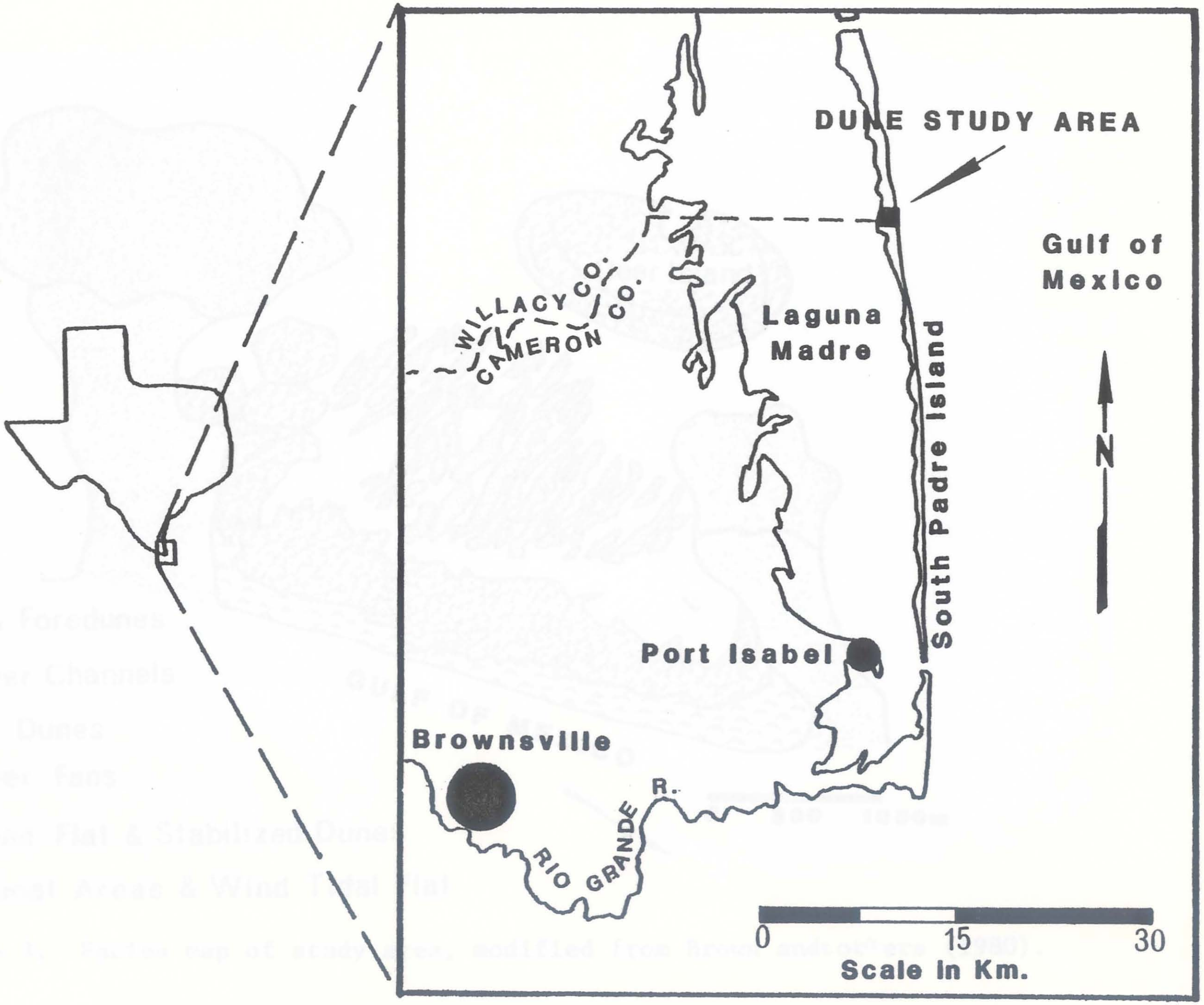


Figure 2. Location of dune study area on South Padre Island, Texas.

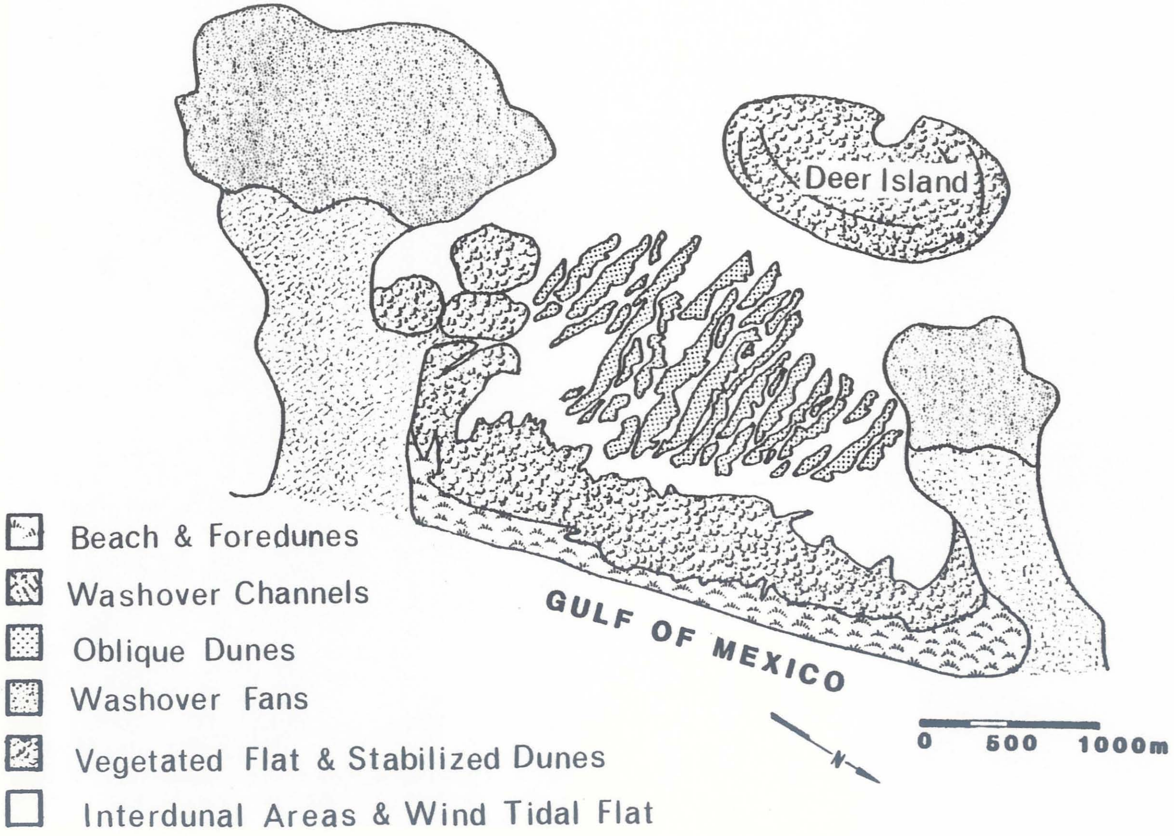


Figure 3. Facies map of study area, modified from Brown and others (1980).

Plate 1. Incipient vegetated ("wind shadow") dune in interdunal area. This dune type formed as vegetation baffled sand-carrying wind, and sand was deposited in the zone of wind separation. The three-foot (0.9 m) tall dune shown here, in a southeastern view, was observed in June 1980, during prevailing southeasterly winds. Wind ripples on the right-hand slope of this dune formed under the influence of oblique wind components. Remnant etched grainflow cross-strata from adjacent dunes are visible in foreground.

Plate 2. Ten-foot (3.0 m) tall dune stabilized by morning glories (Ipomoea) observed in June 1980. Grainflow on slipface of an oblique dune is visible in center-left of photo.

and interdunal areas.

Dune Stability

The oblique dunes on South Padre Island were probably formed during a drought, before the development of the present vegetated foredune ridges, and migrated westward toward Laguna Madre. The foredune ridges, once formed, reduced the direct influence of the onshore winds, and protected the oblique dunes from hurricane surges and waves. During subsequent droughts the strong winter winds pushed the dunes southward, and reduced vegetation in the foredunes allowed sand from the foredunes to be added to the oblique dunes. Droughts affecting South Padre Island occurred during 1891-1893, 1896-1899, 1916-1918, 1937-1939, 1950-1952, and 1954-1956 (Lowry, 1959). Other periods of little precipitation occurred in 1962-1964, and 1974 (N.O.A.A., 1980).

Formation of Oblique Dunes

Oblique dunes are elongate sand ridges that are modified by two seasonal wind regimes, but are oriented neither perpendicular nor parallel to the resultant wind direction (Fig. 4). Oblique dune is a genetic classification in which dune type cannot be determined until wind regime is known. Based on morphology alone, these dunes would be classified as large reversing transverse ridges, or possibly as longitudinal dunes.

Hunter and others (in preparation) define the orientation of oblique dunes as being 15 to 75 degrees away from the mean sand transport direction. The oblique dunes on South Padre Island are oriented at 90 degrees azimuth, 50 degrees from the sand transport direction of

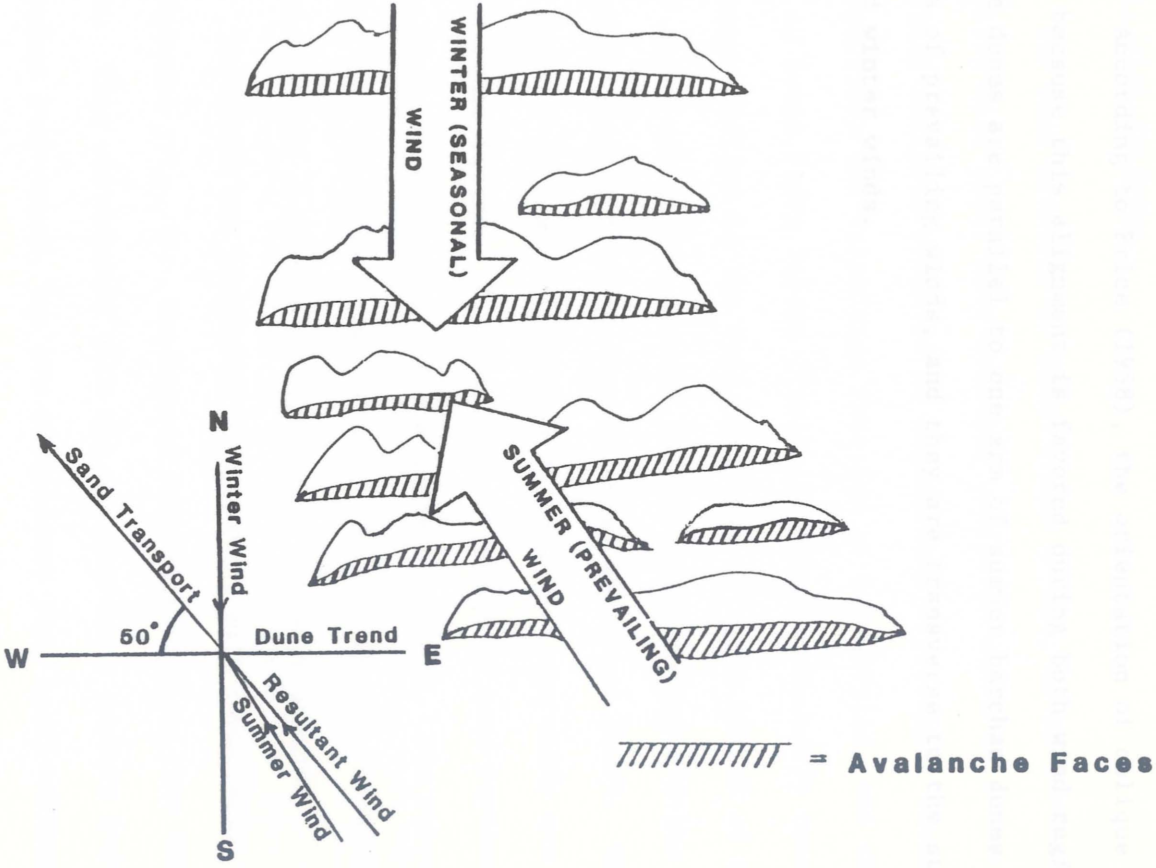


Figure 4. Formation of oblique dunes, with wind and dune orientations of South Padre Island.

320 degrees (calculations use Hunter and others' equations, and are based on Bagnold's, 1954, criteria).

According to Price (1958), the orientation of oblique dunes is stable because this alignment is favored during both wind regimes. The oblique dunes are parallel to one arm of summer barchan dunes during periods of prevailing winds, and they are transverse to the storm-related winter winds.

METEOROLOGICAL PROCESSES

Seasonal Wind Patterns

The wind patterns on South Padre Island, as projected from Brownsville wind data, have remained unaltered since 1951 (Orton, 1964). Statistical analysis revealed no significant differences between the wind directions and velocities recorded at Brownsville, and those recorded on South Padre Island (Table 1). The continuously recording wind gauge utilized in the dune field was set at a height of 23 feet (7.0 m) above sea level, whereas the National Weather Service gauge in Brownsville records from 39 feet (11.9 m) above sea level. The frictional effects at lower elevations suggest that the winds are stronger on South Padre Island. This discrepancy would be most pronounced during the high velocity winds of the winter northers. For reasons of accuracy, the values recorded on South Padre Island were utilized in the calculations performed in this study whenever possible.

The winds are bimodally distributed, with components from north and southeast (Fig. 5). The annual resultant wind is from 140 degrees azimuth. This corresponds with the southeasterly onshore breezes that are present year-round, but are predominant from April through September. The southeasterly summer winds blow 92 percent of the time. Northerly winds account for only 2 percent of the wind distribution during the summer wind regime. Observed velocities of the southeasterly winds were often as high as 15 to 25 miles per hour (6.7 to 11.2

	SOUTH PADRE ISLAND		BROWNSVILLE	
Date	Speed	Direction	Speed	Direction
6/9/80	7	77	5	120
6/10/80	4	58	5	50
6/11/80	8	79	7	80
6/12/80	8	93	8	90
6/13/80	10	108	9	110
6/14/80	13	115	10	130
6/15/80	17	131	13	150
6/16/80	15	131	14	150
6/17/80	17	129	13	140
6/18/80	14	155	11	150
6/19/80	19	155	17	160
6/20/80	15	161	14	160
Mean:	12.3	116.0	10.5	124.2

Table 1. Comparison of South Padre Island and Brownsville wind data in June 1980. Wind speed and direction are daily resultant values (Speed = miles per hour; Direction = degrees azimuth). P is much greater than 0.50 for both speed and direction according to chi-square analysis, so statistical differences between South Padre Island and Brownsville data are nonsignificant.

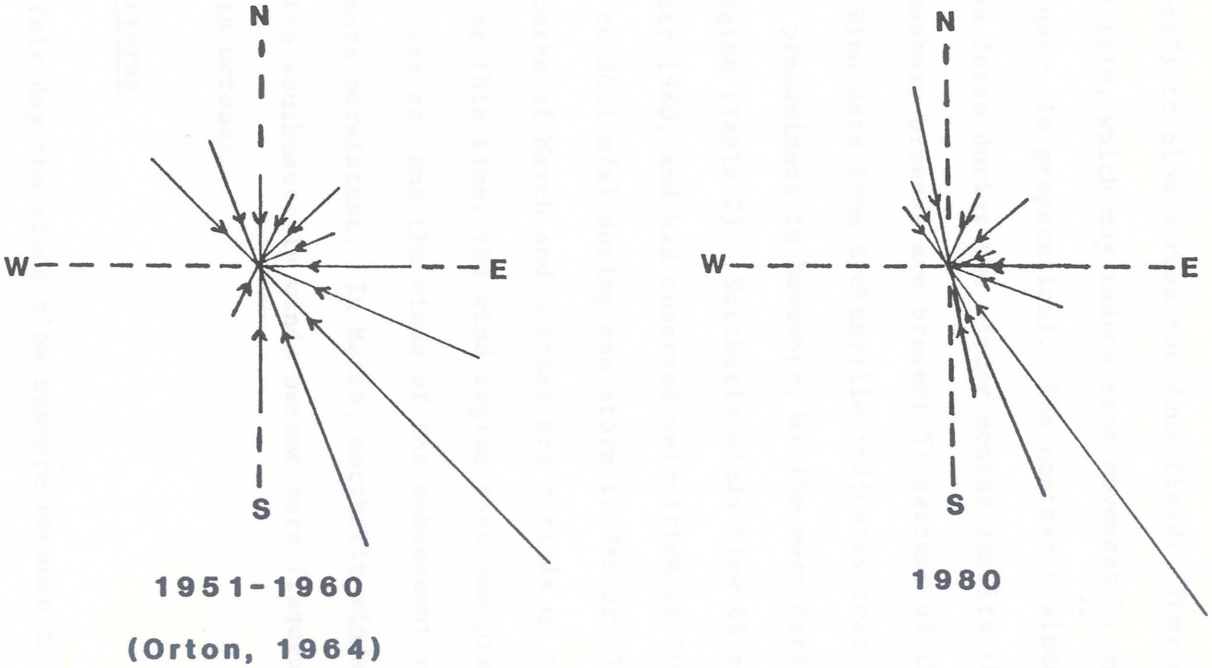


Figure 5. Annual wind durations, using values from the Brownsville weather station.

m/s).

From November through February, frontal systems generated by the passage of high pressure zones in the atmosphere cause strong northerly winds ("northers") to blow across the dune field. They are commonly accompanied by rain, which may reduce sand movement by up to 62 percent (Hunter and others, in preparation). The northerly winds are the predominant eolian force during the winter months despite the fact that fair-weather onshore breezes are present 51 percent of the time during this period. Wind data from Brownsville indicates that the northerly winds are most predominant in November, at the very beginning of the winter wind regime (Table 2). Northerly winds blew 86 percent of the time in November 1980, and had observed velocities of 20 to 45 miles per hour (8.9 to 20.1 m/s) during one storm in January 1981.

The months of March and October are periods of transitional wind regime. At this time, the wind regime that was previously predominant becomes less so, and the winds of the subsequent regime become stronger and more persistent. In March, northerly winds become less important as the southeasterly winds become more frequent; the opposite is true in October.

Daily Wind Patterns

On a fair day the winds blow onshore because the land heats faster than the water. These winds are strongest when the temperature differences are greatest, normally around 4 or 5 p.m. As the sun sets, in many coastal areas, the land cools faster than the water, so the winds diminish and blow offshore. On South Padre Island, however, the

	DISTRIBUTION OF PREDOM. WINDS (%)				DISTRIBUTION OF RELATIVE WINDS (%)				TOTAL MILES
MONTH	N	E	S	W	N	E	S	W	OF WIND
11/79	49	1	50	0	45	1	54	0	16,050
12/79	55	0	45	0	51	0	49	0	12,969
1/80	23	1	76	0	20	1	79	0	11,997
2/80	34	1	65	0	30	1	69	0	19,329
3/80	16	3	81	0	15	2	83	0	23,793
4/80	12	3	85	0	13	2	85	0	21,513
5/80	1	4	95	0	1	3	96	0	23,082
6/80	0	1	99	0	0	2	98	0	27,216
7/80	0	1	99	0	0	1	99	0	20,550
8/80	0	6	94	0	0	6	94	0	21,663
9/80	1	18	81	0	0	16	84	0	14,202
10/80	19	1	80	0	7	1	92	0	14,937
11/80	86	0	14	0	89	0	11	0	10,128
12/80	61	0	39	0	56	0	44	0	11,712
1/81	48	2	50	0	40	1	58	1	9,456
2/81	27	3	70	0	27	2	71	0	13,647
3/81	15	2	83	0	11	1	87	1	17,364
4/81	1	1	98	0	1	1	98	0	17,784
5/81	1	3	96	0	0	1	99	0	23,106
6/81	0	4	96	0	0	3	97	0	18,735

Table 2. Wind duration and velocity values expressed in percent from each direction (frequency). Values are greater than 9.3 miles per hour (4.2 m/s), as recorded at three hour intervals at Brownsville. (Wind values concurrent with rainfall were not included in this tabulation).

Predominant wind = duration x velocity (Brown and others, 1980).

Relative wind = duration x velocity^2 (Price, 1933).

Miles of wind = total duration from each direction x sum of 3-hour velocity values.

winds are strong during the day, but diminish at night without blowing offshore (possibly because of thermal buffering by Laguna Madre). This results in maximum sand transport during the daylight hours. Storm-related winds overpower this daily cycle, and can move sand during the day or night.

Rainfall Distribution

South Padre Island is located in a subtropical, semi-arid zone (N.O.A.A., 1980). Maximum rainfall, generally associated with thunderstorms, occurs during May, June and September. Rainfall reduces the effectiveness of the prevailing southeasterlies that occur during this time period. Exceptionally heavy rainfall may be related to the passage of hurricanes. Hurricanes are most likely to strike the Texas coast between June and September.

DUNE MORPHOLOGY

Introduction

Seasonal changes in oblique dune norphology were observed in June 1980 (summer wind regime), in January 1981 (winter wind regime), and in March 1981 (transitional period). Visual observation and detailed profiles (Fig. 6) provided data on dune height, changes in cross-sectional area, migration rates, and the amount of erosion and deposition across the dunes.

Net annual migration of the oblique dunes, as determined from sequential aerial photographs, is negligible; dune positions prior to 1967 are uncertain, however, because of the high altitudes from which the photos were taken. Increasing density of vegetation, and the gulfward migration of Deer Island (because of accretion on its eastern edge) were also evident on these photographs.

Summer Wind Regime

In June 1980, the prevailing winds were from the south and southeast, with a resultant orientation of 140 degrees azimuth. These winds generated north-facing slipfaces on the oblique dunes. The slipfaces moved northward a total of 7.6 feet (2.3 m) between June 9th and 20th, and a projected 65 feet (19.8 m) during the entire summer wind regime. As the slipface of one closely-monitored dune migrated, 4.7 percent of the windward slope was removed by erosion, and the height of

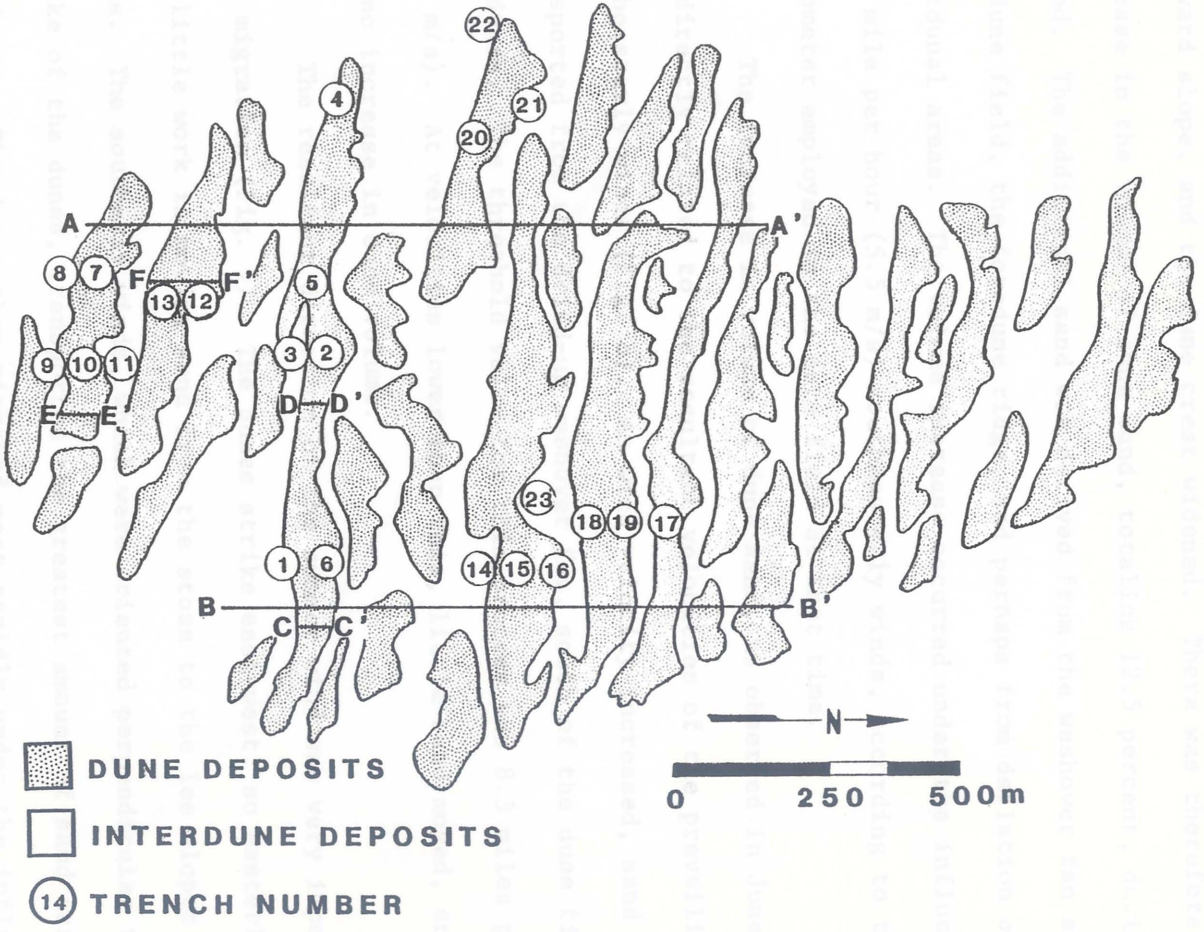


Figure 6. Location of profiles and trenches in study area.

the dune crest remained unchanged (Fig. 7). The volume of sand added to the leeward slope of the dune was greater than that removed from the windward slope, and the dune crest widened. There was therefore a net increase in the volume of dune sand, totaling 12.5 percent, during this period. The additional sand was derived from the washover fan south of the dune field, the foredune ridge, and perhaps from deflation of the interdunal areas. The volume increase occurred under the influence of 12.3 mile per hour (5.5 m/s) southeasterly winds, according to the anemometer employed in the dune field at that time.

The increase in volume of dune sand, as observed in June 1980, was directly related to the resultant velocities of the prevailing southeasterly winds (Fig. 8). As wind velocity increased, sand was transported from the dried-up washover fan, south of the dune field, to the dunes. The threshold value for this process was 8.3 miles per hour (4.2 m/s). At velocities lower than this, little sand moved, and there was no increase in dune volume.

The resultant direction of the summer wind was very important to dune migration (Fig. 9). The dunes strike east-west, so easterly winds did little work in moving sand from the stoss to the lee slopes of the dunes. The southerly winds, which were oriented perpendicular to the strike of the dunes, transported the greatest amount of sand across the dunes. The dunes thus migrated most rapidly under the influence of the southerly winds. This is especially important because the source of the dune sand is south of the dune field as well.

In order to relate the sand carrying capacity of the wind to dune migration, vector analysis may be performed on the wind data. This

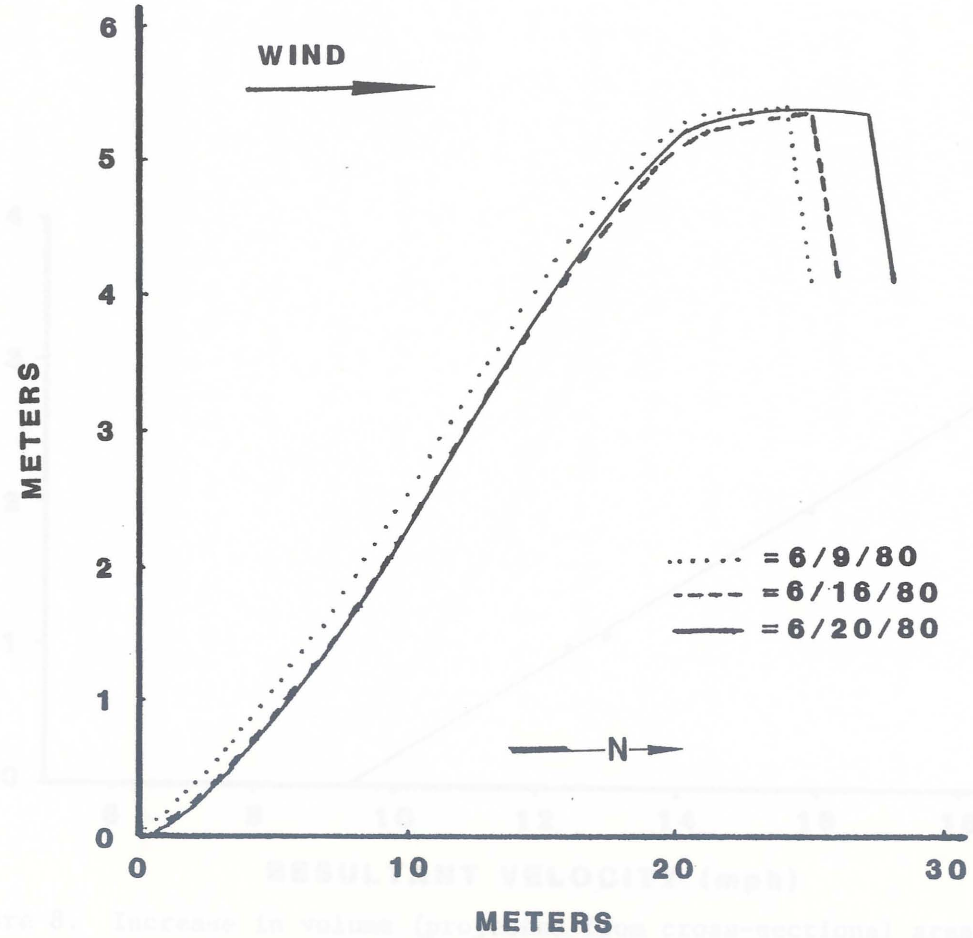


Figure 7. Dune migration associated with prevailing southeasterly breezes, June 1980. Profile along C-C' (Fig. 6). Vertical exaggeration = 5x.

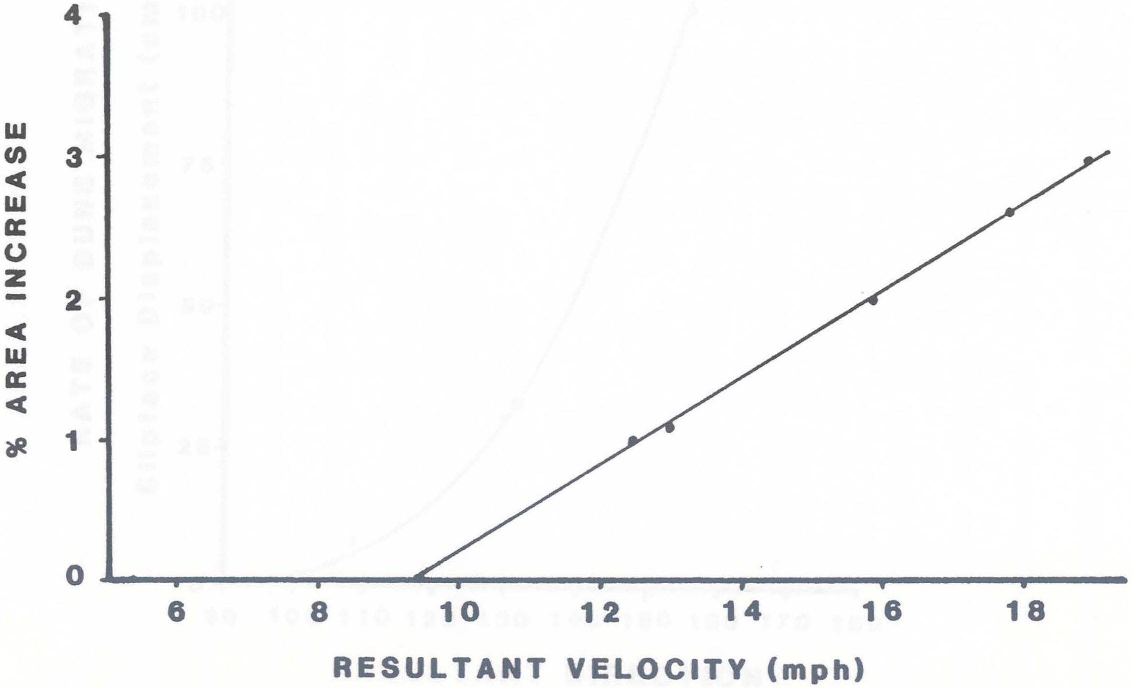


Figure 8. Increase in volume (projected from cross-sectional area) of dune sand as related to wind velocities recorded on South Padre Island.

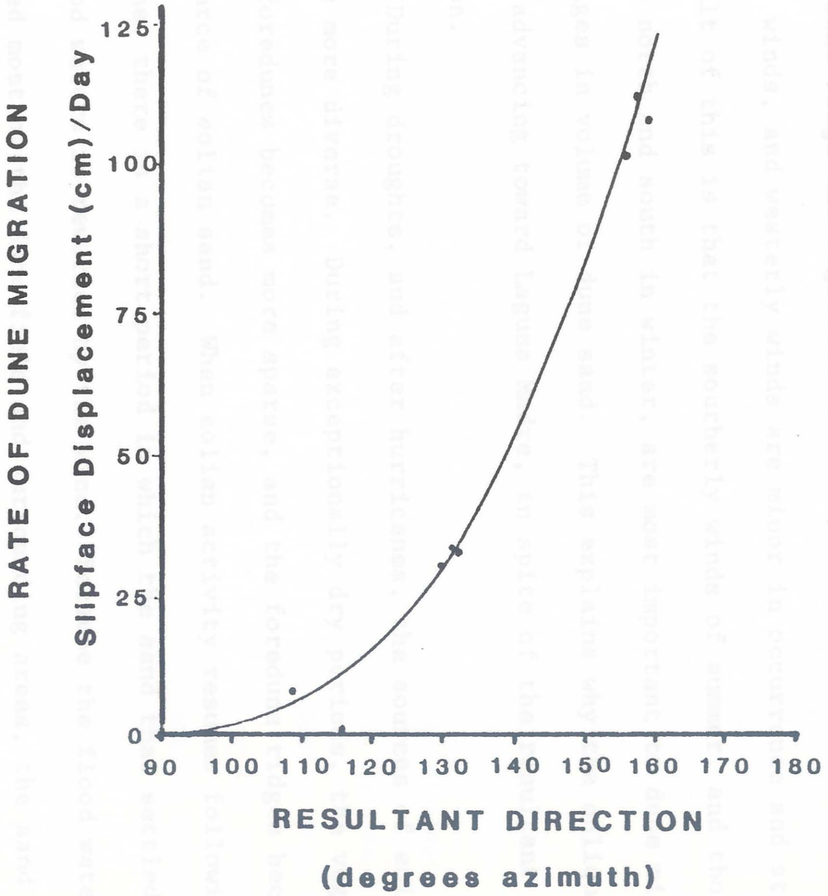


Figure 9. Dune migration and wind orientation as recorded on South Padre Island, June 1980.

breaks the wind into components which are parallel and perpendicular to the strike of the dunes (Gutman, 1977; Fryberger, 1979). This type of calculation is useful in determining the source of the eolian sand, and the relative effects of wind direction on dune migration, but it assumes equal availability of sand from all directions. This is not the situation in this particular dune field under normal meteorological conditions. The most important source areas are washover fans located perpendicular to the strike of the dunes, north and south of the dune field. The foredune ridge and vegetated flat trap most of the sand from the easterly winds, and westerly winds are minor in occurrence and strength. The result of this is that the southerly winds of summer, and those from both the north and south in winter, are most important to dune migration and changes in volume of dune sand. This explains why the oblique dunes are not advancing toward Laguna Madre, in spite of the resultant wind direction.

During droughts, and after hurricanes, the sources of eolian sand are more diverse. During exceptionally dry periods, the vegetation on the foredunes becomes more sparse, and the foredune ridges become a good source of eolian sand. When eolian activity resumes following a hurricane, there is a short period in which the sand that settled from the flood waters is reworked by the wind. Because the flood waters inundated most of the dune field and surrounding areas, the sand that is left behind is often spread out across a large area.

Hurricane Season

There is a 0.67 probability of a hurricane striking the Texas coast in any given year (Hayes, 1967). Recent hurricanes of importance on South Padre Island were Carla (1961) and Beulah (1967). The effects of these are discussed by Hayes (1967), Scott and others (1967), and Morton and Pieper (1975).

On August 10, 1980, the eye of Hurricane Allen struck the Texas coast near the Mansfield Channel, approximately seven miles (11.3 km) north of the study area. Accompanying it were gusts of wind estimated at 160 miles per hour (71.5 m/s), a storm surge in excess of 12 feet (3.7 m), and seven inches of rain (17.8 cm) (N.O.A.A., 1980). Allen was the fiercest storm on record, and the first hurricane to strike the area since Hurricane Beulah (1967).

The surge from Hurricane Allen reactivated the washover channels to the north and south of the dune field. Water flowed through these channels onto the wind tidal flat and interdunal areas, inundating all but the crests of the oblique dunes (Plate 3). The debris line from this water was later measured at six feet (1.8 m) above the interdunal areas. The foredune ridge east of the dune field remained unbreached, and protected the oblique dunes from the breaking waves.

Channels were scoured in the interdunal areas to a depth of over three feet (0.9 m). When eolian activity resumed in October 1980, sand from the oblique dunes filled ponded scour zones, thus reducing dune height. The interdunal areas were still slightly concave when observed in January 1981, suggesting that they had not been filled

Plate 3. Oblique photograph looking south-west after Hurricane Allen. Much of dune topography is covered by water. Darkest areas between the dunes indicate deep channelized water. Deer Island and water-covered wind tidal flat dominate background of photo. Beach, washover channel, and vegetated flat are visible in foreground.

to their pre-Allen levels.

Channels were cut across the dunes themselves to a depth of two feet (0.6 m), reworking the eolian stratification in the outer parts of the dunes. Small pieces of uprooted vegetation, that were deposited in these scoured areas, were presumably transported from the foredune ridge or vegetated flat.

Winter Wind Regime

The dune profile of January 1981 differed significantly from the profile of June 1980. Slipfaces shifted to the south side of the dunes because the northerly winds of winter overpowered the onshore breezes (Fig. 10). Interdunal datum levels of January 1981 differed from those of June 1980. Dune height relative to the January datum closely approximated pre-hurricane dune heights associated with the June 1980 datum. This suggests that after scour channels were filled, enough sand was added to the oblique dunes, by northerly winds of late October and November to return the dunes to their original volumes.

Concurrent with the increased volume of sand in the oblique dunes was the lack of interdunal barchans. Sand from washover fans is transported more efficiently as a tractional carpet than by barchan migration during high velocity northerly winds (Plate 4). Because no sand is tied up by barchan dunes, more sand is available to the oblique dunes. Under normal conditions, the oblique dunes might be taller during the winter than the summer, if there were no barchans. Hurricane Allen caused the oblique dunes to have similar heights in both seasons.

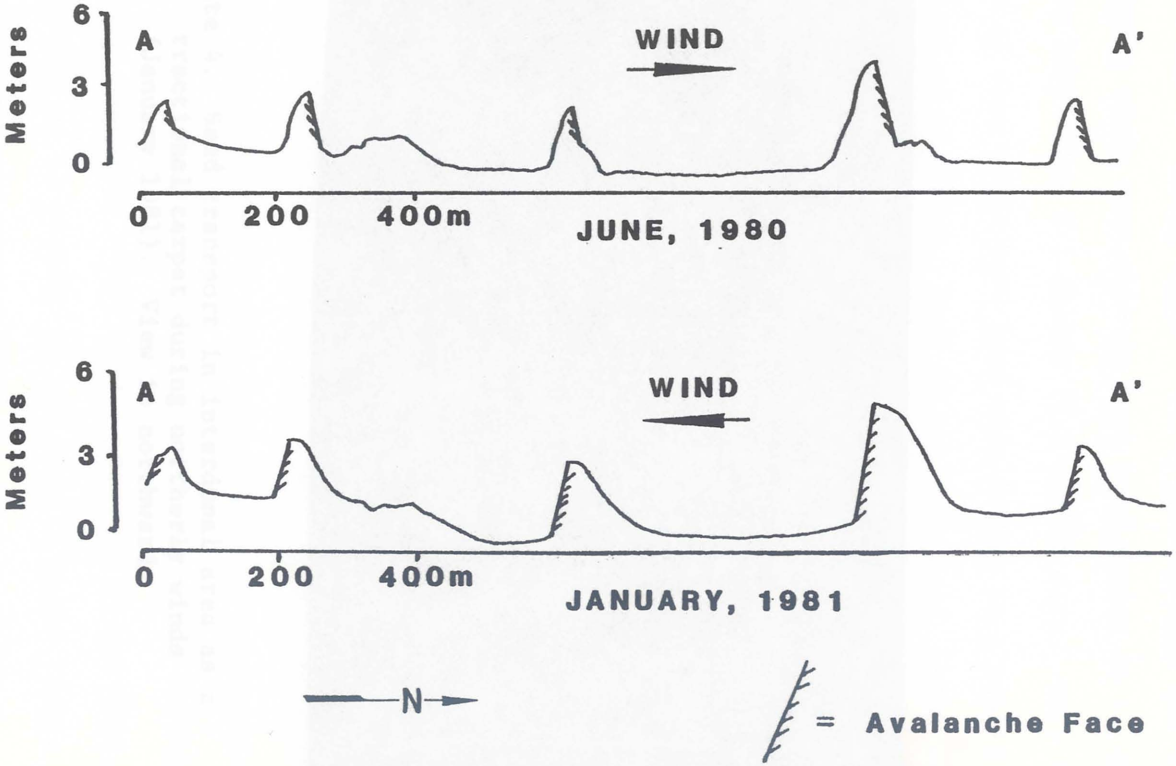


Figure 10. Comparative dune profiles along A-A', in June 1980 and January 1981. Vertical exaggeration = 40x. Datum levels of these profiles differ.

Plate 4. Sand transport in interdunal area as a tractional carpet during northerly winds (January 1981). View is northward.

The oblique dunes of June 1981 would be smaller than those of June 1980 if not for the added source material from the washover fans. Changes in datum levels make such a comparison impossible, however.

An important observation made in January 1981 was that the constant northerly winds were able to move sand grains at a rapid rate, less than an hour after 0.1 inches (0.3 cm) of rain. Only the top few centimeters of sand would have been able to dry as a result of the desiccating effects of the wind. Most of the dune sand, which was wetted to a depth of a few inches, remained stationary. Nevertheless, a sizable volume of sand was moved by these northerly winds. Most of the sand that was transported was deposited from suspension as grainfall on the leeward slopes of the dunes. As a result of this deposition, and distribution of stratification types, the leeward slopes were drier than the windward slopes.

Transitional Wind Regime

The processes observed in March 1981 were representative of a transitional period between winter and summer dominated wind regimes. The amount of time that winds blew from the north gradually decreased, so that by the end of March, there were few days that northerly winds were recorded. Northerly winds blew 27 percent of the time in February 1981, as compared to 15 percent of the time in March (Table 2).

As the northerly winds became less common, there was a dramatic change in the dune morphology. Southerly winds eroded the south-facing slipfaces and dune crests, thus reducing dune height. This produced flatter dunes with broad crests on one or both flanks of the dunes

(Fig. 11). The actual amount of flattening was revealed by reprofiling a dune that was carefully measured in January 1981 (Fig. 12). Whereas this dune was 18 feet (5.5 m) tall in January, it was only 11.5 feet (3.5 m) tall the following March. The dune crest was therefore reduced in height by at least 6.5 feet (2.0 m), or 36 percent, between January and March.

In the largest dunes in the field, those greater than 20 feet (6.1 m), the slipfaces were not eroded to such a great extent, because there was a greater volume of sand to disperse. In these large dunes, the transition time was not long enough to greatly reduce the dune height; the only change was the slight rounding of the dune slipfaces. This rounding occurred by the erosion of the tops of the slipfaces and the deposition of rippled sand on their bases.

In oblique dunes of all sizes, small north-facing barchanoid slipfaces developed on the dune crests as the south-facing slipfaces were being rounded by the southerly winds (Plate 5). These two-foot (0.6 m) tall barchans, supplied with sand from the large eroding slipfaces, migrated from the southern zones of erosion to the northern sides of the dunes. There were often two barchanoid dunes, one windward of the other, migrating at the same time (Fig. 13).

The migration rates of these small barchanoid slipfaces were not obtained because they were destroyed by the passage of subsequent northerly winds. It is therefore concluded that there are commonly several episodes of barchanoid dune advancement and destruction during the transitional periods. The wind shifts also cause winter-oriented grainfall and avalanche deposits to become interbedded with summer-

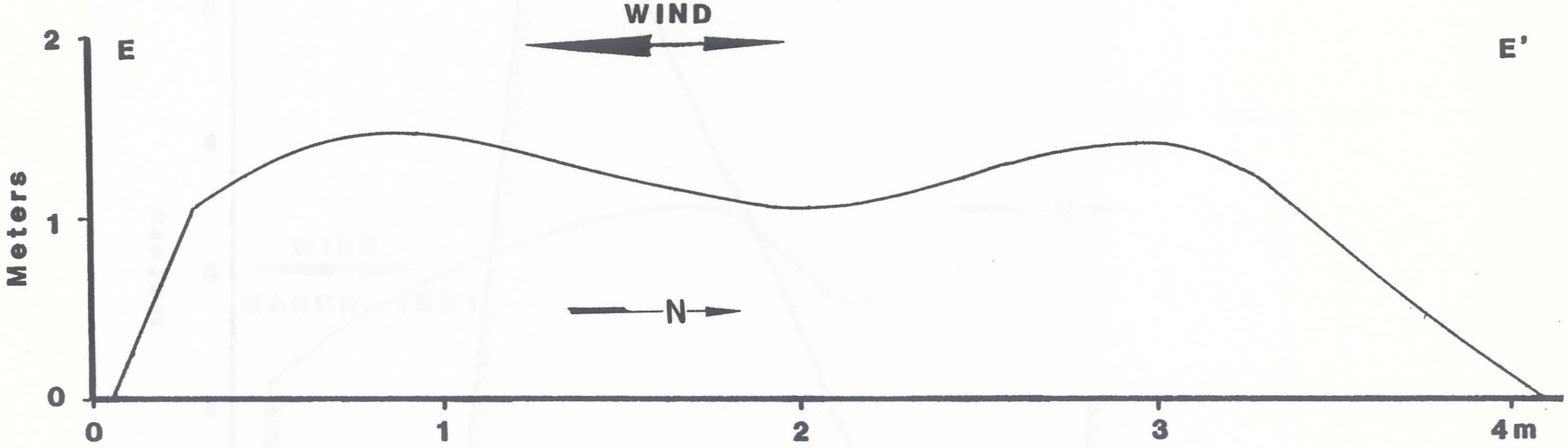


Figure 11. Profile E-E' (Fig. 6) in March 1981. The two dune crests were separated by a broad moderately flat area. A rounded slipface was evident on the southern slope of the dune. Vertical exaggeration = 2x.

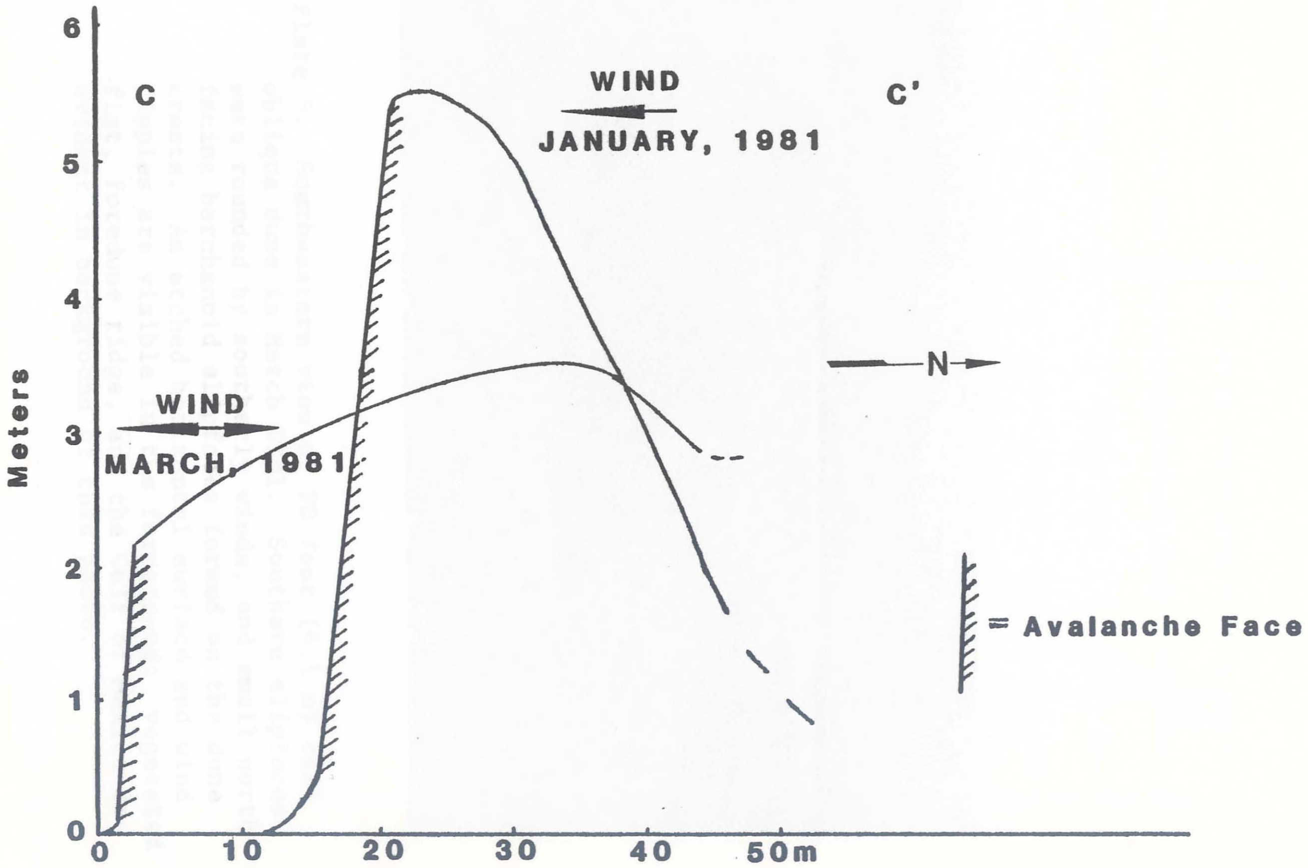


Figure 12. Comparative dune profiles along C-C' (Fig. 6), in January and March 1981. Vertical exaggeration = 10x.

Plate 5. Southeastern view of 20 foot (6.1 m) tall oblique dune in March 1981. Southern slipfaces were rounded by southerly winds, and small north-facing barchanoid slipfaces formed on the dune crests. An etched horizontal surface and wind ripples are visible in the foreground; vegetated flat, foredune ridge, and the Gulf of Mexico are evident in background of this photo.

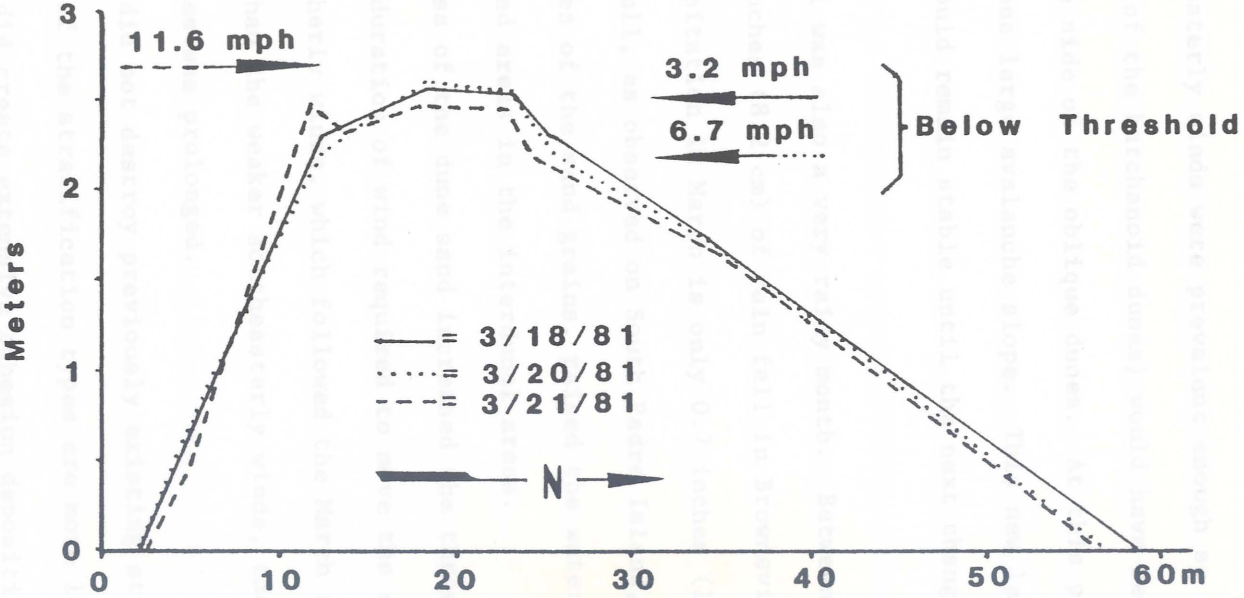


Figure 13. Dune morphology changes along profile F-F' (Fig. 6) during transitional wind regime. Vertical exaggeration = 10x.

oriented rippled deposits at the base of the southern slopes of the dunes.

Wind data from Brownsville (Table 2) suggest that by the end of March, the southeasterly winds were prevalent enough so that the north-facing slipfaces (of the barchanoid dunes) would have been able to migrate to the north side of the oblique dunes. At this point they would coalesce to form one large avalanche slope. This new larger north-facing slipface would remain stable until the next change in wind regime in October.

March 1981 was also a very rainy month. Between March 10th and 11th alone, 3.3 inches (8.2 cm) of rain fell in Brownsville, although the average precipitation in March is only 0.7 inches (1.8 cm)(N.O.A.A., 1980). The rainfall, as observed on South Padre Island, increased the cohesive properties of the sand grains, raised the water table, and created many ponded areas in the interdunal areas.

The wetness of the dune sand increased the threshold value for the velocity and duration of wind required to move the sand grains. Since strong northerly winds, which followed the March rain, moved more of the wet sand than the weaker southeasterly winds, the winter orientation of the dunes was prolonged.

The rain did not destroy previously existing stratification, even though some of the stratification types are more loosely packed than others. It did create extensive adhesion deposition in the interdunal areas, as well as zones of contact between eolian and subaqueously deposited strata.

Rain may also have played a part in flattening the dunes. If there was a rising water table because of rain, much of the wet sand on the windward slopes of the dunes would have remained stationary as the dunes migrated southward. This would reduce the volume of sand blowing across the slipfaces of the dunes, and so the slipfaces would have become smaller as they advanced. This mechanism for reducing the height of the dunes is not clearly responsible for the dune flattening observed in March 1981; there was not enough rain between January and March to retain a high water table. It may have played a minor role however, and would be an important process following extensive rains, provided that there is a strong unidirectional wind.

Summary of Morphological Changes

The oblique dunes studied may be classed as reversing dunes since they migrate north in the summer and south in the winter. The amount of seasonal migration evens out during the course of the year. In January and February, the frontal-related northerly winds alternate with the fair weather southeasterlies. The northers are able to do more work, so the dune slipfaces remain on the southern side of the dunes.

In March, the number of northers decreases, and the southeasterly winds are gradually able to erode the southern slipfaces. The smaller dunes are flattened and increase in width without losing volume. Both the large and the small dunes have their southern flanks reshaped into a series of small, north-facing avalanche slopes which migrate toward the northern sides of the dunes.

In April, the reshaping of the dunes into their north-facing orientation is completed; the southern slopes are eroded, and the deposits are incorporated by northern slopes. The southeasterly winds entrain any available sand from the washover channel south of the dune field, and deposit this sand on the northern flanks of the dunes.

From April through September, the dune slipfaces migrate northward, and the dunes may increase in volume. Precipitation, whether associated with the thunderstorms of May, June and September, or with the possible hurricanes of late summer, reduce the effectiveness of the southeasterly winds. This reduces dune migration rates.

In late October, strong northerly winds rapidly shift the slipfaces to the southern sides of the dunes. This is probably similar in depositional style to the March transition period. Because of the strength of the northerly winds, the transitional dune morphology of October should be shorter in longevity than in March; the northers can erode and redeposit the sand faster than the southeasterly winds do in March.

In November and December, the northerly winds associated with storms are more prevalent than the fair weather winds. The slipfaces of the dunes migrate southward in a short period of time, so that by the end of the winter wind regime in February, the dunes have moved as much as 65 feet (19.8 m) from their early November positions. There is no net migration of the dunes overall, and the central cores of the dunes remain stationary throughout the year, resulting from mounding of the water table within the dunes. Until the source of sand-sized grains is depleted and later replenished by processes related to hurricanes, the northerly winds pick up sand from the washover fan north of the dune field, depositing this sand onto the leeward slopes of the dunes.

EOLIAN STRATIFICATION TYPES

Translatent Stratification

Translatent strata are formed by the migration of wind ripples (Hunter, 1977a, 1977b). As the grains proceed tractionally across the ripples, the larger sand grains become segregated from the fine population. Large grains remain stable at the ripple crests, whereas finer grains are deposited in ripple troughs, where wind velocity is reduced. If there is net deposition, coarser grains move over the finer population as the ripples migrate, creating an inversely graded deposit. As a result of this mechanism of formation, the resulting translatent strata are closely packed, and thus are capable of retaining water between the grains.

Wind ripples are most prominent on the windward slopes of the dunes, but they also occur on leeward slopes when there is an oblique component of the wind blowing across the dune slipfaces. In the latter situation the ripples climb in a direction perpendicular to the dip of the slipface. The ripples are best preserved leeward of the slipface on the apron at the base of the dunes. The resulting translatent strata are characterized by shallow-dipping angles of 0 to 20 degrees (Hunter, 1977a). Translatent strata may also be preserved in depressions in windward slopes of the dunes, on flat windward slopes when another dune is climbing over these slopes, and in deflated areas.

The foresets of the ripples, although preserved within the dunes, were rarely visible in translatent strata observed in trenches.

They were, however, sometimes visible on etched horizontal surfaces (Plate 6). The translatent strata in the dunes studied were of the subcritical type, in which the angle of the stoss slope, relative to the former depositional surface, is greater than the angle of ripple climb (Hunter, 1977a, 1977b). Translatent strata observed in the dunes on South Padre Island had an average dip of eight degrees.

Grainfall Laminae

Sand grains are deposited from saltation and partial suspension onto the leeward slopes of the dunes because of wind separation. The grains that are deposited in this manner are referred to as grainfall deposits, and drape the pre-existing leeward surfaces of the dunes. The resulting stratification type is a grainfall lamination.

Grainfall laminae can be recognized in trenches by their intermediate packing and medium to high dip angles, normally 20 to 30 degrees (Hunter, 1977a). Grainfall deposits are modified by grainflow and wind ripple migration (during windshifts) on slipfaces, and by rippling on the toes of leeward slopes. Grainfall deposits are best preserved leeward of the grainflow deposits (Kocurek and Dott, 1981).

Grainflow Stratification

Grainflow deposits form when the grainfall deposits on the upper slipface oversteepen, and the sand grains avalanche down the slope. As the grains slide past each other, dispersive pressures push the larger grains to the surface of the flow, and create an inversely graded deposit (Bagnold, 1954; Kocurek and Dott, 1981). Grainflow

Plate 6. Climbing wind ripple structure exposed on etched horizontal surface, on windward slope of an oblique dune. Pencil indicates north.

strata exhibit open packing, and average an inch (2.5 cm) in thickness in the dunes observed in this study. Because the dune slopes are at, or greater than, the angle of repose during avalanching, grainflow strata commonly have dip angles of 28 to 34 degrees (Hunter, 1977a). They average 32 degrees in the oblique dunes studied on South Padre Island.

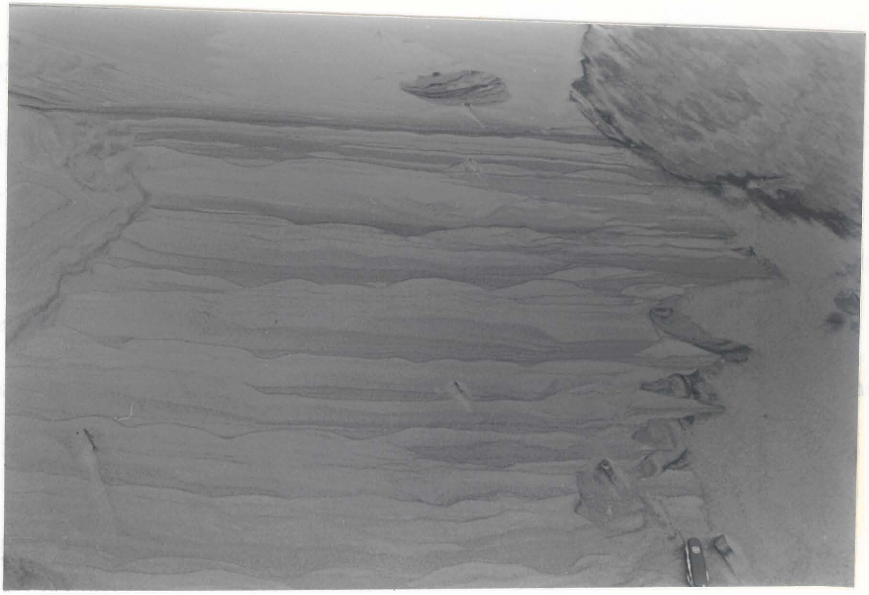
The process of grainflow is inhibited by wet conditions, which increase the cohesiveness of the sand grains. Wetness allows slipfaces to oversteepen without avalanching, although slumping may result. Slumps were not observed in this study.

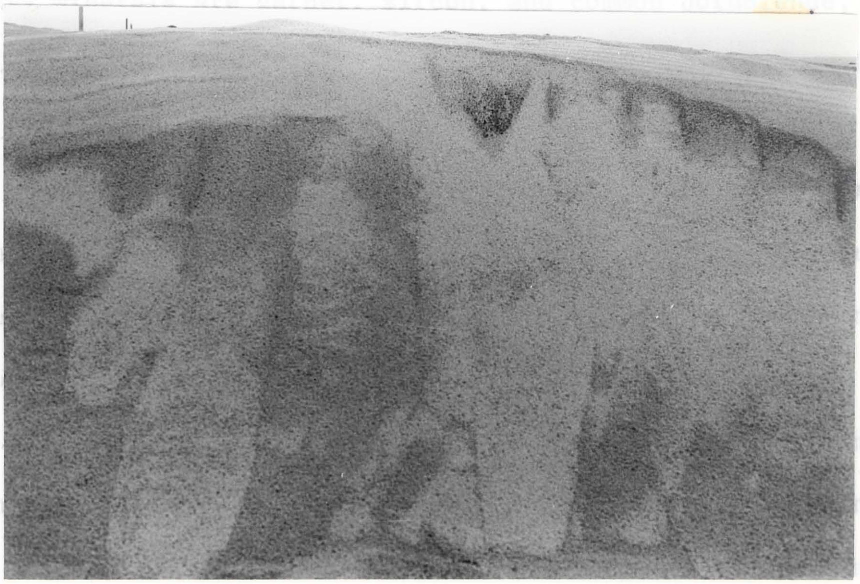
Grainflow deposits are closely related to grainfall deposits, since the process of grainflow can redistribute slipface deposits that were originally laid down by grainfall. Since a grainflow deposit is normally buried by several centimeters of grainfall before over-steepening triggers another avalanche, grainfall and grainflow deposits are commonly interbedded (Plate 7).

Hunter (1977a) and Kocurek and Dott (1981) suggest that grainflow deposits are thicker on large slipfaces because greater volumes of sand can avalanche down these slopes. This conclusion appears to be substantiated in the oblique dunes on South Padre Island. One-half inch (1.3 m) thick grainflow deposits were observed on 3.0 foot (1.0 m) tall dunes (Plate 8), whereas 15 foot (4.6 m) tall dunes exhibited avalanche deposits which were up to 1.5 inches (3.8 cm) thick. The grainfall deposits were generally thicker than the tabular grainflow deposits in these relatively small dunes.

Plate 7. Coalesced lobes of light-colored grainflow deposits (center of photo) interlaminated with layered grainfall deposits (darker in color). Exposure shows an etched surface on a dune crest.

Plate 8. Grainflow down moist slipface of three foot (0.9 m) tall oblique dune (March 1981). View is northward, winds were from the north.





Planebed Laminae

Planebed laminae result from tractional deposition under extremely high velocity winds, and may be distinguished from translatent strata by their poor segregation of grain sizes (Hunter, 1977a). No planebed laminae were observed in the dune trenches on South Padre Island, even though high velocity winds did blow across the area. It is likely that these deposits have a low preservation potential, and are modified by subsequent low velocity winds.

Grain Size Characteristics

The sand grains in the dunes studied may be classed as orthoquartzitic, being composed almost entirely of quartz grains. Heavy minerals account for 0.06 percent of the grains present. The most abundant heavy minerals are garnet, zircon, and common hornblende, and they are indicative of a Rio Grande source area (Foley, 1974). Shell debris is also a minor constituent of the eolian sand.

The sand is fine-grained, averaging 2.47 phi, as determined by Rapid Sediment Analyzer (Table 3). It is mature, very well sorted, and has a mean skewness of +0.09 which suggests a nearly symmetrical grain-size distribution (Folk, 1974).

Samples for textural analyses were taken from surface deposits and trenches. Because of the excellent sorting of the sand, and quantity of samples taken, none of the textural relationships are statistically reliable. Ripple crests were slightly coarser than the inter-ripple troughs. The mean grainsize for ripples and the translatent

Sample	Depositional Type	Location	Mean (phi)	Sorting (phi)	Skewness
A	Inter-ripple	W	2.51	.23	+.11
B	Interdune		2.57	.25	+.04
C	Inter-ripple	W	2.50	.24	+.08
D	Grainfall	C	2.45	.22	+.17
E	Grainflow	L	2.38	.23	+.04
F	Grainfall	L	2.51	.26	+.02
G	Ripple	W	2.44	.21	+.17
H	Inter-ripple	C	2.49	.24	+.06
I	Ripple	W	2.44	.22	+.14
J	Ripple	W	2.46	.24	+.15
K	Inter-ripple	W	2.47	.20	+.02
L	Ripple	W	2.50	.21	+.13
M	Grainflow	L	2.36	.28	+.16
N	Inter-ripple	W	2.51	.25	+.02
O	Inter-ripple	W	2.60	.23	+.04
P	Ripple	W	2.39	.22	+.06
Q	Ripple	W	2.38	.24	+.07
		Mean	2.47	.23	+.09

Mean phi Ripple Crests = 2.40

Mean phi Inter-ripple Troughs = 2.51

Mean phi Grainfall = 2.48

Mean phi Grainflow = 2.37

Table 3. Textural analysis of sand samples.

W = windward slope of dune; C = dune crest;
L = leeface of dune.

strata that they form was 2.49 phi. Grainflow samples, which avalanched down the slipfaces of the dunes, were the coarsest deposits, averaging 2.37 phi. Grainfall deposits, which settled from partial suspension and saltation loads, had a mean grainsize of 2.48 phi; avalanching might have artificially made this value lower (coarser) than unmodified grainfall deposits would have been. A grainfall sample from leeward of the grainflow deposits had a mean grainsize of 2.51 phi, finer than both the ripple and avalanche deposits.

A comparison between ripples on the eastern and western sections of a dune, approximately one mile (1.6 km) apart, revealed that the western samples were 0.17 phi coarser on the average. This was true for both surface samples and trenched samples within the same depositional package. This may be a result of the closer proximity of the western samples to the source material of the washover fans.

DISTRIBUTION OF STRATA

Unidirectional Winds

When one wind direction is prevalent, the strata are distributed as in a migrating transverse or barchan dune. In this situation, the windward slopes undergo erosion, and few windward strata are preserved (Hunter, 1977a; Kocurek and Dott, 1981). The lee slopes are in the zone of separation of the wind, and net deposition occurs on those surfaces (Fig. 14). Grainfall deposits, which can be reworked by grainflow, are only preserved leeward of the slipfaces. Grainflow deposits are interlaminated with those of grainfall, generally being preserved on, or near the base of, the slipfaces of the dunes. Translatent strata are preserved leeward of the slipfaces, and are normally leeward of, and in contact with the grainfall deposits.

Multidirectional Winds

When there are two opposing wind directions, leeward depositional slopes of one wind regime are the erosional, windward slopes of the subsequent regime. Stratification preservation under these conditions occurs mostly in the bottom few feet of the dunes, where the strata are buried during both wind regimes. If rain accompanies one wind regime, the rising water table will preserve all of the deposits beneath the deflation surface (Hunter and others, 1972).

There is no net annual migration of the oblique dunes, under

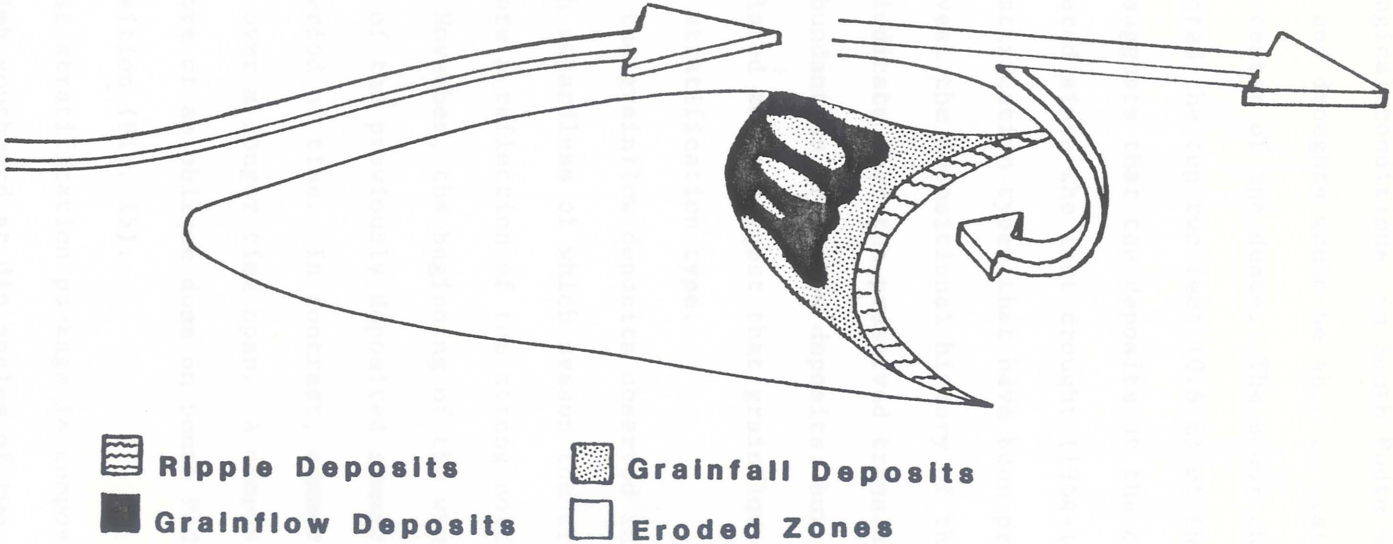


Figure 14. Preserved stratification types under unidirectional winds. Grainfall may additionally be preserved leeward of ripples on dunes smaller than a meter in height. Preservation occurs predominantly in the zone of wind separation. Based on Hunter (1977), and Kocurek and Dott (1981).

normal meteorological conditions, on South Padre Island. Consequently, only hurricanes and droughts would be able to disturb the preserved deposits at the center of the dunes. The scour channels from Hurricane Allen only affected the top two feet (0.6 m) of the eolian deposits, however. This suggests that the deposits at the center of the dunes have been unaltered since the last drought (1954-1956).

The stratification types that have been preserved at the center of the dunes reveal the depositional history of the dunes. Trenches dug into the dunes indicate that the preserved translatent and grainfall strata are as abundant as grainflow deposits, but north-dipping foresets observed in deflated zones suggest that grainflow deposits are the dominant preserved stratification type.

Most of the grainflow deposits observed in the trenches dip toward the south regardless of which season the trenches were dug. These deposits are a reflection of the strong northerly winds which are concentrated in November, the beginning of the winter wind regime. Therefore, most of the previously deposited summer strata are reworked in this short period of time. In contrast, summer reworking of winter deposits occurs over a longer time span. A composite section through the preserved core of an oblique dune on South Padre Island shows four periods of deposition (Fig. 15).

The first stratification package is composed of translatent strata which climb southward at dip angles of two degrees. This is associated with the overlying deposits, which consist of south-dipping grainfall and grainflow deposits (with 35 degree dip angles). These strata represent deposition during northerly winds of winter. The

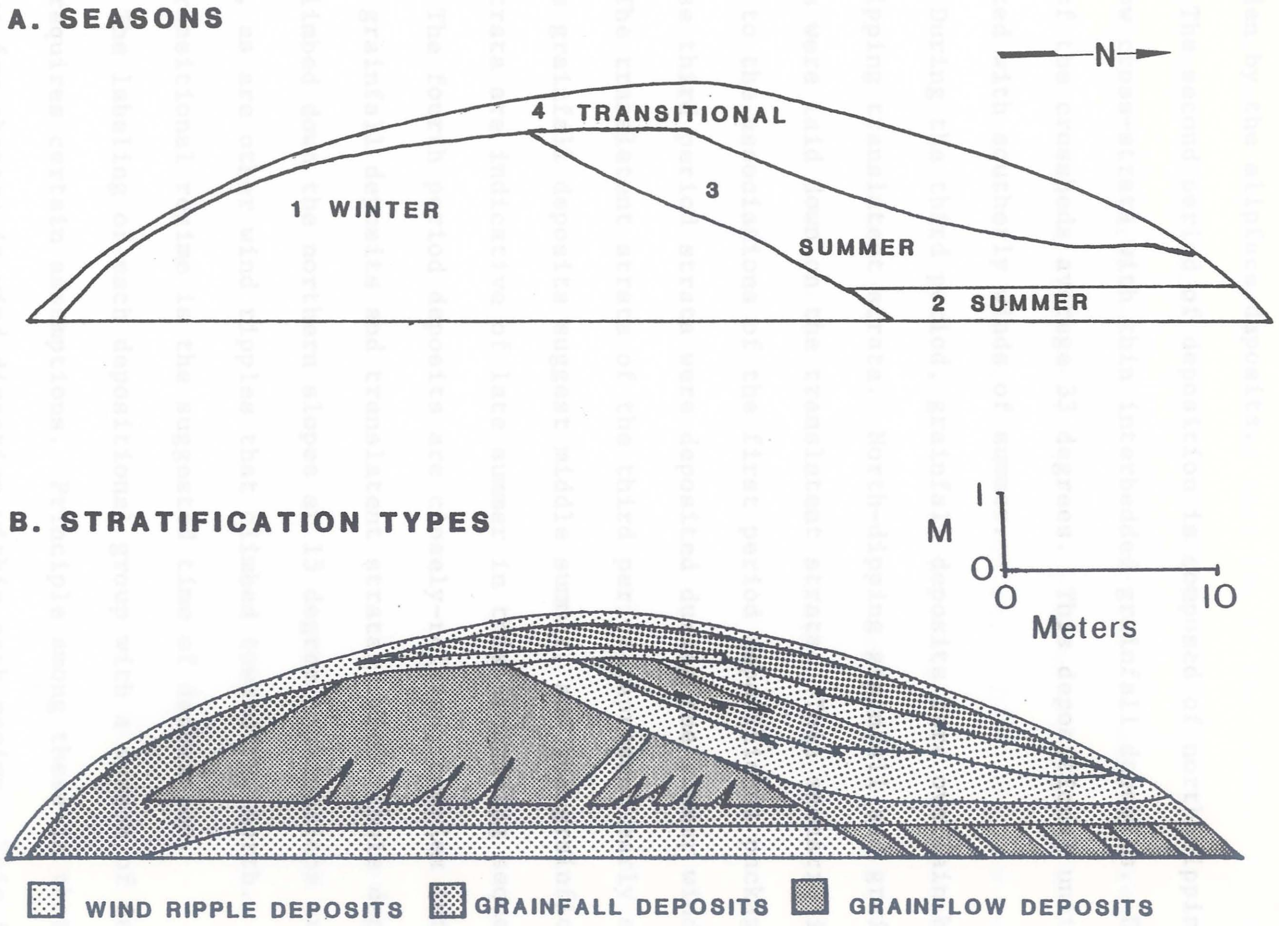


Figure 15. Composite section of a South Padre Island oblique dune core.

translatent strata might have been part of the dune apron, which was overridden by the slipface deposits.

The second period of deposition is composed of north-dipping grainflow cross-strata with thin interbedded grainfall deposits. Dip angles of the crossbeds average 33 degrees. This depositional unit is associated with southerly winds of summer.

During the third period, grainfall deposits were overlain by north-dipping translatent strata. North-dipping grainfall and grainflow deposits were laid down on the translatent strata. This scenario is similar to the associations of the first period depositional packages, but these third period strata were deposited during the summer wind regime. The translatent strata of the third period represent early summer, the grainfall deposits suggest middle summer, and the grainflow cross-strata are indicative of late summer in this prograding sequence.

The fourth period deposits are closely-related, complex interbeds of grainfall deposits and translatent strata. Wind ripple deposits which climbed down the northern slopes at 15 degree inclinations are evident, as are other wind ripples that climbed toward the north. A March transitional regime is the suggested time of deposition.

The labeling of each depositional group with a season of deposition requires certain assumptions. Principle among these is that there are few changes in wind direction within each regime. This is a valid assumption in the summer, but onshore winds are present approximately 50 percent of the time during the winter wind regime. The assumption made here is that if the northerly winds produce south-facing slipfaces, despite the southeast winds, then they are also strong enough to erode away any fair weather deposits.

The other major assumption is that few of the translatent strata climb down-dip. Since leeward slopes of the wind ripples were often not visible in the translatent strata, it is difficult to substantiate this argument. This study assumes that since ripples were observed to be climbing up-dip most of the time, and across most of the exposed surfaces of the dunes, few ripples that climb down-dip would be preserved within the dunes. Those that do not climb up- or down-dip can represent either season, and are best identified by comparison with associated grainfall and grainflow deposits.

OTHER SEDIMENTARY FEATURES

Yardangs

Yardangs are eolian erosional features which were observed near the brinks of some dunes in January 1981 (Plate 9). They occurred as a series of low ridges with shallow interyardang gullies, and were aligned parallel to the predominant northerly winds. Yardangs form when initial surface irregularities, such as gullies formed from rilling, direct and concentrate the strong winds (Blackwelder, 1934).

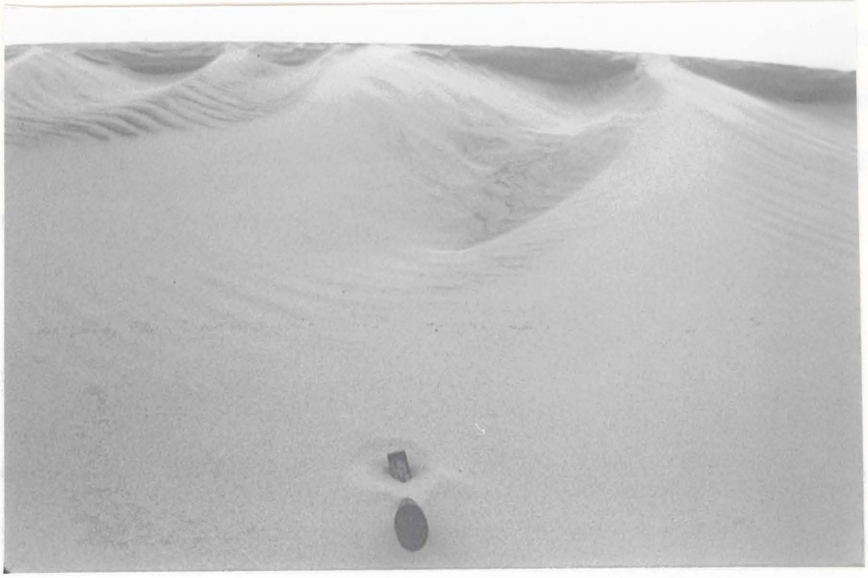
The yardangs formed during the winter wind regime because the winds were strong, and the dampness of the sand caused the strata to be differentially resistant to the wind. Loosely packed grainflow strata retain little water, and were preferentially eroded into gullies, whereas overlying, tightly packed wind ripple strata retained more water and were not eroded. The yardangs should be reworked when the sand dries, with sand from the ridges avalanching down the dune slipface, and interyardang troughs being filled by grainfall deposits.

Adhesion Ripples

Adhesion ripples were observed in the wet interdunal areas in January and March 1981 (Plate 10). These structures are defined as tiny ridges which are elongate perpendicular to the wind, and form by accretion on their windward sides by the adhesion of saltating grains (Reineck, 1955; Hunter, 1973, 1980; Kocurek and Fielder, in press). Because adhesion ripples require wet conditions, their presence during

Plate 9. Yardangs leeward of dune crest, observed during wet conditions and strong northerly winds (January 1981). View is toward the north. Hammer handle for scale.

Plate 10. Adhesion ripples in wet interdunal area (March 1981). Wind direction is from bottom to top of this photograph.



northers, and in the wet periods in May, June, and September, would be expected. They were not observed on the dunes themselves because the rainwater soaks into the dunes quickly, leaving the dune surfaces dry. Adhesion deposits are, in general, favored in (and diagnostic of) interdunal areas because of high water table levels and the presence of algal mats.

Etched Horizontal Surfaces

When wind deflates sand down to the water table, underlying strata are etched into relief (Plates 6,7). These etched surfaces were observed throughout the year, and occur primarily on the windward slopes of the dunes, and in zones where leeward eddy currents are active. Inasmuch as different stratification types do not retain equal amounts of water, the distribution of the underlying strata are apparent in the etched surfaces.

Remnant Foresets

Remnant north-dipping foresets from previous seasons of eolian deposition were observed north of some dunes in June 1980, and in January 1981 (Plate 11). These avalanche deposits, which were up to six inches (15.2 cm) tall, were elongate parallel to the dune crests. The sand grains of which these deposits were composed were bound together by moisture and salt. Wind-shadow deposition occurred leeward of these structures during the winter wind regime.

The absence of the remnant foresets in March 1981 was evidently a result of strong March rains flushing out the intergranular "cement".

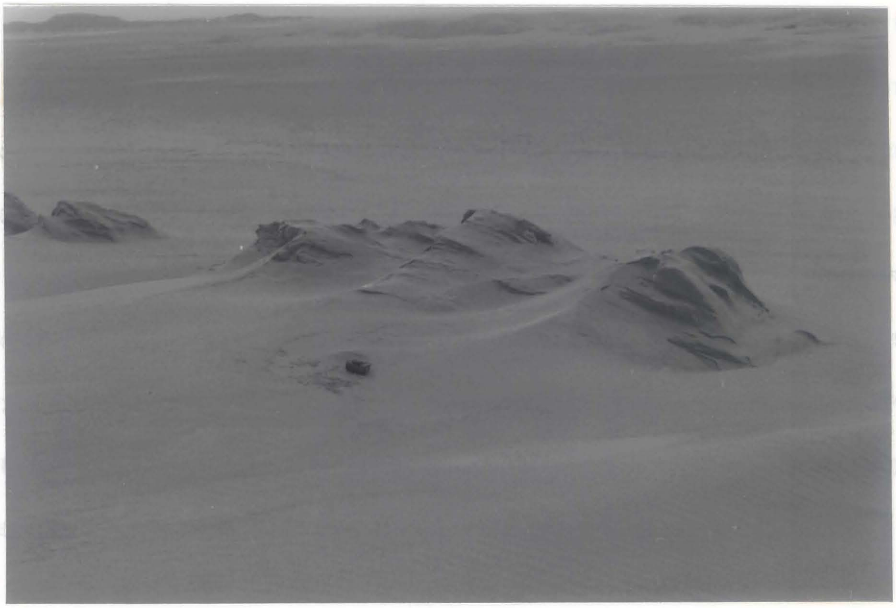


Plate 11. Western view of remnant foresets with wind shadow deposition on southern flanks (January 1981). Brunton compass in foreground for scale. Part of Deer Island is visible in upper-left corner of photo.

The foresets observed in January either formed after Hurricane Allen, or more probably, the dunes migrated far enough to envelope the remnant deposits before the hurricane struck. The absence of south-dipping remnant foresets suggests that the north-dipping deposits were stratigraphically lower, and so were more likely to be preserved in the deflation areas.

There were no remnant foresets on the southern side of the dunes, hence, it is likely that those north of the dunes represent a previous dune position. Although there is no net dune migration under present meteorological conditions, it is possible that the dunes did migrate in the past. Droughts would affect dune migration patterns. During long, dry periods, there would be little rain to check the strong northerly winds, and the dunes would migrate southward. The preserved foresets might therefore be remnants of a stable dune position prior to the last drought (1954-1956).

Structureless Deposits

Shallow-dipping structureless deposits were observed in some trenches. They formed as a consequence of grainfall of well-sorted sand into ephemeral interdune ponds (Fig. 16). Because of this dependence on ponded water, structureless deposits should form most readily in relation to winter rains, and should be commonly associated with deposition immediately leeward of dune slipfaces during northerly winds. Structureless deposits formed after summer thunderstorms should be thinner, since the ponds would dry faster. Some of these deposits would form after hurricanes, but only after the water table is low

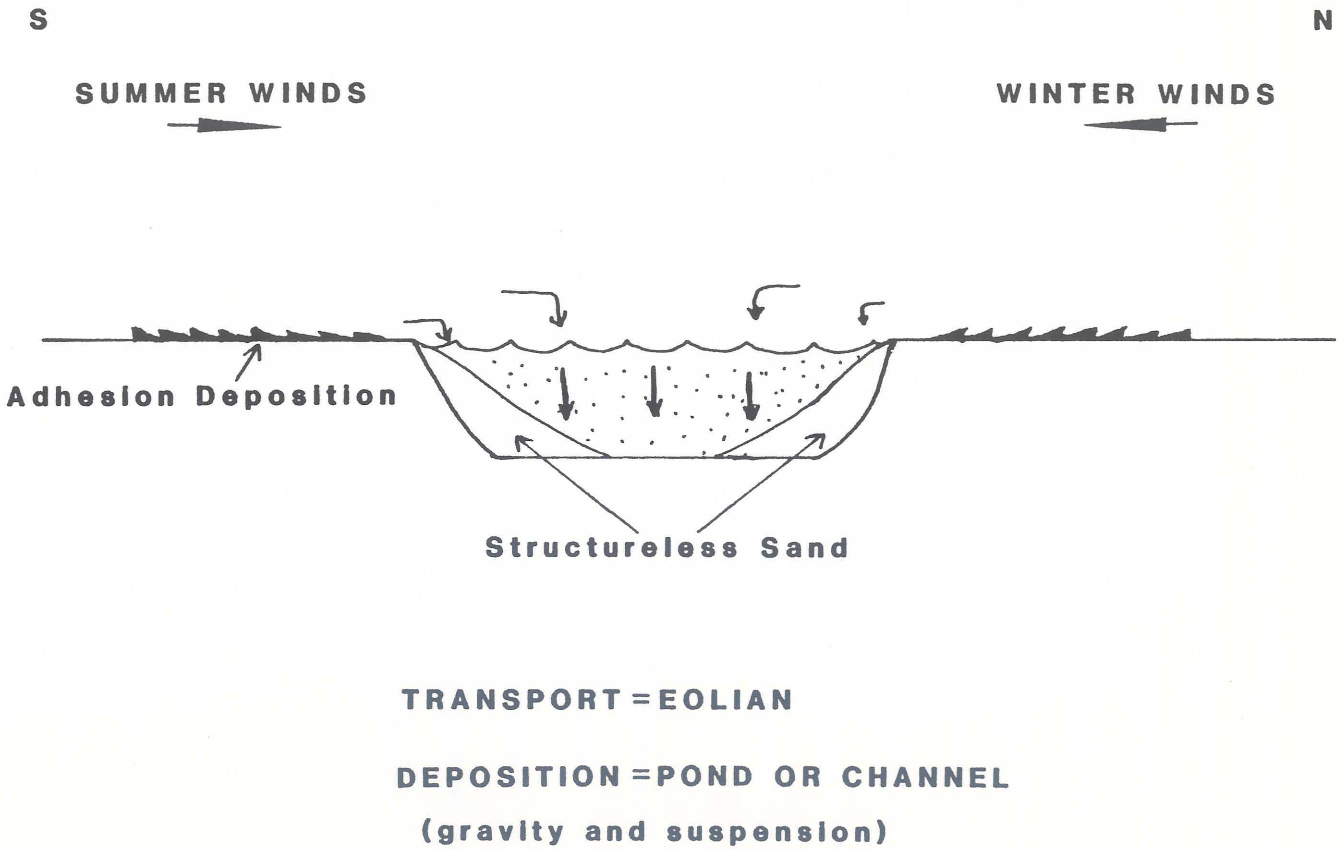


Figure 16. Formation of structureless sand deposits in interdunal ponds.

enough to permit eolian activity. Structureless deposits form contemporaneously with adhesion structures, as observed in March 1981.

APPLICATION TO ANCIENT EOLIAN DEPOSITS

Preserved oblique dune deposits should be similar to those of longitudinal and reversing transverse dunes, since these dune types have strata that dip in opposite directions. Proportions of strata that dip in opposite directions would depend on the dominance of each wind direction, and the orientation of the dunes to these directions. Since oblique dunes are not morphologically classed, and since detailed meteorological data are not well known for ancient dunes, oblique dunes would be difficult to distinguish in the geologic record. Also, as a result of this, ancient oblique dune deposits might have been mislabeled in the literature.

Small-scale stratification types, as shown by Hunter (1981) and Kocurek and Dott (1981) can be distinguished in ancient eolian deposits. It is likely that the larger stratification packages described in this study (i.e., Fig. 15, period 1 and 3 deposits) will be observed in the rock record, as stratification styles of ancient eolian deposits come under close scrutiny.

CONCLUSIONS

The oblique dunes on South Padre Island are reversing dunes which are dominated by southeasterly onshore winds from April to September, and northerly, storm-related winds from November through February. The dune slipfaces migrate north in the summer, and south, at a much greater rate, in the winter. Although the slipfaces may move as much as 65 feet (19.8 m) during each wind regime, there is presently no net annual migration of the dunes.

Winter deposits dominate the internal stratification of the dunes. This is partly a result of strong northerly winds that erode and redeposit the pre-existing summer deposits. Southerly winds blow often enough to maintain the oblique orientation of the dunes. The winter deposits would also be dominant if the dunes underwent net migration south, during dry northers of drought periods.

Hurricane Allen did little to alter the dunes in spite of its intensity. Although the washover fans, which the hurricane created, provide a source of sand for the dunes, the long-term effects of Hurricane Allen on the oblique dunes will be negligible.

The oblique dunes of South Padre Island will continue to be stable features in the short-term unless their protective foredunes are breached during a hurricane, an unusually heavy rainy season allows the oblique dunes to become vegetated, or a severe drought allows them to migrate close to the adjacent washover channel. Eventually the dunes will be destroyed by the encroachment of Deer Island or shoreline erosion.

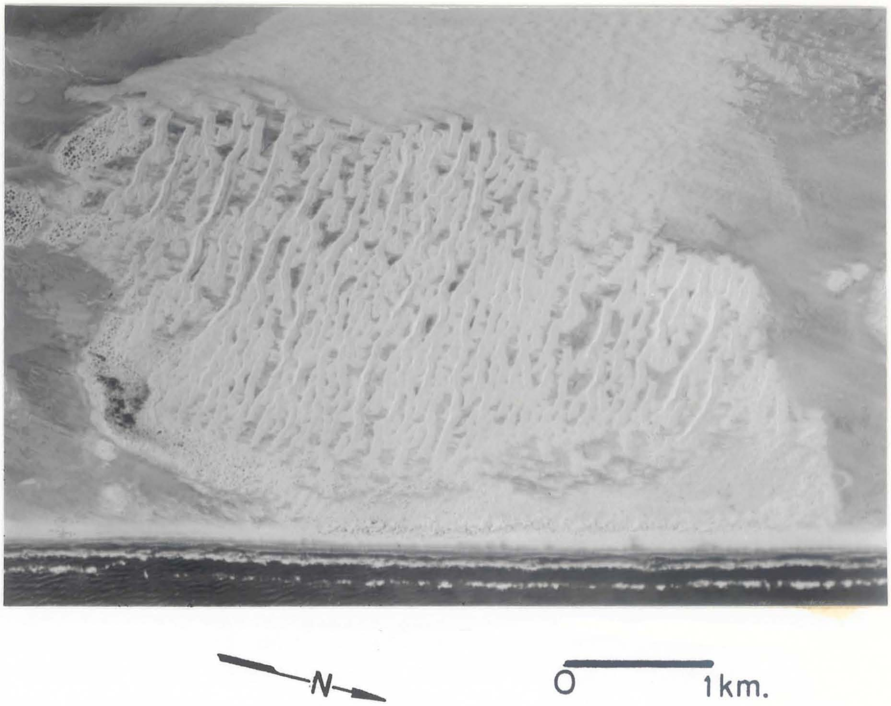
APPENDIX I

Selected aerial photographs, taken by the Texas General Land Office, are exhibited in this appendix. These photos illustrated changes in the dune field with respect to different meteorological phenomena, and date from 1954 to 1980. Related meteorological events, wind regimes, and brief descriptions of each picture are provided.

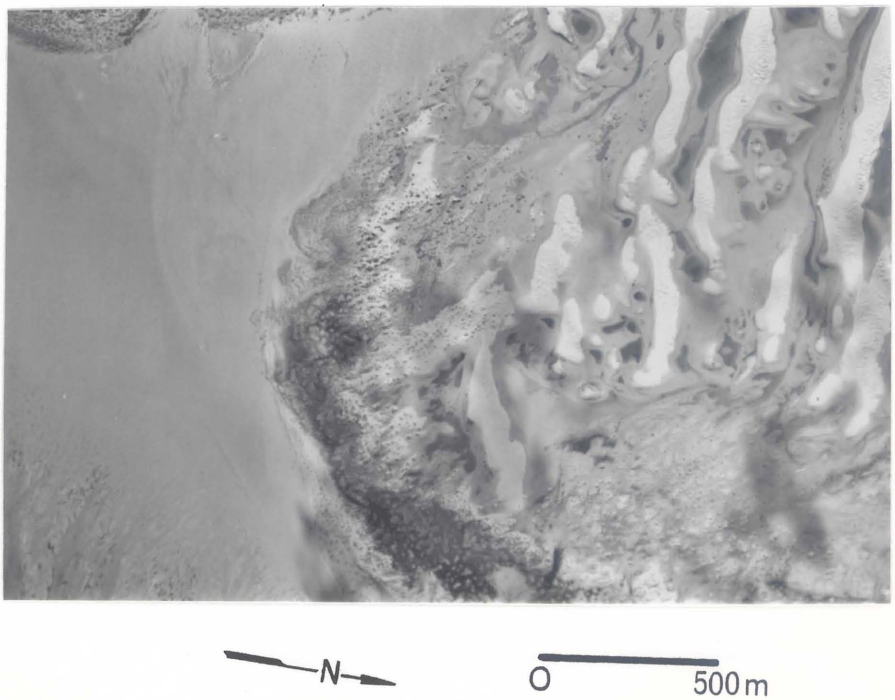
A. January 6, 1954 (winter wind regime). View of dunes during a major drought period; little apparent vegetation. There are many dune crests and narrow interdunal areas. Avalanche faces are on southern (left) slopes of the dunes. The western-most portions of some dunes are elongate parallel to northerly winds. Three small islands south of the dune field are not well developed, washovers are dry, and Deer Island is out of view to the west.

B. September 25, 1967 (summer wind regime). View of the southeastern part of dune field, adjacent to washover channel. The drought of 1954-1956 has been replaced by more humid conditions. Foredune ridges have therefore become more densely vegetated protecting the back-island dunes from the storm waves of Hurricane Beulah (September 20, 1967). Dunes are partly submerged, and the washover channel is filled with water. Not visible in this photograph are two small breaches in the foredunes. The three islands adjacent to the washover channel are better stabilized by vegetation.

A



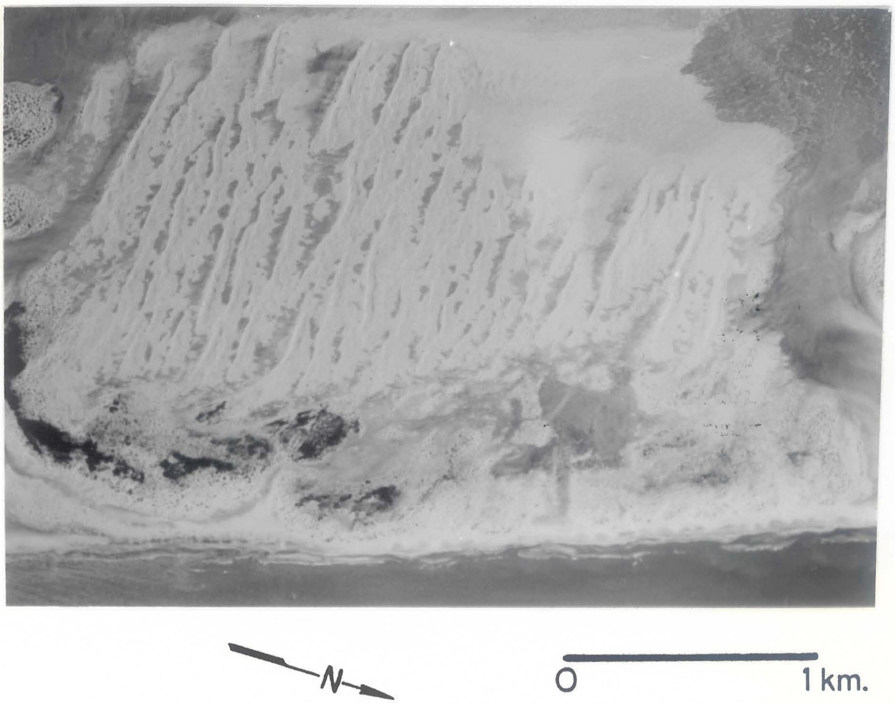
B



C. November 9, 1969 (winter wind regime). The dune field has recovered from Hurricane Beulah, although channels are still present near the three islands and in the foredunes. Vegetation has continued to spread, and the number of oblique dunes is reduced from the 1954 level.

D. June 11, 1979 (summer wind regime). Vegetation expansion and widening of interdunal areas has continued. Channels in the dune field from Beulah are filled by vegetation and eolian deposition. Deer Island has advanced toward the oblique dunes. Avalanche faces are on the northern slopes.

C



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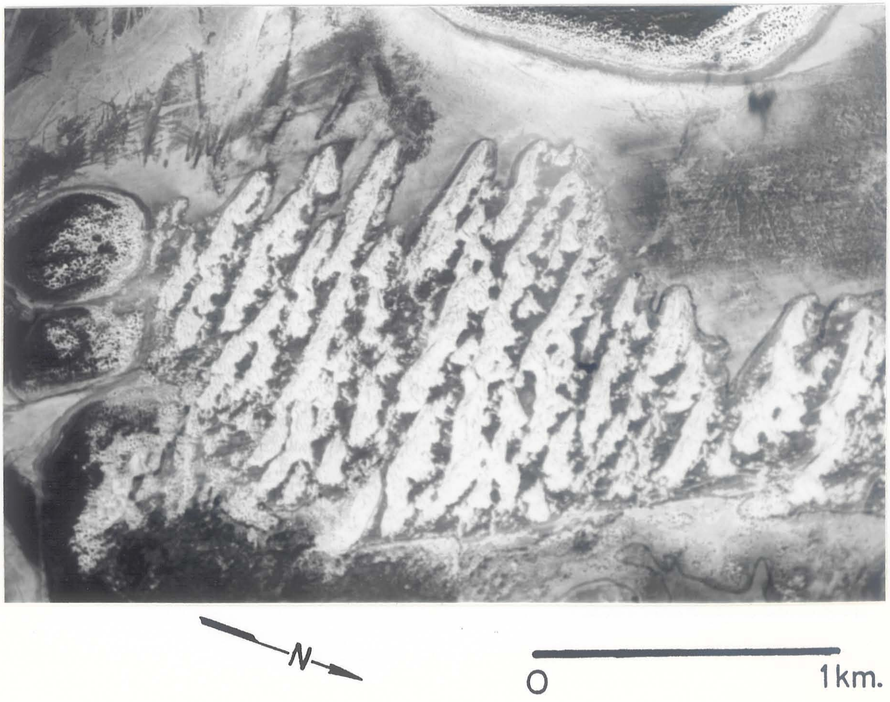
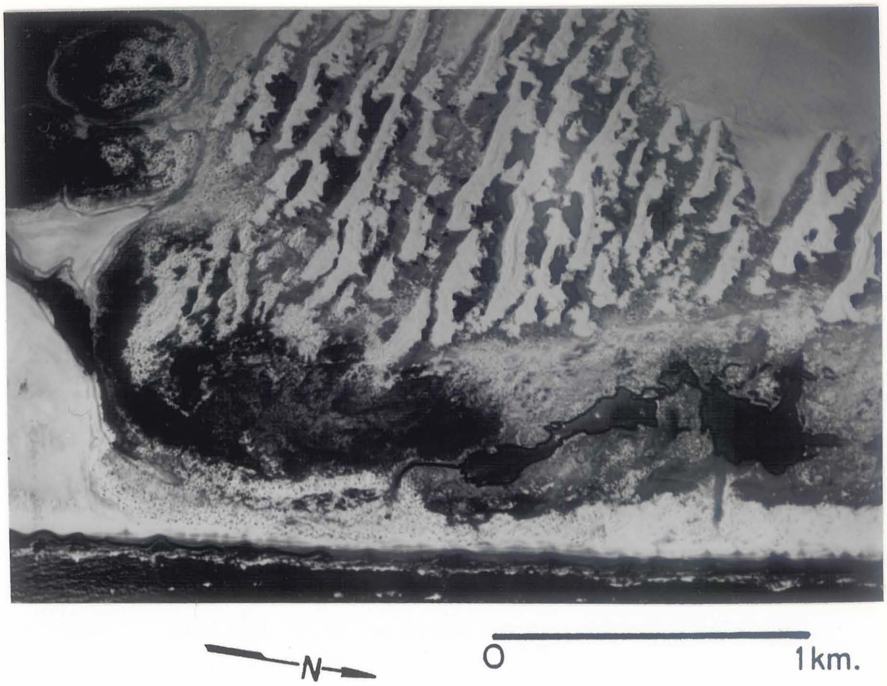


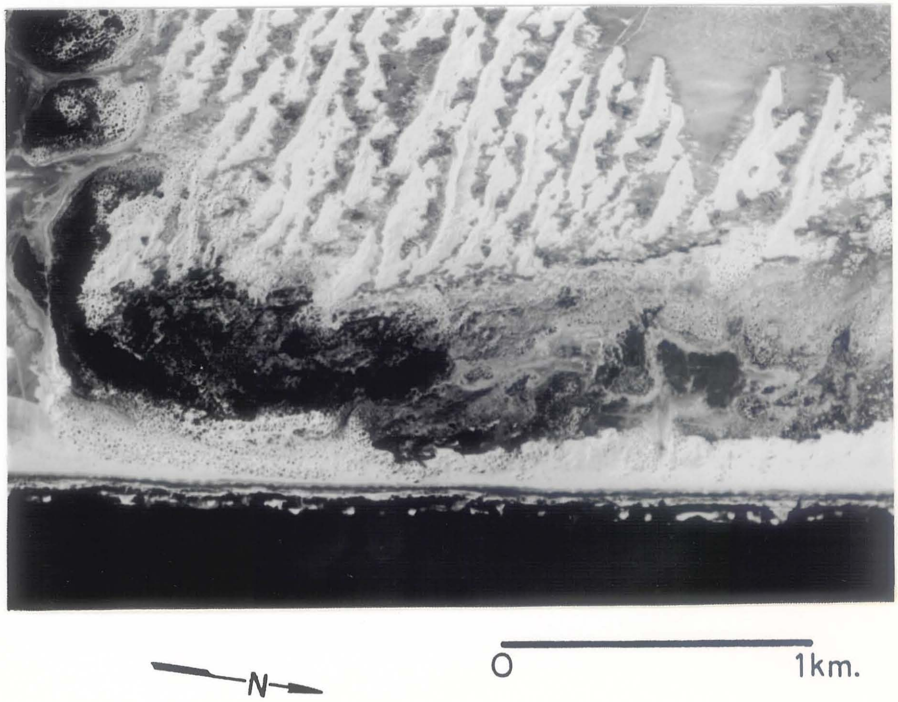
E. October 5, 1979 (transitional wind regime). Avalanche faces are central on the dunes.

F. January 14, 1980 (winter wind regime). Avalanche faces are on the southern dune slopes.

E

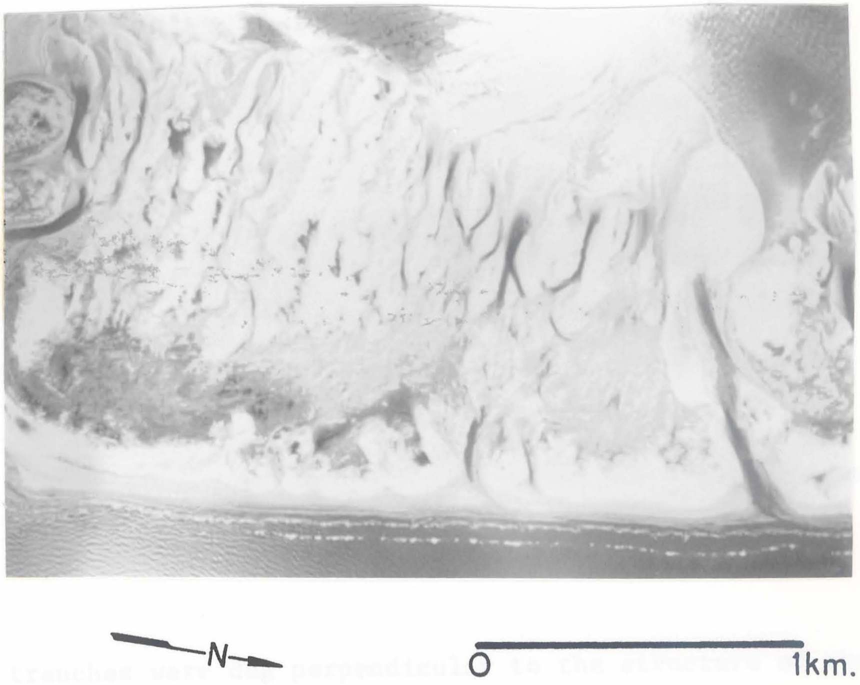


F



G. August 28, 1980 (summer wind regime). Washovers are reactivated. Channels in foredunes and through oblique dunes as a result of Hurricane Allen (August 10, 1980). Breaches in foredunes coincide with those caused by Beulah in 1967. Fan deposits are associated with channels. Subaqueously deposited dune-forms are evident between the oblique dunes and Deer Island.

G



APPENDIX II

Trench photographs are exhibited. Position on the dune and time of digging are indicated. No photographs were taken of trenches dug in January 1981.

Interpretation of the stratification types are presented verbally and graphically. Patterns used to describe each stratification type are as follows:

░ = Translatent strata

▒ = Grainfall deposits

▓ = Grainflow cross-strata

□ = Interdune deposits, structureless deposits, hurricane deposits

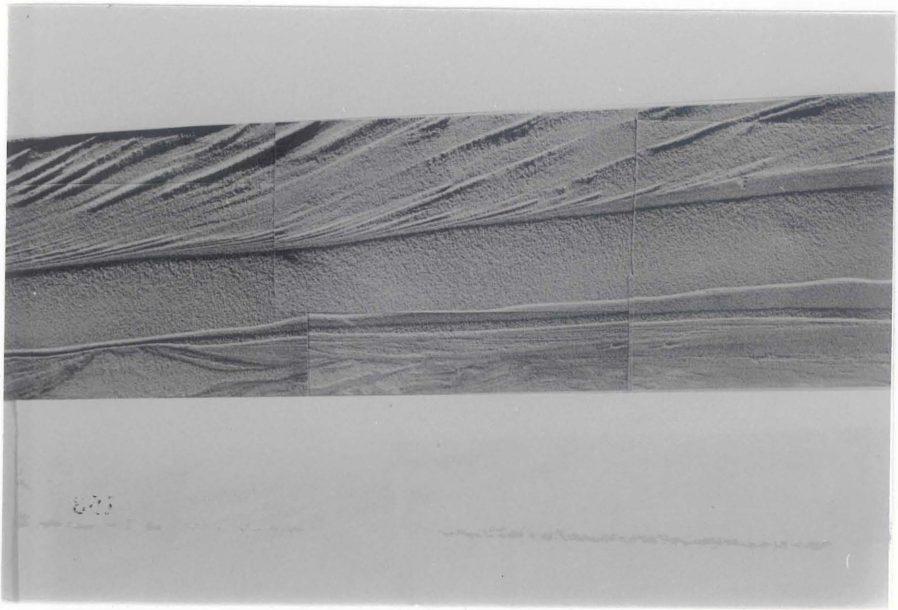
All trenches were dug perpendicular to the structure of the uppermost unit.

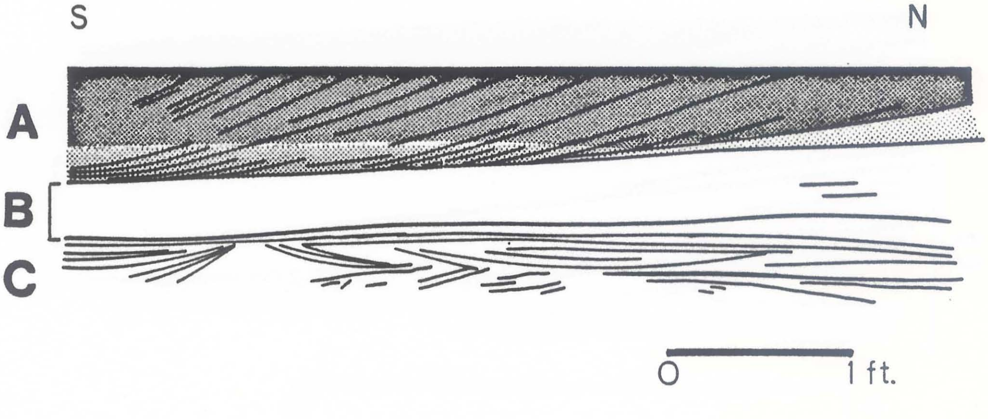
Trench 1. West face, southern slope, June 1980.

A. Thick grainflow deposits (dipping 26 degrees south) overlie grainfall deposits (19 degree dips) and translatent strata (11 degree dips).

B. Structureless sand from deposition into interdunal pond.

C. Interdune deposits.

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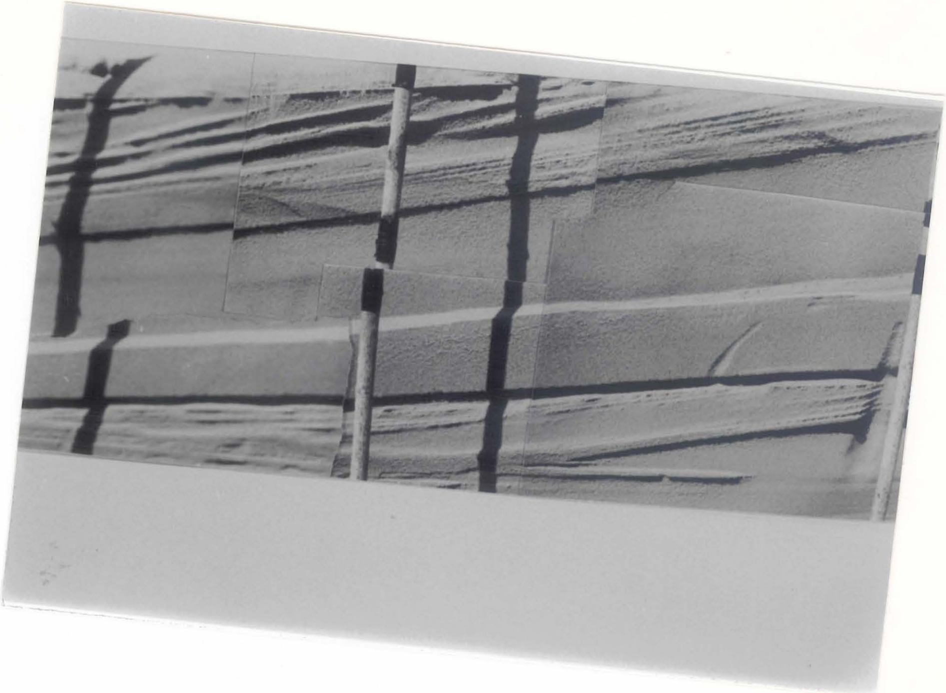
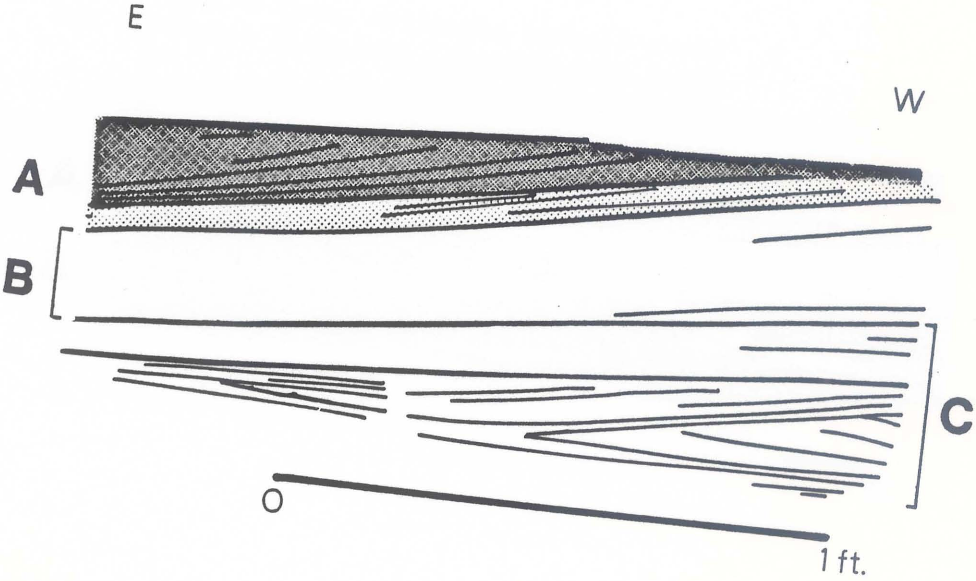
Trench 1. South face, southern slope, June 1980.

A. Grainflow deposits overlie translatent strata.

B. Structureless sand.

C. Interdune deposits.

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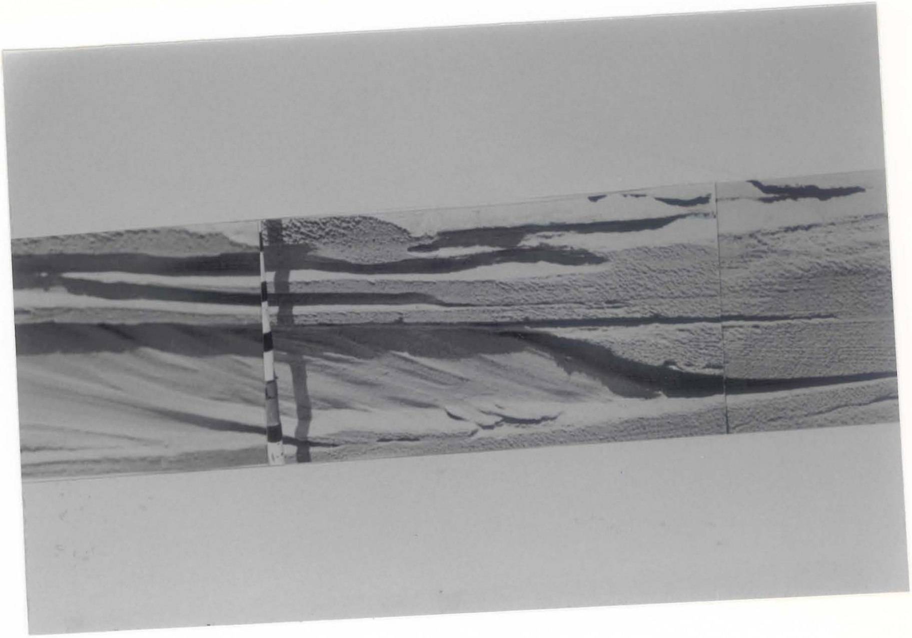
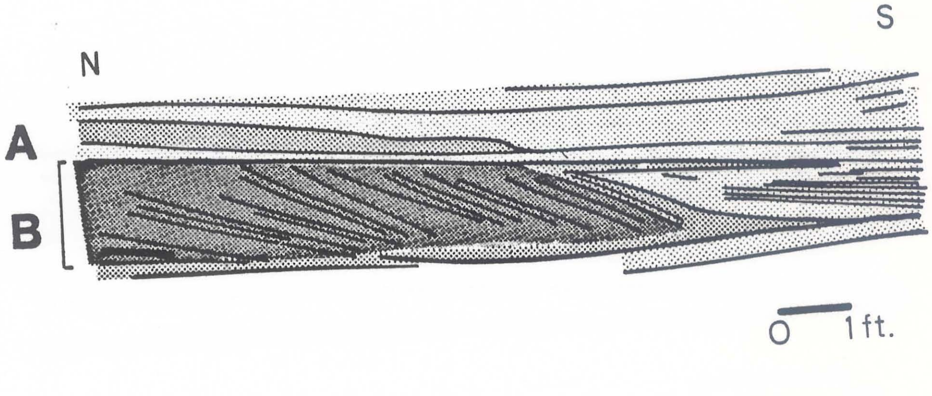
Trench 2. East face, southern slope, June 1980.

A. Translatent strata (climbing 4 degrees north) with grainfall deposits (dipping 14 degrees south).

B. South-dipping grainflow cross-strata (28 degree dips) with marginal grainfall deposits, and translatent strata.

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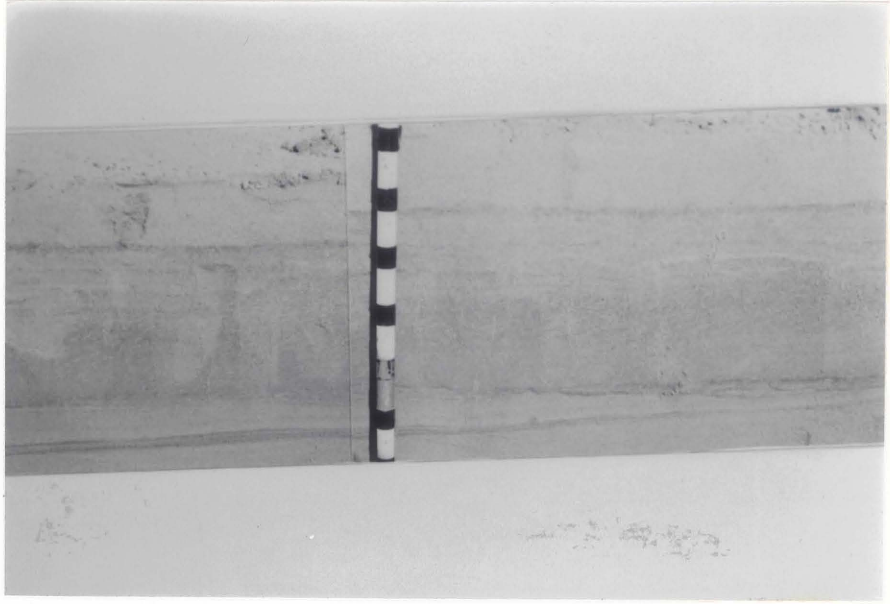
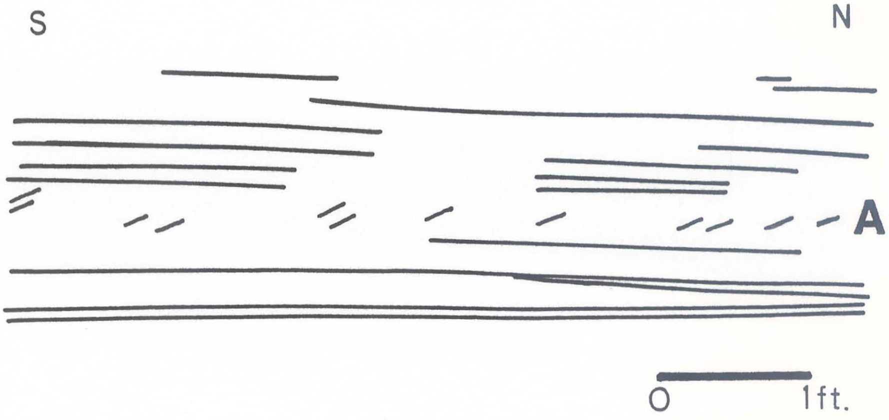
Trench 3. West face, interdunal area, June 1980.

A. Adhesion ripple zone amidst other interdunal deposits.

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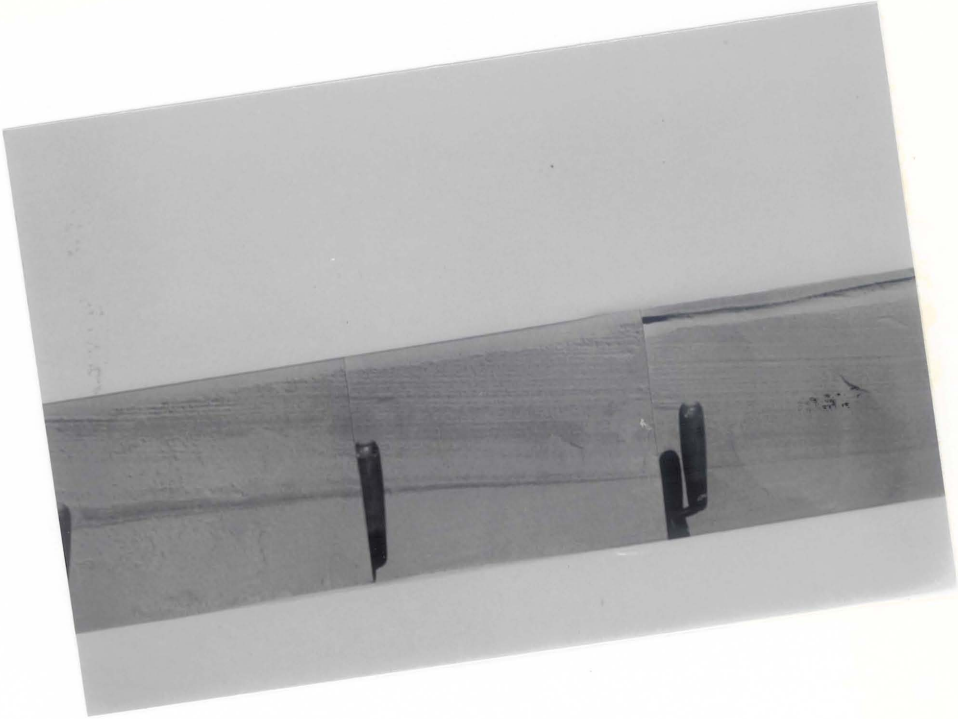
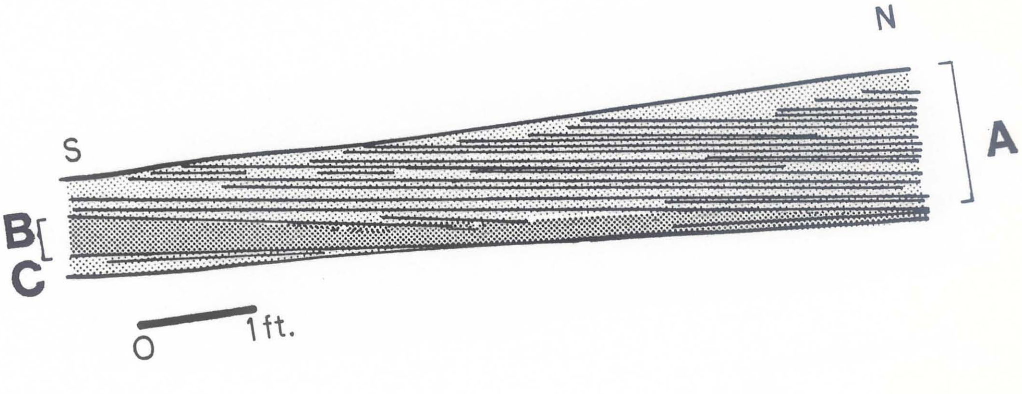
Trench 4. West face, southern slope, June 1980.

A,C. Translatent strata dipping 10 to 14 degrees southwest.

B. Interlaminated grainfall deposits and translatent strata.

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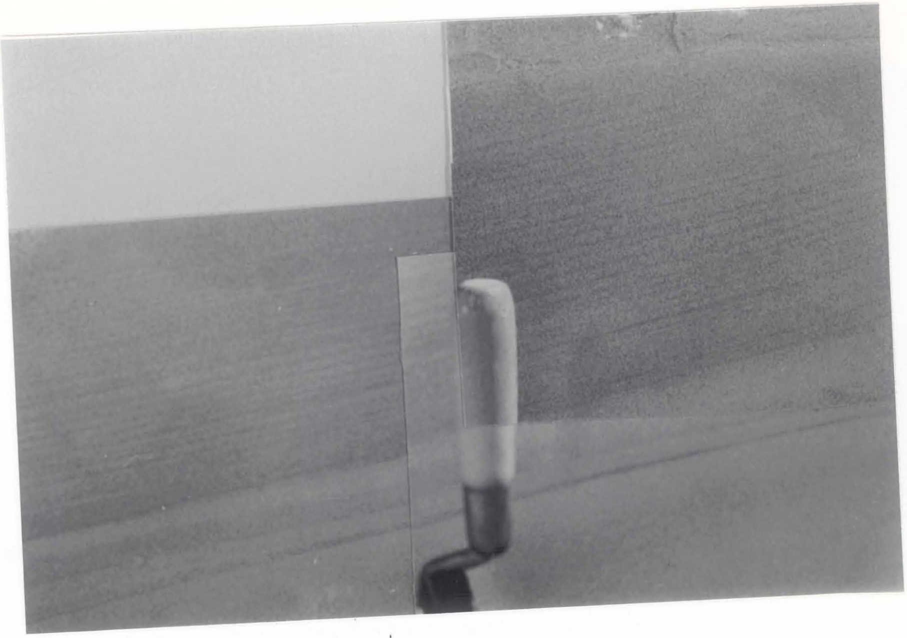
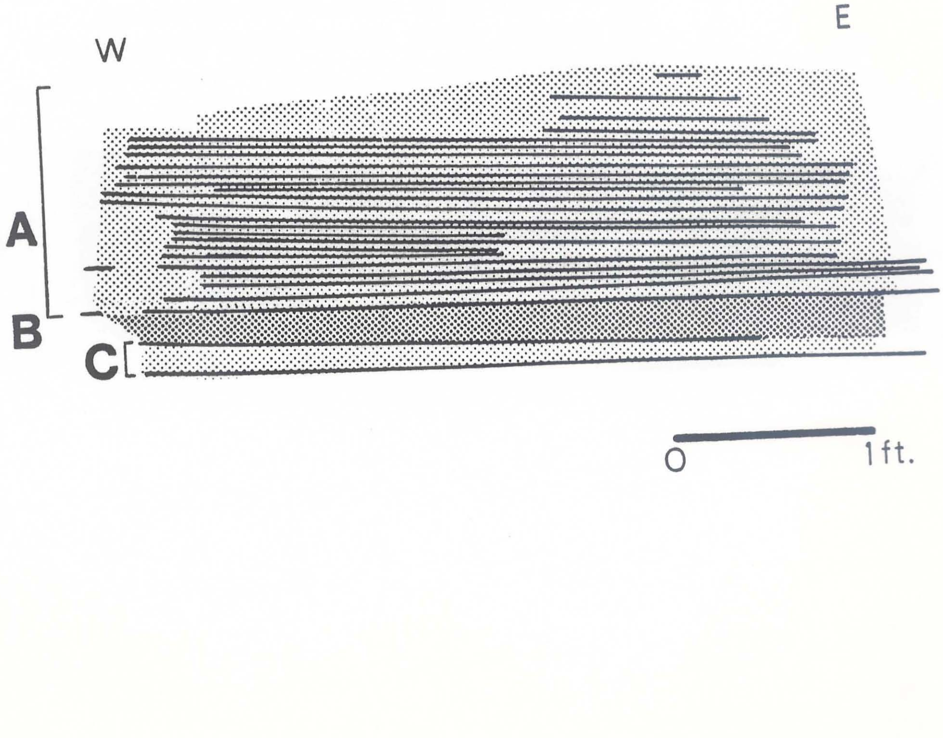
Trench 4. North face, southern slope, June 1980.

A,C. Translatent strata.

B. Interlaminated grainfall deposits and translatent strata.

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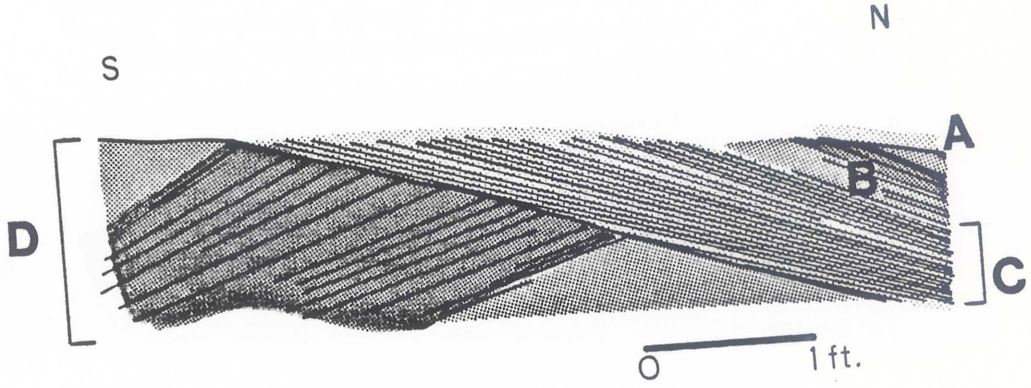
Trench 5. West face, dune crest, June 1980.

A. Translatent strata climbing 8 to 10 degrees south.

B. North-dipping grainflow cross-strata and grainfall deposits.

C. Translatent strata.

D. South-dipping grainflow cross-strata (28 degree dips) interbedded with grainfall deposits.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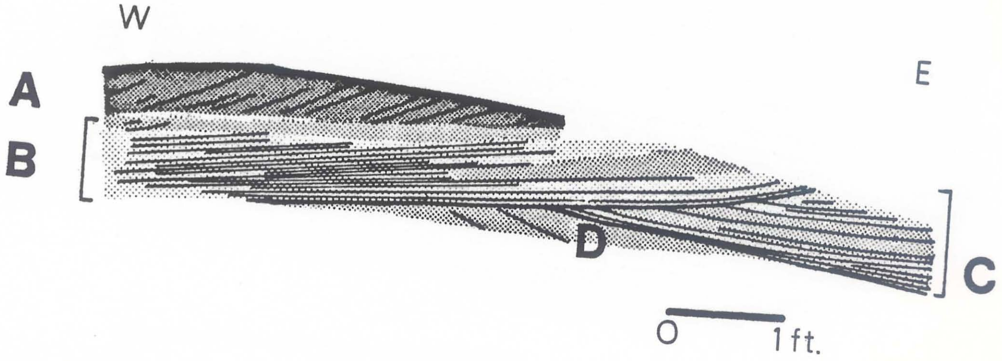
Trench 5. North face, dune crest, June 1980.

A. Grainflow cross-strata, dipping 26 degrees southwest, overlie grainfall deposits.

B. Translatent strata, dipping 12 degrees southwest, with minor interbedded grainfall deposits.

C. Interbedded grainfall deposits and translatent strata (3 degree southwest dips) which truncate against upper bounding surface.

D. Grainfall deposits dipping 19 degrees northeast.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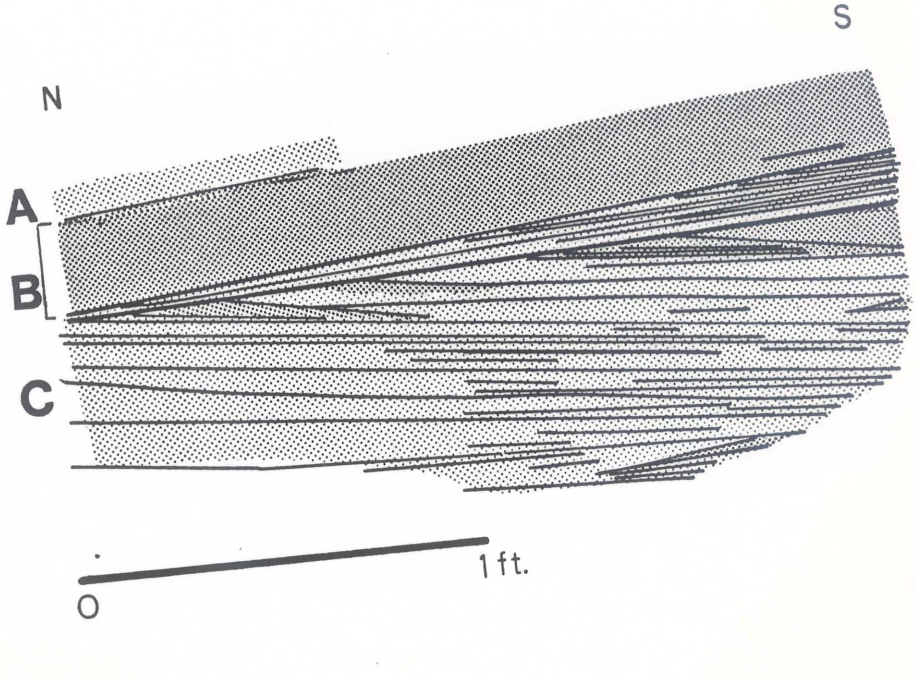
Trench 12. East face, northern slope, March 1981.

A. Translatent strata dipping 6 degrees south.

B. Grainfall deposits.

C. Translatent strata (6 degree south dips) with minor interbedded grainfall deposits.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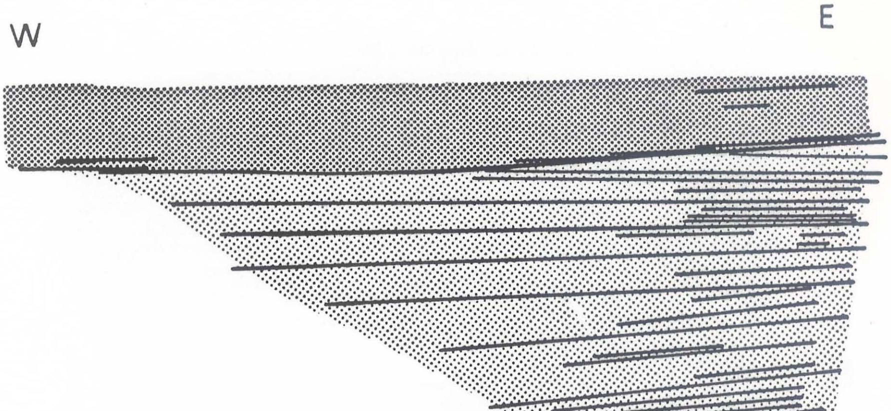
Trench 12. North face, northern slope, March 1981.

Grainfall deposits overlie translatent strata.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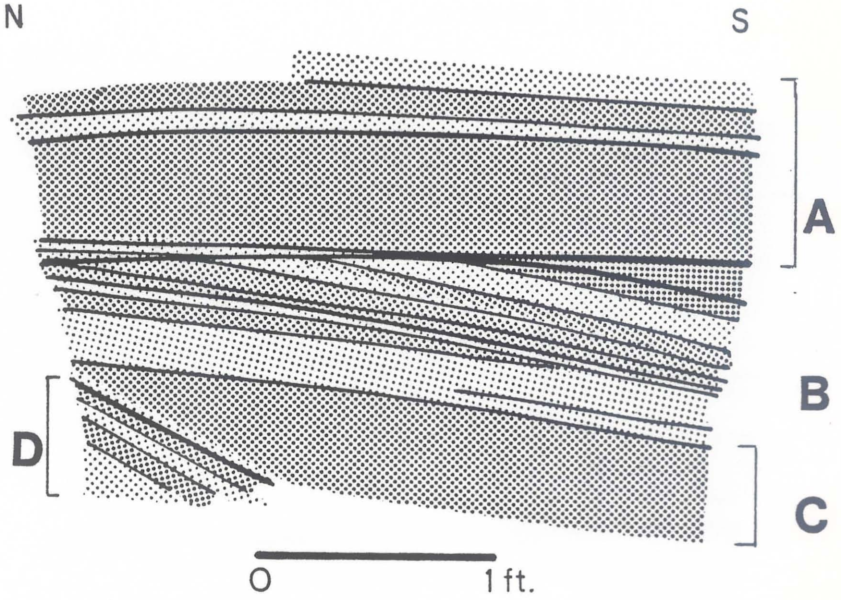
Trench 13. East face, southern slope, March 1981.

A. Thick grainfall deposits with minor interlaminated translatent strata.

B,D. Interlaminated and interbedded translatent strata and grainfall deposits.

C. Grainfall deposits.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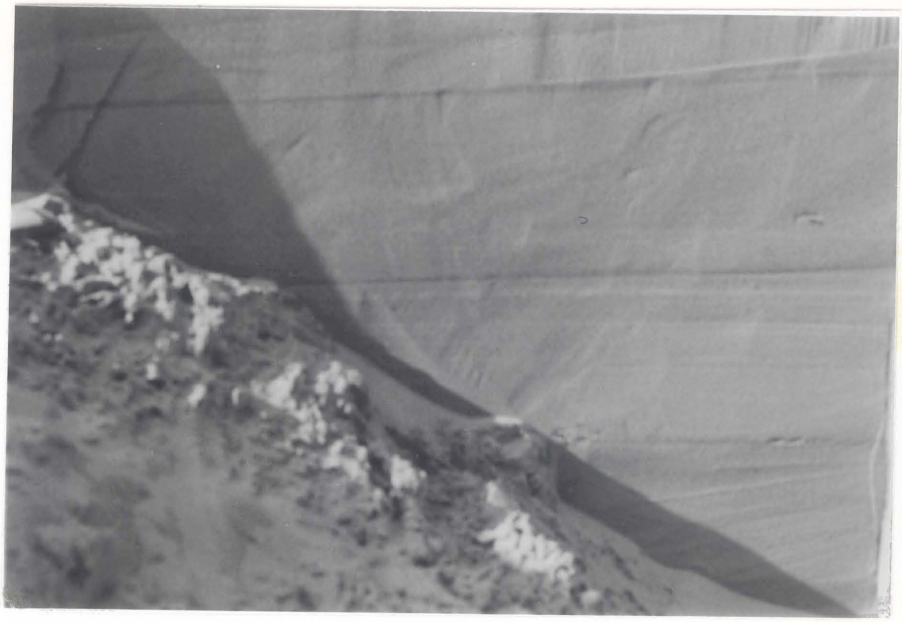
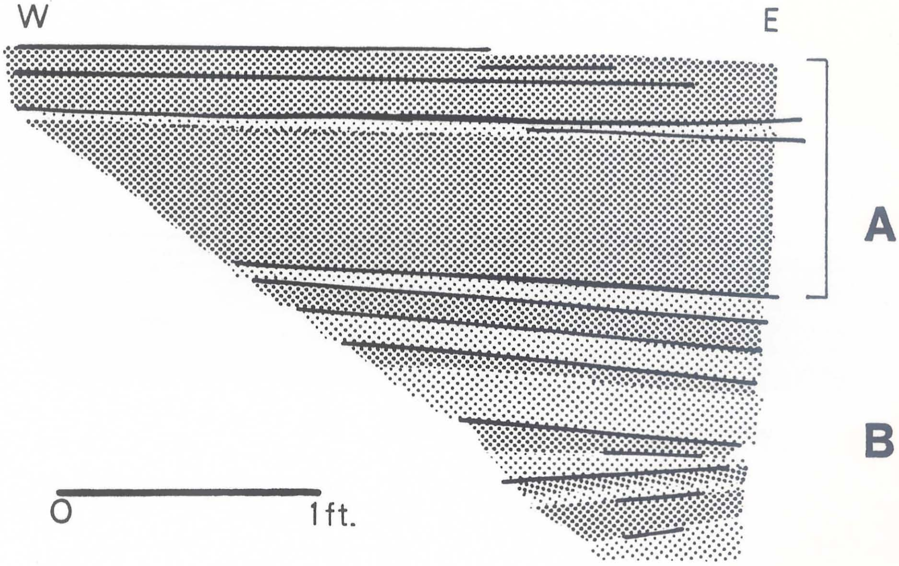
Trench 13. North face, southern slope, March 1981.

A. Thick grainfall deposits with minor interlaminated translatent strata.

B. Interlaminated translatent strata and grainfall deposits.





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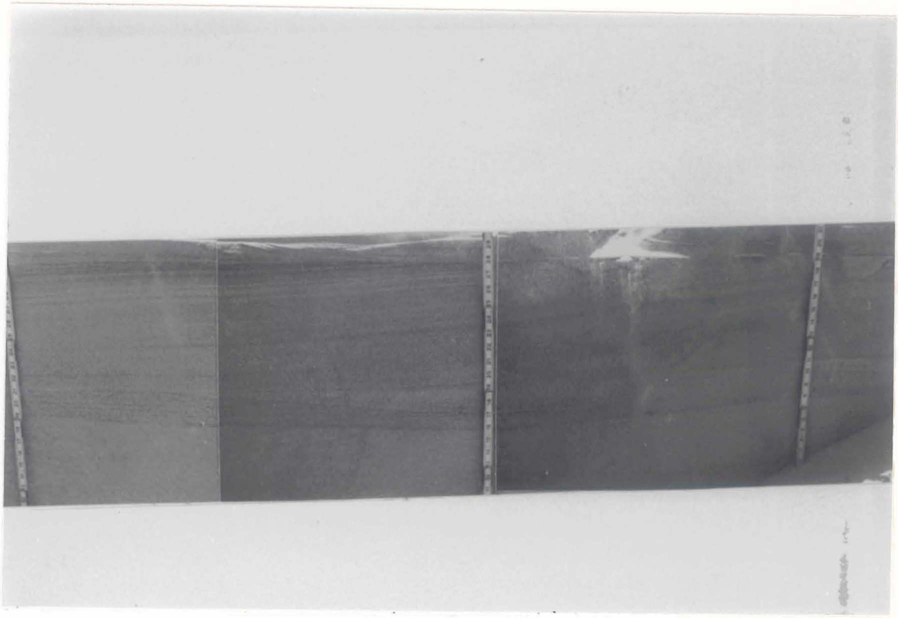
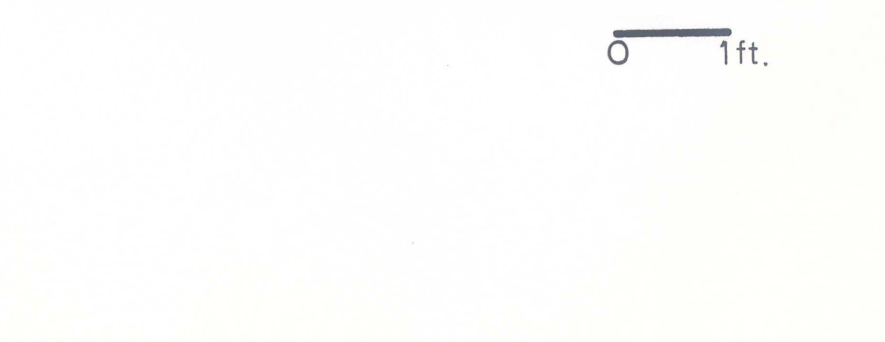
1 ft.

Trench 15. West face, dune crest, March 1981.

Interbedded translatent strata (climbing 12 degrees north) and grainfall deposits. Minor translatent strata within grainfall units.

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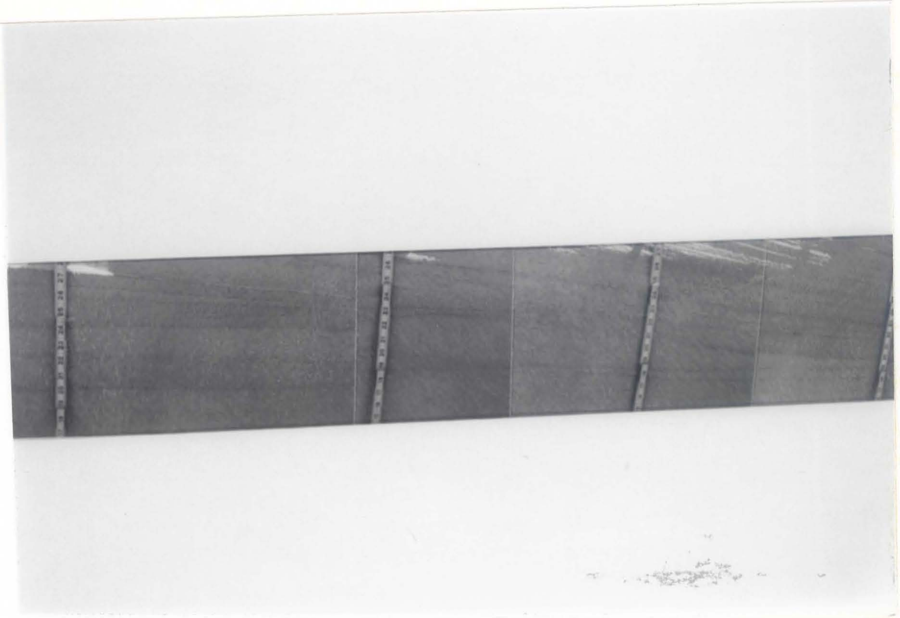
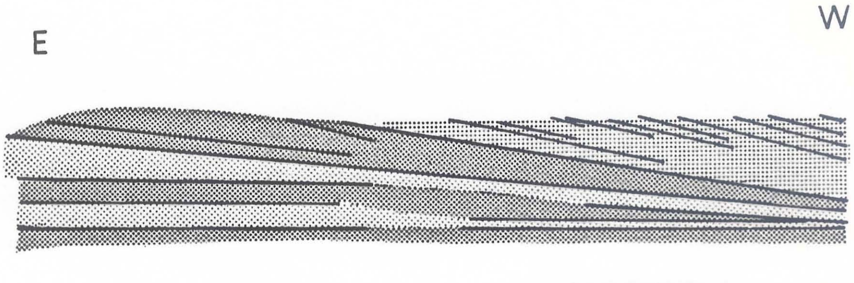
1ft.

Trench 15. South face, dune crest, March 1981.

Interbedded translatent strata and grainfall deposits.




E
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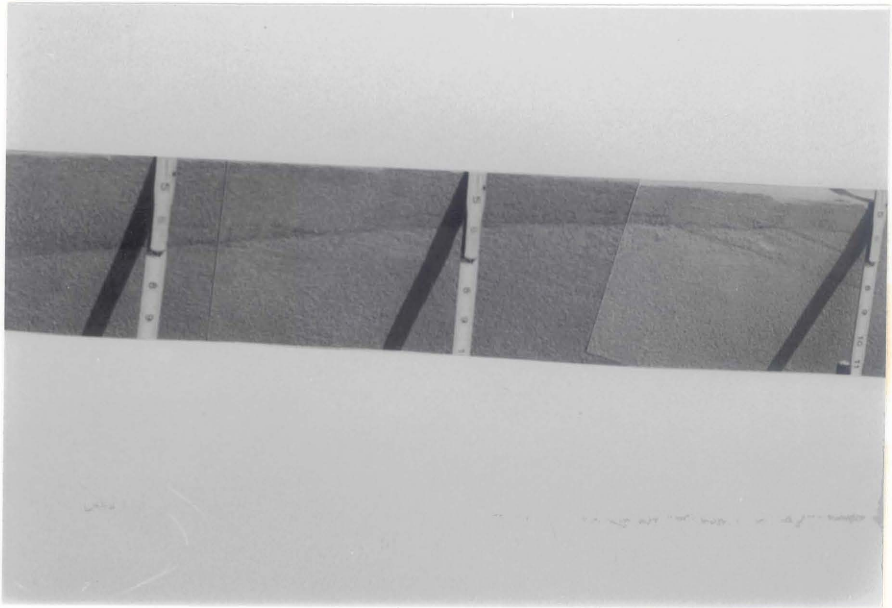
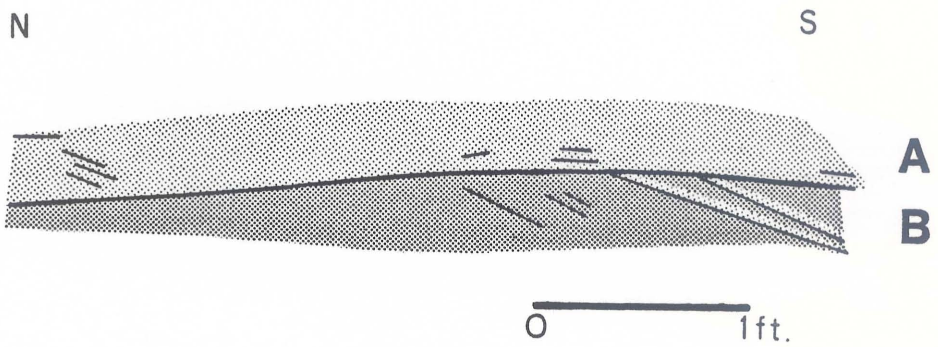
1ft.

Trench 16. East face, northern slope, March 1981.

A. Translatent strata.

B. Grainfall deposits with minor translatent interlaminae which climb 13 degrees north.

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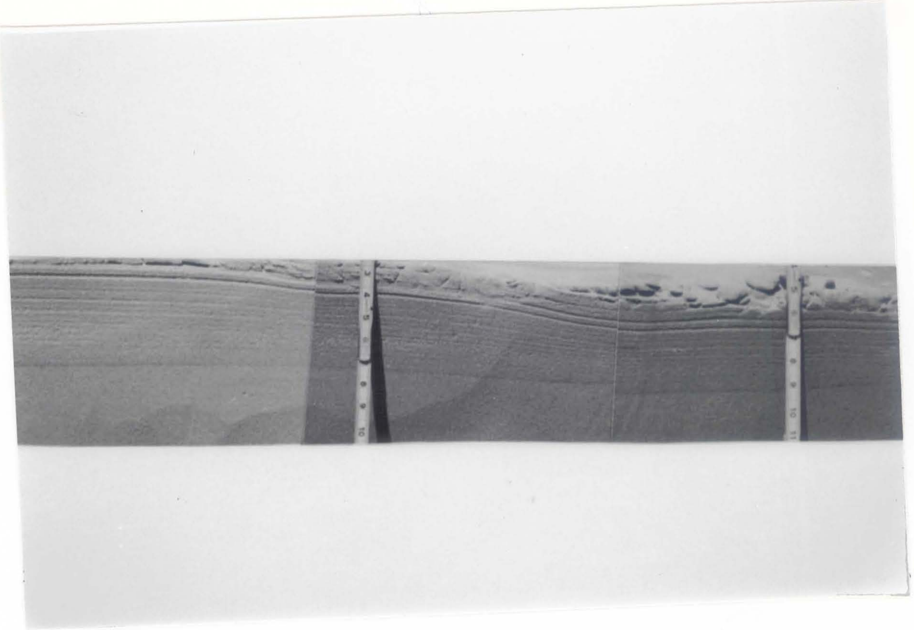
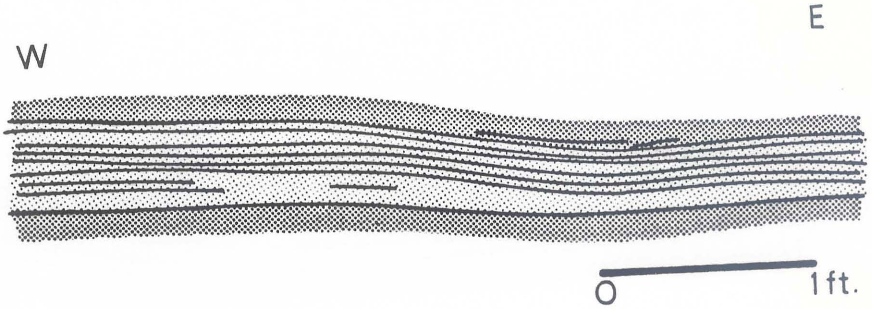
Trench 16. North face, northern slope, March 1981.

Interbedded grainfall deposits and translatent strata.




W
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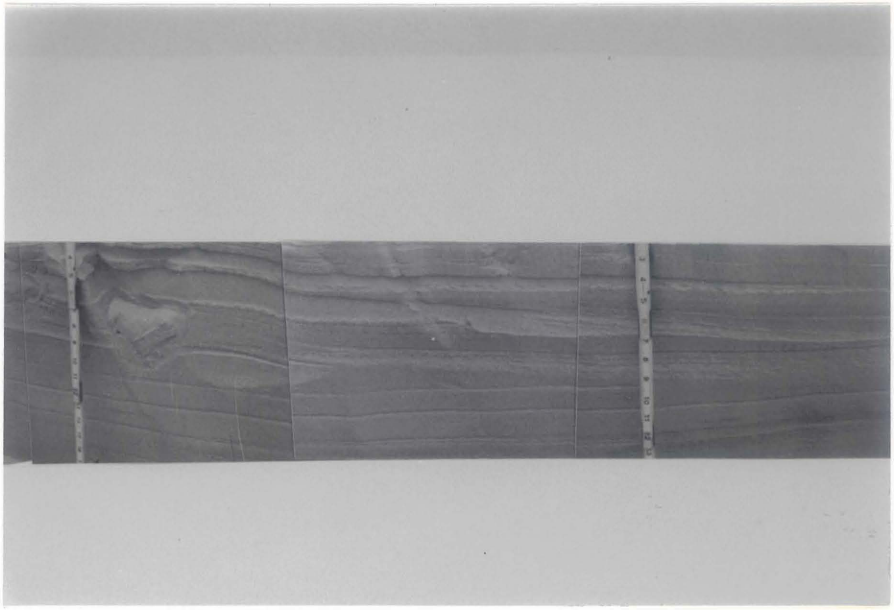
Trench 17. West face, dune crest, March 1981.

A. Interbedded translatent strata and grainfall deposits.

B. Interlaminated translatent strata and grainfall deposits.

C. Interdune deposits.




S
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0 1 ft.

Trench 17. South face, dune crest, March 1981.

A. Translatent strata with minor interbedded grainfall deposits.

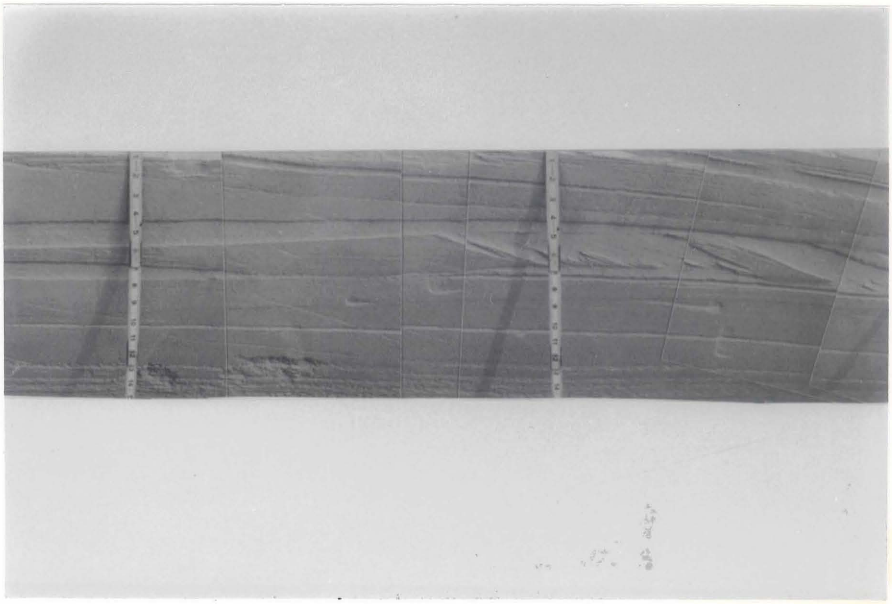
B. Interlaminated grainfall deposits and translatent strata.

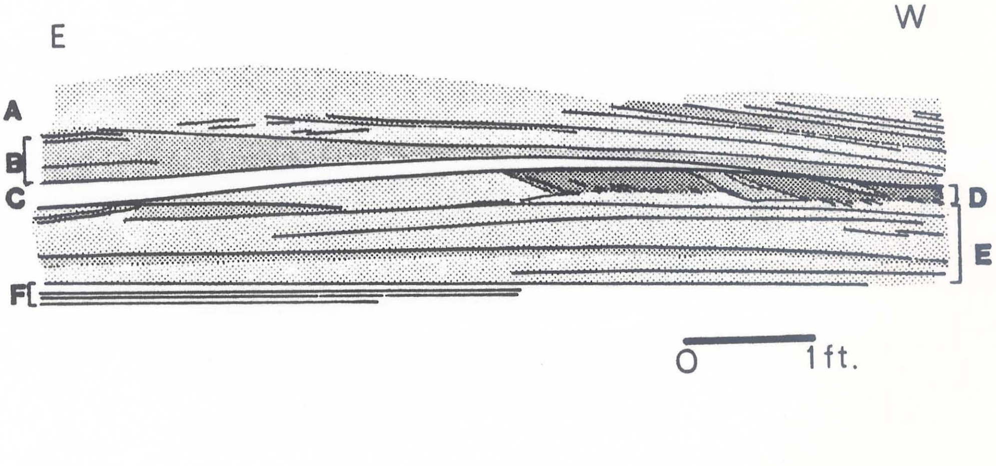
C. Hurricane deposits.

D. Grainflow cross-strata and interbedded grainfall deposits.

E. Interbedded translatent strata and grainfall deposits.

F. Interdune deposits.

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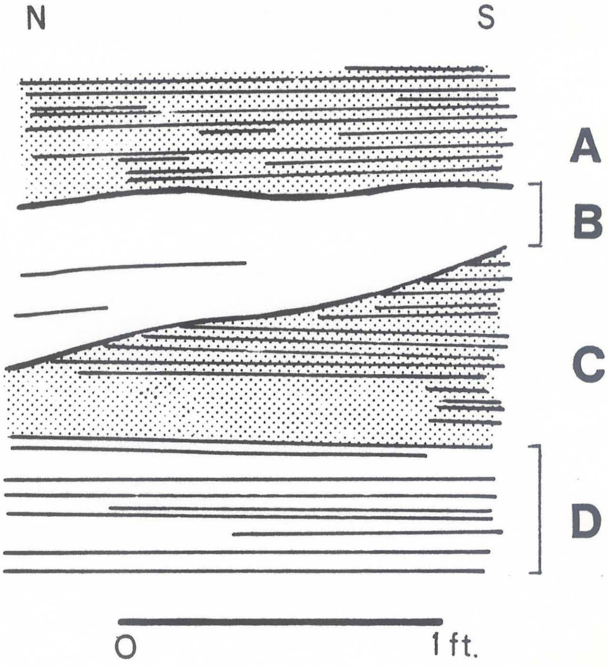
Trench 17. East face, dune crest, March 1981.

- A,C. Translatent strata.
- B. Channelized hurricane deposits.
- D. Interdune deposits.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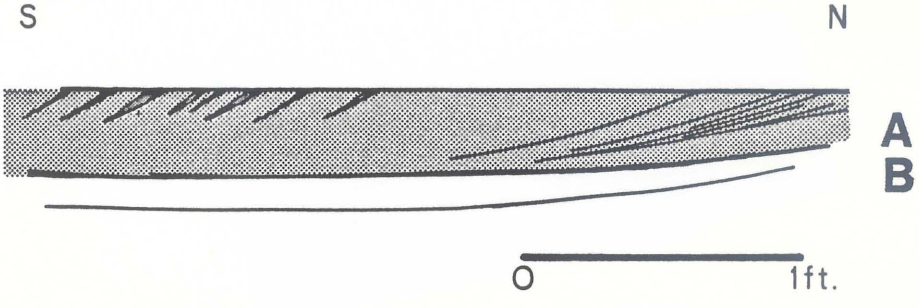
1 ft.

Trench 18. West face, dune crest, March 1981.

A. Grainfall deposits dipping 32 degrees south, with small tongues of grainflow cross-strata.

B. Possible interdune deposits.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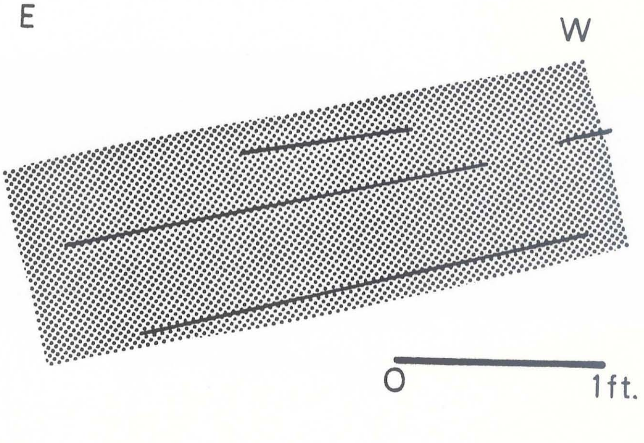
Trench 18. South face, dune crest, March 1981.

Grainfall deposits with possible interdune deposits below.


E
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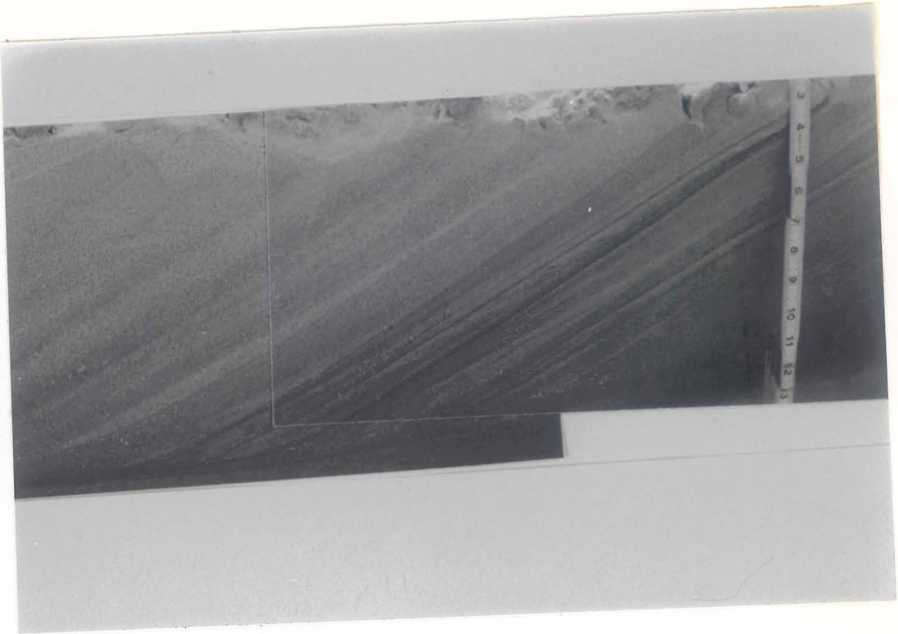
1ft.

Trench 19. West face, dune crest, March 1981.

Grainfall deposits with intertonguing grainflow cross-strata (dipping 36 degrees southwest).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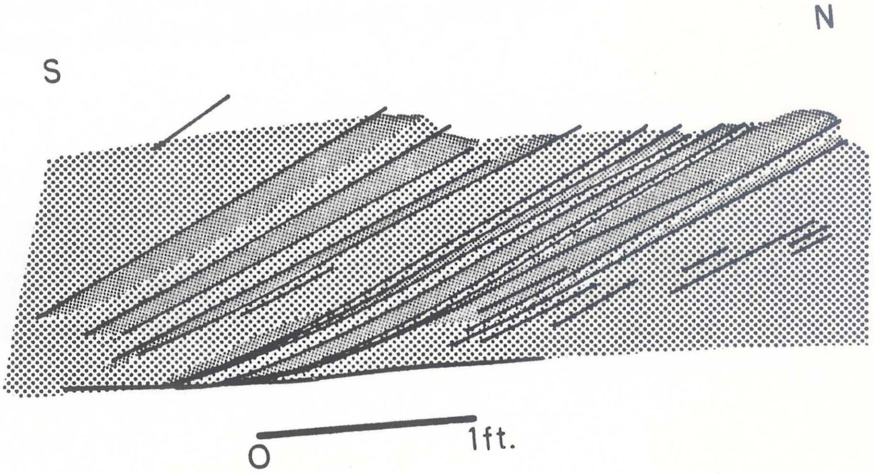
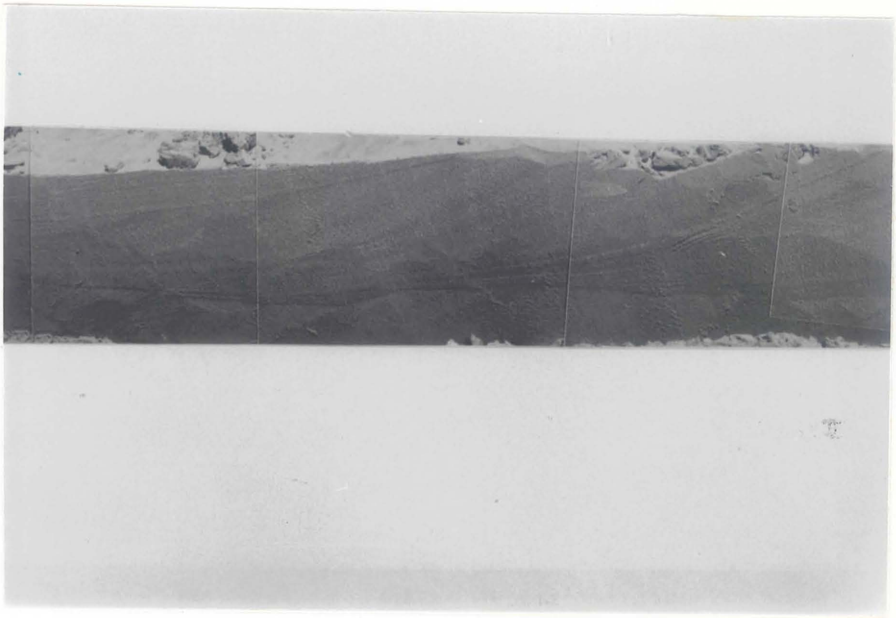
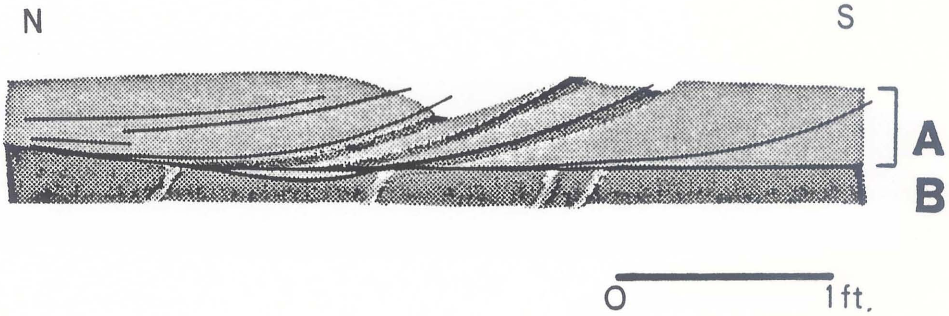

S
N
O
1ft.

Trench 21. Northern part of east face, northern slope, March 1981.

A. Grainfall deposits with minor north-dipping tongues of grainflow cross-strata (dipping 31 degrees north).

B. Thick, north-dipping grainflow cross-strata with minor interbedded grainfall deposits.




N
S
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1 ft.

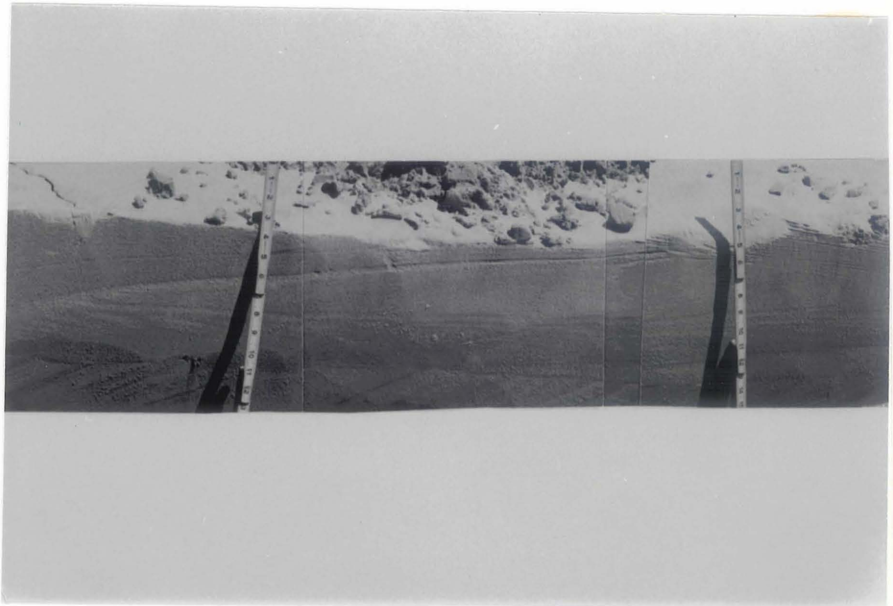
Trench 21. Southern part of east face, northern slope, March 1981.

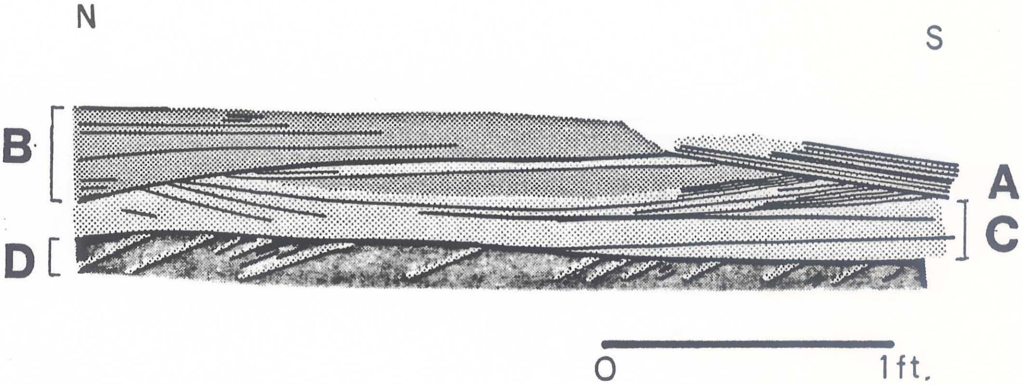
A. Translatent strata climbing 10 degrees north.

B. Grainfall deposits dipping 12 degrees south.

C. Interlaminated and (minor) interbedded translatent strata and grainfall deposits.

D. Thick, north-dipping grainflow cross-strata with minor interbedded grainfall deposits. Grainflow deposits dip 36 degrees.




N
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B
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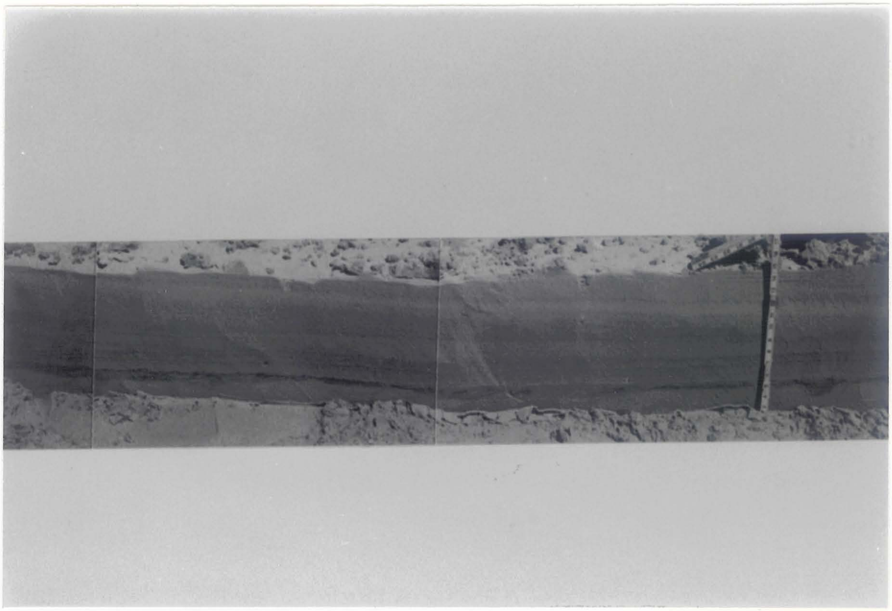
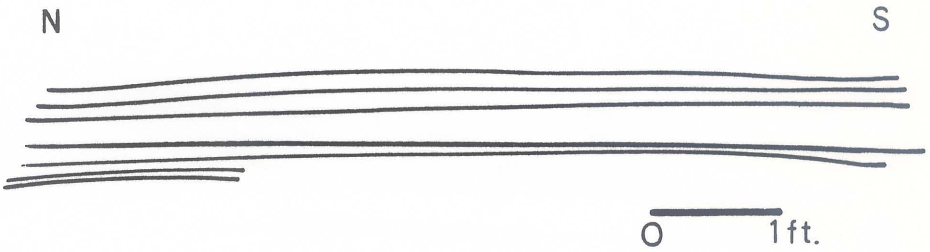
0
1ft.

Trench 22. East face, interdune, March 1981.

Interdune deposits.

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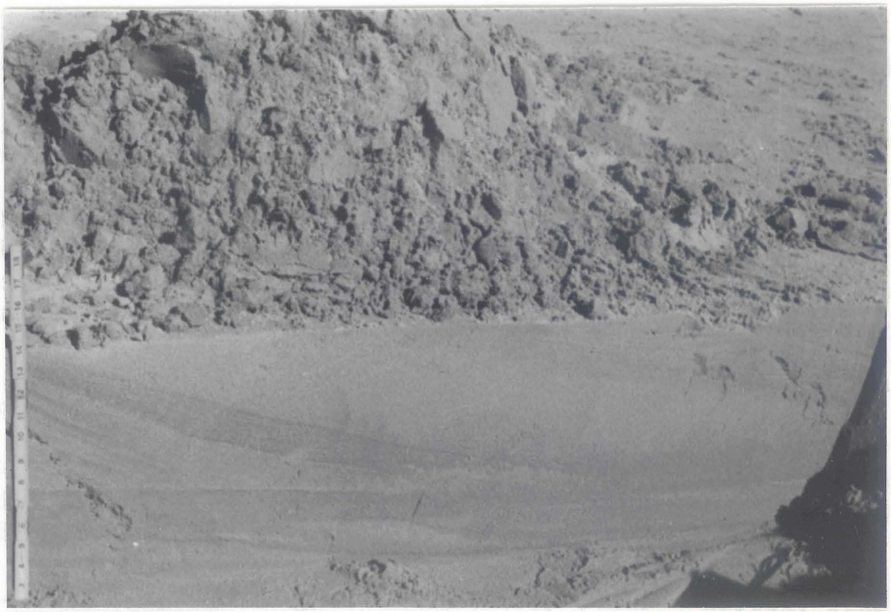
Trench 23. East face, interdune, March 1981.

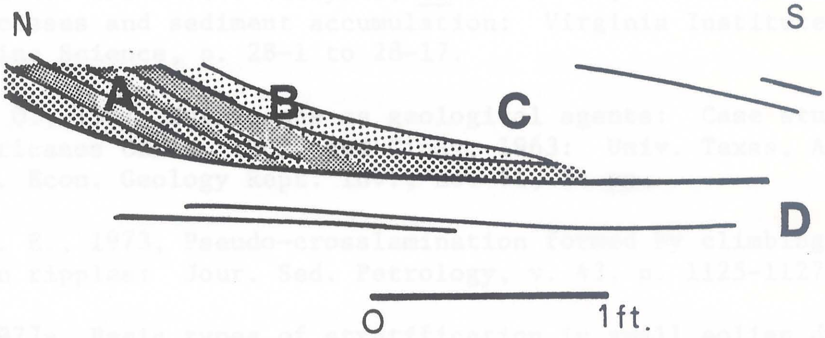
A. Intertonguing grainflow cross-strata and grainfall deposits.

B. Translatent strata.

C. Structureless sand.

D. Interdune deposits.

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VITA

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