PETROGRAPHIC AND TEXTURAL ANALYSIS OF A BARCHAN DUNE SOUTHWEST OF THE SALTON SEA, IMPERIAL COUNTY, CALIFORNIA

A Thesis
Presented to the
Faculty of
California State
University, San Diego

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
in
Geology

by
Robert John Christensen
June 1973
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CHAPTER I

INTRODUCTION

Purpose

Active desert sand dunes have been discussed in the literature with emphasis mainly on their geomorphological aspects. Many investigations have dealt with changes in volume, variations in form and rates of movement. Concerning the sedimentological aspects, however, very little work has been done. Specifically, there have been almost no detailed examinations of the texture or morphology of desert dune sand, and almost no systematic investigations of desert dune grain-size characteristics.

Beach dunes, on the other hand, have been studied in considerable detail using statistical analyses of grain-size parameters. Investigators have examined environmental differences between coastal dunes and beach dunes, but only in one instance between coastal dunes and inland dunes. Only recently have studies been made of the individual eolian environments across a desert dune field using textural analysis of the sand grains. Yet, it is still not understood how differences in
sand grain-size characteristics vary across the sub-environments of individual dunes.

The purpose of this investigation is to utilize the methods of systematic grain-size analysis and apply them to a study of inland barchan dunes located near the southwestern side of the Salton Sea, California. For this report, the dunes shall be known as the Salton Dunes.

The primary objective is to examine the grain-size properties of a suite of sand samples collected systematically across a single barchan, representative of the Salton Dunes, in order to determine what differences in grain-size characteristics occur across the sub-environments of a barchan dune, how grain-size parameters vary with transport over the surface and through the interior of a barchan, and what effect barchan morphology has on grain-size distributions. Such studies of modern dune environments are necessary in order to understand and interpret ancient inland dune deposits and to identify them with confidence in the geologic record.

A secondary objective concerning the Salton Dunes is to make a detailed examination and comparison of samples from the dune with samples from
the surrounding rock formations and alluvial sediments in order to determine the source of the sand for the barchans.

**Location and Accessibility**

The Salton Dunes are contained within a five square mile area on the west side and near the southern end of the Salton Sea. They are shown on the 1956 Kane Spring NE and NW 7-½ minute quadrangles. The dune field is located immediately east of California State Highway 86 about eight miles south of Salton City, California (Figure 1). A related but isolated barchan is located five miles to the west on the south side of Tule Wash.

A large number of the Salton Dunes are within the Atomic Energy Commission Salton Sea Test Base. A portion of the dunes outside the AEC Test Base is easily reached by foot from Highway 86. Vehicles can be parked on the east side of the highway about one mile north of the access road to the AEC Base. Unfortunately, only a few of the Salton barchans are outside the base. The southern dunes within the base are easily reached by foot from the base access road. The security guard at the base entrance must be notified upon arrival to avoid
Figure 1. Index map of the Salton Dunes.
trespass violation, but there is no objection to legitimate investigations of the dunes. The northern dunes are located in a high security area of the base. Permission to enter this area must be secured from the commanding officer of the El Centro Naval Air Facility. Cameras are not allowed in this high security area.

Investigation of the Salton dune field was undertaken during the winter of 1972 and spring of 1973. The winter months are recommended as temperatures reach over 100°F, daily during the summer.

**Previous Work**

The Salton Dunes were treated as a physiographic feature of the Salton Sea region by Mendenhall (1909), MacDougall and others (1914), Brown (1923) and Kniffen (1932). Russell (1932) gave some attention to the origin and formation of the dunes. Rempel (1936) sought to determine the ecological relationships between the barchans and the vegetation.

More recently, the geomorphology of the barchans has been investigated. Long and Sharp (1964) determined the rate of movement of the dunes
from comparison of maps and surveys covering a fifteen year period from 1941 to 1956, and for a subsequent seven year period between 1956 and 1963. Norris (1966) studied the migration of the barchan at Tule Wash over a nine year period from 1955 to 1964.

**Geographic Setting**

The Salton Basin is a low desert region eighty-five miles long and up to thirty miles wide, extending from the Gulf of California northwestward into Southern California to just north of Palm Springs, California. The basin is flanked by the Peninsular Ranges on the west and the Little San Bernardino, Oroopia and Chocolate Mountains on the east.

The Salton Sea occupies the central portion of the basin. It represents the most recent flooding of the trough and was formed in 1905-1906 when the Colorado River broke into the basin during floods. The average surface elevation, 230 feet below sea level, has been maintained by runoff of irrigation water from agriculture which is the most active industry in the area. The previous inundation of the Salton Trough, called Lake Le Conte (Bailey,
1902) or Lake Cahuilla (Blake, 1907), is evidenced by lacustrine shells and travertine, as well as wave cut shore line and beaches around the margins of the basin at elevations ranging from twenty-five feet to sixty feet above sea level (Sykes, 1914).

Streams intermittently drain the flanking mountain areas to the west and northwest. These streams carry quantities of sand and gravel from igneous and metamorphic sources. Most of the recent sediment covering the basin is brought by the San Gorgonio and Whitewater Rivers, by San Felipe Creek and occasionally by the Colorado River flowing into the southern end.

Climate and Vegetation

The Salton Basin has an arid climate similar to most low-lying rain shadow deserts of the world, and is characterized by low rainfall and humidity and very high summer temperatures (Hely and Peck, 1964). Weather Bureau records show an average of 3.20 inches of rainfall per year at the Indio, California, station over a period of seventy-three years, and an average of 3.23 inches per year over a period of fourteen years at the El Centro, California, station. Precipitation occurs as late winter rains and as
infrared heavy to torrential late summer showers (Arnal, 1961). Temperature records at Anza Borrego Desert State Park Ranger Headquarters show a mean annual temperature of about 73°F. Temperatures range from about 53°F. during the winter months, with lows below 30°F. in February, to about 90°F. in the summer months, with highs up to 120°F. in July.

This arid climate supports a sparse vegetation dominated by xerophytes, a highly specialized group typical of low-desert flora. The most prevalent plant cover in the Colorado Desert (Jaeger, 1961) consists of the creosote bush (Larrea tridentata), the burro weed (Franseria dumosa) and the brittle bush (Encelia farinosa). Additional plants include the ocotillo (Fouquieria splendens), sand burr (Cenchrus palmerii) and cat's claw (Acacia oreggii). Typical large forms of vegetation include the smoke tree (Dalea spinosa), palo verde (Cercidium floridium) and, rarely, the desert fan palm (Washingtonia filifera). The most numerous of the perennial shrubs observed in Salton Sea dune field is the creosote bush, with the burro weed second most abundant.
Regional Geology

The Salton Trough is the northern extension of the structural depression of the Gulf of California which began forming during Miocene time (Hamilton, 1961, 1966). Continental and marine sediments were deposited in the trough from Miocene until Middle Pleistocene time. During the Middle Pleistocene the Colorado River built its delta across the Gulf of California trough to form the topographic and depositional Salton Basin. Lacustrine, alluvial fan, fluviatile and eolian sediments have been deposited.

The oldest formation reported in the Salton Basin is the Split Mountain Formation. It is a coarse basal fanglomerate of Middle Miocene age (Dibblee, 1954) which overlies older crystalline basement rocks.

Next is the shallow marine Imperial Formation composed of claystone with interbedded arkosic sandstones and calcareous oyster-shell banks. According to Stump (1972), it is Early Pliocene in age.

Overlying the Imperial Formation are the Palm Spring and Borrego Formations. The terrestrial
Palm Spring Formation is a thick sequence of interbedded gray arkosic sandstones and reddish clays of Early Pleistocene age (Woodard, 1963). It grades upward into the Borrego Formation which is considered by Dibblee (1954) to be a lacustrine facies of the Palm Spring Formation. The Borrego Formation is composed of light gray claystones with minor buff sandstone.

Overlying the Borrego Formation with local unconformity is the Ocotillo Conglomerate composed of gray granitic-pebble conglomerate; the Brawley Formation is composed of light gray clays and buff sandstones. The Brawley Formation is the lacustrine and basinward facies of the terrestrial Ocotillo Conglomerate, and is lithologically very similar to the Borrego Formation (Dibblee, 1954). Arnal (1961) believed the Brawley Formation was deposited in a Late Pleistocene lake of Colorado River origin under conditions similar to the present Salton Sea except that the water was less saline as indicated by the fauna in the sediments.

The youngest unit exposed is made of alluvial material reworked from older sediments into Late Pleistocene to Recent Lake Cahuilla deposits (Hubbs
and Miller, 1948). It is upon these Lake Cahuilla deposits that the Salton Dunes have formed.
CHAPTER II

THE SALTON DUNES

Description of the Dunes

Most of the Salton Dunes are individual barchans displaying generally crescentic form with the hollow of the crescent facing to leeward of the prevailing winds (Rempel, 1936). A number of dunes observed in this area, however, are not true barchans. Low sand mounds were found leeward of the horns of some of the barchans and probably represent preliminary forms of new barchans. Also, large dunes with complex contours were observed, resulting from the coalescence of two or more barchans or from the modification of a single barchan.

Field measurements show that the size of the true barchans varies considerably. The smaller barchans are about thirty feet from horn to horn and about six feet high at the crest of the lee slope. The largest dunes measure over four-hundred feet between the horns and over forty feet high. The windward slopes of the barchans are long and gently
rising at 6-10° while the leeward slopes are steep at 30-33°.

The deposits upon which the dunes rest form a hard, smooth substratum that slopes gently eastward and northeastward toward the Salton Sea at forty to one-hundred feet per mile (Long and Sharp, 1964). Elevations of the dune substratum range from 20-230 feet below sea level (Norris, 1966). Relief is generally flat except for a number of shallow dry stream washes which appear to interfere with the movement of the dunes and distort their shape away from symmetrical crescents.

The ground surface between the dunes is composed of a residual gravel armor of pebbles, concretions and rock fragments derived from the underlying Brawley Formation and Lake Cahuilla deposits (Norris, 1966). Accumulations of windblown sand are sparse between the dunes except as small sand shadows leeward of the scattered vegetation and in some of the washes.

Wind Direction and Velocity

Wind patterns are very important in attempting any analysis of dunes. Although meteorological observations in the Salton Basin are
not complete, some detailed information is available. Arnal (1961) made use of data from the Central Weather Bureau in Los Angeles, collected at Indio and El Centro, which indicated that the component wind direction at the northern end of the Salton Basin was from the west to northwest, and the component wind direction at the southern end was from the west to southwest. Using wind records made available by the Atomic Energy Commission collected at the Salton Sea Test Base from 1943 to 1945, Long and Sharp (1964) reported that the prevailing wind direction over the Salton dune field was from the west, but they gave no indication of the velocities.

Rempel (1936) established two weather stations in the vicinity of the Salton Dunes. A four-cup standard anemometer and wind vane were installed near Kane Spring in order to determine precise wind velocities and direction near the dunes. Although the record is sporadic, numerous readings were obtained for two-hundred days during a period from March 1933 to February 1934. The station then was relocated near the northernmost dune in the field and a daily record was kept until June 1934. The total record showed that the wind was from due west
46.4 percent of the time. The remaining percentage of winds was from the other directions, ranging from the south to the northeast.

The complete daily records give some indication of wind velocities from various directions. The highest average velocity for a period of twenty-four hours was 30.3 miles per hour attained by the west wind. Average velocities for similar periods of time for winds from other directions were all below twelve miles per hour. The highest peak velocities of the west wind were 40.3 and 46.1 miles per hour. Average velocities of ten miles per hour or more for twenty-four hour periods were recorded for twenty-five days out of a total of seventy-two days for the west wind. Average wind velocities in the fall are higher than those of the summer months, and the highest velocities occur during the spring months.

On the basis of the data collected by Rempel (1936) and Long and Sharp (1964), augmented by field observation of the direction of dune movement and eastward facing avalanche slopes as well as the unanimous testimony of inhabitants of the region, it can be concluded that the prevailing wind direction in the vicinity of the Salton Dunes is from the west.
Bagnold (1941) reported that winds with velocities of fifteen or more miles per hour were necessary to move sand in any considerable amount. The recorded velocities of the west wind are, therefore, more than sufficient, especially during spring months, to move sand and influence the formation, growth and character of the Salton Dunes.

**Localization of the Dunes**

Except for the large barchan near Tule Wash, all the Salton Dunes are confined to a five square mile dune field. Several factors seem to be responsible for localizing the dunes.

The rough ground surface and the dissected relief may be principle factors in localizing the dunes (Norris, 1966). West of Highway 86 the ground surface of the Salton sink is made very rough by outcrops of slabby sandstone and bands of concretions weathering out of the Palm Spring and Borrego Formations (Dibblee, 1954). Sand dunes fail to develop because the length of grain trajectories increases over a rough surface preventing dune initiation, although much sand may move across the area (Bagnold, 1941). Stream erosion has dissected the region west of the dunes into a dendritic system.
of steep-sided gullies five to fifteen feet deep and as much as 150 feet wide (Norris, 1966). This abrupt relief tends to prevent the formation of new sand dunes and may dissipate those moving across it. East of the highway the surface is covered by a smoother veneer of lacustrine deposits, and the gullying is much less pronounced providing a more favorable area for dune formation.

The supply of sand is also a factor. The amount of wind-driven sand almost certainly increases eastward across the source area; where it first attains the critical amount, dunes will form if other conditions are correct (Bagnold, 1941). An important influence appears to be the funneling of sand into the dune field by the San Felipe Hills. On a windy day it can be observed that the amount of sand drifting eastward across Highway 86 just west of the dunes is much greater than elsewhere in the vicinity, and sand is fed into the dunes in considerable quantities.

Finally, the vegetation appears to exert a minor effect on the dune formation. Nearly all the plants in the dune field have accumulations of sand on their lee sides. Where the plants are grouped close together, the sand mounds coalesce to form
larger mounds. These mounds again coalesce with others to form the early stages of "coppice dunes" (Melton, 1940). The vegetation does not gain a sufficient foothold to allow the complete formation of coppice dunes. During the summer the lack of moisture and the intense heat prevent plant growth on the surface of the dunes (Rempel, 1936). During the balance of the year when there is occasional precipitation, the wind shifts the sand enough to prevent plant growth. As the depth of sand increases in the embryonic coppice dunes, the plants which cannot elongate are killed and lose their capacity as sand binders, and the sand mounds can become converted into barchans (Melton, 1940).

All the conditions for the formation and localization of barchans are met east of Highway 86. The surface is relatively level and the relief is low. An adequate supply of sand is funneled into the area by prevailing west winds. Somewhat more abundant vegetation serves to trap the sand and enhances the dune building.

Age of the Dunes

All the Salton Dunes have been constructed upon a thin veneer of lacustrine sediments deposited
in Lake Cahuilla, the forerunner of the present Salton Sea. Norris (1966) reported that the highest shore line of Lake Cahuilla laid approximately seven miles west of the dune field. The history of this lake, based in part on radiocarbon dates, is considered in detail by Hubbs and Miller (1948), Hubbs and others (1960, 1963), Hoyt (1965), Hubbs and Bien (1967) and Fergusson and Libby (1962, 1963). They concluded that Lake Cahuilla existed for a period of about 1,600 years ending with complete evaporation about three-hundred years ago. Forbes (1965) cited archeological evidence which suggested earlier desiccation of the lake, perhaps five-hundred to seven-hundred years ago.

Long and Sharp (1964) reported that no direct evidence had been found on or in the dunes to suggest that they had ever been submerged. However, evidence of submergence would only be preserved in dunes that had become stabilized and not in actively migrating barchans. During the 1905-1907 rise of the Salton Sea, the lower part of the dune field between 195 and 230 feet below sea level was submerged. MacDougal (1914) showed a photograph of a barchan in this area partially submerged by the 1907 high water stage at about 195 feet below sea level.
level. No evidence of this submergence was found in this dune since it resumed migrating. Nevertheless, it is not likely that dunes formed prior to Lake Cahuilla and subsequently submerged could have withstood the longshore currents and wave action described by Norris and Norris (1961) and survived.

In all likelihood, the formation of the Salton Dunes postdate the evaporation of Lake Cahuilla and have formed directly upon the lacustrine deposits, rather than resuming migration over sediments laid down during submergence. Long and Sharp (1964) calculated that a dune moving at an average rate of sixty feet per year would require a little over three-hundred years to pass from the western margin through the dune field and into the Salton Sea. This suggests that none of the dunes presently in the field are older than three-hundred years.
CHAPTER III

EOLIAN SAND MOVEMENT AND FORMATION OF BARCHAN DUNES

General Statement

The most extensive study of dunes and the physical relationships between sand and wind was made by Bagnold (1941). The formation of dunes in general is described in early accounts by Cornish (1897, 1914), Beadnell (1910) and Stuntz and Free (1911). King (1918) described the manner in which barchans formed on desert pavement. Kerr and Nigra (1952) reviewed the theoretical considerations of eolian sand movement and dune formation. Finkel (1959) discussed conditions causing the formation of barchans in Southern Peru. Sharp (1963a) tested some of the concepts relating to the formation of desert dunes.

Elaborate schemes have been proposed for the classification of dunes on the basis of shape and origin. Haltenberger (1913) proposed one of the earliest genetic classifications of eolian deposits. Melton (1940) introduced a detailed classification describing various types of dunes, but his terms
have not been widely used in the literature. Hack (1941) suggested the dune classification used popularly at the present.

The formation of dunes is dependent upon the transportation and deposition of windblown material. Bagnold (1941) made a detailed study of eolian transport and desert dunes, and the following discussion, unless otherwise noted, is based on his work.

**Transportation by Wind**

The wind velocity at which a sand grain begins to move is called the threshold velocity and varies with the diameter of the particle. Generally, the threshold velocity decreases with decreasing grain size to a minimum diameter of 0.1 mm (3.25Ø). For grains smaller than this, the threshold velocity increases rapidly. According to Bagnold (1937a), this increase in the threshold velocity as the size decreases is due to a change in the surface conditions from a rough to a smooth surface and an increase in the coherence of smaller grains. The movement of sand is initiated by a sudden gust of wind stronger than the steady prevailing wind. Once set in motion, the grains move downwind under the
influence of a wind of lower velocity. Average dune sands begin to move when wind attains a velocity of thirteen miles per hour, and in the open desert the wind becomes visibly charged with sediment at about twenty-three miles per hour (Beadnell, 1910). The movement of sand is intermittent rather than steady.

Wind transports material by suspension, saltation and surface creep. Material less than 0.062 mm (4.00) is frequently carried by suspension up into the atmosphere and transported out of the desert. Material coarser than 0.062 mm (4.00) is transported by saltation and surface creep. Sand grains moved by saltation bounce or hop along the ground following a "characteristic path" determined by wind velocity and grain size. Small gusts of wind pick up individual grains and carry them upward and forward until they strike the ground at a flat angle between 10° and 16°. Grains striking a rocky surface rebound much more readily than those striking a sandy surface. Material in saltation generally travels within six feet of the ground, with about 95 percent of the grains moving within ten inches of the ground (Kerr and Nigra, 1952). Sharp (1964) conducted measurements of saltating sand driven by a strong, unidirectional wind across a
barren, bouldery, alluvial plane and found that 50 percent of the grains, by weight, travel within five inches of the ground and 90 percent within twenty-five inches. Surface creep is restricted to grains rolling along the surface, and is produced by the pressure exerted by the wind against individual grains and by impact of grains moving by saltation. Particles too large to be transported by saltation or suspension may be moved by creep. Bagnold (1937b) estimated that about 25 percent of eolian material is moved by creep. Surface creep and saltation work simultaneously in sandy areas and are the most important mechanisms transporting sand across dunes.

Deposition

Deposition of eolian material occurs when a sand-laden wind decreases in velocity and loses some of its transport competency. A decrease in velocity may result because of obstacles in the path of the wind, such as vegetation, rocks, mounds or hollows. Bagnold (1937a) observed that deposition will also occur on a sandy patch surrounded by desert pavement. A wind transporting sand by saltation over a surface of rock fragments is able to proceed at a
higher velocity than the same wind over a sandy surface because no energy is lost in producing surface creep. A wind laden with sediment that passes from this pavement surface to a sandy surface loses part of its load as the velocity diminishes resulting in a deposit that may eventually evolve into a dune.

**Evolution of Barchan Dunes**

Most authors agree that barchan dunes form under conditions where loose sand is available for transport by a unidirectional wind of moderate velocity moving over a non-sandy surface nearly free of vegetation. Barchans arise from previously existing mounds or hills of loose sand. Wind tends to contour around the mound of sand instead of blowing straight over it, and advances sand grains more rapidly at the sides than over the top forming cusps or "horns" pointing to the leeward of the prevailing wind. As a barchan evolves, the windward side continues to receive drifting sand forming long, gently rising slopes from 10° to 14° leading up to the crest which separates the windward slope from the leeward sleepface. Cornish (1897) believed that the mounds continued to grow until they were so
high that the wind blowing over the top began to eddy in the lee side. He thought this eddy resulted in the formation of a steep lee slope because the direction of air movement along the ground to leeward was opposite the direction of the prevailing wind. Consequently, the movement of sand down the leeward slope was checked, and the steep lee slope typical of barchan was formed. Experiments with smoke by King (1918) and Sharp (1963a, 1966) led to the conclusion that no strong fixed eddy lays to the lee of barchan dunes that would significantly influence dune behavior and morphology. Instead, the steep slip face resulted from the character of the curve into which the wind shaped the dune and from the nature of sand moving by gravity on a stable dune form.

Sand transported over a barchan is either trapped on the slip face or removed at the horns. Material leaving a barchan may form mounds to the lee of the horns that can grow into additional barchans if sand accumulation continues. If sand is removed at the horns faster than sand is added to the windward slope, the dune becomes smaller or, conversely, if sand is added at a greater rate than it is removed, the dune grows larger. Equilibrium
is reached when the amount of material added to the dune is equal to the amount of material removed.

Movement by Gravity

Maximum deposition occurs on barchan dunes at the top of the lee slope receiving sand from windward by saltation and surface creep. The slope gets steeper and steeper as the sand accumulates until the angle of repose is reached, after which the sand surface shears and slides downslope under the influence of gravity forming a lee slip face. Angles on newly formed lee slopes range from $34^\circ$ at the top to $31^\circ$ at the bottom (Sharp, 1966).

Experimental data presented by Van Burkalow (1945) suggests these are valid angles of repose for eolian sand. Furthermore, lee slopes are preserved in the interior of dunes as large scale cross strata. McKee (1966) found that nearly all the laminae were inclined at angles of $30^\circ$ to $34^\circ$. Poole (1962) also recorded angles up to $34^\circ$ from cross-stratified eolian sandstones of Late Paleozoic to Middle Mesozoic age on the Colorado Plateau. Lee slopes approaching $34^\circ$ are metastable, and movement is easily initiated on them either naturally or artificially.
Gravity movement on the lee slope takes place by slumping and sand flow along bands extending from the crest to the base of the slip face (McKee and others, 1971). In movement by slumping, a small band slides downslope in the form of a miniature landslide. The grains do not roll downslope individually but move as a unit. In movement by sand flow, individual sand grains slide or roll down the lee slope with a streaming motion. During the process, sand grains move at different speeds and along different courses. It is by this shearing of the slip face that dunes migrate.

Dune Migration

The rate of dune migration is dependent upon the size of the dune, the supply of sand and the velocity, direction and frequency of the wind. The smaller the dune, the more rapid is its advance. The higher the velocity of the wind, the more rapid is the advance. Topography and vegetation retard the movement of sand and thereby affect the rate of advance (Finkel, 1959).

The bulk of dune migration in desert areas takes place during the windy season which usually lasts only a few months. Rempel (1936) indicated
that a small barchan of the Salton dune field migrated thirty-seven feet between April and May 1933. The same dune moved only three feet from June until September 1933 due to the low velocities of the summer winds. The dune moved seventeen feet from September to December 1933 as the winds increased with the approach of winter. During a period from February 1933 to July 1934 a large dune in the field migrated a total of sixty-nine feet, while an adjacent small dune advanced a total of 133 feet for the same one year, five month period.

Long and Sharp (1964) determined the rate of migration of some of the Salton Sea dunes from comparison of maps and surveys. The movement of forty-seven of the barchan dunes ranged from 325 to 925 feet over a seven year period from 1956 to 1963, an average of eighty-two feet per year. During the fifteen years between 1941 and 1956, the movement of thirty-four of the dunes ranged between 350 and 1,200 feet, an average of fifty feet per year.

Norris (1966) made detailed observations of the isolated barchan dune at Tule Wash from November 1955 to March 1964. Fifteen plane table surveys were made, from which rate of movement and
volume change determinations were made. The rate of movement of the Tule Wash barchan correlated well with volume changes only when compared on an annual basis; the rate of migration increased as its volume decreased, and the migration decreased when the dune was growing. Short-term changes in rate of movement were apparently due to seasonal variations in the wind pattern, and to the effects of gullied topography which impeded the forward movement of the dune.
CHAPTER IV

THE SALTON BARCHAN

General Statement

The Salton Dunes were carefully examined during the spring of 1973 in order to find a barchan dune that possessed all the features observed on any of the barchans within the field. Such a representative barchan was located due west of the intersection of two power lines approximately 2.8 miles from the start of the AEC Test Base entrance road. It is called the Salton barchan in this report because it appears to be typical of the barchans within the Salton Dunes. In addition, the Salton barchan appears typical of the "classical barchan" described in the literature as a crescent-shaped accumulation of windblown material that trends at right angles to the direction of the prevailing wind. It moves slowly across a relatively flat, non-sandy surface, generally free of vegetation (Hack, 1941).

A map of the Salton barchan was made in the field by a brunton-tape survey (Figure 2). Three sampling traverses were laid out along string lines
Figure 2. Map of the Salton barchan showing sample locations.
stretched out over the barchan from the apex of the windward slope to the tip of each horn and across the asymmetric northern flank. In addition, sample stations were located at the summit and at the base of the slip face.

Form of the Salton Barchan

The Salton barchan is an asymmetric barchan with a pronounced bulge of the northern flank and thickening of the northern horn (Figure 2). According to Long and Sharp (1964), the Salton dune field included both symmetrical and asymmetrical barchans, but there was no apparent preference toward either condition. The Tule Wash barchan studied by Norris (1966) showed a pronounced elongation of the south horn.

Finkel (1959) suggested that lack of symmetry in a barchan dune was due to movement across a surface that sloped downward toward the asymmetrical horn or to occasional cross winds. Similarly, Bagnold (1941), as part of the discussion on conversion of a barchan to a seif dune, indicated that asymmetry of dune shape was the result of occasional cross winds. Rempel (1936) suggested that vegetation may have been a factor in briefly
stabilizing dunes or portions of them resulting in periods of asymmetry for partially stabilized barchans. Norris (1966) reported that topography had a secondary influence on the symmetry of barchans.

The asymmetry of the Salton barchan appears to be due primarily to the slope of the ground and the vegetation, with perhaps minor influence from gullied topography. The substratum upon which the dune rests slopes gently eastward and northeastward toward the Salton Sea. This ground slope would normally favor an elongation of the northern horn unless retarded by vegetation. The tops of several creosote bushes can be seen sticking through the top of the northern horn. The vegetation acts as a stabilizing agent that causes the north horn to shorten and fatten from the build-up of sand instead of becoming elongated. Finally, the northern horn is passing through and just beginning to escape a stream gully about eight feet wide and two feet deep. The wash seems to have impaired the forward advance of the north horn, adding to the bulged asymmetry of the barchan.

Long and Sharp (1964) classified the Salton Dunes according to their shapes. They employed for
this purpose the ratio a/c where "a" was the horizontal distance along the axis of symmetry from the windward edge of the dune to the upper edge of the slip face, and "c" was the distance between the tips of the horns. An a/c ratio of over 1.0 is said to be fat; one of about 0.75 is pudgy; one of 0.50 is normal; and one of about 0.25 is slim. They found a considerable range in the a/c ratios for the Salton dune field, but were unable to find any clear-cut relationship between this ratio and other characteristics of the dunes. Rempel (1936), however, noted that changes in dimension occurred relative to a growing barchan. As a barchan increased in size, the horns were built up by sand drifting around the dune and the "c" value became larger. This caused the windward slope to broaden presenting a wider, less rounded front to the prevailing wind and the "a" value became smaller.

Norris (1966) attempted to determine the relationship between dune shape and volume changes in the Tule Wash barchan and was unsuccessful. The Tule Wash barchan is a relatively large barchan that varies from 0.26 to 0.42 in a/c ratio which placed it in the slim category. It remains relatively slim despite volume fluctuations of 40 percent,
suggesting that the a/c ratio might be governed by factors other than sand flux—perhaps the irregular topography over which it migrates or perhaps by more subtle influences such as variations in the width or the strength of the oncoming sand stream.

The Salton barchan is of roughly medium size compared to the other barchans in the Salton dune field. If Rempel's (1936) idea concerning the relative broadening of a barchan with an increase in size is correct, then the Salton barchan should have a roughly normal to pudgy shape. The a/c ratio of the Salton barchan is .75, which puts it in the pudgy category, and indicates that perhaps there is some relation between increase in the ratio and increase in the size and volume of a dune, provided the inhibiting factor of topography is removed and the wind regime and volume of incoming sand remains relatively constant.

Sand Ripples

The most common surface feature found on the Salton barchan is wind ripples. Sharp (1963b) distinguished two types of wind ripples: (1) sand ripples composed of windblown sand with a median diameter roughly between 0.30 mm (1.75") and 0.35 mm
(1.50\(\Omega\)) and (2) granule ripples composed of particles approaching granule size, 2-4 mm (-1.0 to 2.0\(\Omega\)). Sand ripples are the only type of wind ripples that occur in the Salton Dunes.

Wind ripples are commonly measured by the dimensions of wavelength and height. Wavelength is the distance between ripples from crest to crest and appears to be a direct function of wind velocity (Bagnold, 1937a, 1941). Wave height is the difference between trough and crest and seems to be a direct function of the grain size of the material which makes up the ripples (Sharp, 1963b).

Sand ripples are eolian traction deposits produced by surface creep initiated by saltation impact. They have been described by Cornish (1914), Twenhofel (1932), Bagnold (1941) and Norris and Norris (1961) as small transverse piles of sand grains that contain coarse material at the top and finer grained material at the bottom. Sharp (1963b), however, impregnated ripples in order to study their internal relationships. He found sand ripples to be homogeneous piles of relatively coarse-grained sand resting on a platform of relatively finer material.

Experiments by Bagnold (1937a, 1941) indicated that ripples originated from small
irregularities in the sand surface. The number of grains moving in saltation that strike the windward side of the irregularity is far greater than the number that strike the leeward side. A ripple is developed by surface creep as more grains are driven up the windward slope from the impact of saltation. The height of the ripple increases until the grains are removed as fast as they are added. Grains moving in the saltation curtain tend to be concentrated downwind from lee side of a ripple by a distance equal to one saltation jump. The concentration of saltating sand grains, downwind from the first, initiates surface creep to form another ripple one saltation jump away and so on until a series of sand ripples is formed with wavelengths equal to the characteristic path length of the saltating grains.

The sand ripples observed on the Salton barchan appear very similar to those described by Sharp (1963b) on the Kelso Dunes in the Mojave Desert. The Salton barchan sand ripples are asymmetrical piles of relatively coarse sand grains resting on a base of finer sand. The ripples do not represent an average sample of the immediately underlying material. The ripples are not wholly
devoid of finer grains, but the amount is subordinate to the larger grains. The fine particles are incorporated in the ripple by capture in hollows between larger grains or by lee-side deposition of fine-grain forsets during periods of reduced wind velocity.

**Ripple Distribution**

The wind pattern over the Salton barchan can be inferred from the distribution of sand ripples across the dune. Bagnold (1941) observed that ripple wavelength decreased with a lessening in wind velocity.

The ripple distribution across the Salton barchan indicates a wind pattern of maximum velocity on the windward slope that decreases to a minimum on the crest. It increases again over the horns and has a relatively dead air pocket on the lee slip face. Ripples with the longest wavelength occur on the windward toe of the dune (Figure 3). The wavelength and height begin to decrease higher up the windward slope (Figure 4) and reach a minimum at the crest (Figure 5). Ripples on the horns of the dune increase in wavelength and height relative to the ripples on the crest (Figure 6).
Figure 3. Large, coarse-grained sand ripples on toe of windward slope.

Figure 4. Intermediate, medium-grained sand ripples midway up windward slope.
Figure 5. Small, fine-grained sand ripples at crest.

Figure 6. Intermediate, medium-grained sand ripples on south horn.
CHAPTER V

PROPERTIES OF THE SAND GRAINS

Mineralogy

Three surface samples were collected from the dune at the base of the windward slope, the crest and the slip face. Each sample was split to approximately one ounce, impregnated with epoxy resin and hardened into a one square inch block from which a thin section was cut. A point count of two-hundred grains was made for each thin section using a mechanical stage. The mineralogy of each thin section is shown by the first three samples in Table 1.

The sand is composed of 66-68 percent quartz, 16-17 percent feldspar, up to 10 percent rock fragments, minor amounts of heavy minerals, traces of biotite and occasional lacustrine shell fragments. All the minerals tend to occur in the same proportion regardless of location on the dune. There is a slight increase in the amount of heavy minerals and volcanic rock fragments in the smaller size fractions. The heavy minerals tend to form originally in smaller crystals, and the volcanic rock
Table 1. Mineralogy of Selton Barchan Sand and Possible Source Sands

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<tr>
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<td>Chert &amp; Metamorphic Rock Fragments</td>
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<td>6.5%</td>
<td>6.5%</td>
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<tr>
<td>Carbonate or Shells</td>
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**Sample Identification**

SB-A  Sand from windward slope of Salton barchan.
<table>
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<th>Sample</th>
<th>Identification (continued)</th>
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<td>SB-N</td>
<td>Sand from crest of Salton barchan.</td>
</tr>
<tr>
<td>SB-0</td>
<td>Sand from slip face of Salton barchan.</td>
</tr>
<tr>
<td>SR-6</td>
<td>Sandstone matrix from Ocotillo Conglomerate, Sec. 32, T. 11 S., R. 9 E., about twelve miles west of Salton Dunes.</td>
</tr>
<tr>
<td>SR-7</td>
<td>Palm Spring Formation, Sec. 33, T. 11 S., R. 9 E., about ten miles west of Salton Dunes.</td>
</tr>
<tr>
<td>SR-8</td>
<td>Palm Spring Formation, Sec. 35, T. 11 S., R. 9 E., about eight miles west of Salton Dunes.</td>
</tr>
<tr>
<td>SR-9</td>
<td>Sandstone from Borrego Formation, Sec. 19, T. 11 S., R. 10 E., about six miles west of Salton Dunes.</td>
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<tr>
<td>SR-2</td>
<td>Alluvial playa, Sec. 33, T. 11 S., R. 8 E., about sixteen miles west of Salton Dunes.</td>
</tr>
<tr>
<td>SR-3</td>
<td>Sand from San Felipe Creek, Sec. 35, T. 11 S., R. 8 E., about fourteen miles west of Salton Dunes.</td>
</tr>
<tr>
<td>SR-4</td>
<td>Drift sand from Tule Wash, Sec. 24, T. 11 S., R. 9 E., about seven miles west of Salton Dunes.</td>
</tr>
</tbody>
</table>
fragments are easily weathered and abraded. Sedimentary rock fragments occur rarely in sizes greater than 1.0 mm. Apparently these fragments are easily broken up into their smaller component grains or are too large to have been generally transported by the wind. There is also a decrease in the amount of plutonic rock fragments in the smaller size fractions due to their being broken up into the component grains.

The quartz grains are made up of two-thirds plutonic quartz, one-quarter metamorphic quartz and about one-tenth vein quartz. The plutonic quartz grains usually have abundant vacuole trains with occasional biotite, rutile and zircon inclusions, and rarely microlites. The metamorphic quartz is generally the stretched variety showing sutured borders. Grains of the recrystallized variety occur usually in the large size fractions of the individual sample. Apparently, these grains easily break apart into their sub-individuals. The vein quartz variety has very abundant vacuoles, which gives a cloudy appearance to the grain. The vein quartz grains are slightly smaller relative to the other quartz varieties.
The roundness of the quartz grains varies from angular to rounded. The degree and abundance of angularity increases with a decrease in grain size. Of the individual varieties, the plutonic quartz is most rounded in the large size fraction, whereas the metamorphic quartz is the most angular, having the crenulated boundaries of the sub-individuals. The vein quartz is more rounded in the intermediate size fraction. In the small size fraction the plutonic quartz is more angular than the other two varieties, due probably to the breakup of larger composite quartz grains.

The feldspars are made up of orthoclase and slightly more abundant plagioclase. Minor amounts of microcline are present, and rarely perthite. Although the climate is arid, the feldspars are usually fractured and generally altered, particularly in the larger size fractions. The weathered appearance of the feldspars is probably the result of the low relief and gradient in the area and perhaps the multicycle origin of the sediments.

The feldspars are usually smaller and more rounded than the quartz grains in the same sample. They are mostly all rounded to subrounded in the
large size fractions, becoming slightly subangular in the small size fractions. The orthoclase tends to be slightly more rounded than the plagioclase and microcline.

The rock fragment component of the sand is predominantly made of metamorphic fragments, with lesser amounts of volcanic fragments, occasional plutonic fragments and rare sedimentary fragments. The majority of the metamorphic rock fragments appear to be fine-grained silica that has undergone metamorphism so that its appearance in thin section resembles stretched metamorphic quartz with micro-crystal units of elongate, lenticular shape and pronounced crenulated borders. These rock fragments might be chert or volcanic ash that has undergone metamorphism. Metamorphic rock fragments composed of an elongated composite of biotite and quartz occur rarely. The volcanic rock fragments appear as weathered grains displaying a texture of interlocking feldspar laths; some are slightly metamorphosed. The occasional plutonic rock fragments are a composite of quartz and orthoclase or plagioclase and occasionally mica. The rare sedimentary rock fragments appear to be iron-stained siltstone fragments.
The size and roundness of the rock fragments are influenced by the physical properties of the material composing the fragments. The sedimentary rock fragments occur only in the large size fractions and are very rounded due to the softness of the matrix. The plutonic rock fragments are generally rounded in the large fractions, becoming subrounded to slightly subangular as they are broken up into smaller sizes. The volcanic rock fragments are more abundant in the intermediate and small size fractions because they are easily abraded. They are subrounded in the large fractions and become progressively rounder as they are abraded into smaller sizes. The metamorphic rock fragments are equally abundant in all size fractions and show very little evidence of weathering; however, all the grains are subrounded to well rounded, suggesting long or repeated cycles of transport.

The heavy minerals consist mostly of amphiboles, primarily hornblende and occasionally pyroxene. They are usually very fractured and highly altered. The heavy minerals are most abundant in the smaller size fractions because they tend to form originally as small crystals and are more subject to weathering.
Shell fragments composed of aragonite occur in all size fractions. Due to their softness, all the grains are very rounded.

Iron oxide occurs rarely as remnant stain on some of the quartz grains. This iron stain was added at the source area because the stain on the dune grains had been almost completely abraded off and is only present in recesses.

**Source of the Sand**

Several sources of sand for the Salton Dunes have been considered in the literature, but no effort has been expended to provide a quantitative estimate of the importance of the various sources suggested. Rempel (1936) commented that the beach line of ancient Lake Cahuilla was located about eight or ten miles west and northwest of the barchans, and suggested that this beach sand was the chief source of sand for the dunes. Long and Sharp (1964) considered sources located as much as twenty-five miles away, including the Cenozoic strata west of the dune field, sandy beaches of Lake Cahuilla and fresh alluvium from large areas in Borrego and Clark Valleys. A relatively local source is indicated by the pronounced angularity of some
grains and because the sorting is less perfect in the Salton Dunes than in other California dune sands (Norris, 1966).

In order to determine the relative importance of the possible sources of sand, each suggested source area was visited and sampled. A thin section was prepared from each sample. The mineralogy was determined by point counts of two-hundred grains from each slide using a mechanical stage. Mineralogical comparisons were made between the source samples and the dune samples and are recorded in Table 1 (page 43).

Samples were collected west of the Salton Dunes from Late Cenozoic strata mapped by Dibblee (1954). The mineralogy of these samples compares very closely with the mineralogy of the dune sands (Table 1, page 43). In addition, extensive wind scour of these Cenozoic rocks is quite evident, particularly in the Palm Spring Formation. Throughout the area, upwind from the dunes, are small accumulations of windblown sand in protected spots. The close comparative mineralogy strongly indicates that an important source of sand is the easily weathered Cenozoic sediments west of the Salton Dunes.
In spite of several references to Lake Cahuilla beaches in the literature, none could be found west of the dune field during this study. It is believed that such beaches were not extensively produced on the western side of the basin, or they had been considerably disrupted by the action of recent stream drainage. The old shore line of Lake Cahuilla is quite obvious along Highway 86 near Travertine Rock where it appears as a prominent line of pale-buff travertine along the base of the Santa Rosa Mountains. Recessional strand lines are easily recognized, but these are considerably north of the Salton Dunes. Sykes (1914) observed that the northeast shore of Lake Cahuilla would be subjected to the most intense wave action, whereas the southwestern shore would receive the least, being upwind and sheltered under the lee of the mountains. Norris and Norris (1961) determined that the probable currents in Lake Cahuilla would have increased wave energy along the eastern shore. And, indeed, the shore line features along the northeast and eastern sides are better developed than anywhere else around the rim of the basin, whereas along the western side the shore line is generally less prominent, but is locally preserved and recognized on the alluvial
slopes as wave cut terraces (Free, 1914). Van De Kamps (1973) collected samples from Lake Cahuilla beaches developed on the south and southeastern margins of the Salton basin. The mineralogy of those samples is included in Table 2. Comparison of those samples and dune samples indicate that Lake Cahuilla shore deposits are not a significant source of sand for the Salton Dunes.

Samples of alluvium were collected during the present investigation from large playas and stream channels west of the dune field (Table 1, page 43). None of the alluvium samples agreed even closely with the mineralogy of the dunes except, perhaps, for a sample taken from a small wind drift in Tule Creek which approached the composition of the dune sands. Norris (1966) suggested that a share of sand in the Tule Wash dune, at least, was derived from local stream sands. He observed that about 5 percent of the sand grains from the Tule Wash barchan were composed of rounded, reddish aggregates of fine-grained silt. These aggregates were approximately the same size as the ordinary sand grains of the dune with which they were mixed. Because the silt aggregates were very soft, easily abraded and crumbled readily when wet, they could not
<table>
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<td>VK-12</td>
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Table 2 (continued)

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<th>Mineral</th>
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<td>VK-12</td>
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<tr>
<td>Volcanic Rock Fragments</td>
<td>72.7%</td>
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<tr>
<td>Plutonic Rock Fragments</td>
<td>8.7</td>
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<tr>
<td>Sedimentary Rock Fragments</td>
<td>3.6</td>
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<td>Carbonate or Shells</td>
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Sample Identification

- VK-12: Beach at Hot Mineral Spa, Sec. 36, T. 8 S., R 12 E.
- VK-13: Beach south of Niland, Sec. 20, T. 11 S., R. 15 E.
- VK-14: Beach east of Brawley, Sec. 35, T. 13, S., R. 16 E.
Table 2 (continued)

<table>
<thead>
<tr>
<th>Sample Identification (continued)</th>
<th>Description</th>
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<td>VK-15</td>
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<td>VK-16</td>
<td>Beach foreshore, Sec. 34, T. 13 S., R. 16 E.</td>
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<tr>
<td>VK-17</td>
<td>Beach crest, Sec. 35, T. 13 S., R. 16 E.</td>
</tr>
<tr>
<td>VK-18</td>
<td>Beach east of Holtville, Sec. 23, T. 15 S., R. 16 E.</td>
</tr>
<tr>
<td>VK-19</td>
<td>Beach east of Holtville, Sec. 23, T. 15 S., R. 16 E.</td>
</tr>
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</table>

Source:
have been transported very far. It was further observed that the material was identical with that forming the mud curls and dried puddle surfaces found in low spots along Tule Wash and other drainages.

The same rounded reddish aggregates were observed during this study, rarely in the larger size fraction of the sand comprising the Salton Dunes. Russell (1932) referred to crusts that developed on the Salton Dunes which were attributed to cementation of limy material. Very little limy material was observed in the thin sections except as occasional shell fragments. These crusts were more likely produced when the silt aggregates on the surface of a dune were sufficiently softened by rains to act as a weak binding agent (Norris, 1966). The presence of these soft silt aggregates suggested that some of the sand forming the Salton Dunes may have been derived from nearby stream washes.

In summary, the comparative mineralogy of the dune sand with possible source samples indicates that Lake Cahuilla beaches and recent alluvium are not important direct sources of sand for the Salton Dunes. The only grains obviously contributed to the dunes from Lake Cahuilla sediments are the occasional
detrital shell fragments. The principle source of sand for the Salton Dunes seems to be the poorly consolidated Late Cenozoic strata west of the dunes, and perhaps a minor secondary contribution from nearby stream washes.

**Color**

The color of the Salton barchan sand is weak to strong, very light yellow-brown (10 YR 7/2, 3, 4) from the Munsell Color Chart. The coarsest sand from the ripples on the toe of the dune is the lightest in color—weak, very light yellow-brown (10 YR 7/2). This is probably due to the abundance of large, clear quartz grains which dominate the sands and tend to pale the color. The sands become stronger in saturation of hue with a decrease in grain size, as the paling effect of the quartz grains lessens, by allowing the creamier feldspars and darker minerals to more fully control the color. The darkest sands are found in the very fine-grained wind shadows in front of the slip face; they are strong, very light yellow-brown (10 YR 7/4).

The yellow coloration of the barchan dune sand may be related to the stages of oxidation coloration for dune and barrier sands described by
Price (1962). Stage 0 represents an unoxidized condition, and sands have no added coloration. Quartz grains are clear and deposits are lightly to barely grassed. Stage 1 represents an early oxidized state. A light accumulation of a yellowish to brownish oxidation coating appears on a large enough percentage of grains to make the sand a slight but distinct yellow to light yellow-brown. Deposits are usually well grassed. Stage 2 represents advanced oxidation with little or no humus. Sands are a well-developed golden yellow to reddish brown. Stage 3 represents advanced oxidation with added humus. Sands are dark reddish brown to brownish black. The barchan dune is completely devoid of grass, and the grains range in color from almost clear to light yellow, suggesting that the sand may represent a transition zone between Stage 0 and Stage 1.

Price (1962), Norris and Norris (1961) and Norris (1969) concluded that the stage of coloration might be an indication of relative age. Sand grains apparently acquire a coat of ferric oxide that persists despite abrasion, thereby imparting to the sands a darker reddish color as they become older. It has been observed that sand grains newly
deposited and forming ripples on the surface of the Salton barchan are slightly more clear than the grains from the interior of the dune, which suggests that sand grains from the ripples are apparently fresher than the dune sand and have not undergone significant oxidation. Sand from the interior of the dune, however, has been retained for a longer period of time and becomes more oxidized imparting a yellow coloration to the grains.

Price (1962), Norris and Norris (1961) and Norris (1969) also observed that there was a decrease in the amount of original iron-rich minerals in dune sand with an increase in reddish coloration. The Salton barchan sand has very few original iron-rich minerals, and those that do occur are found in the finer size fractions usually in a very fractured and weathered condition. It may be that through leaching of these few minerals enough iron is produced to impart a slight yellowish coloration to the sand. Rainfall during the winter months and occasional summer showers may be sufficient to initiate chemical weathering of the iron-rich minerals in the zone of saturation. During the dry periods when the sands are dry and unconsolidated, migration will serve to
thoroughly mix the sand and provide a new layer of sand to the next rain.

**Surface Frosting**

The sands of the Salton barchan, when viewed under binocular microscope, exhibit the highly pitted surface typical of eolian frosting. The frosting resembles closely-spaced pockmarks and has rendered the grains slightly translucent. The frosting occurs with equal frequency on small grains as well as large grains. The entire surface of grains, including embayments, appears evenly frosted.

Desert frosting is thought to be due in minor degree to mechanical abrasion, but mainly to chemical action (Kuenen and Perdok, 1962). Experiments by Kuenen (1960) showed that mechanical abrasion was rather coarse, seldom visible on eolian sands and was limited to the corners and edges where it produced rounding of grains. They did not, however, account for the frosting that occurred in the furrows and embayments of desert sand grains, including the Salton barchan sand. Experiments by Kuenen and Perdok (1962) indicated that the pitted appearance of frosted desert grains was due to solution etching during chemical reaction. At the
same time, rough mechanical abrasion effects were healed by solution which resulted in a frosted grain evenly marked on flat and embayed surfaces as well as rounded corners.

The agent responsible for the chemical action causing surface frosting in desert areas is most probably dew. Dew occurs very commonly in desert areas, and was suggested by Engle and Sharp (1958) as a potential chemical agent in connection with the origin of desert varnish.
CHAPTER VI

SIZE ANALYSIS OF SURFACE SEDIMENTS

Procedure

The surface sediments of the Salton barchan represent deposits accumulated into sand ripples. Any observable variation in the surface sand ripples is the result of changes in surface creep and saltation, which are controlled by the local wind. Any analysis of the grain-size properties of surficial dune deposits must, therefore, consider the wind regime that passes over a dune. Bagnold (1941) observed that the form of a barchan caused an incoming wind to divide around the dune as well as be deflected over the top. A "dead air" pocket is created on the lee side by the sheltering effect of the dune. The wind pattern over the Salton barchan has been discussed earlier by noting the distribution of sand ripples.

In order to examine the distribution of grain-size parameters across the surface of the Salton barchan, sampling stations were established approximately every forty-five feet along each of the three traverses (Figure 2, page 32). This
Spacing was used because observable changes in ripple dimension occurred. Several ounces of sand from the ripple type present at each station were collected down to the underlying fine sediments upon which the ripples rested and were stored in marked plastic bags. The sand ripples at each station were described. Each sample was split in the laboratory and analyzed by the Emery (1938) settling tube method.

Data were plotted as cumulative probability curves. The graphical statistics were calculated using the formulas of Folk and Ward (1957) to obtain mean size, standard deviation, skewness and kurtosis (see statistical data in Appendix). The mean size is the average grain diameter of a sample. Standard deviation, or sorting, is a measure of the uniformity of grain size in a sample. Skewness is a measure of asymmetry of a size distribution. Symmetrical distribution has a skewness of 0.00. Positive skewness indicates an increase in the proportion of fine material or a decrease in proportion of coarse material relative to a normal distribution; the sediments are fine skewed. Negative skewness indicates an increase in coarse material or a decrease in fine material, relative to
a normal distribution; the sediments are coarse skewed. Kurtosis measures the peakedness of a size distribution. It shows the relationship between the sorting of the central 50 percent of a size distribution and the sorting of the tails of the same distribution. If the center is better sorted than the tails, the distribution is leptokurtic; if the tails are relatively better sorted than the center, the distribution is platykurtic. If the center and the tails are comparatively equally sorted, the distribution is mesokurtic. The statistical results were plotted on a map of the Salton barchan prepared in the field, and were contoured to obtain distribution diagrams for each grain size parameter over the surface of the dune.

**Mean Size**

The distribution of mean grain size on the surface of the Salton barchan is shown in Figure 7. The dune is coarsest at the windward toe, finer to the crest and again coarser outward on the horns. The finest grain sizes are found on the lee slip face and in wind shadows in front of the slip face.

Mean grain-size data related to position on a dune are reported in the literature with contrary
Figure 7. Distribution of mean grain size on the dune surface.
results. Folk (1971) noted that about half the dunes discussed had crests that were coarser grained than the flanks, whereas about half the dunes had crests that were finer grained. This apparent contradiction may have been due to the depth at which samples were collected from the dunes, as will be seen later in the examination of sand samples collected from the interior of the Salton barchan. Unfortunately, in most of the early literature it is not clear if samples were taken on the surface of the dunes or at some depth into the dunes.

Some dunes reported in the literature have indications that the samples may have been collected from the surface. Cornish (1927) indicated that lee slopes of dunes were finer than dune crests. Bagnold (1935, 1936, 1941) stressed that crests were finer than windward flanks. Sidwell and Tanner (1939) collected surface samples from a West Texas barchan and found that coarse grains tended to accumulate on the windward side of the dune and on the horns, while fine grains collected on the crest. Eymann (1953) analyzed surface samples from a barchan dune near Kane Spring and noted that windward samples were noticeably coarser than leeward samples. Amstutz and Chico (1958) measured grain size from barchans
in Peru and found windward slopes to be coarser than crests or horns. Sharp (1966) also found that coarse grains accumulated on the windward slopes of the Kelso Dunes in California.

The variation in grain size across the Salton barchan is apparently due to the selective action of the wind leaving coarse grains on the windward side and transporting finer grains farther up the dune. On the windward slope coarse grains drop out of the incoming saltation curtain and form into ripples as the wind velocity is checked by the dune. Differential rates of surface creep concentrate the coarsest grains into slow moving large ripples on the toe of the barchan (Figure 3, page 40). Finer-grained ripples migrate faster up the windward slope producing a decrease in grain size up the windward slope to the finest grains in smallest ripples at the crest (Figure 5, page 41). Lee slope sands represent "dump" deposits of the finest grain sizes transported by the wind over the dune summit and into the lee. The mean grain size increases on the horns due to the return of the prevailing velocity as the wind passes around the barchan. Here, the fine grain sizes are transported
off the surface and away from the dune, and intermediate length, medium-grained ripples are formed (Figure 6, page 41).

**Standard Deviation**

The distribution of standard deviation or sorting on the surface of the Salton barchan is shown in Figure 8. The sorting ranges from moderately sorted to well sorted. Moderate sorting occurs on the toe and northern flank and horn. The degree of sorting improves toward the crest and on the southern flank. The best sorting occurs on the slip face and the wind shadows.

Very little information regarding sorting of dune surface deposits is recorded in the literature. Bagnold (1935, 1936, 1941) reported that dune crests were usually better sorted than the flanks. Eymann (1953) noted that the degree of sorting for a barchan near Kane Spring improved from the windward side to the leeward side. McKee and Tibbits (1964) found lee avalanche faces to be better sorted than the windward slopes.

The variation in sorting across the Salton barchan seems to be due to the winnowing effect of the wind in removing fine grains from the windward...
Figure 8. Distribution of standard deviation or sorting on the dune surface.
side and depositing them to the lee. The windward part of the barchan is subjected to scouring action that removes the fine sand fraction and leaves behind a relatively worse sorted lag of coarser grain sizes. Since only the fines reach the lee, except during storm winds, the material on the lee and wind shadows is better sorted. The northern flank retains a relative poor sorting because of the vegetation which sticks through the encroaching horn. The shrubs prevent the free transport of fine sand which then accumulates as small piggyback ripples upon larger, coarse-grained ripples (Figure 9). The mixing of the two size fractions results in the worst sorting on the barchan.

**Skewness**

The distribution of skewness across the surface of the Salton barchan is shown in Figure 10. Most samples are near symmetrical. The pattern shows weak positive skewness on the toe and horns, and weak negative skewness increasing up the windward slope to the crest. The lee slip face is also weakly negatively skewed.

Skewness data on desert dunes in the literature are very meager. Desert dunes are
Figure 9. Large, coarse-grained sand ripples with small, fine-grained "piggyback" ripples superimposed; on north flank.
Figure 10. Distribution of skewness on the dune surface.
reported to be positively skewed, but the samples were collected from areas underlying surface ripples as will be discussed later.

Variation in skewness depends on a notable increase in proportion of very coarse or very fine "tail" sizes relative to the rest of the sample. The variation in skewness across the Salton barchan is apparently the result of surface roughness which serves to protect finer grains from the winnowing action of the wind. Bagnold (1941) noted that for rough surfaces there was a zone of zero wind velocity that occurred up to a height of one thirtieth the height of the object causing the roughness. It has already been observed that sand ripples with the largest wavelength and coarsest grain size occur on the lower windward slope and become progressively smaller and finer grained toward the crest. The fine grains mantling the lower windward slope fine protected refuge in the hollows between the coarser grains. This sheltering effect results in an increase in fine "tail" sizes on the toe of the dune and provides the positive skewness. As the surface roughness decreases toward the crest, the protected refuge for the fine sand sizes is effectively reduced so that the skewness passes into
the near-symmetrical range. Higher on the windward slope the roughness shelter is lost and finer grains are winnowed out leaving behind relatively coarse tail sizes, which account for the negative skewness. There is a slight trend toward the near-symmetrical range on the lee side of the summit due to the "dumped" nature of slip face and wind shadow deposits which have a more random distribution. The trend toward capture of the finer sizes in protected hollows improves as the surface becomes rougher out on the horns resulting in slight positive skewness.

Kurtosis

The kurtosis on the surface of the Salton barchan is based on the more normal function of transformed kurtosis, \( K'g = Kg / (Kg + 1) \) (Folk and Ward, 1957), and the distribution is shown in Figure 11. A generally indistinct pattern is developed across the dune. Most samples fell in the mesokurtic range \( (K'g = 0.48 - 0.52) \). A small area of the north windward flank is slightly leptokurtic \( (K'g = 0.54) \). Lee slope sands show nearly normal kurtosis \( (K'g = 0.50) \). There is no data on kurtosis of surface deposits from desert dunes reported in the literature.
Figure 11. Distribution of kurtosis on the dune surface.
The distribution of surface kurtosis is not very distinct; therefore, only general conclusions can be drawn. The variation in kurtosis over the surface seems to be due to the sorting action of the wind on grains in saltation compared to grains in surface creep. Most of the sand that moves over the barchan is transported by saltation, which selects a limited range in grain size favored by the local wind regime (Bagnold, 1941). Sorting within this range might be expected to be random, thus producing generally normal kurtosis. The movement of sand over the barchan by surface creep might cause the slight departures into the mesokurtic range that occur on the dune.
CHAPTER VII

SIZE ANALYSIS OF INTERIOR DUNE SAND

Procedure

Sand in the interior of a dune represents sediments that have been collected into a depositional structure instead of merely in transit over the surface. Being part of a depositional structure, the sediments are a product of the depositional properties of the local wind regime as well as the reworking effects of migration processes. Bagnold (1941) explained that the movement of sand over and through a dune in migration followed a clockwise motion. Grains are rolled over the surface by surface creep and are transported in the saltation curtain from the trailing edge of the windward slope to the crest where they drop to the base of the leeward side. Sediments from the lee side are mixed into the dune as it advances and travel backward to be eventually exhumed on the windward slope. Any analysis, therefore, of the sediments within a barchan must be explained in terms of this clockwise "conveyor belt" movement of sand grains over and through the migrating dune.
In order to examine the textural characteristics of sand grains inside the Salton barchan, additional samples were collected at each station established previously along the three traverses over the surface of the dune. At each station a hole one foot deep was dug and cased with a metal cylinder to prevent caving of the sides and contamination from the surface sediments. Several ounces of sand were collected from the bottom of each hole and stored in labeled plastic bags. Samples were split and analyzed in the laboratory by the Emery (1938) settling tube method. The data were plotted as cumulative probability curves, and the graphical statistics were calculated following the formulas of Folk and Ward (1957) (see statistical date in Appendix). Results of the statistical calculations of the individual parameters were plotted on a sampling plan prepared from the survey of the barchan. Contouring of the values provided distribution diagrams of each grain size parameter within the barchan.

Mean Size

The distribution of mean grain size in the interior of the Salton barchan is shown in
Figure 12. The mean size of the sand throughout the dune falls between 2.35 and 3.20ø (fine sand with minor very fine sand). The coarsest grain sizes occur near the dune summit. The windward slope is finer grained than the crest, but coarser than the flanks and horns. Finer grain sizes are located on the horns, and the finest sizes occur in the slip face and wind shadows.

Udden (1898) observed that the mean grain size most favorably transported by wind was 0.25 and 0.125 mm (2-3ø) because the dynamic properties of wind tended to select that size range. Bagnold (1935, 1936) roughly confirmed that size range with wind tunnel experiments. Desert dunes with crests coarser grained than the flanks were described by Ball (1907) in Egypt, Lewis (1936) in the Kalahari, Simonett (1960) in Kansas and Folk (1971) in Australia. Cornish (1897) observed crests to be coarser and thought that finer material was winnowed out of the "smoking crest" while a lee eddy allowed fines to accumulate on the slip face. King (1918) experimented with smoke and found that lee eddies did not exist, but that the lee side was a dead wind area protected by the bulk of the dune. Udden (1914)
Figure 12. Distribution of mean grain size in the dune interior.
found sand in the lee to be finer than other dune areas.

The variation of mean grain size through the interior of the Salton barchan is the result of the clockwise "conveyor belt" motion of sand within the migrating dune, and is controlled by the position with depth within the dune. Bagnold (1941) observed that the movement of sand over a typical barchan grades the sand within the dune. Coarse sand is driven up to the crest by surface creep and over into the shelter of the slip face where it is incorporated into the dune as it advances. Very fine material is deposited from the saltation curtain in the fore of the dune due to calm lee side conditions. Inverse size grading throughout the dune is the result because coarser sand deposited near the crest remains high in the dune, whereas the finer material deposited in low foredune areas eventually forms the whole of the underside of the barchan. A core through the Salton barchan would show a progressive coarsening from the base to the summit. This inverse grain-size distribution is likewise reflected by the geomorphology of the dune when samples are collected at a constant depth from the surface. Marginal areas, being low, exhibit
fine grain size while central areas show progressively coarser grain size in areas where the dune is thicker.

**Standard Deviation**

The distribution of standard deviation or sorting within the interior of the Salton barchan is shown in Figure 13. The sorting ranges from well sorted to moderately sorted. The best sorting occurs in a central belt roughly along the axis of symmetry of the barchan. The degree of sorting becomes progressively worse outward from this belt toward the northern and southern flanks. The toe and crest have moderately well-sorted values. The lee is slightly better sorted than the crest. The sorting becomes moderate out on the horns.

Friedman (1961) calculated moment measures for some dune sands. He concluded that eolian sediments had sorting values lower than 0.500 and suggested that sorting might be used to distinguish beach and dune sands. This value is different from the sorting values found within the Salton barchan. Mason (1957) found that beach dune sands from Mustang Island in South Texas were slightly better sorted than beach sand (0.27 vs. 0.31). Waitt (1969)
Figure 13. Distribution of standard deviation or sorting in the dune interior.
found the sorting to be about the same (0.31) over
crests, lee slopes and windward flanks in desert
dunes from West Texas. Folk (1971) found crests to
be better sorted than dune flanks in Simpson Desert,
Australia.

The sorting values from the Salton barchan
compare closely with the inland dunes of Waitt
(1969) and Folk (1971). These inland dunes exhibit
worse sorting than the beach dunes reported by
Mason (1957), Bridges (1959) and Hayes (1965) from
coastal areas of Texas. Moiola and Weiser (1968)
compared beach dunes and inland dunes and found the
inland dunes to be more poorly sorted than the beach
dunes.

The difference in the sorting between inland
dunes and beach dunes is apparently due to the
nature of the source sediments from which the sand
forming the respective types of dunes is derived
(Friedman, 1967). Most desert dunes are derived
from wind acting on poorly sorted fluvial sediments,
whereas most beach dunes are derived from moderately
well sorted beach sand. The dunes in both
environments are better sorted than the source
material because of the selective action of the wind,
but, to some extent, the sorting of the source is inherited by the dune sands.

The variation in sorting in the Salton barchan seems to be due to the shape of the migrating dune and the action of the wind over the flanks. As the migrating barchans travel with the wind, sand grains are sorted by the selective action of the surface creep. When these well sorted grains fall over the lee slope, they become buried in the dune and are eventually exhumed on the windward slope to go through another cycle of transport. Each one of these cycles serves to improve the sorting of the interior sand. It has been seen earlier that an incoming wind splits and separates around the flanks of a barchan (Bagnold, 1941). This splitting is due to the fact that a barchan is thicker along the axis than at the flanks. Sand traveling through the thicker portion of a barchan is less subject to erosion by strong winds than sand traveling through thinner areas of the flanks. Also, more selectively sorted sand is received at the thicker portions than at thinner regions. A sorting trend is developed, therefore, reinforced by the morphology of the dune, such that
the thick regions are best sorted and outward toward the thinner flanks, the sorting becomes progressively worse.

**Skewness**

The distribution of skewness for the interior of the Salton barchan is shown in Figure 14. Most samples are in the near symmetrical range. A belt of positive skewness occurs somewhat off center of the axis of symmetry of the barchan. Skewness values decrease away from this central belt outward toward the flanks and horns which are slightly negatively skewed. The crest and lee slope are more positively skewed than the windward slope.

Many data on skewness of sands have been reported in the literature, usually as a means of differentiating dune and beach sands. Folk (1971) provided a review of this literature which concluded that beach sands were negatively skewed, whereas dune sands were positively skewed. Concerning desert dunes, however, little on skewness has been reported. Harris (1957) reported marked amounts of sand in the finer size grades in Egyptian dunes which would yield positive skewness. Moiola and Weiser (1968) found that inland dunes were positively skewed. Waitt
Figure 14. Distribution of skewness in the dune interior.
(1969) found West Texas dunes to average near symmetrical; however, the windward slopes were more positively skewed than the lee slopes. Folk (1971) found Australian dunes to be mostly positively skewed, with dune crests being the most positively skewed, windward flanks intermediate and lee sides least. However, he noted there was much overlap between the dune environments so that the differences might not have been too meaningful. Friedman (1967) believed that the strong, positive skewness of desert dunes was the result of the abundance of fine "tail" grains derived from fluvial sediments. Fine "tail" grains were winnowed out of the source sand for beach dunes by wave action.

The distribution of skewness in the interior of the Salton barchan forms a pattern similar to the sorting pattern, and the reason is the same in both cases: the morphology of the dune. It was shown earlier that relatively fine grain sizes are deposited on the lee slip face and foredune wind shadows, and are then incorporated into the dune. A greater amount of fine sand is deposited in the center of the lee slope than on the horns. Once deposited, the thick central portion of the dune seems to protect the inherited fine size fraction.
from removal by wind, resulting in a central belt of positive skewness roughly along the axis of dune symmetry. Away from this central belt, the dune becomes thinner, and the winnowing action of storm winds in removing fines becomes increasingly effective, especially on the flanks. This results in a progressive trend toward negative skewness in thinner regions of the barchan.

Kurtosis

The kurtosis values in the interior of the Salton barchan are based on the transformed kurtosis (Folk and Ward, 1957), and the distribution is shown in Figure 15. Most samples fall in the mesokurtic range. A trough of low kurtosis passes north-south through the slip face resulting in a slightly meso-platykurtic lee slope. There is an increase in kurtosis values up the windward slope from a mesokurtic toe to a slightly leptokurtic crest. The horns become progressively leptokurtic downwind from the low kurtosis trough.

Kurtosis values for desert dunes are mentioned only briefly in the literature. Moiola and Weiser (1968) indicated that their desert dunes ranged from mesokurtic to leptokurtic. Waitt (1969)
Figure 15. Distribution of kurtosis in the dune interior.
found the inland dunes of West Texas to be generally mesokurtic, but that lee slopes were slightly more platykurtic. Folk (1971) found the desert dunes in Australia to be almost all mesokurtic, but that crest and windward sands tended to be somewhat more leptokurtic and leeward sand to be more platykurtic.

The rough trend exhibited suggests that the variation in kurtosis is the result of addition or removal of tail "fines" to the turnover regime of the migrating barchan. Fine, well-sorted grains at the lee side are continually incorporated into the barchan resulting in meso-platykurtic lee slopes. Other areas of the dune are not subject to this absorption of well sorted fine "tail" sizes and so tend to be more mesokurtic. The leptokurtic horn tips are the result of winnowing of the fine size fraction during storm winds. The leptokurtic area on the crest is the result of the reworking of sand which already exhibits the best overall sorting.
CHAPTER VIII

SUMMARY

The Salton Dunes are actively migrating barchans southwest of the Salton Sea, California. The dunes have been constructed on a hard, generally smooth substratum of Quaternary lacustrine sediments that slopes gently northeastward. Prevailing wind direction is from the west at velocities sufficient to transport large quantities of sand, especially during the spring. The dunes probably formed within the last three-hundred years and appear to have been localized by favorable conditions of smooth, generally level ground surface, adequate sand supply and limited vegetation.

Dunes are formed as accumulations of wind-blown sand transported by suspension, saltation and surface creep. Saltation and surface creep are the active processes transporting sand over the surface. Barchan dunes form from previously existing mounds of loose, dry sand acted upon by a unidirectional wind. The size, shape and rate of migration of a barchan is dependent on the nature of the wind, the supply of sand and the character of the substratum.
Migration of a barchan is accomplished by avalanching of sand on the lee slip face, and a clockwise turnover of sand through the interior of the dune.

A typical dune, called the Salton barchan, was examined to determine what differences in grain-size characteristics occur across the sub-environments of a barchan dune, how these properties vary with transport across and through a migrating barchan, and what effect barchan morphology has on the textural parameters. The Salton barchan is a medium-sized, asymmetric, "pudgy" dune with a pronounced bulge of the northern flank and thickening of the northern horn. The asymmetry seems to be due to the gentle northeastern slope of the substratum which would normally elongate the northern horn. However, vegetation and shallow stream gulllying at the northern horn tend to retard the movement of sand causing thickening of the horn and flank. The pudgyness of the barchan might be a function of its size. Shrinking barchans tend to be slim; growing barchans tend to be fat. Additional study needs to be done concerning this relationship as other factors may apply.
Sand ripples are the most common surface feature on the Salton barchan. They are asymmetrical piles of homogeneous, relatively coarse sand resting on a platform of relatively finer grained sand. They do not appear to be an average sample of underlying dune sediments worked into ripple form. Apparently, they are a concentrate of coarse sand grains brought to the dune by the local wind and deposited on the surface where they are selectively sorted into piles by surface creep initiated by saltation impact. Large sand grains move more slowly in surface creep than do smaller sand grains.

The wavelength of ripples is a function of the wind velocity. The pattern of the wind velocity across the Salton barchan can be determined by the wavelength of the ripples on the surface. Wavelengths on the surface of barchan ripples are maximum on the toe and minimum on the crest, which suggests that the velocity of wind near the dune surface decreases as it rises to the crest. Ripple wavelength increases around the flanks and out on the horns indicating that the wind splitting and contouring around a barchan maintains a higher velocity than over the dune, probably due to reinforcement from the wind stream outside the
influence of the obstructing dune. Ripples are rare and very poorly developed in the lee pocket of barchans, suggesting a relatively calm area with no appreciable eddy.

The mineralogy of the Salton barchan sand was determined by point counts of two-hundred grains in thin sections prepared from samples collected on the toe of the windward slope, the crest and the slip face. The sand was composed of 66-68 percent quartz, 16-17 percent feldspar, up to 10 percent rock fragments, minor amounts of heavy minerals, traces of biotite and occasional lacustrine shell fragments. The mineralogy of the dune sand remained generally constant regardless of the location of the sample or the mean size of the grains.

Several possible sources of sand for the Salton Dunes have been suggested in the literature, but the relative significance of these sources was never indicated. During this investigation, the mineralogy of these suggested source rocks was determined by point counts of two-hundred grains in thin section. The comparative mineralogy between the Salton barchan sand and possible source sands revealed significant indications on the relative importance of various source areas. Lake Cahuilla
beaches were not observed to be extensively developed upwind of the dunes as had been suggested, nor did the mineralogy of Lake Cahuilla beach sand to the south resemble the mineralogy of the dune sand. The only grains obviously contributed to the Salton barchan from Lake Cahuilla sediments were the occasional detrital shell fragments. Alluvium from large playas and major stream courses did not compare closely with the dune sand. However, very soft, reddish siltstone fragments present rarely in the barchan sand suggest a possible minor contribution from local stream washes. Very close agreement in comparative mineralogy indicated that the most important source of sand for the Salton barchan was the poorly consolidated Upper Cenozoic strata that crop out west of the dunes.

The color of Salton barchan sand is weak to strong, very light yellow-brown. The yellow coloration seems to be due to a mild oxidation state of the sand indicated by patchy stain of ferric oxide, probably resulting from the leaching of iron-rich minerals during the winter months when the rainfall in the area is highest.

The Salton dune sands exhibit typical eolian surface frosting of probable chemical origin. The
agent responsible is probably dew. Dew occurs commonly in desert areas and has been linked as a potential chemical agent in connection with the origin of desert varnish.

The sediments on the surface of the Salton barchan represent traction deposits accumulated into sand ripples and controlled by the action of wind passing over the dune. The mean grain-size distribution of surface sediments across Salton barchan is apparently due to the selective action of wind acting on the grains in surface creep. Coarse grains move the slowest and are unable to rise with the slope of the dune; therefore, they are concentrated mainly at low marginal areas. Finer grains move faster and are scattered up the windward slope in progressively finer mean size up to the crest. The finest grains moved by surface creep tumble over the crest and accumulate down the slip face where they mix with fine grain sizes lost from the saltation curtain.

The variation in standard deviation or sorting on the Salton barchan surface is due to the winnowing effect of prevailing winds in removing fine grains from the windward side and depositing them to the lee. The morphology of the dune influences the
wind patterns which affect the degree of winnowing on the windward slope and form the wind pocket to receive deposition on the lee. The degree of sorting across the barchan surface becomes increasingly better from the windward side to the lee.

The variation in skewness of the surface sediments depends on the relative increase in fine "tail" sediments relative to the rest of the sample. The increase in fine grain sizes results from capture in hollows between coarse grains on a rough surface. The morphology of the dune influences the distribution of ripples which produces the surface roughness. Rough surfaces are the most positively skewed, and smooth surfaces are more negatively skewed. Apparently, skewness is related to grain size because areas with larger grain size are more positively skewed, and areas with fine grain sizes are more negatively skewed. The distribution, therefore, is toward positive skewness on the toe and horns, and negative skewness on the crest and lee.

The variation in kurtosis of surface sediments is apparently due to the sorting action of the wind affecting grains in surface creep versus
grains in saltation. Saltation randomly sorts grains that, when deposited to the lee, result in a mesokurtic distribution. Surface creep on the windward slope is an active transporting agent, and the skewness of the sample may be important. Where the distribution is positively skewed, sands tend to be generally meso-platykurtic because of the increased sorting of the finer "tail" sizes. Where the distribution is more coarse skewed, the sand tends to be meso-leptokurtic because of the lack of fines and the relative better sorting of the central sizes.

The interior sand of the Salton barchan represents sediments that have been reworked from the surface and mixed into the "conveyor belt" turnover system of migration. As such, the sediments possess entirely different statistical parameters than those expressed by the surface sediments. The statistical parameters for the interior of the Salton barchan seem to be the result of inherited properties from surface sediments deposited on the lee side of the dune and mixed into the interior as the dune migrates. The variation in the parameters is apparently related to the morphology of the
barchan which influences the "conveyor belt" turnover of material.

The mean grain size in the interior of the Salton barchan ranges between 2.35 and 3.200. This general range in mean size tends to occur in most desert dunes, and seems to be the size range most favorably selected by the dynamic properties of wind. The variation in mean grain size within the Salton barchan seems to result from the reworking of material through the migrating dune and the position with depth within the dune. The barchan is inversely graded from coarse at the top to fine at the bottom because coarse grains are not transported as far over the slip face as fine grains. Coarse sizes are then collected into the migrating dune higher up, whereas finer grains are mixed in near the base producing inverse grading. The morphology of the barchan influences the depth position of a sample and, hence, the grain-size distribution. Low marginal areas are fine grained, whereas thick areas are more coarse grained. It might be inferred that barchan dunes will exhibit this type of grading although the absolute sizes may vary. The inverse grading appears to be strictly dependent on the selective transporting action of wind and the
morphology of the barchan, and is independent of other factors that affect dune growth and migration. Applied to eolian deposits in the geologic record, inverse grading of mean grain size might suggest a barchan environment.

The variation of standard deviation or sorting within the Salton barchan is apparently due to the inheritance of good sorting from the surface which is then retained in the dune to varying degrees related to the protective qualities afforded by barchan shape. A much greater amount of well sorted sand collects in the lee pocket of a barchan than on the horns or flanks. As the sand is reworked through the migrating dune, the greater volume of sorted sand along the axis of the dune is better protected from scour during storm winds than is the lesser volume of sorted sand on the flanks. The overall result is a distribution of sand through the dune that is better sorted on the axis and progressively worse sorted on the flanks. Such a distribution might only be valid on isolated barchans. Coalescing barchans and complex migrating dune forms have different shapes that probably produce different surface wind patterns resulting in different inherited sorting distributions.
Like sorting, the variation in skewness in the interior of the Salton barchan is apparently related to the protective qualities of the morphology. The dune tends to retain relative fine material deposited in the lee pocket that is transported back through the axis and sheltered by other grains. Sheltering is not so effective out on the flanks because the winnowing action of the wind is stronger. The result is a central distribution from a positively skewed axis becoming progressively negatively skewed out on the flanks.

Sorting and skewness appear to be closely related to each other in the interior of the Salton barchan as a result of their dependency on the morphology of the dune, but independent of grain size. This independence from mean size suggests that separate factors influence each distribution and that these factors may be independent in their action on dunes. It appears that once incorporated into the dune, the mean inverse grain size of the sands remains roughly constant during the backward travel through the dune, but that the "tail" sizes of the entire distribution are actively reworked and that the degree of reworking is dependent on the geomorphology of the dune.
Perhaps the grain-size distribution in a barchan is the result of the selective action of gentle prevailing winds which produces inverse grading that, through migration, is transferred throughout the dune. On the other hand, sorting and skewness may be modifications made on the tail size of the graded distributions brought about by gusty winds whose active scour pattern is strongly influenced by barchan morphology.

The distribution in kurtosis within the Salton barchan does not show truly discrete trends. The variation seems to be due to the addition or removal of "tail" fines during the reworking of migration and may be related to the sorting and skewness of the barchan. The increase of well sorted fines results in platykurtic areas, whereas a decrease in fines in areas subject to wind scour is more leptokurtic.

Until more is known about the nature of modern desert dunes, little can be extrapolated to ancient dune deposits. Many factors appear to influence the statistical parameters of dunes, including the velocity of winds affecting the dunes, the seasonal variations in winds, the geomorphology of dunes, the environment of deposition and the
character of the source sediments. Further study of the textural characteristics of other desert dunes is important so that valid conclusions can be applied to eolian deposits in the geologic record.
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Table 4. Grain-Size Data from the Interior of the Salton Barchan

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ABSTRACT

Actively migrating barchan dunes near the southwestern shore of the Salton Sea formed within the last three-hundred years on a hard, nearly level, lightly vegetated substratum of Quaternary lacustrine sediments under the influence of a prevailing west wind. Comparative mineralogy between sand from a dune and from upwind areas indicates that the principle sand source for the dunes is the poorly consolidated Upper Cenozoic sedimentary rocks that crop out west of the dune field.

A representative dune, termed the Salton barchan, was examined to determine the grain-size characteristics of surface sediments and interior sediments. Contour patterns of the statistical grain-size parameters show separate distributions between surface sediments and interior sediments, suggesting that the controlling factors are different in the two regimes.

The surface sediments of barchan dunes represent material transported by saltation and surface creep and accumulated into sand ripples. The ripple sediments are traction deposits that are dependent on the action of the prevailing wind and
are not representative of the underlying dune material. The mean grain-size distribution of surface sediments across a barchan is due to the selective action of wind acting on the grains in surface creep. The standard deviation, or sorting, is due to the winnowing effect of prevailing winds that remove fine grains from the windward side and deposit them to the lee. The variation in skewness of surface sediments depends on the relative increase in fine sediments resulting from capture in hollows between coarser grains on a rough surface. The variation in kurtosis is apparently due to the sorting action of wind affecting grains in surface creep opposed to grains in saltation.

The interior sand of barchan dunes is composed of material that has been reworked from the surface and incorporated into the dune during migration. The characteristics of the interior sediments are dependent on the "conveyor belt" turnover of material selected from the surface. Interior dune sand is more commonly preserved in the geologic record; therefore, the interior grain-size parameters are the most useful statistical measures to be compared to ancient dune deposits. The mean grain size in the interior of the Salton barchan
ranges from 2.35 to 3.200. The distribution of mean grain size in the interior of the dune is inversely graded with coarser grains near the summit becoming progressively finer toward the base. The variation in standard deviation or sorting within the barchan is the result of inheritance of sorted material from the surface and protection in selected areas determined by the dune morphology. Likewise, the variation in skewness is dependent on the morphology of a migrating barchan in selectively favoring the retention of fine grains. The distribution of interior kurtosis values does not provide discrete trends, but the general variation seems to be due to the addition or removal of well sorted fines during the turnover of sand as the dune migrates.