NEW MEXICO INSTITUTE OF MINING AND TECHNOLOGY

GEOLOGY AND SEDIMENTATION ALONG THE LOWER RIO SALADO IN NEW MEXICO

by

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Master of Science

Geology

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Contents

Abstract

The surface exposures consist of Tertiary deposits. Popotosa Formation includes playa sands, silts, gypsum and bentonite overlain by volcanic conglomerates. Santa Fe Group includes the gray-white fluvial sands of the Loma Blanca facies overlain by the mixed sands and gravels of the upper facies. All deposition probably was in a semi-arid climate. North-south trending normal faults are the principle structures, and they have influenced the geomorphology. Nonopaque heavy minerals from sands in the area indicate that the provenance of the formational units was crystalline rock and transport was minimal. A light green, [illegible]-etched mineral, identified as augite, occurs in some of the Santa Fe Group and Popotosa Formation. [illegible] in the [illegible] part of their [illegible] [illegible] New Mexico and closely [illegible] local topography, [illegible] two northern quadrants have had effect on dune shapes than winds from the southern two quadrants. Statistical analysis of local sediments indicates that Friedman's (1960) graphs only suggest the depositional environment.

Geology & Sedimentation Along the Lower Rio Salado In New Mexico

Introduction

The geomorphology and Tertiary geology of the lower part of the Rio Salado drainage are closely related to the history of the local sand dunes. Dunes form along the north bank of the Rio Salado for 7 miles upstream from the mouth, and on the south bank along the east side of Loma Blanca (Pl.1A).

Denny (1940, 1941) reported that the dune sand came from the Rio Salado. Since the Rio Salado drainage includes extensive outcrops of Cretaceous rocks, the dunes were expected to contain a Cretaceous type heavy mineral suite (Allen & Balk, 1954, Pl.1B). However, the dunes contain a heavy mineral suite typical of crystalline rocks.

The geomorphology is dominated by Quaternary pediments modified by gullying. The pediments apparently reflect changing base levels of the Rio Grande and Rio Salado.

The Rio Salado is a typical large desert arroyo with intermittent stream flow which flows from west to east in central New Mexico. Within the mapped area it empties into the Rio Grande which is the north

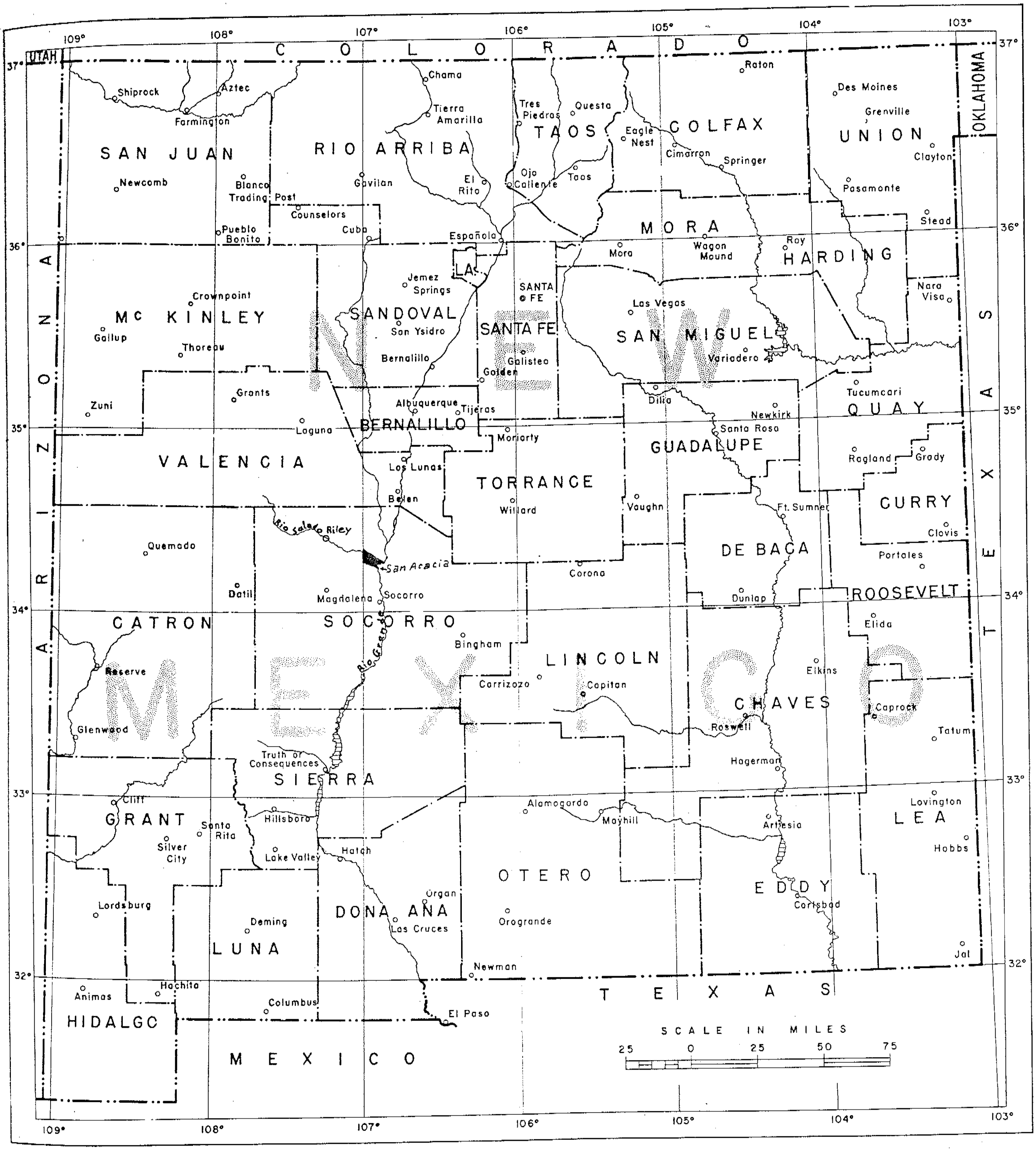


FIGURE 1. INDEX MAP

Plate 1.

A. Dunes along the lower Rio Salado. View looking southwest. From northeast to southwest: dunes, Rio Salado, Cañada Mariana pediment, dunes, Loma Blanca, and Lemitar Mountains.

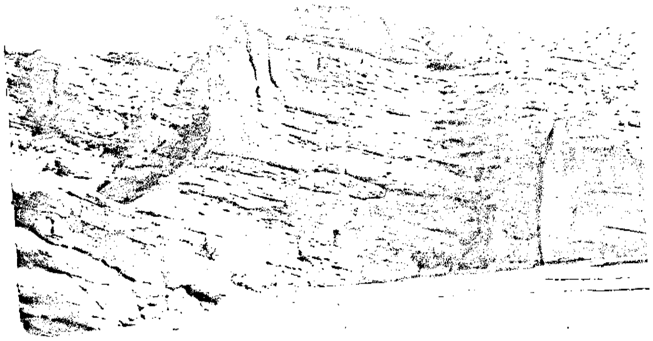
B. Popotosa conglomerate in winding canyon cut by Rio Salado west of M11. Wind has modified the erosion forms.

C. Rio Salado cutting through Popotosa conglomerate in winding canyon cut by Rio Salado west of M11. The wind has helped shape the erosion surfaces.

D. Playa deposits dipping 30° west, and grading up into conglomerates along west side of Valle Pritosa near Cañada de la Tortola. Ladron Mountains in background.

A

B



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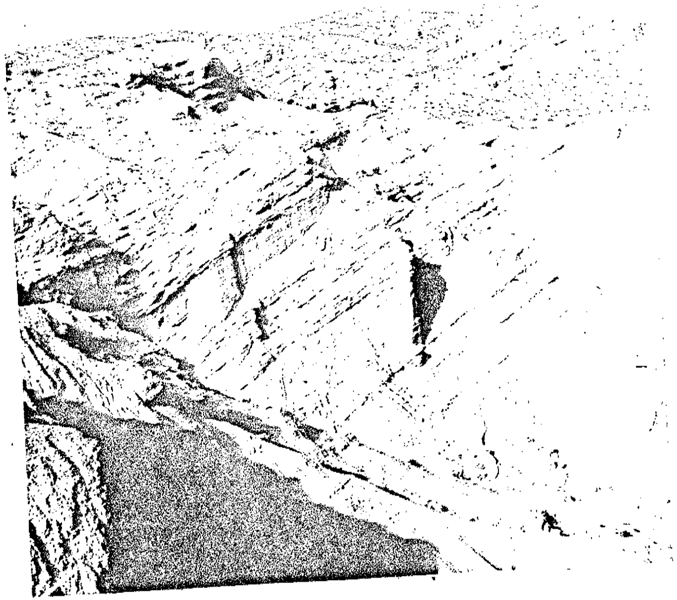

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south trunk drainage stream in this part of New Mexico (Fig.1). The mouth of the Rio Salado is about 15 miles north of Socorro, New Mexico and about 2½ miles north of the small farming community of San Acacia. The mapped area includes the lower 9 miles of the Rio Salado and the land for about 2½ miles on each side of the channel. This area contains over 45 square miles. Reconnaissance geology and sample collecting were extended as far west as Riley, N.M. (Fig.2).

The object of this report is to present the results of a geologic, geomorphic, sedimentary and petrologic study along the lower Rio Salado, and their relation to the sand dunes. The study was initiated to fulfill part of the requirements for a Master of Science degree at New Mexico Institute of Mining and Technology. It was carried out during the year 1961.

The United States Geological Survey, San Acacia and La Joya 1:24,000 sheets published in 1952, and the Riley 1:62,500 sheet published in 1959 were used as base maps for field work.

Darton (1928, p.57) thought it probable that the sediments included in the area of this report were of the middle to late Tertiary Santa Fe Group; specifically he recognized an older conglomerate, ".... on Rio

Salado where its' beds are steeply tiled in the vicinity of the Lemitar and Ladron uplifts" (Pl.1,B,C,D). Denny (1940, 1941) studied the Tertiary and Quaternary geology in this area, and named the above mentioned older conglomerate the Popotosa Formation. Rittenhouse (1944) collected channel samples in the Rio Salado at Santa Rita (Riley) N. M. and at the old U.S. 85 bridge (location M23 in this report), and determined mineral frequencies. Bryan (1926) published a short report on increased erosion in the vicinity of Riley, N.M. Nobel (1950) wrote a Master's thesis on the southern end of the Ladron Mountains. Slingerland, Larson, Hanson and Richter wrote senior theses in 1950 on the northern end of the Lemitar Mountains.

Vegetation along much of the Rio Salado is sparse with bare patches of ground between the plants (Pl.2A,B). Very active dunes have no vegetation, but do include partly buried trees (Pl.2C). A few hardy plants may survive on dunes, which are moderately active, only to be left behind by deflation when the dunes move (Pl.2D). Salt cedar trees grow in the Rio Salado and a few juniper trees are scattered over the rest of the area. Creosote bush, cactus, tumble weed and grasses grow throughout the area except in very active erosion zones. These plants support a few cattle. Jack rabbits, cotton tail rabbits, bobcats, foxes, lizards, snakes, birds and insects normally inhabit the area. Occasionally

Plate 2.

A. Dunes that may receive sand from the Rio Salado and Rio Grande. Rio Grande at upper right of picture. Note sparse vegetation around dunes. Location near M29.

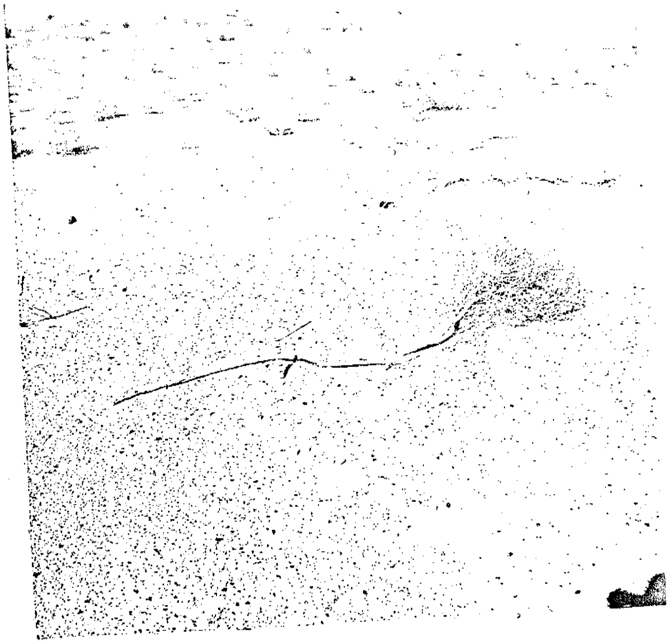
B. Rio Salado from U.S. 85 bridge. Ladron Mountains in background.

C. Salt cedar tree buried by dune at M12.

D. Plant left behind by deflation near M22.

A

C



D

deer may wander down from the higher elevations.

I would like to express my appreciation for the instruction, guidance, ideas, criticisms and philosophy of Max E. Willard and Clay T. Smith. The staff of the New Mexico Bureau of Mines has been most helpful and patient in answering my questions. Further, without the generous loan of equipment from the New Mexico Institute of Mining and Technology geology department and the New Mexico Bureau of Mines this work could not have been accomplished. My wife did the typing and some of the drafting. The work of Bob Price and Ray Molina in drafting the map was appreciated.

Stratigraphy

Popotosa Formation

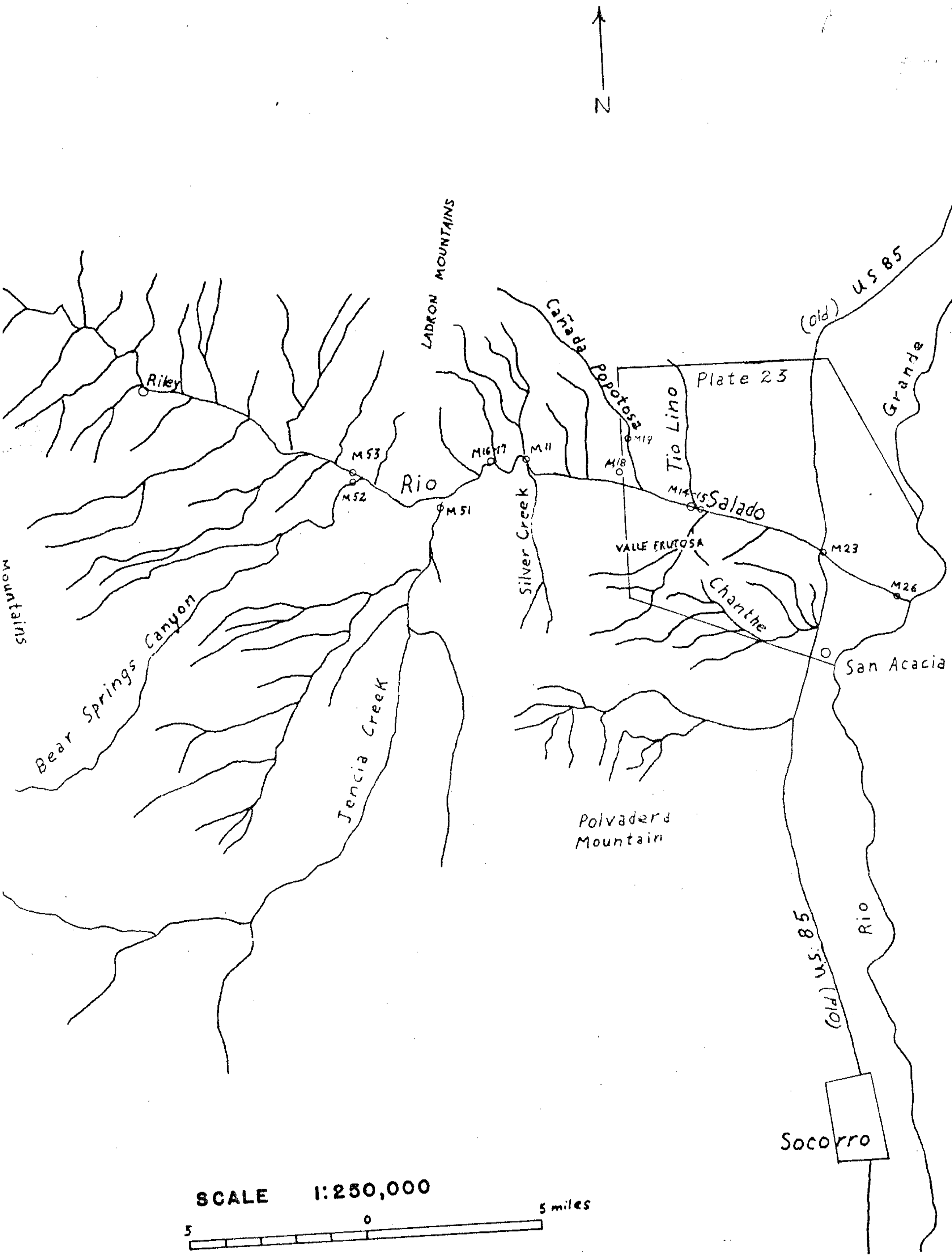
The type locality of the Tertiary Popotosa Formation is along Silver Creek 3½ miles west of the San Acacia quadrangle.(Fig.2). Denny estimates the thickness of the Popotosa to be between 3000 and 5000 feet. It consists of red-brown silts and sands grading upward into thin, brown-weathering, calcite-cemented sandstones, and gray to brown volcanic conglomerates. The conglomerates become more massive to the west and upward in the section (Pl.1B,C,D). Gypsum beds up to 1 inch thick are interbedded with the red-brown silts and sands; gypsum veins are common.

On the southern end of Valle Frutosa gypsum beds grade out west of the faults crossing Arroyo Rendija. Bentonite beds shown here and at M41 are overlain by thin-bedded, calcite cemented, brown weathering sandstone containing clay balls. These bentonite beds are about 10 feet thick. Bentonite crops out in the canyon of the Arroyo Rendija near the faults, but the outcrops are too small to be shown on the map.

Cañada Popotosa is floored by alluvium resting on the Popotosa Formation. Near location M19 a thin bed of gray-brown sandstone crops out in the Arroyo. Most of the sands and silts contain less gypsum than in Valle

SAMPLE LOCATION INDEX MAP

M-11 Sample Location



Frutosa. Bentonite is thicker here than in Valle Frutosa. It is mined for use in drilling mud, and for sealing earth under stock tanks. The bentonite bed is included within red-brown silts and sands. A fault scarp along the east side of the valley is formed by brown-weathering conglomerate on the north end which grades into sandstone to the south. The conglomerate-sandstone lies conformably over the silts and sands.

A composite sample of the Popotosa sands and silts (M61) has a median of +2.8ϕ*, a mean of +2.78ϕ and a Phi standard deviation of 0.70 (Pl.38). Eighty-seven percent of the grains have a diameter between +2ϕ and 4ϕ; thus it is classified as a fine to very fine sand.

A frequency count of the nonopaque heavy minerals in sample M61 (Tab.3), shows 59% hornblende and 23% barite. The barite is authigenic. Four percent of the hornblende is basaltic, and about 1 - 2% is blue-green. Other minerals in the sample are apatite, augite, biotite, epidote, garnet, kyanite, monazite, sphene, tourmaline, and zircon. The augite grains are irregular. Their ends have numerous sharp points (sometimes called coxomb or concertina structure).

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* See section on Mechanical Analysis for definition of Phi units and conversion to millimeters.

Santa Fe Group

The Tertiary Santa Fe Group in the mapped area includes two facies. The older of the two is called the Loma Blanca facies, and the younger, which rests on the Loma Blanca facies, is referred to as the upper facies of the Santa Fe Group. As mapped, the Santa Fe Group only appears east of the Loma Pelada Fault zone. It is possible however that some of the upper facies have been misclassified as pediment gravel.

The Loma Blanca facies is gray-white sand except for occasional small yellow-weathering sandstone lenses. The sands are usually unconsolidated yet they may form steep slopes. The lenses are commonly cemented with calcite. Pebble conglomerates, olive colored clay lenses, and clay balls are common. Cross-bedding, flow structures and slump structures are also common, but usually not well exposed (Pl.36A,B).

In the vicinity of Arroyo Tio Lino the Loma Blanca sands are partially capped by gravels that often form steep slopes. When the gravels are missing or are not cemented the slopes are gentle. Weathering processes do not permit the internal structure of the sand to be seen in this area.

Yellow weathering calcite cemented sandstone lenses cap Loma Blanca at M10, M32, and M34. A 3-4 inch

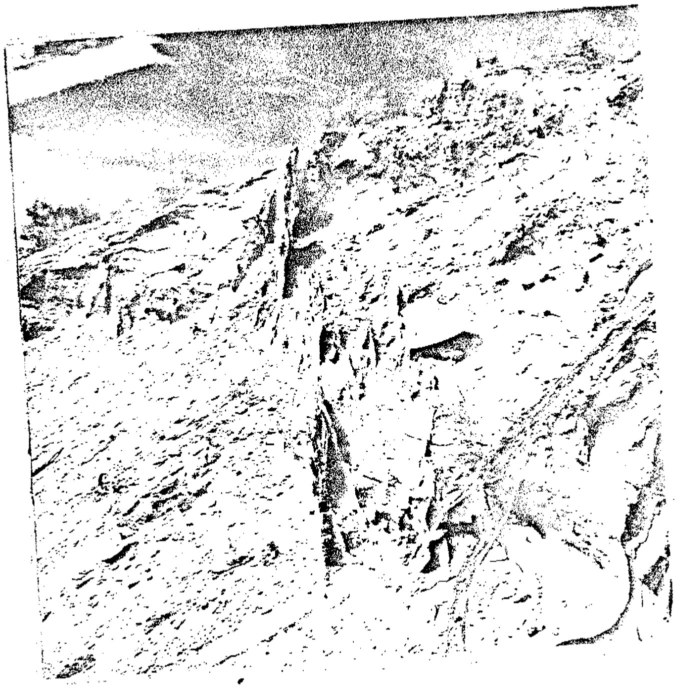
Plate 3.

A. Loma Blanca facies crisscrossed by calcite veins along Arroyo Chanthe. Location M44.

B. Sandstone lens in unconsolidated Loma Blanca facies along Arroyo Chanthe. Scale division 1 inch. Location M45.

C. Clay bed showing slump structure in Loma Blanca facies along Arroyo Chanthe. Note calcite veins. Scale divisions 1 inch. Location M44.

D. Flow structure in calcite-cemented, yellow weathering sandstone lens on top of Loma Blanca facies. Scale divisions 1 inch. Location M34.



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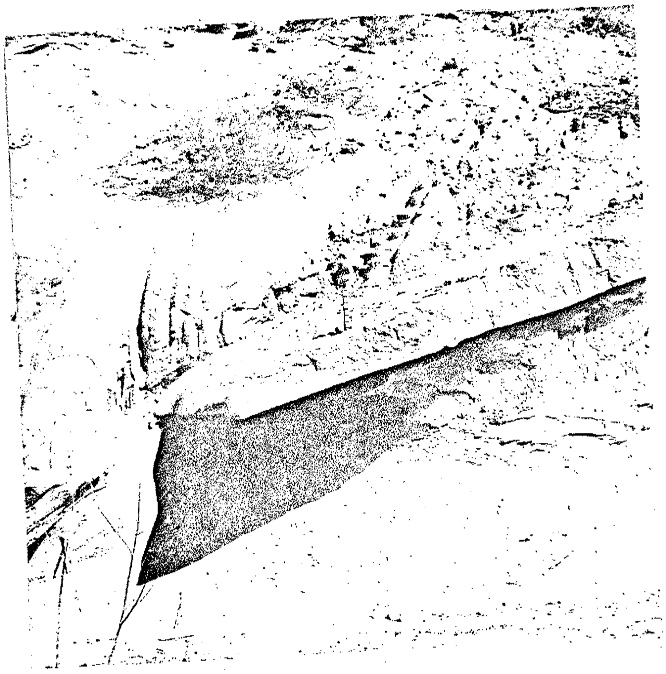

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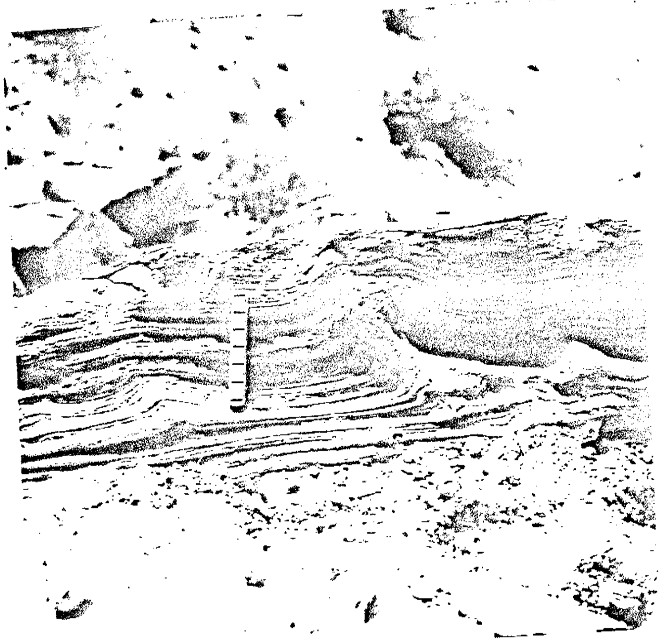


D

caliche bed occurs between the sandstone lenses at M34. A few hundred feet south of M10 the sand was blown away to expose a small patch of yellow weathering clay or soft shale.

Four samples of Loma Blanca facies show a median ranging from 1.2ø to 2.8ø, a mean ranging from 1.43ø to 2.88ø and Phi standard deviation ranging from 0.67 to 0.95 (Pl.35,37,38).

Frequency counts of the nonopaque heavy minerals in four Loma Blanca facies samples show hornblende (Tab.3) ranging from 14% to 72% with only M34 showing blue-green hornblende. Augite ranges from 2% to 50%. Other minerals present are acmite, apatite, barite, epidote, fluorite, garnet, kyanite, sphene, tourmaline, zircon, and zoisite. The augite has developed concertina structure.

Clastic dikes form small ridges at M46 and M9. The dikes are coarser than the surrounding sand, and are generally cemented with calcite. But at M46 the dike is cemented with a manganese oxide mineral. An emission spectrograph powder analysis of sample M46 made by R. Shaffer showed strong concentrations of calcium, aluminium, iron, silicon, magnesium and manganese; medium concentrations of sodium and titanium; and weak concentrations of lead, molybdenum, vanadium and potassium.

The upper facies of the Santa Fe Group designates tan weathering, interbedded, lenticular sands and gravels. One flow of andesitic lava is also included in this facies. Pediment gravels are difficult to distinguish from the upper facies, and in places appear to grade into it. Lithologically the gravels of the pediments and upper facies each contain boulders up to 6 inches in diameter of sandstone, limestone and igneous rock. Some of the limestone boulders contain fossils which appear after the boulder is etched with weak hydrochloric acid. Calcite and caliche are common cementing agents, but their distribution is irregular and lenticular.

The upper facies seldom is clearly exposed along the north bank of the Rio Salado, but small outcrops may be seen along the south bank, and it forms cliffs along the Rio Grande.

One sample was taken of the upper facies which had a median of 0.8Ø, a mean of 0.89Ø and a Phi standard deviation of 1.11 (Pl.32).

Pediment Gravels

Pediment gravels are mapped as separate units only west of Arroyo Tio Lino and Loma Blanca but they may extend east of these areas on any of the pediments. The gravels may be as much as 35 feet thick according to Denny (1941). They are lithologically similar to the upper facies of the Santa Fe Group and appear to grade into the upper facies.

The tan-weathering pediment gravels contain boulders of limestone, sandstone, jasper, chert and igneous rocks as much as 1 foot in diameter. Some of the limestone boulders contain fossils which appear when the boulders are etched with weak hydrochloric acid. Lenticular sands and silts are interbedded with the gravels. Caliche and calcite are irregularly distributed, cementing agents.

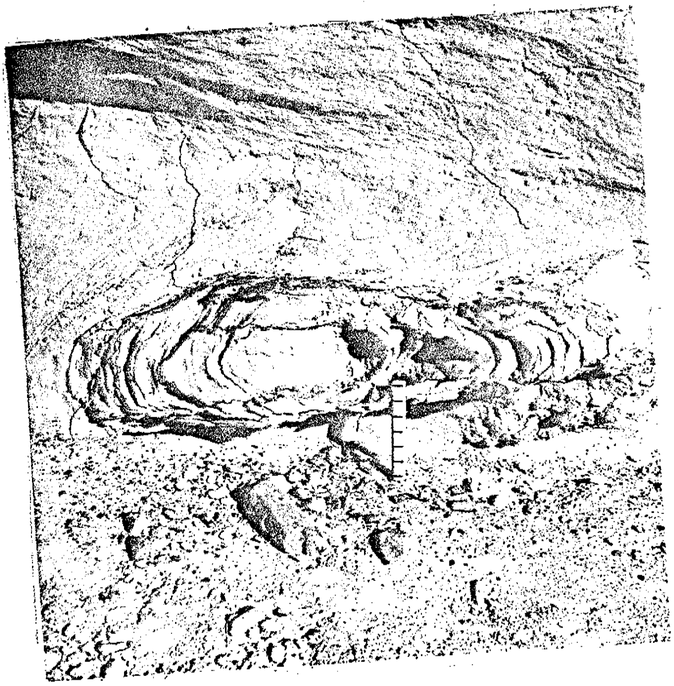
Along the north bank of the Rio Salado between Cañada Popotosa and Arroyo Tio Lino a pediment gravel approximately 30 feet thick contains gravel layers which are cemented for several hundred yards. The pediment gravel overlies both Loma Blanca facies and Popotosa Formation. Elsewhere in the mapped area extensive cemented gravel layers within pediment gravels are not seen (Pl.4C).

Plate 4.

A. Clay and sand flow structure in Loma Blanca facies along Arroyo Chanthe. Location M45. Scale division 1 inch.

B. Clay balls in Loma Blanca facies along Arroyo Chanthe. Alluvium unconformably overlies Loma Blanca facies. Scale division 1 inch.

C. Pediment gravels unconformably overlying Popotosa playa deposits. Dip 25° south. Location about 1500' NE of M59.



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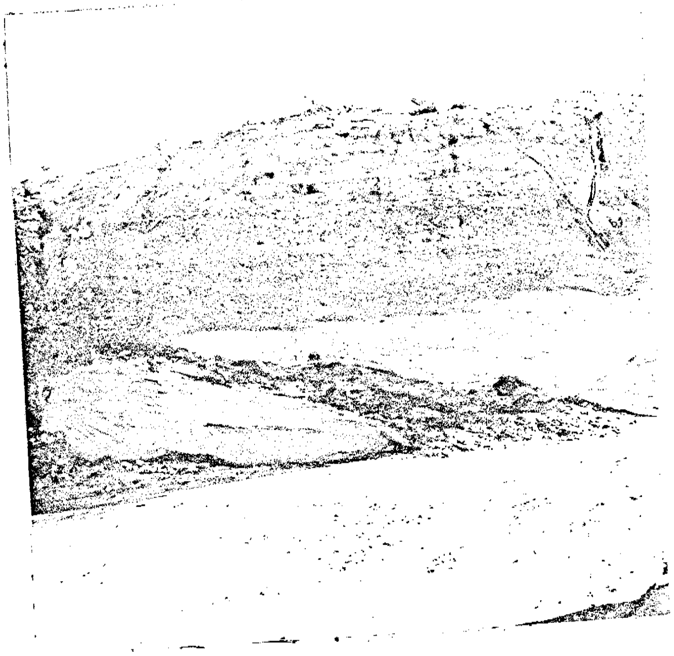

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Quaternary Alluvium

The Quaternary Alluvium consists of deposits similar to the Santa Fe Group, but it contains less conglomerate, and it is nowhere consolidated. In places it is being eroded by the arroyos which deposited it (Example: Cañada Popotosa).

Along Cañada Popotosa and in Valle Frutosa the alluvium is almost all silt and sand similar to the Popotosa playa deposits, but it is a little browner. The Rio Salado channel alluvium contains gravels intermixed, and generally covered with sands, the medians of which range from 0.9∅ to 2.8∅. The Upper and Lower Terrace alluviums are more tan colored then the alluvium of the Valle Frutosa and the valley of the Cañada Popotosa. All alluvial deposits are poorly sorted and do not exceed pebble size grains.

Structure

The mapped area is situated on the western edge of the Rio Grande structural depression which is formed by generally north-south trending normal faults that produce a horst and graben structure. Some geologists prefer to place the edge of the Rio Grande depression as far west as the faults along the Bear Mountains on the Colorado Plateau. The Ladron Mountains and the Lemitar Mountains just west of the area mark the edge of the Colorado Plateau (Hunt, 1956, p.3).

The major structural feature in the mapped area is the Loma Pelada Fault zone. It has a possible displacement of at least 1000 feet. It is a north-south trending steeply dipping fault zone which brings the Loma Blanca facies down against the silts and sands of the Popotosa Formation. Other small faults in the area probably related to the Loma Pelada zone have displacements ranging from a few tens of feet to less than two hundred feet. At the entrance to the narrow gorge [illegible] a small thrust fault may be seen in the outcrop. Small faults near [illegible] offset a bentonite bed in the Popotosa Formation.

The Popotosa Formation is broken and tilted by these faults, but only slightly folded. Sediments on the west side of Valle Frutoso are tilted to the west whereas those on the east side are tilted eastward. Cross section

AA' on Plate 23 shows the structural and stratigraphic interpretation. Dips in the Popotosa are generally around 30°, but at M38 a dip of 71° was recorded. Dips along the east side of the Cañada Popotosa are generally southward (Pl.4C). Dips within the Loma Pelada zone are very irregular.

Loma Blanca facies shows only minor deformation along the west side of Loma Blanca. The absence of general evidence of deformation in the Loma Blanca facies may be due to their lack of consolidation or distinct bedding except in the area just mentioned.

The pediment gravels are undisturbed by the faulting except for a slight displacement near the Arroyo Rendija. Usually they rest unconformably on the Popotosa Formation.

It is conjectured that the north-south trending, steeply dipping, clastic dike, in the Loma Blanca may be associated with faulting. The dike dips 72° to the east at M9 and is steeply dipping at M44.

Geomorphology

Drainage and relief

The topography is typical of a semiarid climate. Socorro averages less than 10 inches of rain a year, but more rain falls in the mountains. It is these mountain rains and snows which provide the intermittent flow for the usually dry Rio Salado (Pl.2A). West of the mapped area the Rio Salado often has a small flow of water between sample M16 and M11 (Fig.2) which disappears into the subsurface before reaching Cañada Popotosa.

Across the San Acacia and La Joya quadrangles the Rio Salado has a fairly uniform gradient of about 35 feet per mile. The gradient of the Rio Grande is about 4 feet per mile in this area. Elevations range from a little less than 4700 feet above sea level at the mouth of the Rio Salado to over [illegible] feet west of Valle Fumosa. The total relief in the area is about [illegible] feet. The depth of the channel [illegible] the [illegible] flows is variable. Its depth increases upstream toward the Sierra Ladron. It also narrows westward passing through a winding canyon several hundred feet deep north of Cerro Colorado in the Riley quadrangle (Pl.10,D). The channel is a mile wide (Pl.13) where it enters the Rio Grande and narrows to 3/4 of a mile just before entering the Riley quadrangle.

Arroyos tributary to the river generally occupy narrow valleys; their width depends upon the size of their drainage basin, and the resistance of the sediments through which they flow. Cañada de la Tortola and Cañada Popotosa have built flood plains within their valleys, but at present they are deepening their channels.

Pediments and terraces.

Quaternary pediments have been recognized in this area. They are defined by their "approximate elevation of grade above (the) flood plain of (the) Rio Grande" (Denny, 1941, p.229). The Cañada Mariana (Pl.1A) pediment is defined as 50 feet above grade. The Valle de Parida pediment is 150 feet above grade. The Tio Bartolo pediment is 250 feet above grade. The Ortiz pediment is 400 feet above grade. Other surfaces recognized are "remnants above Ortiz or Tio Bartolo surfaces", and " dissected surfaces, undifferentiated" (Denny, 1941, p.229). The lower 3 pediments and the "dissected surfaces, undifferentiated" were mapped during this study. The Ortiz pediment is not an obvious surface within the San Acacia quadrangle.

Thornbury introduces the following definition of a pediment: "The term pediment is used to designate the rock-floored plains adjacent to or interpenetrating mountain masses in desert regions which have developed by planation of the mountains at altitudes dependent upon those of the interior basins into which the mountains drain" (Thornbury, 1954, p.191). Later in a discussion of major land forms in arid regions he describes the problem of identifying pediments in the field. "The surface of a bajada is undulatory in character when traversed parallel to the mountain front. In contrast, a pediment surface is nearly flat or slightly concave when viewed at right angles to the bordering mountain front. A pediment may or may not have an alluvial veneer over it, but it is basically a bedrock surface, although it may have developed across older alluvial deposits. Pediments may have a thin veneer of gravel over them adjacent to the mountains, or this may be lacking, but away from the mountains they become more and more obscured by bajada deposits and thus become concealed pediments; then it becomes difficult to distinguish them from the bajada unless well records are available. Even where concealed, a pediment is believed to be most typically a concave rock surface which "plunges" beneath the bajada that conceals it. Individual pediments at the point where mountain valleys discharge onto a piedmont slope may expand to form coalescing pediments, which may in time practically consume a mountain mass. Some pediments exhibit a considerable degree of dissection and are referred to as dissected pediments" (Thornbury, 1954, p.285).

In this area most of the "pediments" might better be called surfaces because bed rock seldom obviously floors the plains. The problem here not only is with "concealed pediments", but also with pediments on "older alluvial deposits". Therefore the "pediments" outlined on Plate 23 are of plains and remnants of plains which form the surface topography today. The names and the term pediment are retained from Denny (1941).

In this area the youngest pediment, Cañada Mariana, may not be a pediment, but instead may be a terrace deposit associated with the ancestral flood plains of the Rio Salado and Rio Grande. The surfaces north and south of the Rio Salado seem to be related, but along the east side the northern surface drops 200 feet to the flood plain of the Rio Grande. This makes it difficult to define the northern Cañada Mariana using Denny's definition. Denny, (1941, p.229), considers the identification of this northern Cañada Mariana pediment questionable also.

The "dissected surfaces undifferentiated" are younger than the Valle de Parida pediment and formed on horizontal Santa Fe Group sediments. The surfaces are covered by loose sand and gravel, but in outcrops along the Rio Grande channel an irregular bed of caliche appears just beneath the surface.

Valle de Parida is clearly an aggraded surface, but the relationships between the present topography and the buried topography are not shown clearly on the map (Pl.23). In places underneath the Valle de Parida pediment upturned beds of the Popotosa Formation are covered by calcite cemented gravels (Pl.4C). The distinction between upper facies gravels and pediment gravels is not sharp because the gross lithologies are similar and the overlying gravels may be thick. This problem is well illustrated in the bluffs along the north bank of the Rio Salado west of M58. West of M58 the gravels are mapped as pediment gravels on the Valle de Parida surface (following Denny, 1941) and similar to those topping the bluffs forming the south end of Valle Frutosa. But the gravels north of the Rio Salado are up to 30 feet thick whereas those south of Valle Frutosa are probably not more than 5 feet thick.

Tio Bartolo is the highest pediment (Denny, 1941) and was formed on horizontal Santa Fe upper facies. This pediment has the smallest areal extent. It may have covered the entire area at one time, and the other pediments have been cut from it. If this is true, it follows that the Santa Fe Group completely covered the Popotosa Formation when the Tio Bartolo pediment was formed. If the surface on the Popotosa Formation under the 30 foot thick gravels is a pediment, and these gravels are Santa Fe upper facies emnants, then this surface predates the Tio Bartolo.

The terraces formed on Quaternary Alluvium have been delineated on the map. The Upper Terrace segment near M27 probably correlates with the Upper Terrace segments near Arroyo Chanthe. But the M27 terrace may have been formed by the Rio Salado (note remnants of the Upper Terrace near M8) while the Arroyo Chanthe terrace was formed by the Rio Grande.

The Lower Terrace is related to the Rio Grande and is a remnant of a surface that formed just prior to the development of the present flood plain.

Structural effects

The effect of structure on the physiography along the Loma Pelada Fault zone is indicated by the line of steep slopes formed by resistant beds on the downthrown side of the fault. The number of faults near where Arroyo Rendija enters Valle Frutosa suggests structural control for this narrow canyon. Faulting may control the straight front that forms the west side of Valle Frutosa, but other field evidence was not found to substantiate this hypothesis.

A series of base level changes for the Rio Grande and hence the Rio Salado may be due to general uplift in this area or to structural changes along the Rio Grande depression. The Rio Grande channel formerly was further east (Denny, 1940, p.96), and it may be that structural movements have relocated the river to its' present channel. Whatever the local reason for these base level changes the pediments have been profoundly modified by them. As each pediment has been raised relative to the local base level, the Rio Salado has lowered its' channel, and triggered the dissection of the existing pediments. The succession of seven surfaces identified in the area, and the channeling of the arroyos through their alluvium suggests that the structural adjustments may still be occurring.

Denny (1941, p.242) proposes that the lower Rio Salado did not have its' present drainage area when the Tio Bartolo pediment was being formed. The lower Rio Salado is supposed to have inherited its' present drainage system by piracy of an earlier drainage pattern which entered the Rio Grande south of Socorro. The meanders of the Rio Salado in the deep winding canyon west of the mapped area (Fig.2) suggest that the Rio Salado cut the canyon after the meanders were formed on the Tio Bartolo surface.

<u>Aeolian Sand Deposition</u>

Thornbury (1954, p.307) cites Bagnold's (1933) efinition of a <u>dune</u> as a "mobile heap of sand whose existence is independent of either ground form or fixed wind obstruction" (Pl.5). This definition is useful along the Rio Salado if one is not too rigid concerning the effect of topography on the dunes. What needs to be emphasized is the mobility and self perpetuating character of the dune. "A <u>sand shadow</u> is an accumulation of sand to the lee of and in the shelter of an obstruction, such as a boulder, bush, or cliff, which interferes with streamline air flow and checks the wind's velocity. Sand shadows may also form where wind sweeps over a cliff or escarpment. Such deposits have also been called <u>sandfalls</u>" (Thornbury, 1954, p.306).

Sand sheets refer to sand deposits of relatively uniform thickness and relief on a flat surface. Sparse vegetation is common, but there are few sand shadows. As the thickness of the sand sheets increases, vegetation thins, and ripple marks, sand shadows and incipient dunes may form on the surface. Sand sheets are sometimes called sand drifts, but sand drift has another meaning. Sand sheets form to the lee of the dunes on the north bank of the Rio Salado.

Plate 5.

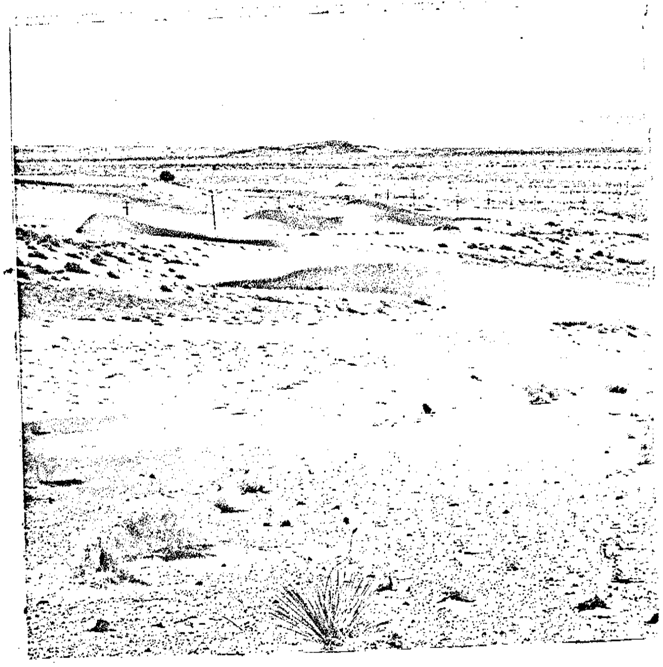
A. Looking south across dunes, U.S. 85, and the mouth of the Rio Salado. The Rio Grande is just north of the pediment.

B. Longitudinal dune and barchan dune. The 180° curvature of the barchan in the foreground is caused by the wind shifting to south. The sinuous crested dune has a similar cause. This may be a sigmoidal dune as described by Holm (1960, p.1371).

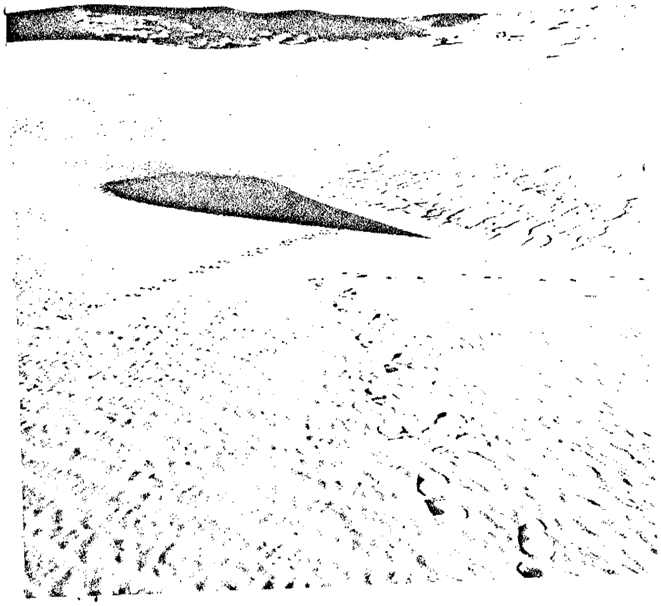
C. Barchan sand dune migrating up to Cañada Mariana pediment near M1.

D. Dune migrating across Arroyo Tio Lino near M 12.

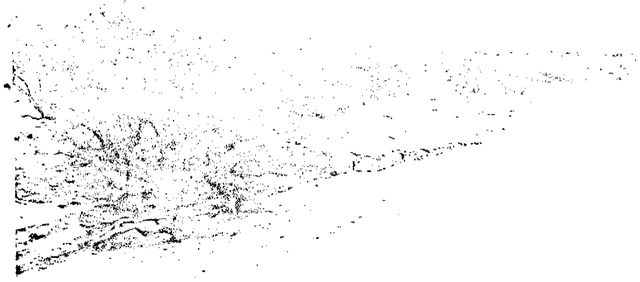
A



B



C



D

Two basic types of dunes form in the mapped area. "A *barchan* is a crescentic-shaped dune with tips extending to leeward, making this side concave in plan and the windward side convex. The slip face, if present, is transverse to the wind. A *seif* or *longitudinal dune* instead of being transverse to the prevailing wind is parallel to it" (Thornbury, 1954,p.308). The crests are ridges with many peaks and sags. (Pl.5B).

A small sandfall was encountered at M8 on the south bank of the Rio Salado. Sand falls occur more often along the west bank of the Rio Grande. Sand shadows are common in the area of thick sand sheets, and along the edge of dunes where there is some vegetation.

Most of the dunes along the north bank of the Rio Salado are barchans. An exception occurs at M21 where there is a longitudinal dune. The direction of movement of the barchans varies with the nearby topography. The most westerly dunes in the Rio Salado move down the valley in an easterly direction. The more easterly dunes shift their direction of movement gradually to the north. During the summer of 1962 the dunes near U.S. 85 shifted until they were moving north-northwest. Casual observers of the dunes have the impression that over the last few years the dunes near U.S. 85 generally moved toward the northeast. Several years ago dunes were observed crossing U.S. 85 from the northwest, that is moving toward the southeast. Aerial photographs taken in 1952 show the dunes essentially as they are now, but Denny's dune crest lines indicate an effective wind from the WNW in 1939.

Dunes along the eastern side of the Loma Blanca are longitudinal dunes or sandfalls. A few incipient dunes form on the south and west side of the Loma Blanca about halfway up the slope from the Arroyo Chanthe. A dune at M49 appears to receive sand from winds around the south end of Loma Blanca. At M48 small dunes form on either side of the ridge depending upon the direction of the wind. These dunes depend upon the ample supply of loose sand in the Loma Blanca, and are almost stationary although they are not covered by vegetation.

Wind blown sand grains move along a surface by two processes; saltation and surface creep. When the wind reaches the threshold velocity, grains are lifted and carried forward a distance proportional to the wind velocity, grain size, shape, and density. Grains in dunes have fairly uniform characteristics due to the sorting; so the distance the majority of the grains move forward is close to constant. This results in the distance between crests of ripple marks varying within a small range for a particular wind velocity. The range observed on one of the Rio Salado dunes was from 4 to 6½ inches with the average around 5½ inches

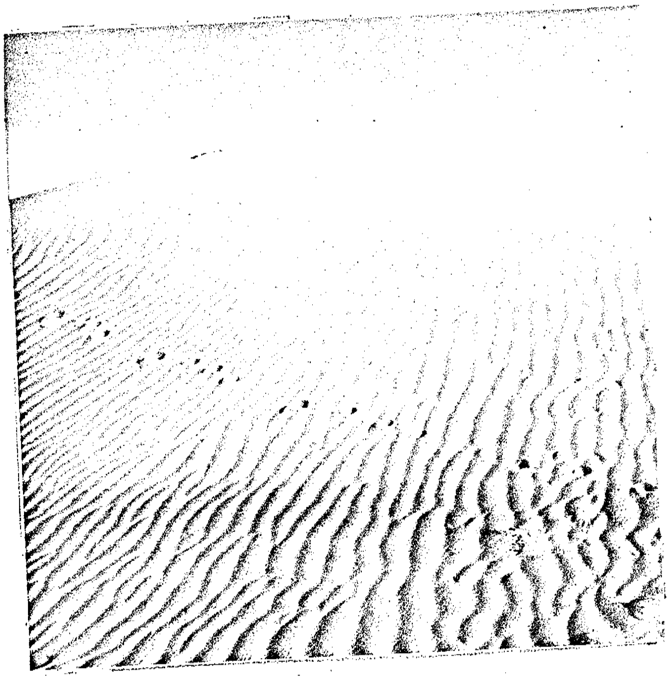
Plate 6.

A. The distance between major ripple marks is about 5½ inches. Location near old U.S. 85.

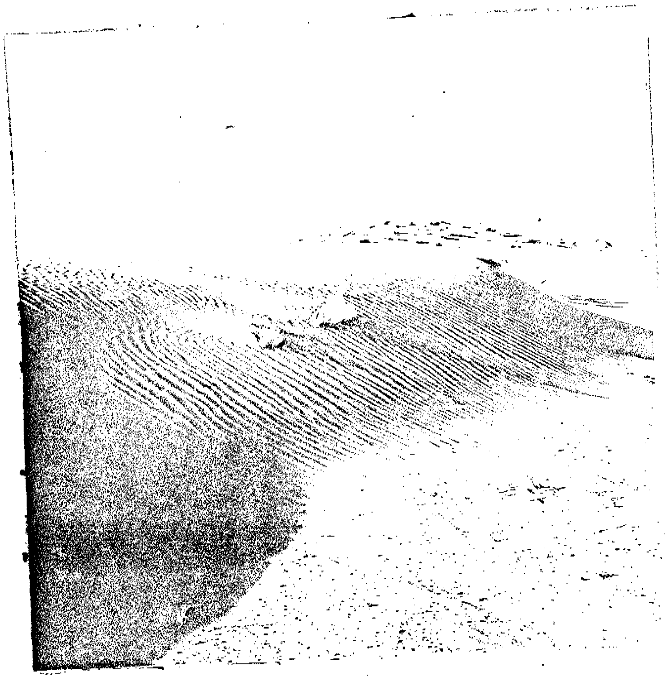
B. Note pattern of ripple marks on dune showing how wind shifts direction as it crosses dune. Location near M1.

C. Ripples and cross ripples on active sand dune at location M30. Scale division 1 inch.

D. Sand dune with lip at top of avalanche slope probably caused by a change in wind direction. Geology pick near lip for scale. Location near old U.S. 85.

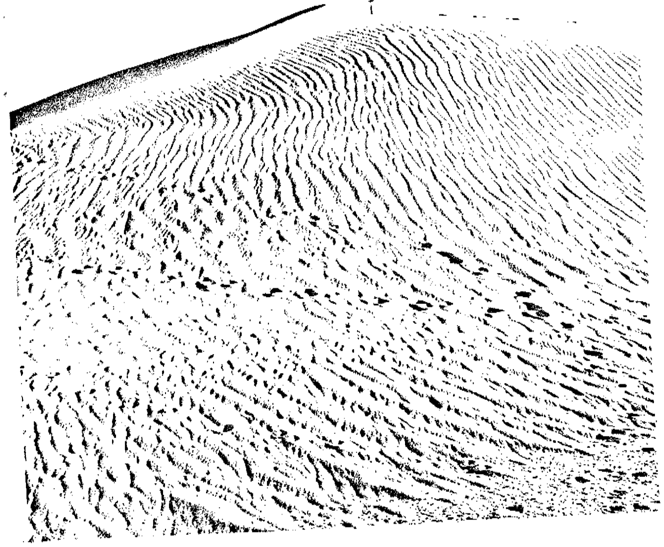


A



B

C



D

(Pl.6). Grains strike the surface of the dune and propel other grains into saltation. The grains not propelled move aside leaving a small crater where the grain struck. The general movement of the grains not propelled into saltation is in the direction of the wind. This process is known as surface creep.

Dunes build when there is an ample source of sand which is not held down by water or vegetation, and where strong winds blow generally from one quadrant for a period of time. The vegetation needs only to be dense enough to slow the surface wind below the threshold velocity. These conditions are obviously met near the Rio Salado. Dunes form in the lee of hills, behind ledges or even behind clumps of vegetation (Pl.5A). Dunes perpetuate themselves by trapping the blowing sand on their lee sides. Wind increases in velocity in passing over the dune ([illegible], 1952, p.1545). At the crest the wind loses some of the' increased velocity, [illegible] and drops [illegible] its' load just beyond the crest. Even if the velocity does not drop below threshold, saltation ceases when there is no surface off which the grains may rebound. As the sand accumulates near the crest, it eventually exceeds the angle of repose and slumps down the lee slope. The maximum angle of repose is about 34° (Dunbar, 1958, p.20). The angle of repose observed in this area is about 30°. Varying condi-

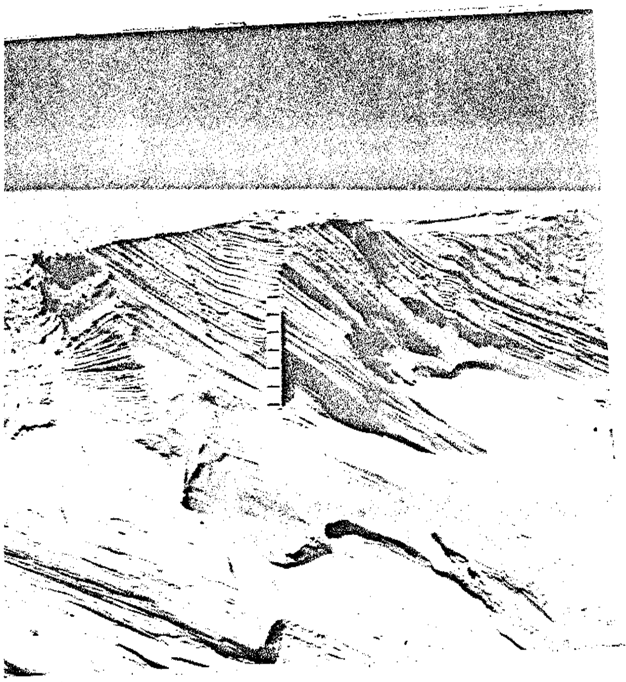
Plate 7.

A. Cross-bedding in active sand dune intersecting surface of dune. This dune surface is normal for a dry dune. Location M31. Scale division 1 inch.

B. Surface of wet dune being dried by wind shows cross-bedding intersecting surface. Location M31. Scale division 1 inch.

C. Cross-bedding in active sand dune overlying river deposits at location M31. Scale division 1 inch.

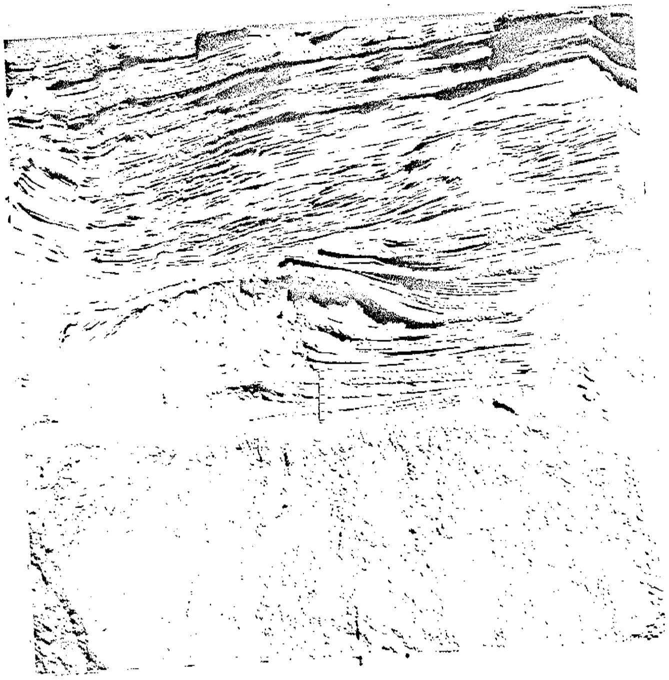
D. Cross-bedding in active dune overlying river deposits at location [illegible]. Scale division 1 inch.



A.

B

C



D

tions of wind and moisture produce bedding within the dunes (Pl.7).

Wind patterns

Wind patterns for Socorro, New Mexico during 1962 are shown by rose diagrams on Plates 9 - 21. Socorro winds are probably not exactly the same as those in San Acacia. The wind data for Albuquerque, New Mexico (Tab.1) does not agree with the Socorro data, because the method of observation is different. The dune shapes in the Rio Salado during the summer of 1962 generally are consistent with the wind data for Socorro.

The Socorro wind observations are made 4 times daily at 4:30 A.M., 10:30 A.M., 4:30 P.M., and 10:30 P.M. The observation station is 37 feet above the ground on the top of a building on the New Mexico Institute of Mining and Technology campus. The nearest obstruction is 100 feet to the [illegible] [illegible]. The U.S. Department of Commerce Weather Bureau maintains the weather station under the supervision of Dr. M.H. Wilkening.

In the rose diagrams (Pls.9-21) the average wind velocity for each of the 16 points of the compass is indicated by the green column. The number of times the wind was observed to blow from a particular direction is shown in blue. For example, during the month of January

	Socorro, New Mexico					Albuquerque, New Mexico	
	Direction of Maximum		Prevailing wind from	Avg. vel, all directions	Total wind, all directions	Prevailing wind from	Avg. vel, all directions
Month	NI	NR					
January	NNW	NNW	N	6.0	683	N	7.4
February	NW	SSW	S	5.5	577	N	7.6
March	SSW	SW	S	7.9	919	N	8.5
April	S	SSW	S	6.9	735	NW	8.8
May	S	SSW	S	6.7	737	S	8.5
June	S	[illegible]	S	[illegible]	625	N	8.4
July	S	SSE	S	5.4	624	S	7.4
August	S	[illegible]	S	5.2	662	SE	7.7
September	[illegible]	[illegible]	S	5.4	[illegible]	SE	7.7
October	[illegible]	[illegible]	[illegible]	4.9	595	SE	[illegible]
November	N	N	N	5.3	602	E	7.0
December	N	NNE	N	6.4	936	N	6.0

Table 1. Wind directions, velocities and volume indicators for Socorro, New Mexico during the year 1962 and comparative data from Albuquerque, New Mexico. The velocities are measured in miles per hour. Abbreviations NI and NR stand for Net Index and Net Resultant defined in the text. "Total wind, all directions" is the sum of the individual total winds from particular directions.

1962 the wind was observed to blow from the north 28 times, and had an average velocity of 6.2 miles per hour. The wind blew from the north-northwest 24 times during the month with an average velocity of 7 miles per hour. The number in the circle, 7 for NNW indicates the number of times the wind was observed to blow over 10 miles per hour. In order to obtain some idea of the volume of air moving in any particular direction a figure called the total wind is used by the U.S. Department of Commerce Weather Bureau. The total wind is the sum of the wind velocities observed from a particular direction. Inasmuch as the object of this wind study is to determine the effect of the wind on the shape and mechanical composition of the dunes the Weather Bureau's "total wind" figure has been modified. The number (2127) beside the circled 7 for January 1962 is called by the author the Net Index. To obtain this number the total wind from the NNW was multiplied by the number of observations over 10 miles per hour (7 observations), and a similar multiplication was made for the SSE. The [illegible] were then subtracted to obtain a Net Index [illegible] is defined as positive, and placed on the rose diagram beside the direction from which the greatest volume of air came. The number (N322) beneath the Net Index preceded by the letter N is called by the author the Net Resultant. The Net Resultant is obtained by summing the total wind for 3 adjacent directions and subtracting from this total the sum of the total wind from the opposite 3 directions. Again this number is defined as positive. The Net Resultant is placed by the center direction of the three adjacent wind directions totaled. For example: the total wind for NW, NNW and N was added; the total wind for S,SSE and SE was added; then the two sums were subtracted. The positive difference was 321, and came from the northern quadrant. The prevailing wind (Tab.1) is defined as the direction from which the wind has been observed to blow the greatest number of times for a given period without regard to the velocity.

Bagnold's (1937) experiments showed that wind velocities above 10 miles per hour had more effect in shaping a dune than winds of lower velocities. The 40 - 100 foot high longitudinal dunes of the Australian sand ridge deserts are formed parallel to a prevailing wind whose average maximum is 20 miles per hour (Madigan, 1936). A wind blowing from one direction will have its' effect on the dune canceled by a wind from the opposite direction. Bagnold's studies also showed that the greatest mass of sand may be moved by the gentler winds, but the dune shape may be determined by higher velocity winds from another direction. (Fig.3).

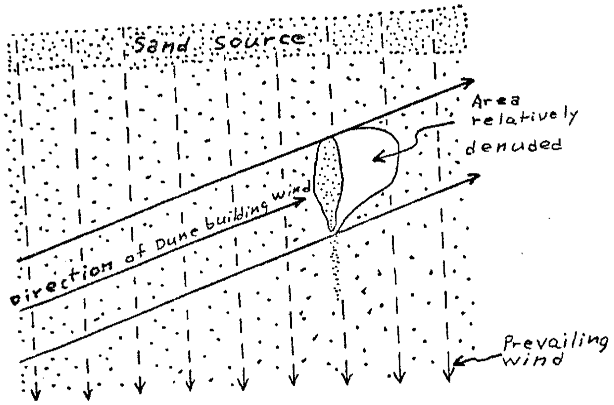


Figure 3. Possible relations between sand moving and dune building winds (Bagnold, 1937, Figure 9).

The attitudes of the Rio Salado dunes were first observed by the author on 1 March 1962. At that time they showed an effective dune shaping wind direction from the WSW. Later in April 1962 a more accurate estimate of the effective wind direction which shaped the barchans was made. The effective wind appeared to be from the WSW. In June 1962 the effective wind direction had shifted to the SSE. All the above observations were made on dunes near U.S. 85. Study of the wind rose diagrams shows quite clearly that the potentially most effective winds came from the NW during January, and the wind still did not fit the barchan structures in February. One can conclude only that the northerly winds were not effective in shaping the dunes .

The dunes were damp enough on March 1 that holes dug into them maintained vertical walls. These dunes lie in the lee (to northerly winds) of a bluff which is part of the trough of the Rio Salado. This drop in elevation may be sufficient to destroy the effectiveness of the northerly winds. As you can see by the map (Pl.23), the main Rio Salado dunes do not generally climb out of the trough and onto the Cañada Mariana surface. This may be due to these northerly winds sweeping the sand back into the trough. The Albuquerque wind data show a prevailing wind direction from the north for 5 years prior to 1962 (Tab.1).

Study of wind records of all the Egyptian oases for 10 years by Bagnold (1953,p.93) produced the following remarks. "From these I calculated the resultant wind directions at each place, taking into consideration the wind strength according to the experimental law of sand movement. I then compared the directions of these wind resultants with the any directions of the nearest major dune ranges. There was but little agreement when the resultants were calculated for the whole year, but there was a very good agreement when only the hot months were included". He goes on to suggest that the winds became turbulent near the surface during the hot months, and therefore had an increased sand moving capacity.

Mechanical Analysis of Sands

Methods and treatment

Where practical, samples were collected with the shovel by digging a hole about a foot deep and then collecting the samples along the side of the hole in order to obtain a representative sample of several populations. These are referred to as "depth samples". "Surface samples" of one population, were collected by skimming the surface of the sand deposit with the shovel. Where digging a hole was not easily accomplished or the sediments were cemented, the samples were collected by selecting small samples such that several populations were represented. These are designated "composite samples."

Field samples weighed between 500 and 700 grams, and were split to about 100 gram samples for mechanical analysis. However, sample K1 was split to 34 grams. The 100 gram samples were sieved for at least ten minutes using a Ro-Tap Shaker and United States Standard Sieves spaced whole ∅ units apart. Phi (∅) units* have been used through out the calculations.

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*∅ = $-\log_2 d$, where d is the diameter in millimeters of the grain. Therefore the divisions of the Wentworth scale become whole numbers, that is: - 1 ∅ = 2mm, 0∅ = 1 mm, +1∅ = 0.5 mm, +2∅ = 0.25 mm, +3∅ = 0.125 mm, +4∅ = 0.062 mm, +5∅ = 0.031 mm.

In the computation of the statistical parameters (Tab.2) the methods of Friedman (1961) were used because of their added sensitivity. Friedman studied the petrographic characteristics of recent sands from known dune, beach and river environments to determine if there were mineralogical or textural characteristics which permit diagnosing the environment of deposition. Textural characteristics are chiefly related to the mode of transportation, and the energy conditions of the transporting medium. Most of his 240 samples were composed of quartz. Field samples were taken parallel to the bedding, where possible, to avoid mixing of populations. Grain-size determinations were made on these samples by conventional sieving using ¼ϕ sieve intervals. Less than 5% of the grains are larger than +1.0ϕ for all his samples.

For this paper Median is defined as the ϕ diameter read from the cumulative percent curve for 50 weight percent. Mean is defined as the first moment:

$$M_\phi = \frac{\Sigma f m}{100}$$

where f = % by weight for each grade size

m = midpoint in ϕ units of the grade size

Sorting is defined as standard deviation:

$$\sigma_\phi = \left[\frac{\Sigma f (m - M_\phi)^2}{100} \right]^{\frac{1}{2}}$$

Skewness is defined as the third moment:

$$\alpha_{3\phi} = \frac{\Sigma f (m - M_\phi)^3}{100\, \sigma_\phi^{\,3}}$$

Kurtosis is defined as the fourth moment:

$$\alpha_{4\phi} = \frac{\Sigma f (m - M_\phi)^4}{100\, \sigma_\phi^{\,4}}$$

Comparison of textural characteristics

A very limited size range of grains can be transported by wind because of the great difference in density between the air and the grains. For instance a grain of quartz, the most common constituent of sand dunes, weighs approximately 2000 times as much as an equal volume of air. The sieve analyses of samples collected for this report shows the narrow size range transported. Bagnold (1941, p.6) found a grain size range for desert sand between +2.6ø and -1.5ø. The size range for these dunes is somewhat broader with a range of 0ø to +5ø. Bagnold (1936, p.596) reported a range from -1.5ø to +6.2ø for the desert. Wentworth's ([illegible]) analyses of 61 sand dunes scattered across the United States showed that a large percentage of the sand falls within the range of +3ø to +1ø. Bagnold (1936, p.596) observed that curves of percentage weight plotted against grain size have peaks which occur at greater ø units than 2.6ø. He also found that the peak of the curve was narrowest for samples taken from the crest of the dune. The Rio Salado sand dunes have the

Table 2. Statistical parameters derived from mechanical analysis of sands in the vicinity of the lower Rio Salado. Samples arranged according to geographic location and lithologic association. (See Plate 23 for exact location). All the parameters are based upon Ø units. The standard deviation formula was used to compute sorting.

	Median Ø	Mean Ø	Sorting	Skewness	Kurtosis	
	SAND DUNES					
M 12	2.5	2.45	0.85	0.24	2.06	
M 56	2.0	2.05	0.69	0.09	3.86	
M 1	1.4	1.53	0.93	0.85	2.05	
M 2	2.0	2.10	0.77	0.55	9.64	
M 3	1.5	1.72	0.91	1.05	4.12	
M 4	1.3	1.27	1.18	0.98	1.75	
M 5	2.0	2.03	0.81	0.53	3.31	
M 21	2.1	2.30	0.61	0.09	2.94	
M 30	2.5	2.39	0.75	0.50	2.97	
M 49	2.0	1.93	0.81	0.12	2.97	
	SPECIAL AEOLIAN SAMPLES					
M 27	2.5	2.47	1.10	-0.66	3.45	Sand shadow
M 7	2.3	2.20	1.05	0.017	2.76	Sand sheet
M 8	2.1	2.15	0.60	0.39	3.26	Sand fall
	RIO SALADO					
M 53	1.9	1.82	1.37	0.07	2.38	
M 17*	1.4	1.14	1.39	-0.32	2.75	
M 11	2.3	2.52	1.34	-0.85	4.42	
M 14	2.1	2.13	1.27	-0.27	3.49	
M 15*	1.8	1.24	1.43	-0.42	2.79	
M 23	2.4	2.46	1.31	-0.87	4.42	
M 26	0.9	0.92	0.97	0.63	3.74	

* Large pebbles rejected.

Table 2. - continued.

	Median ∅	Mean ∅	Sorting	Skewness	Kurtosis	
	<u>ARROYOS</u>					
M 16*	0.1	0.54	1.82	0.55	2.14	No name
M 18	0.7	1.02	1.69	0.39	2.28	Cañada Popotosa
M 19	1.7	1.65	1.67	-0.22	2.32	Cañada Popotosa
M 13	1.0	0.64	1.53	0.11	2.01	Tio Lino
	<u>LOMA BLANCA FACIES OF SANTA FE GROUP</u>					
M 44	1.2	1.48	0.95	0.65	3.93	
M 34	2.8	2.88	0.67	0.90	3.45	
M 58	2.3	2.46	0.76	0.25	3.47	
M 62	1.4	1.43	0.81	0.24	7.29	
	<u>UPPER FACIES OF SANTA FE GROUP</u>					
M 22*	0.8	0.89	1.11	0.50	2.84	
	<u>POPOTOSA PLAYA SANDS AND SILTS</u>					
M 61	2.8	2.78	0.70	0.60	3.98	

* Large pebbles rejected.

ove properties.

Samples M1 to M5 were collected across a single une (Pl.8C) starting on the windward side, and ending at he bottom of the lee slope. Surface samples(M1,3,4) were kimmed off the surface of the dune with a small shovel. Surface sampling should have the effect of sampling a single opulation. Depth samples (M2,5) were collected by digging a hole about 1 foot deep and about 8 inches in diameter, and then sampling from the side of the hole in order to get a mixture of populations. The dune sand was damp on the day of sampling; thus the walls of the sample hole on the windward side of the dune remained vertical. The depth samples collected on the lee slope were mixed due to caving.

Plates 24-26 show the results of mechanical analyses of samples M1 to M5. From these plates it seems that a single population may be collected by skimming the surface of a dune, and the method of sampling affects the interpretation of mechanical analyses. The differences in the energy of environment for essentially the same population only separated by tens of feet and a slight increase in elevation indicate that surface samples of dunes are only of value where very precise knowledge of a particular environment is desired. For these reasons "depth samples" and composite samples" were collected through out the remainder of the area.

Plate 8.

A. Internal drainage of sand dunes. Note lack of gully erosion of active dune yet the picture was taken after a 1 inch rain. Location west of old U.S. 85.

B. Remnant of dune left by deflation. Scale division 1 inch. Location west of old U.S. 85.

C. Sand dune where samples M1 to M5 were taken. Mesa in background is capped by andesite.

A

B

C

None of the statistical parameters show geographical trends for the dunes (Tab.2). But some grouping is noticed on Figures 4 and 5. The skewness vs. sorting plot shows a good grouping of samples M2,5,12, 49, and 56. It is not clear why M21 is not of the group since it is close to M2 and M5 in the field. Samples M2, 5,49 and 56 exhibit good grouping when mean is plotted against sorting. Note that M49 is within the group yet it lies across the river from M2 and 5, and M56 is from Cañada Mariana. From this one can conclude that the significance of local groupings of dune samples on the graphs within the areas bounded by the dividing curves is not clear.

Rio Salado channel sand samples are more closely grouped on the skewness vs. sorting graph than they are on the mean vs. sorting graph. There is but one exception, M26, which may be strongly affected by aeolian deposition due to its' location in relation to local topography.

The arroyo samples also are more closely grouped on Figure 4 than on Figure 5, but there are fewer samples, and perhaps exceptions were not collected.

It is interesting to note that plotted on Friedman's (1961) published graphs all the arroyo samples lie beyond the range of his skewness vs. sorting graph, and both the arroyo and the Rio Salado samples are beyond

Figure 4. Standard deviation (sorting) plotted against skewness (third moment) using ø units. The solid line is the line of division which Friedman (1961, p.520) found in his study of recent beach and river sands. The dashed line is the apparent division between the recent dune, river and arroyo sediments along the lower Rio Salado. Table 2 may be used to identify individual samples.

Cross-bedding and pebbles in the Loma Blanca facies (Tsc) indicate that they were deposited by a river. Santa Fe upper facies (Tsu) are river or pediment deposits. Popotosa playa sands and silts (Tpp) contain evaporite gypsum beds.

Figure 4.

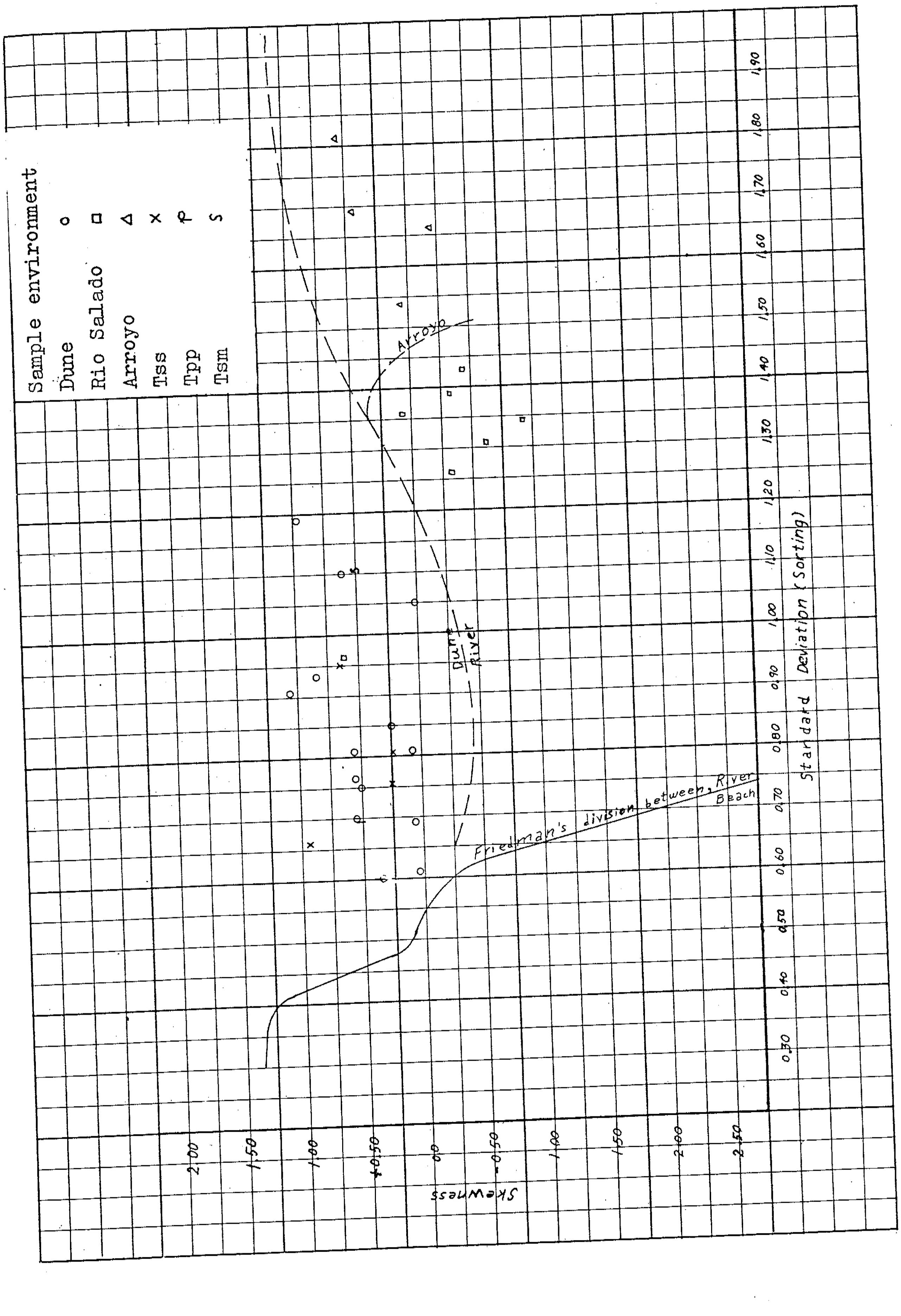
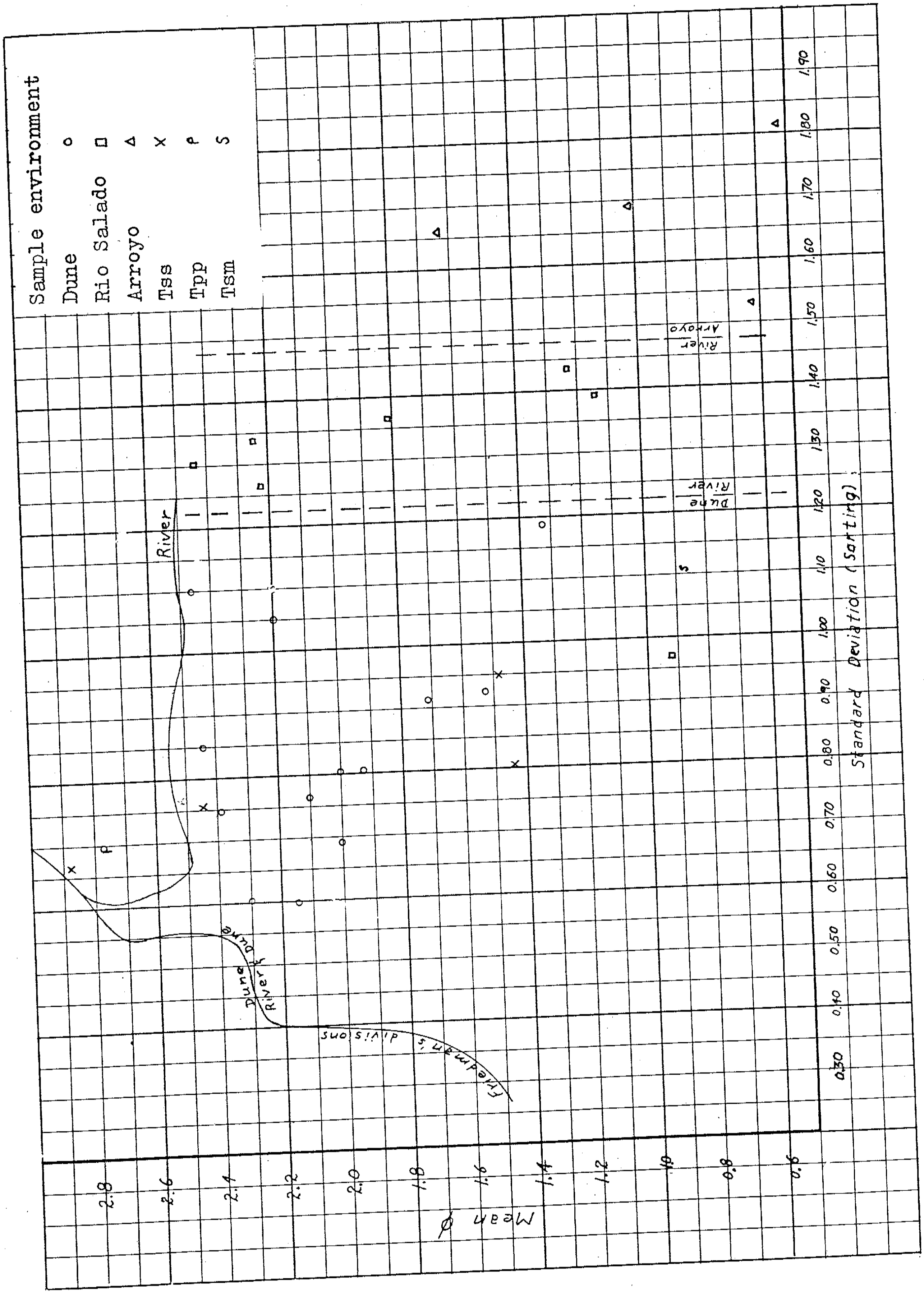

Sample environment
Dune o
Rio Salado □
Arroyo △
Tss x
Tpp P
Tsm S
Arroyo
Dune
River
Friedman's division between River
Beach
Standard Deviation (Sorting)
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
1.90
Skewness
2.00
1.50
1.00
+0.50
0.0
-0.50
1.00
1.50
2.00
2.50

Figure 5. Standard deviation (sorting) plotted against mean using ∅ units. The solid lines mark the division between recent dune and river sands found by Friedman (1961, p.521) in his environmental study. The dashed lines mark the apparent divisions between dune, river, and arroyo sands along the lower Rio Salado. Table 2 may be used to identify individual samples.

Cross-bedding and pebbles in the Loma Blanca facies (Tsa) indicate that they were deposited by a river. Santa Fe upper facies (Tsm) are river or pediment deposits. Popotosa playa sands and silts (Tpp) contain evaporite gypsum beds.

Figure 5.



Sample environment
Dune ○
Rio Salado □
Arroyo △
Tss ×
Tpp ρ
Tsm S
River
Arroyo
Dune
River
River
Dune
River & Dune
Friedman's divisions
Standard Deviation (Sorting)
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
1.90
Mean φ
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6

the range of his mean vs. sorting graph.

Most of the Loma Blanca facies, the upper facies and the Popotosa sands and silts lie in the sand dune area of the graphs with two exceptions. On the mean vs. sorting graph, M34 (Loma Blanca facies) and M61 (Popotosa sand and silt) fall within Friedman's river sample area. Yet it is obvious from field relations that the other samples are not from aeolian deposits.

Conclusions

From the above observations one can conclude that within a general depositional environment, in this case semi-arid, the individual deposits will be separated on the graphs. But if one were to start with a complete unknown, for example a subsurface sample from the Loma Blanca facies, one could only determine whether the sample was from a marine or a continental deposit. This could be done by determining the skewness and the standard deviation. In this particular area of continental deposits sorting seems to be the most sensitive to the depositional or energy environment. The vertical division lines drawn on Figure 3 could also be drawn on Figure 4.

A trend may be seen (Tab.2) in the skewness column of the Rio Salado channel sands. The skewness becomes negative where the Rio Salado enters the narrower winding cayon west of the mapped area and remains that way to M23 (Fig.2). The frequency curves of the samples give some idea of why this happens (Pl.27-36). All the arroyo curves are bimodal and the arroyos have steeper gradients than the Rio Salado. At M14 the Rio Salado frequency curve is not bimodal, but just downstream 100 yards at M15 the frequency curve is bimodal. Upstream from M15 the Arroyo Tio Lino empties into the Rio Salado. The frequency curve at M13 from the Arroyo Tio Lino is similar to the frequency curve at M15 in the Rio Salado. The frequency curves for the sampled length of the Rio Salado are quite sensitive to the stream gradient, and thus to the energy of the transporting medium which deposited the sediments. The steeper the gradient of the stream, the greater the energy of the transporting medium, and the greater the tendency for the skewness to be negative. The greater energy of the transporting medium allows it to carry the more of the fine sand, and in this manner shifts the curve toward the coarser sizes. Friedman (1961, p.524) feels that the greater total energy of the transporting medium is the reason for the negative skewness of beach sands.

Heavy Minerals

Treatment and identification

The grains between $+2\phi$ and $+3\phi$ were separated with tetrabromoethane (specific gravity = 2.94) into heavy and light fractions. The heavy mineral fraction was split until enough for two slides remained. One split was mounted without further treatment, and the other split was mounted after the magnetic grains were removed with a small hand magnet. The heavy minerals were mounted in piperine ($n = 1.68$). A random selection of the light minerals was mounted in canada balsam ($n = 1.54$). The nonopaque heavy minerals were counted usually on the slide from which the magnetic minerals were removed. The mineral identification and counting were done with a petrographic microscope and a mechanical stage. At least 200 grains were counted on each slide.

In recognition of the possibility of miscounting augite, epidote and acmite the total percentage of these minerals is entered at the right of Table 3. The total hornblende percentage is entered because of the gradation between red, brown and green color. Blue-green hornblende although distinct from green hornblende is included with the green for statistical purposes.

									% Hornblende											
Sample	% Acmite	% Apatite	% Augite	% Barite	% Biotite	% Clinozoisite	% Epidote	% Fluorite	% Garnet	Basaltic (Red)	Common brown	Green & Blue-green	% Kyanite	% Monazite	% Sphene	% Spinel	% Tourmaline	% Zircon	% Zoisite	% Augite, Epidote & Acmite	% Hornblende
M 12 Dune		2	8	8			35		1	14	28	2			/			/		43	44
M 56 Dune		6	8	21			35		1	8	18	1	/		1			1	/	43	27
M 2 Dune		3	9	21			29		/	4	31	2	/					/		38	37
M 5 Dune		2	13	11			36		2	4	30	2				/	/	/		49	36
M 30 Dune		1	11	8			36		/	16	19	6			1			1	/	47	41
M 49 Dune	/	2	11	11			48		2	1	16	5*	/		2			1		59	22
M 53 Rio Salado	/	2	8	31			20		3	10	20	4			/			1	/	28	34
M 17 Rio Salado		4	6	16			17		/	5	49	1			1			/		23	55
M 11 Rio Salado		/	4	12			17		1	3	56	6			/				/	21	65
M 23 Rio Salado		1	18	8		/	20		1	23	21	7			1					38	51
M 44 Loma Blanca	2	2	38	7			30		4	2	9	3	/		2					70	14
M 34 Loma Blanca		1	2	9	1		5		2	3	53	16*	3		1		/	2	/	7	72
M 58 Loma Blanca		3	15	22	/		4	/	2	7	20	11	2		11			2		19	38
M 62 Loma Blanca		1	50	13	/		13		2	/	13	3	/		1			2		63	16
M 61 Popotosa Playa		5	2	23	/		3		1	4	39	16*	4	/	1		/	/		5	59

Table 3 Transparent heavy mineral suits from the vicinity of the lower Rio Salado, New Mexico. Samples arranged according to geographic location and lithologic association. Slash mark (/) indicates a mineral frequency less than 1%. See Plate 23 for exact location.

* Contains distinctive blue-green hornblende.

Samples M2 and M5 are depth samples from the same dune taken less than 100 feet apart. These two samples are a good indication of the frequency variability within sediments of the same source and environment.

Augite or more exactly aegerine-augite is of interest because it is usually rare (Tab.4), and because of its' sharp points (Fig.6). It has the appearance of an amphibole. X-ray examination showed that these grains are single crystals rather than bundles. The optical properties of this mineral are as follows: Biaxial positive, α between 1.682 and 1.687 (probably 1.684), β = 1.687, γ between 1.71 and 1.72, length slow (+), 2 V about 60°, generally not pleochroic, birefringence about .030, inclined extinction about 63°, and good cleavage at right angles and parallel to the elongation of the points. The mineral has also been found by R.H. Weber (personal communication) in arroyos on the east side of the Rio Grande, and in sands beneath Black Mesa just north of Elephant Butte Reservoir. Very likely the mineral has been included with epidote by other workers in this area because its' color is similar to epidote. The points are very fragile and could not survive transportation. For this reason it is concluded that they were produced by etching after deposition.

Table 4. Possible provenances for nonopaque heavy minerals from sediments along the lower Rio Salado.

MINERAL	PROVENANCE	OCCURANCE (2)	STABILITY (2)	FREQUENCY (2)
Acmite	Alkaline igneous (4)	Detrital	Moderately stable	Rare
Apatite	Acid igneous (1)	Detrital	Unstable	Rare
Augite	Intermediate & basic igneous (4)	Detrital	Moderately stable	Local
Barite	Reworked (1)	Authigenic	Moderately stable	Local
Biotite	Igneous & metamorphic (4)	Detrital	Moderately stable	Common
Clinozoisite	Metamorphic (4)	Detrital	Moderately stable	Rare
Epidote	High rank metamorphic (1)	Detrital & Authigenic	Stable	Common
Fluorite	Acid igneous, metamorphic (4) & pegmatite (1)	Detrital & Authigenic	Stable	Rare
Garnet	High rank metamorphic or pegmatite (1)			
Hornblende:	Acid igneous & high rank metamorphic (1)	Detrital	Stable	Common
Basaltic	Volcanic			
Common	Acid igneous (1)			
Blue-green	High-rank metamorphic (1)			
Kyanite	High-rank metamorphic (1)	Detrital	Stable	Common
Monazite	Acid igneous & pegmatite (1)	Detrital	Stable	Rare
Sphene	Acid igneous (1) & metamorphic (4)	Detrital & Authigenic	Stable	Rare
Spinel	Metamorphic (3)	Detrital	Stable	Common
Tourmaline	Reworked (1)	Detrital	Stable	Common
Zircon	Igneous, metamorphic (4) & reworked (1)	Detrital	Stable	Common
Zoisite	High rank metamorphic (1)	Detrital	Stable	Rare

1. Pettijohn, 1957, p. 513
2. Milner, 1952, p. 499
3. Milner, 1952, p. 340
4. Milner, 1952, mineral descriptions

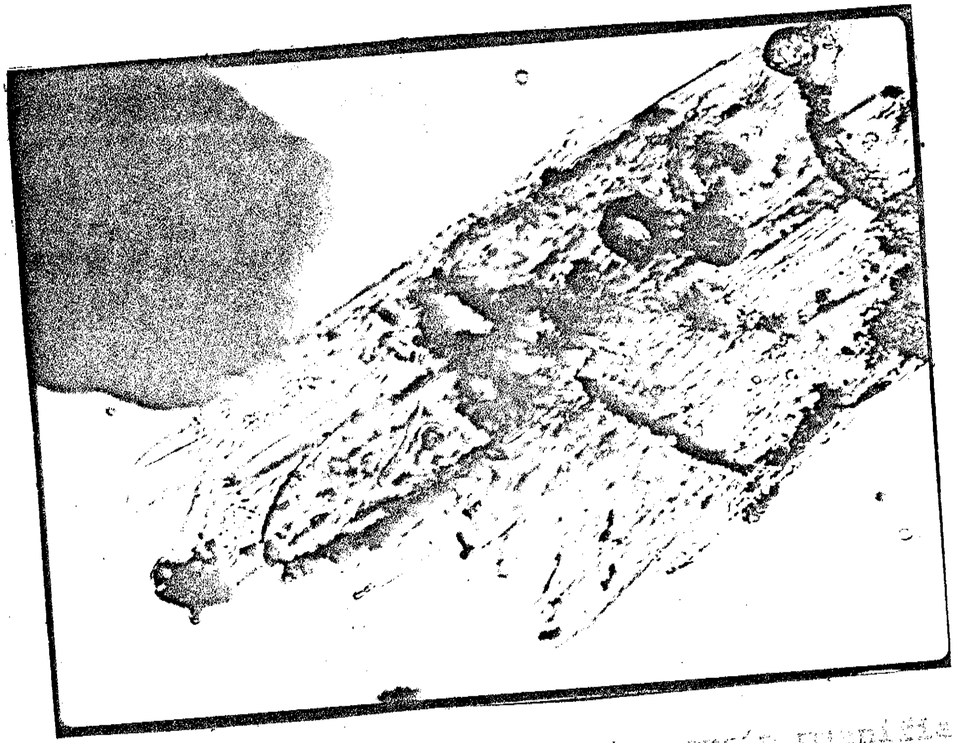


Figure. 6. Etched augite grain magnified 316 times. The widest part of the grain measures 0.171mm. Grain from Loma Blanca facies at location M58. The minerals attached to the side of the grain may be barite.

Mineral provenance

Augite phenocrysts are reported by Hunt (1956, p.50) to be common constituents of Cenozoic basalts on the Colorado Plateau. Rehkemper (1956, p.66) reported green "coxcomb" augite in arkosic sediments of the Datil Formation, and it contains several basalt flows. Thus there seems to be an ample source for augite in volcanic rocks which were probably at the surface when the Popotosa and Santa Fe were deposited. Basaltic hornblende also supports the hypothesis of a volcanic source for some of the sediments.

Small percentages of blue-green hornblende and kyanite suggest high rank metamorphic rocks as a source for some of the Popotosa. The high percentage of epidote in the Loma Blanca facies suggests high rank metamorphic rocks in the provenance.

Sphene and apatite usually come from acidic rocks. The high percentage of common hornblende probably comes from acidic rocks. Thus acidic rocks must be included in the provenance for sediments along the lower Rio Salado.

The nonopaque heavy minerals suites from the vicinity of the lower Rio Salado (Tab.3) suggest that the source of the Popotosa Formation and Loma Blanca facies sediments is crystalline rocks rather than sedimentary rocks (Tab.4). Most of the minerals appear to be comparatively fresh and have sharp edges. Tourmaline, zircon and apatite are well rounded, but their frequency is low.

Sands forming the dunes on the north side of the Rio Salado appear to come mostly from the Rio Salado. But much of this sand has a local source in the Loma Blanca facies which is brought to the Rio Salado both by wind and water (note augite and epidote frequency). Minor quantities of sand probably are blown directly to the dunes from the Loma Blanca facies.

The dune at M49 receives most of its' sand from nearby Loma Blanca, and lesser quantities from Arroyo Chanthe (note blue-green hornblende).

Conclusions

The Tertiary Popotosa playa deposits and conglomerates were tilted and probably faulted before the Tertiary Santa Fe Group was deposited. General uplift or a change in local base levels produced a series of pediments and terraces which are being dissected in a semi-arid climate similar to one which prevailed in Popotosa time.

Denny (1940, p.83) classifies the lower sands and silts of the Popotosa Formation as playa sediments deposited in a semi-arid climate because of the gypsum beds and the regular thin bedding of the red brown sediments. Mechanical analysis supports the classification suggesting a combination of aeolian and fluvial deposition. Denny (1940) supposes a volcanic provenance for the playa deposits similar to that for the overlying conglomerates. The nonopaque heavy mineral suite confirms this. Authigenic barite and concertina augite suggest that there was some diagenesis of the sediments even though they are not lithified. This agrees with Denny's contention that the gypsum veins are of secondary origin. The bentonite bed was probably an ash fall before diagenetic processes altered it to clay.

The Popotosa conglomerates' intertonguing and pinching out to the east suggests a highland source area not far west of the present Popotosa outcrops.

Clay and pebble layers, cross-bedding, and slump structures indicate a fluvial mode of deposition for the Loma Blanca sands. The mechanical analysis supports this theory, and suggest that some of the sand is aeolian. The olive color of the clay indicates that the environment was more reducing than during Popotosa time. Diagensis is indicated by the calcite veins, authigenic barite, and concertina augite. Denny's (1940, p.88) conclusion from the gravel types that the sediments are of crystalline and volcanic origin is confirmed by the nonopaque heavy mineral suite.

The gravels and sands of the Santa Fe upper facies sggest a fluvial deposition for these sediments. Mechanical analysis supports this view, and suggests that some of the sand may be aeolian.

A hypothetical history of the sands in the dunes along the Rio Salado may begin in the Cenozoic igneous rock of the Datil volcanic field where the earliest rocks were basic volcanic flows. The later rocks were acidic flows, pyroclastics or intrusives. The highly metamorphosed rocks were associated with the Ladron Mountain block (Slingerland, 1958, p.27). This ultimate provenance was exposed in a semi-arid climate such that mechanical weathering was faster than chemical weathering. Wind and water transported the newly freed sediments to the playas of the Popotosa Formation.

As the relief in the western source area increased the fine sediments were incorporated with the coarser sediments to form conglomerates. The area of the Popotosa Formation was tilted, eroded, and became a provenance for the Santa Fe Group. The Loma Blanca facies continued to receive sediments from a provenance similar to that of the Popotosa, but transportation was almost all by river. Later as the topographic relief became greater the fine river sands were covered by coarser sands and gravels. Uplift continued so the Loma Blanca and the Popotosa were again exposed to erosion by wind and water which moved sediments to the Rio Salado. These second cycle sediments mingled with sediments being brought from the Datil volcanic field where a provenance similar to that of the Popotosa and Loma Blanca is exposed. Wind transports the sediments from the Rio Salado into the dunes. Thus most of the sands in the dunes are multicycle although their angularity suggests that they are single cycle sediments.

A few dunes migrate out of the Rio Salado at M36, M30, and M28. At M36 and M30 the dunes may be somewhat protected by the embankments to the north. Perhaps a change in the wind pattern and a great abundance of sand explain the dunes at M28. It is not meant to imply that the sands do not cross the Cañada Mariana surface. They obviously do as indicated by the sand sheet covering the surface. Also, sandfalls occur along the west bank of the Rio Grande trough, and sand shadows are very common on the slope west of U.S. 85 where U.S. 85 enters the Rio Grande at the northern edge of the area. The sands from the Rio Salado dunes cross the Canada Mariana surface, but generally not in the form of dunes.

Again looking at the wind rose diagrams one can see that during March the winds were shifting from northwest to southwest. No particular direction is strongly predominant. In April the pattern is obvious, but still not very strong. The Net Indexes and Net Resultants are not large. But in May the shift is strong (NI = 4758). During this month the dunes shifted their orientation. By June they were reoriented, and receiving sand from the SSE. This illustrates the effect of topography on wind direction. In Socorro there were no strong winds from the SSE, and therefore the south winds at Socorro must have shifted by [illegible] before they reach the dunes. The dunes maintained their southerly orientation for the remainder of the year, but from October onward their shapes became rounded and their avalanche slopes indistinct.

Holm (1960, p.1371) made the following observations of desert geomorphology in the Arabian Peninsula. "Streamlined flow in one direction tends to build barchan dunes. Reversal of the wind direction tends to destroy the barchan by cutting off the top of the slipface and building a new one with a convex arc down wind on the back of the old one. Shifting the wind to a side quarter tends to shift the dune sideways, intensifying the slipface on the windward horn and rounding it off on the leeward horn. A shift of 45° tends to elongate the opposite horn (contrary to Bagnold, 1941, p.223) to form an incipient linear dune. If the winds are alternating, roughly equal, and from opposite directions, the barchan is transformed into a sigmoidal dune" (Pl.5B,6A,D).

In 1962 sand dunes along the north side of the Rio Salado were shaped more by southern winds during the hot summer months than by the northern winds during the cooler winter months. The most westward dunes were not greatly affected by the 1962 wind shift which suggests that local topography is the factor controlling the wind effectiveness. During recent years winds from the southeast quadrant have had more influence on the dunes than winds [illegible] quadrants.

Friedman's (1961) textural study of recent sediments from known environments was checked against the known environments in this area. It seems that the depositional environment of a sand sample can only be suggested rather than determined as was hoped. But the known recent depositional environments within the area were clearly separated, with one exception, using Skewness or Mean statistical parameters vs Standard Deviation.

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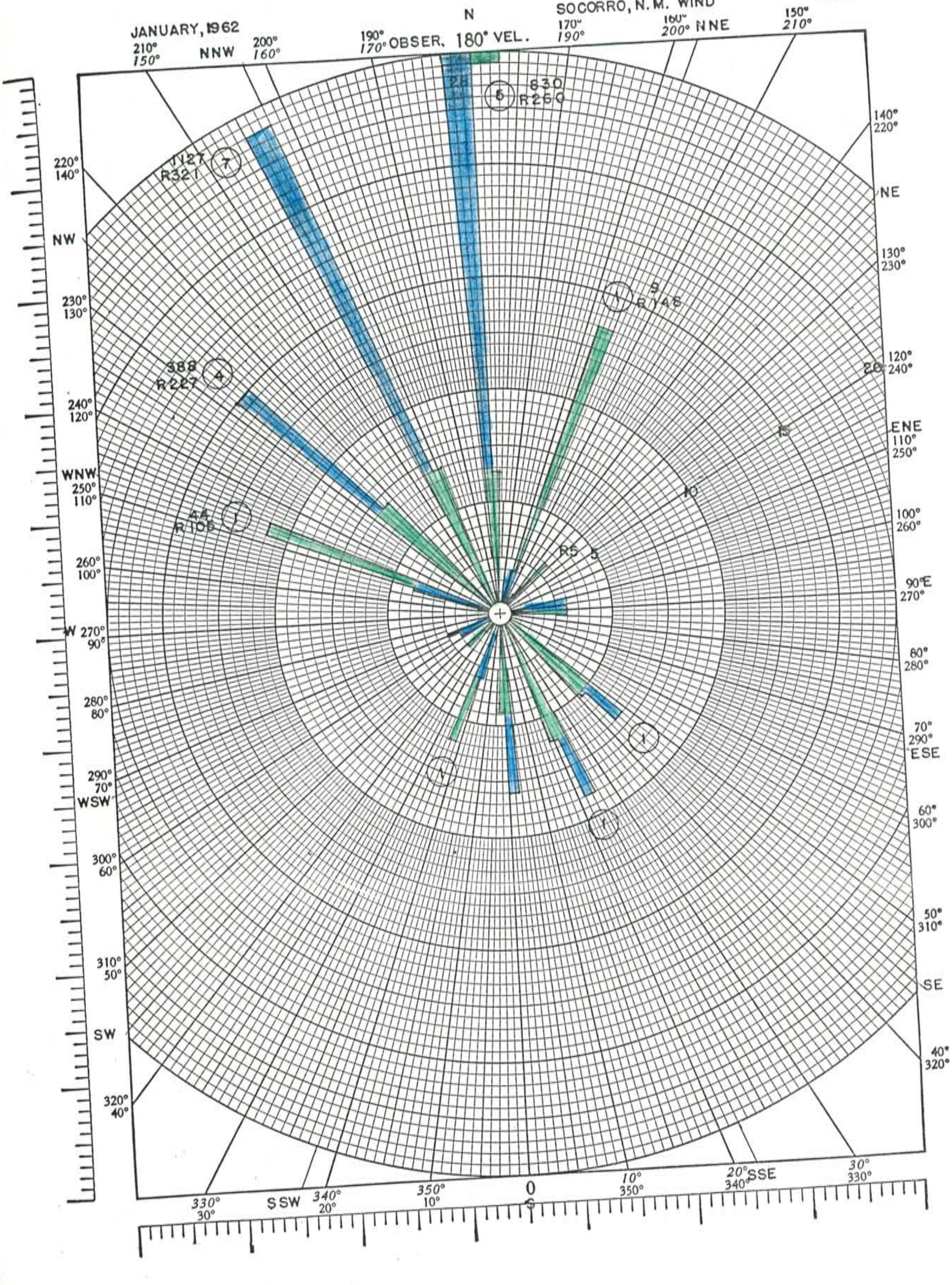
Plates 9 - 21. Rose diagrams showing wind direction, average velocity in miles per hour, and number of observations. Circled numbers indicate numbers of observations of wind velocities over 10 miles per hour. Numbers preceded by "R" are called Net Resultant. Numbers above Net Resultant are called Net Index.

PL. 9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SOCORRO, N.M. WIND
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100° 260°
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240° 120°
230° 130°
NW
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R321
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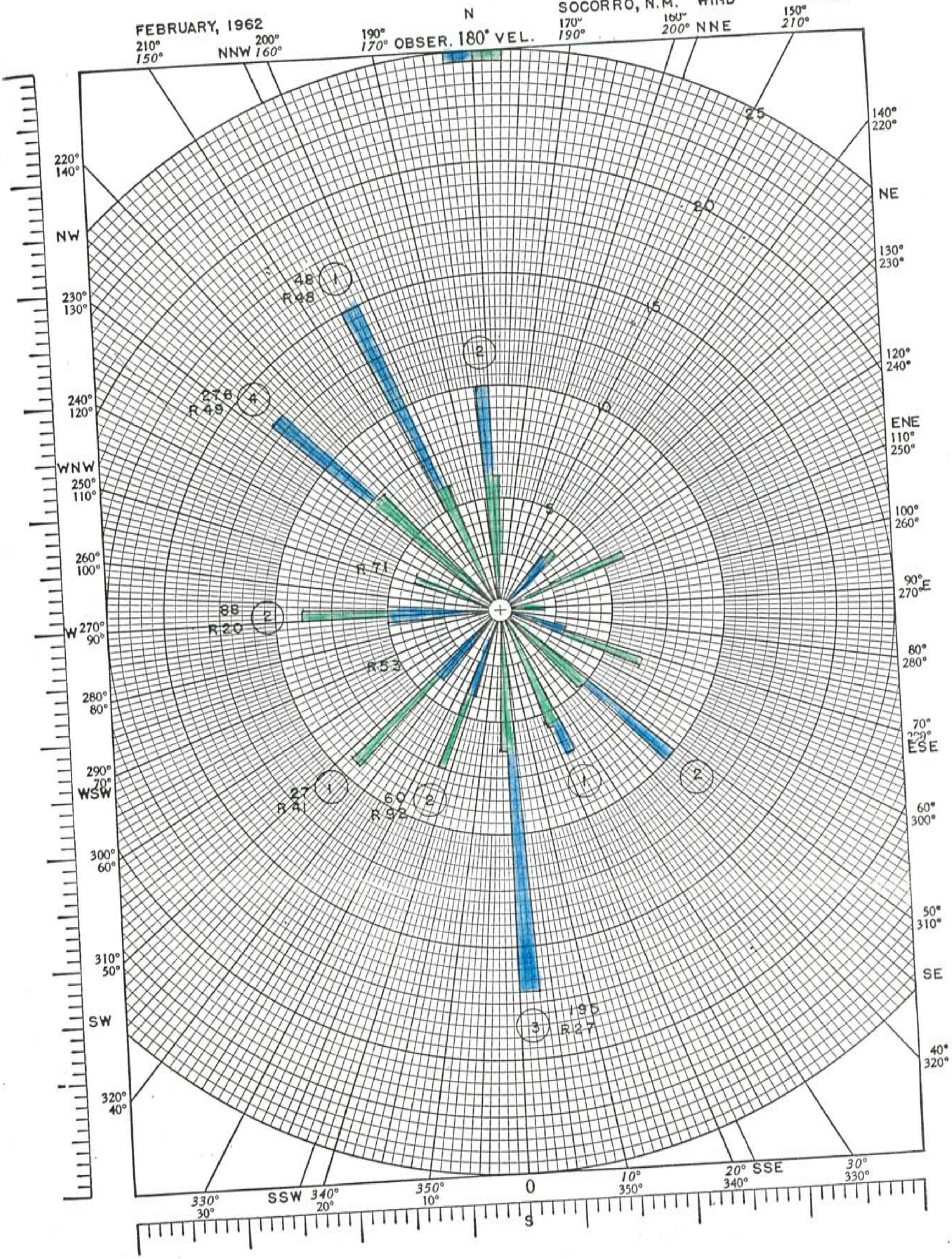
FEBRUARY, 1962

SOCORRO, N.M. WIND

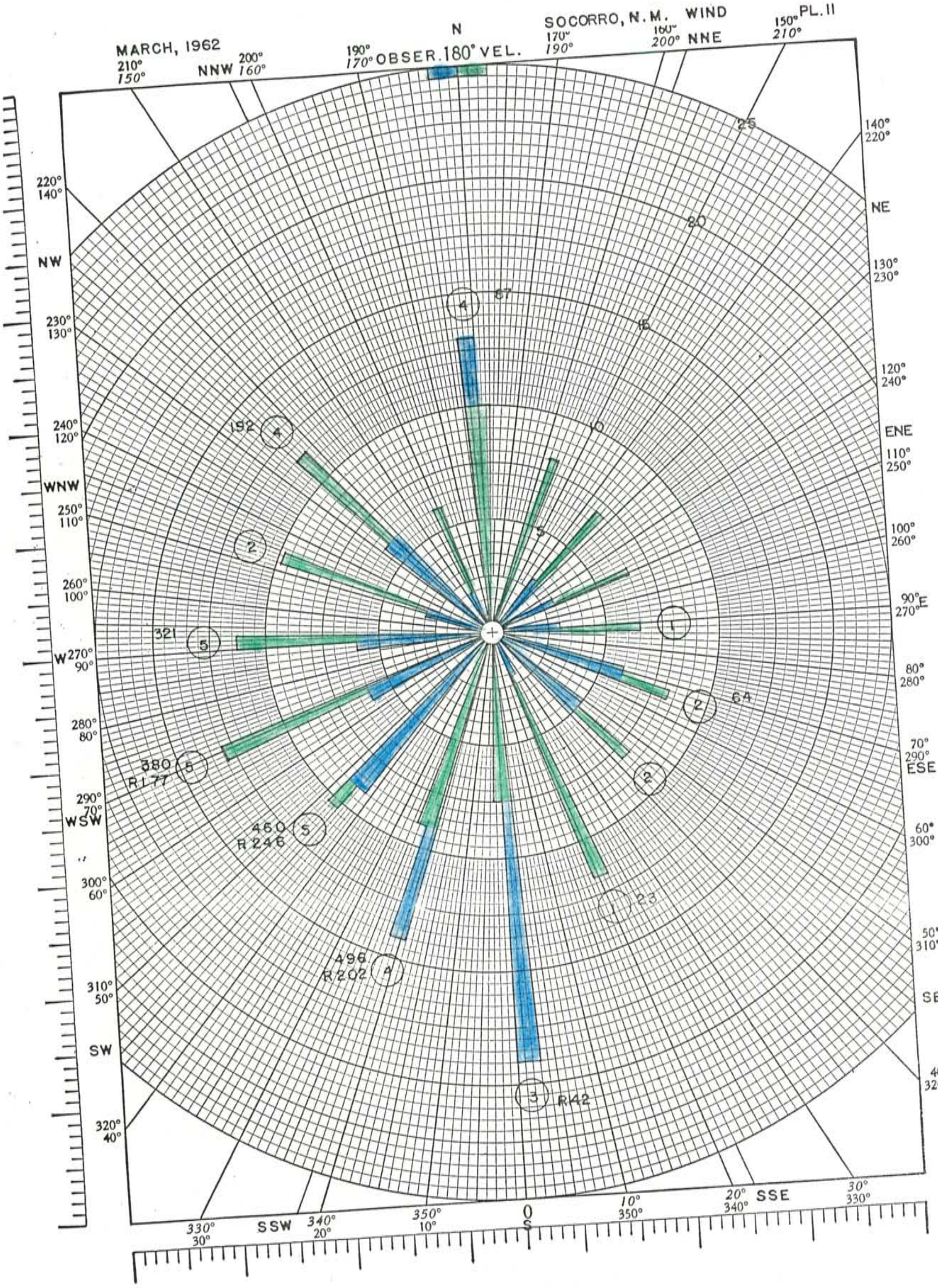
PL.10



MARCH, 1962

SOCORRO, N.M. WIND

PL. II



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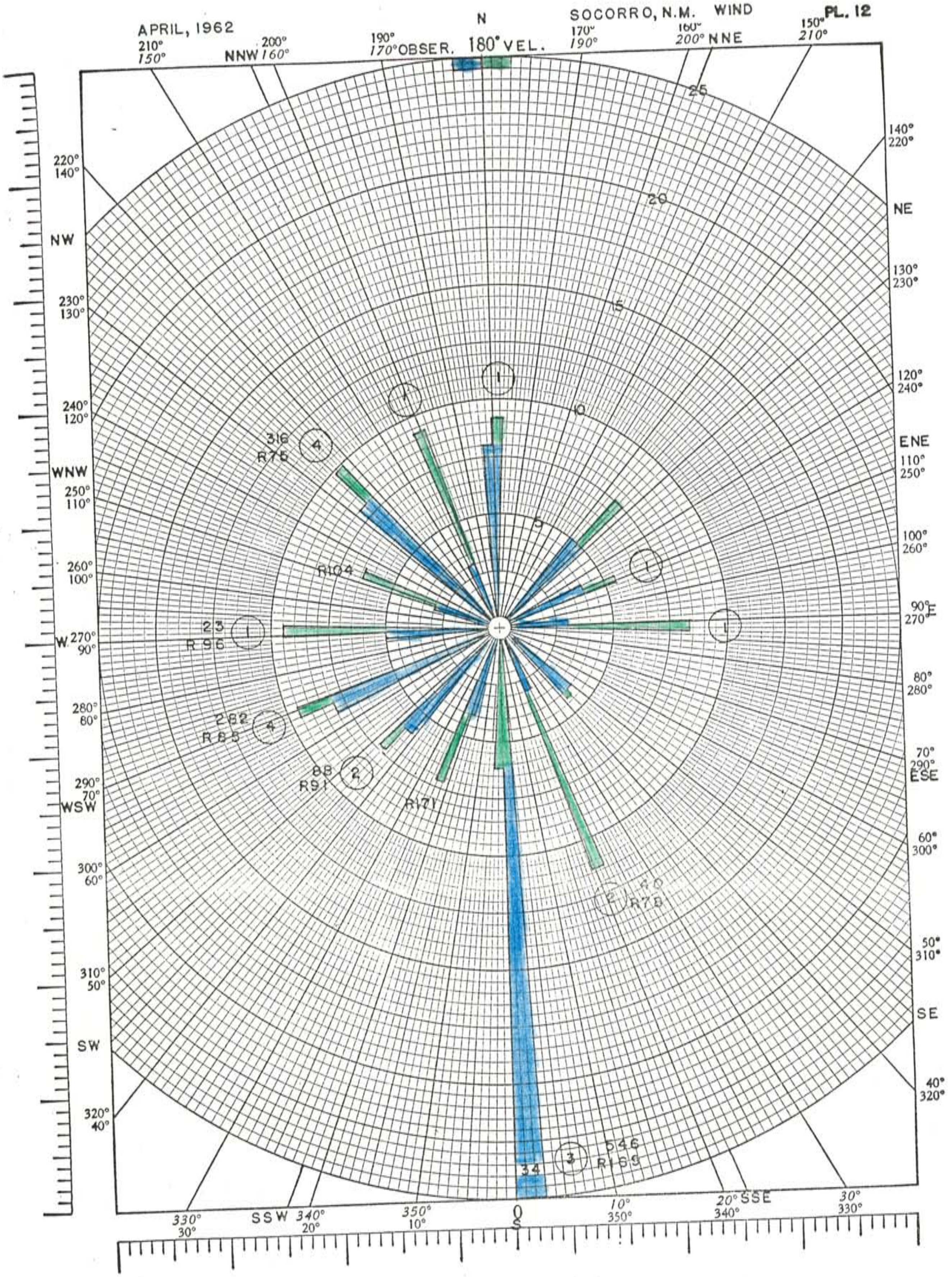
PL. 12



PL.13

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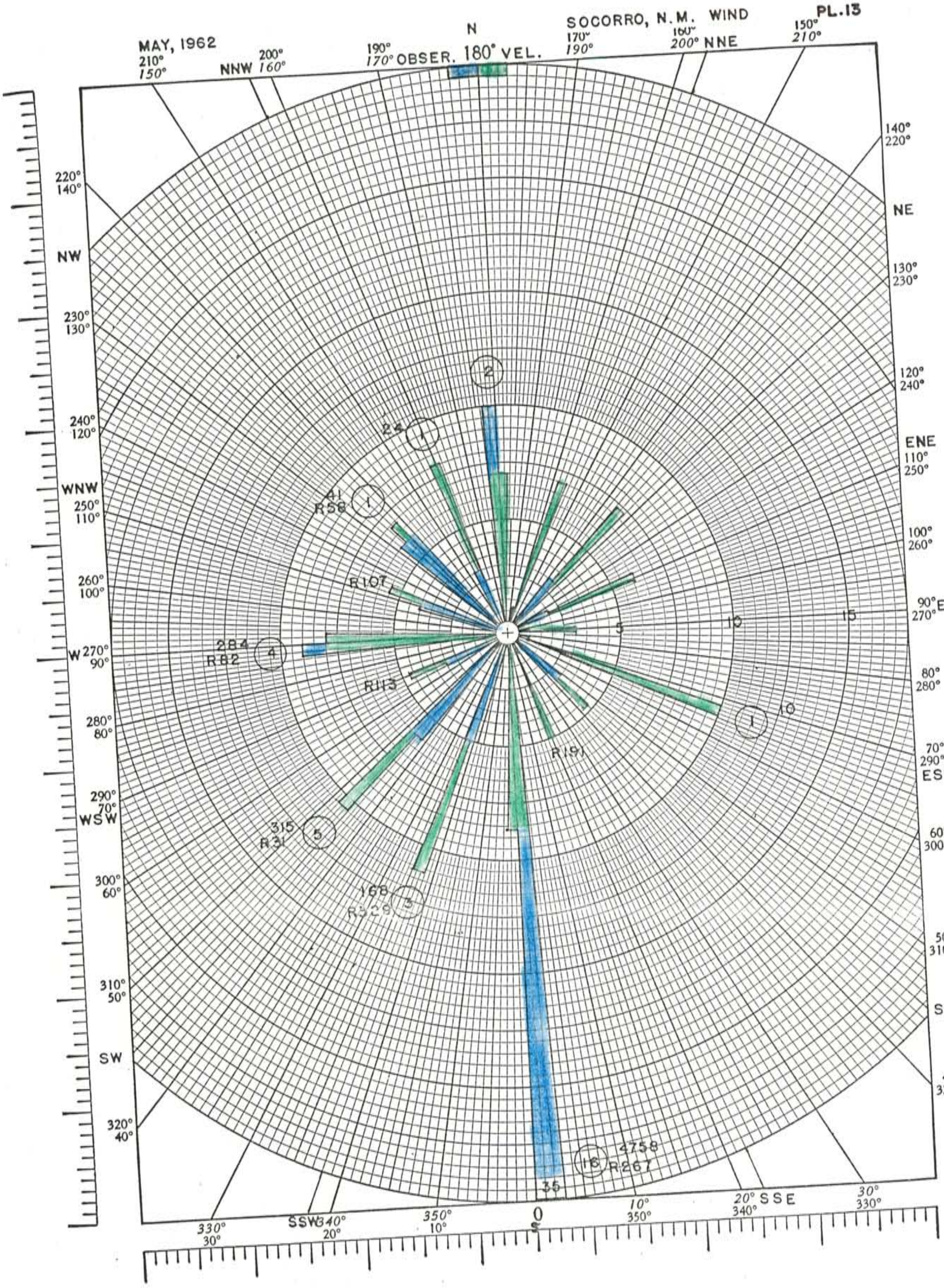

PL.14

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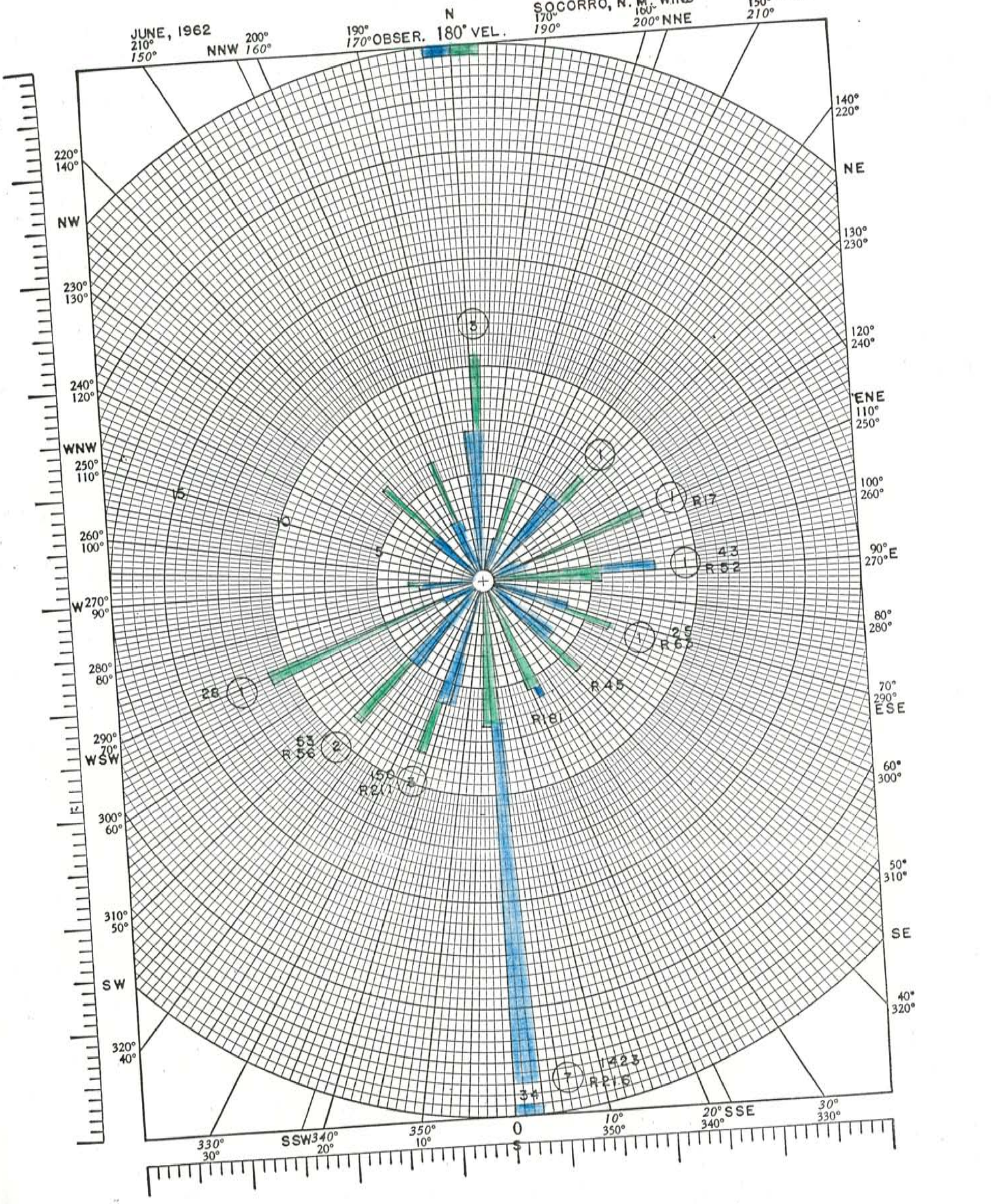
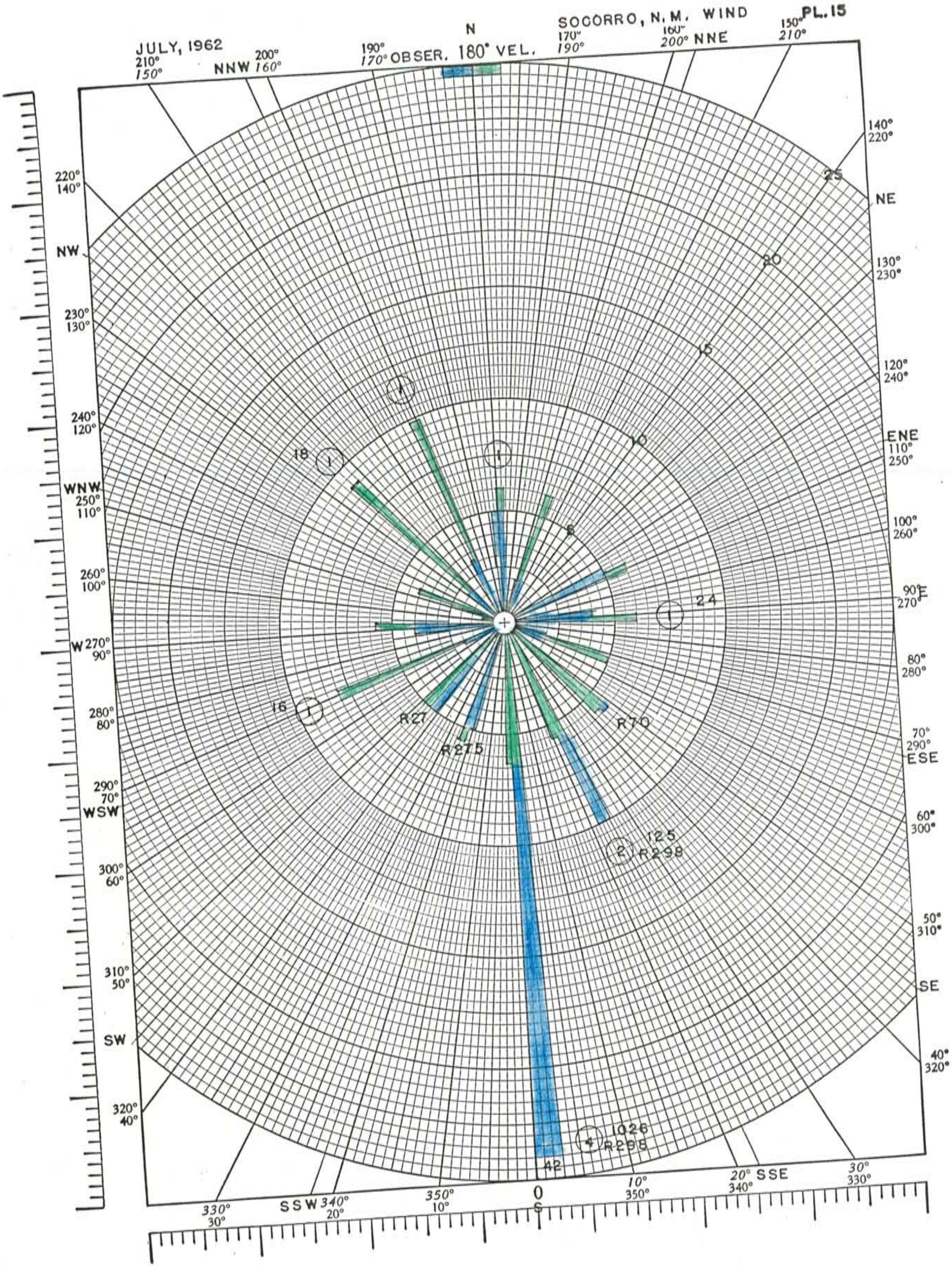




PL.15

SOCORRO, N.M. WIND

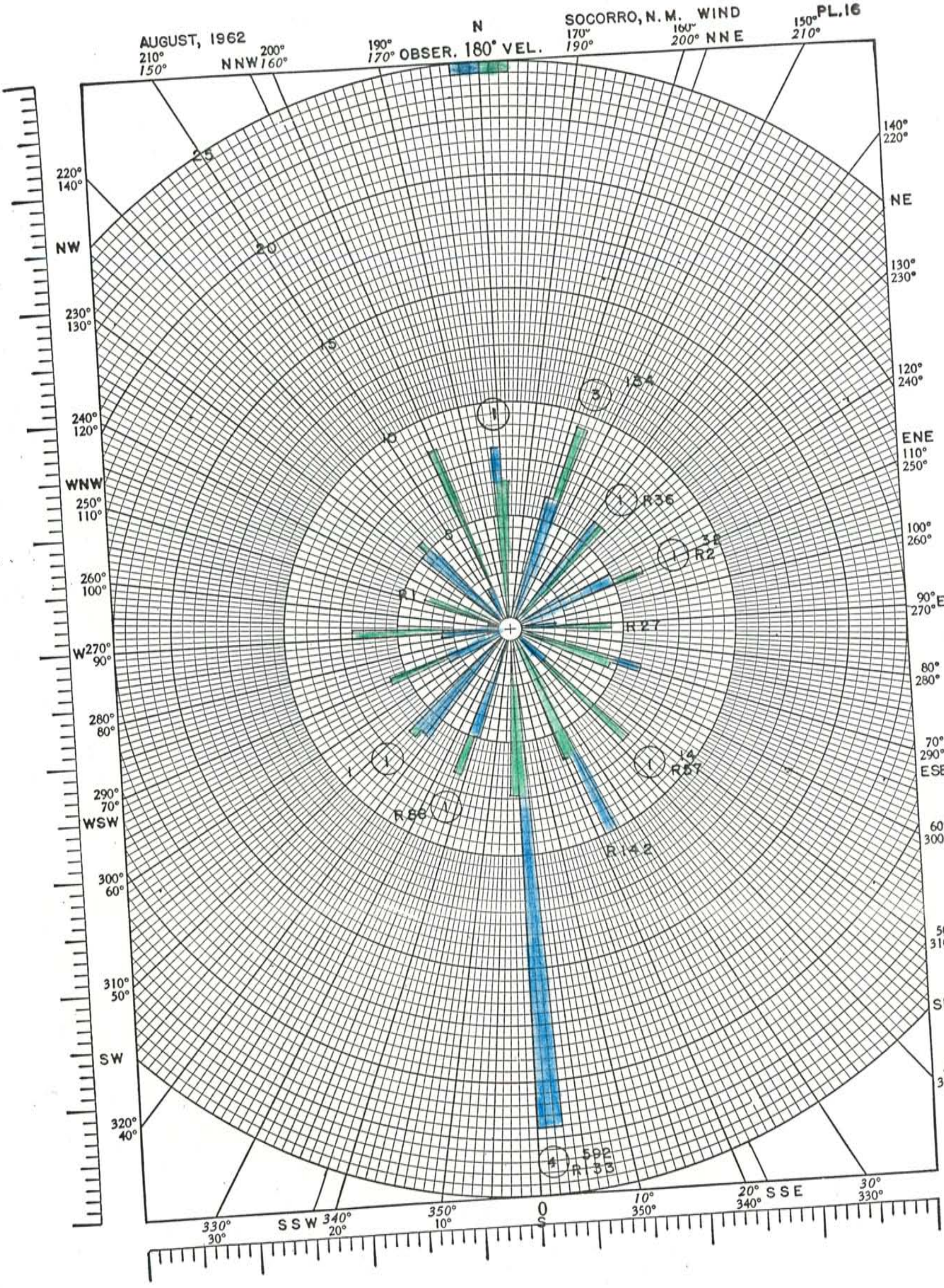
JULY, 1962

PL.16

AUGUST, 1962

SOCORRO, N.M. WIND

OBSER. 180° VEL.



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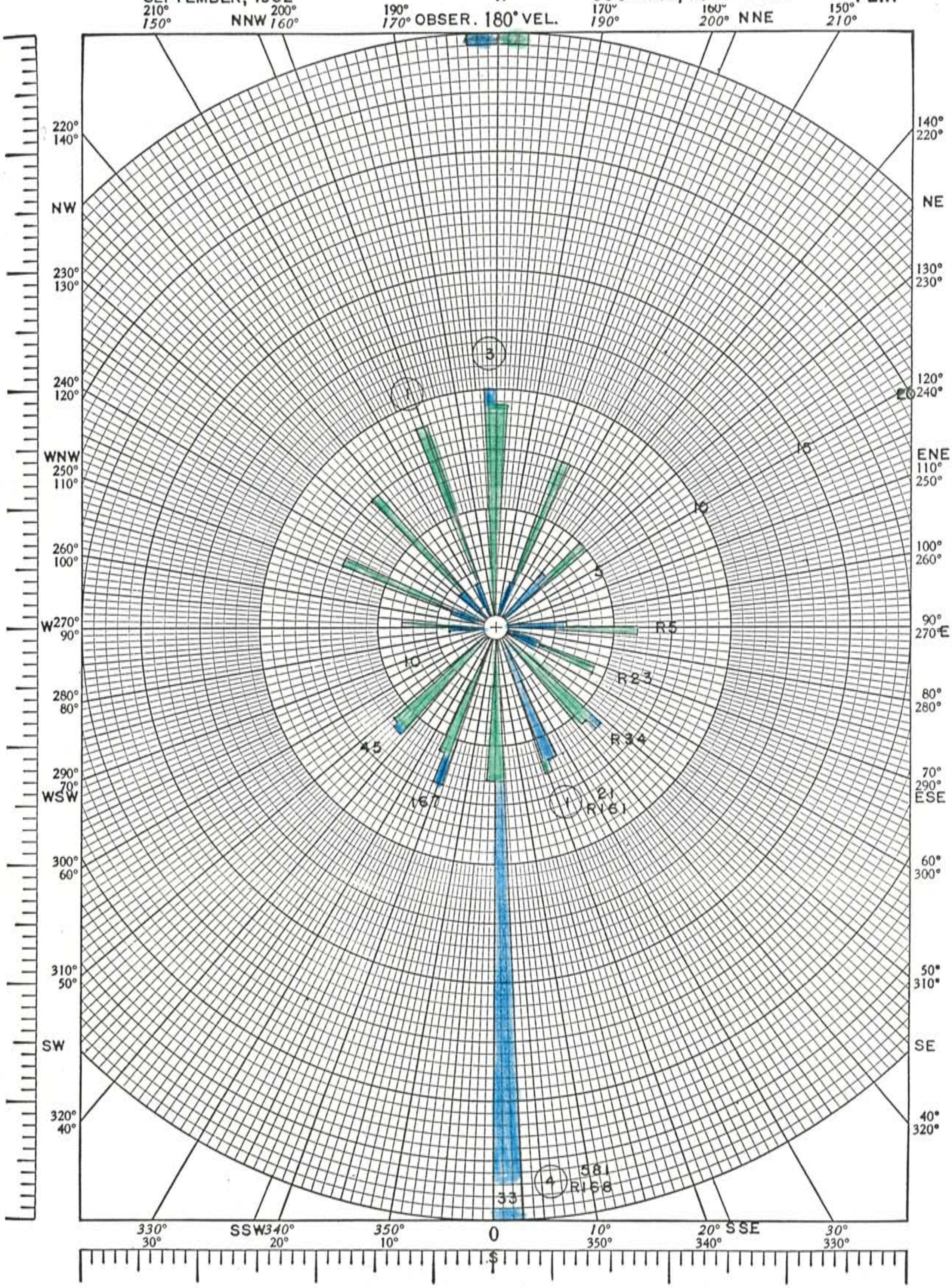

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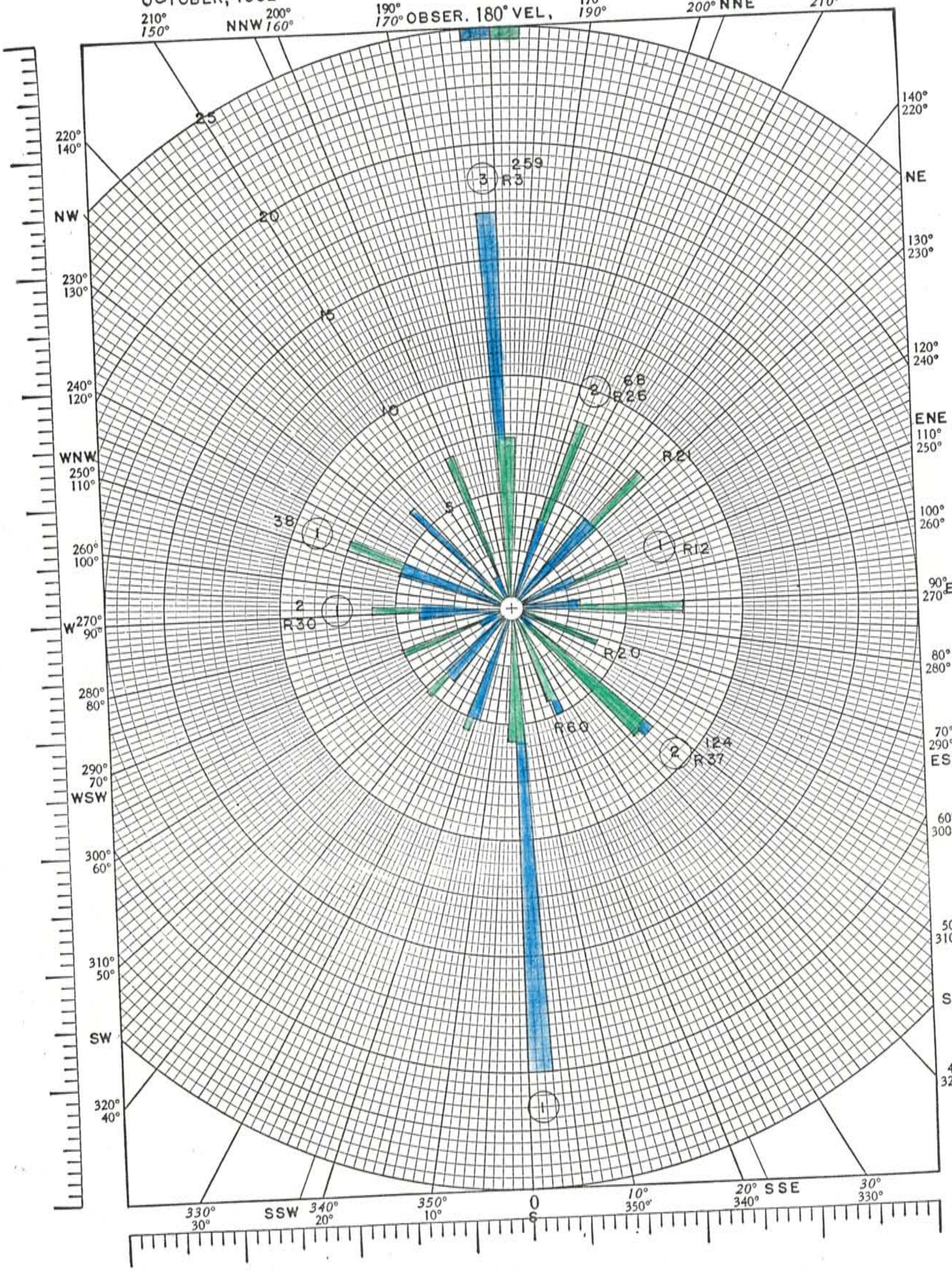
SOCORRO, N.M. WIND

PL.18



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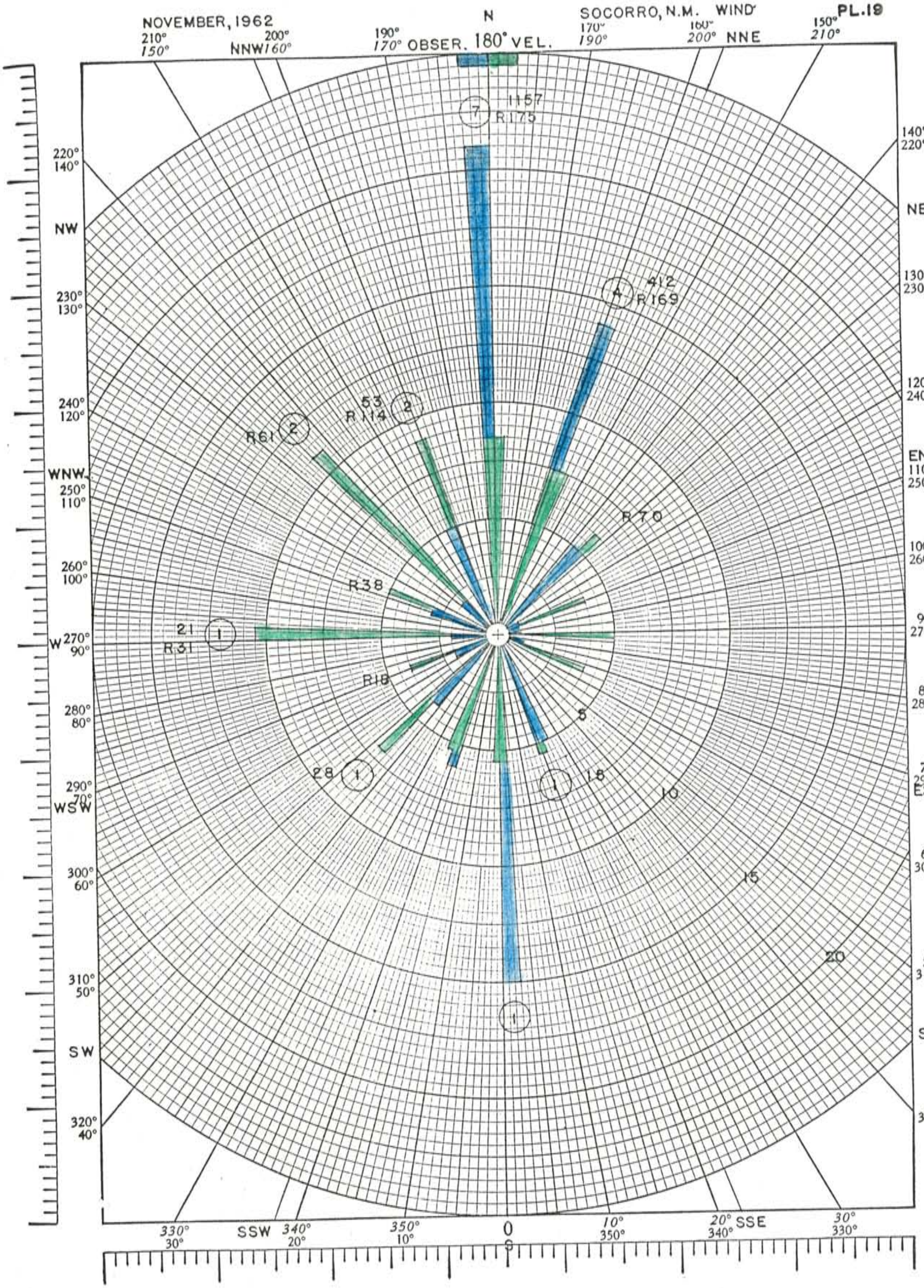
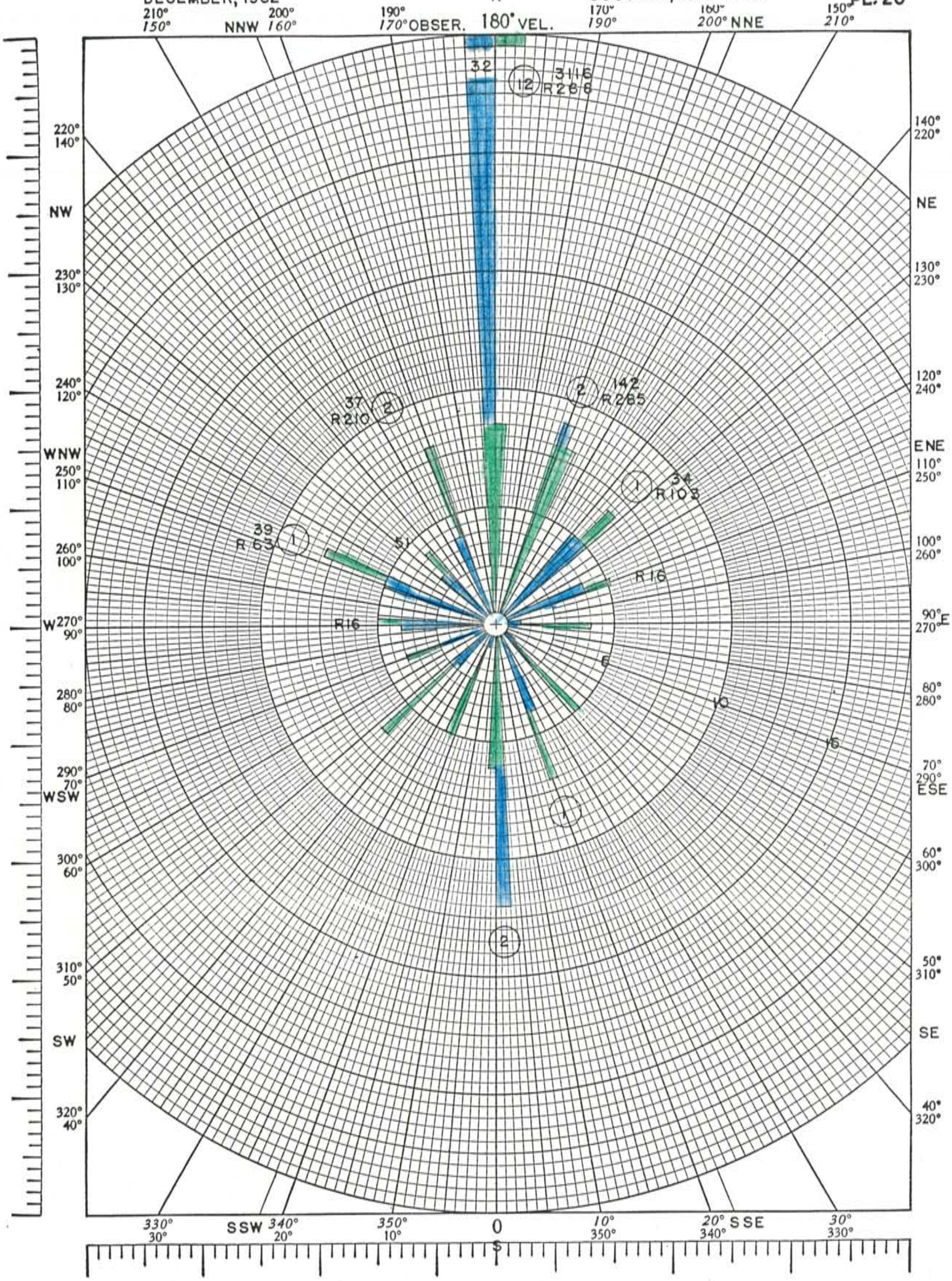


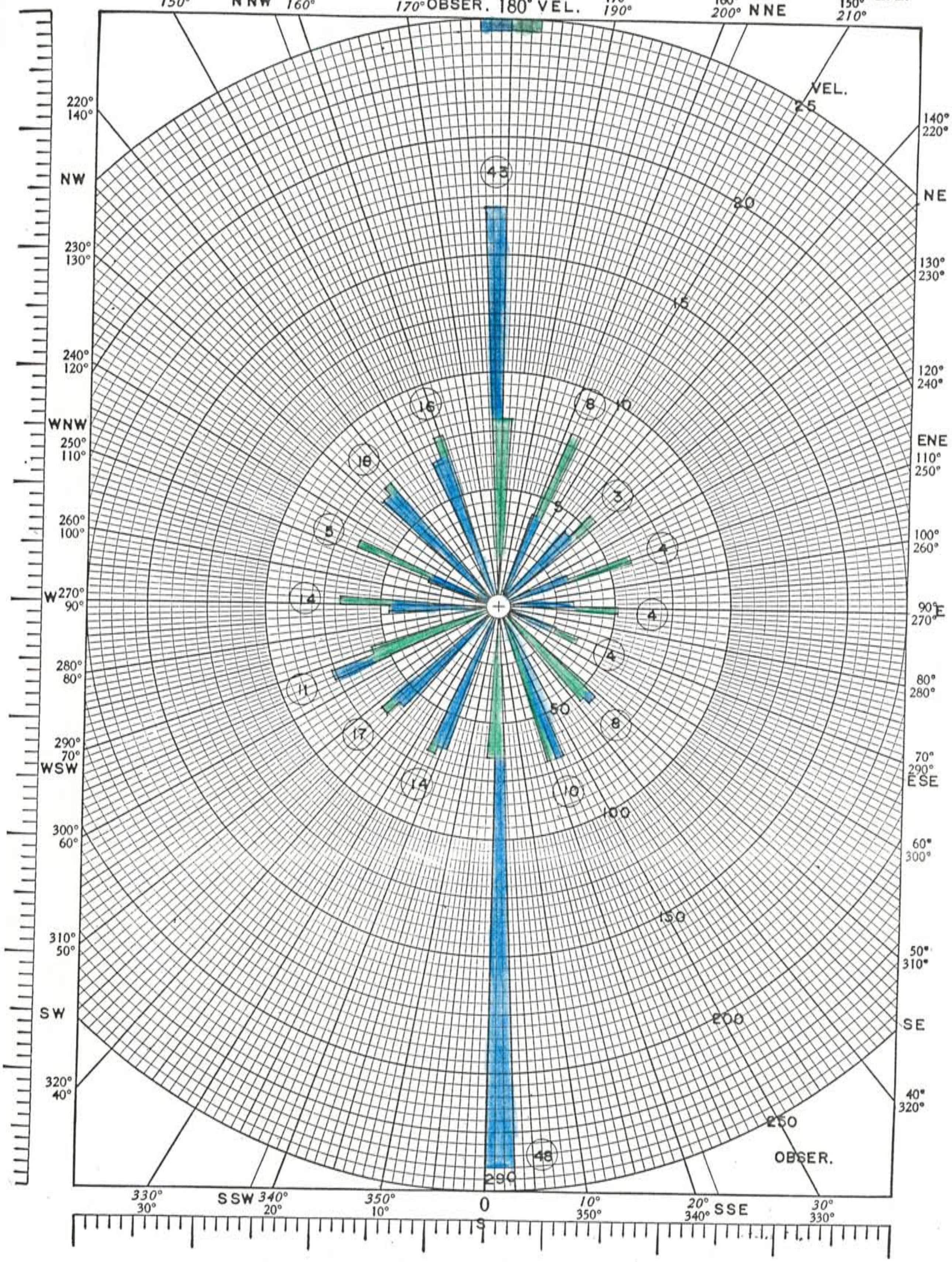
DECEMBER, 1962 SOCORRO, N.M. WIND **PL. 20**



PL. 21

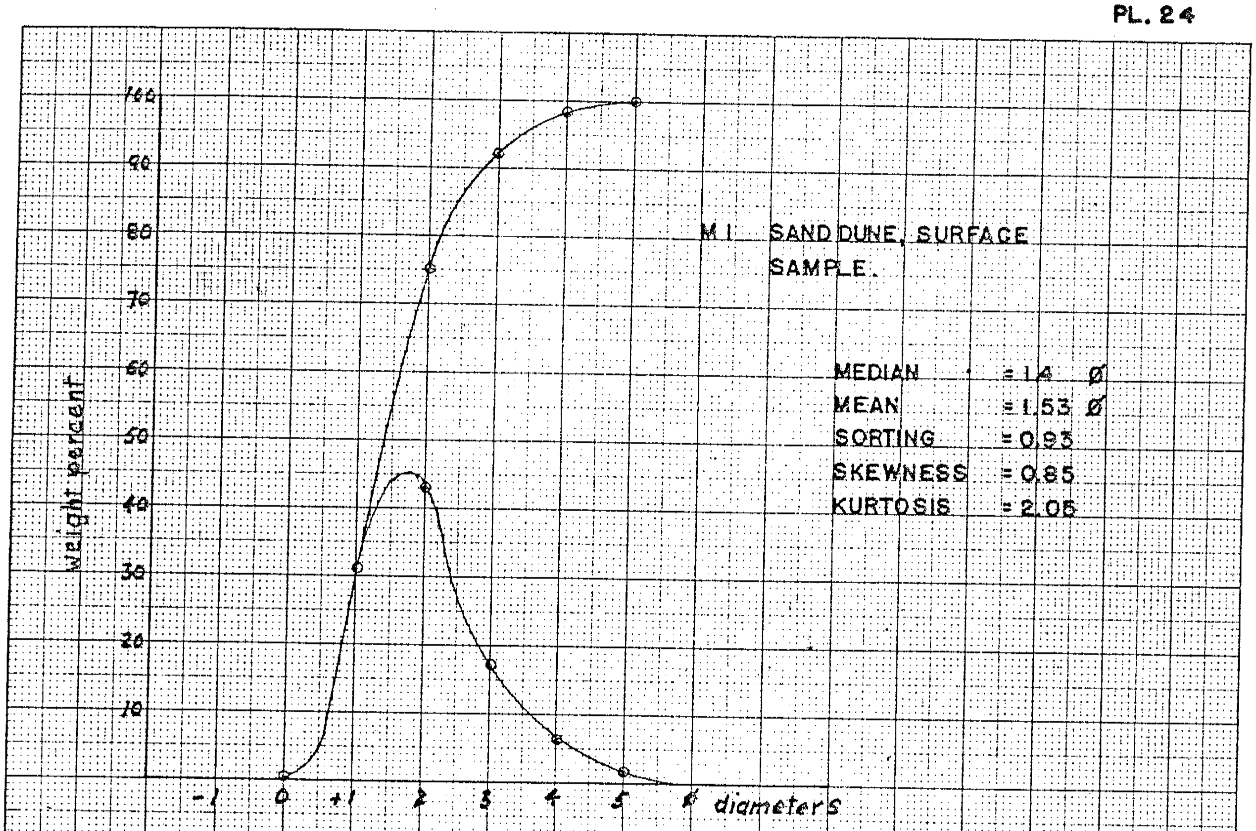
SOCORRO, N.M. WIND

YEAR 1962



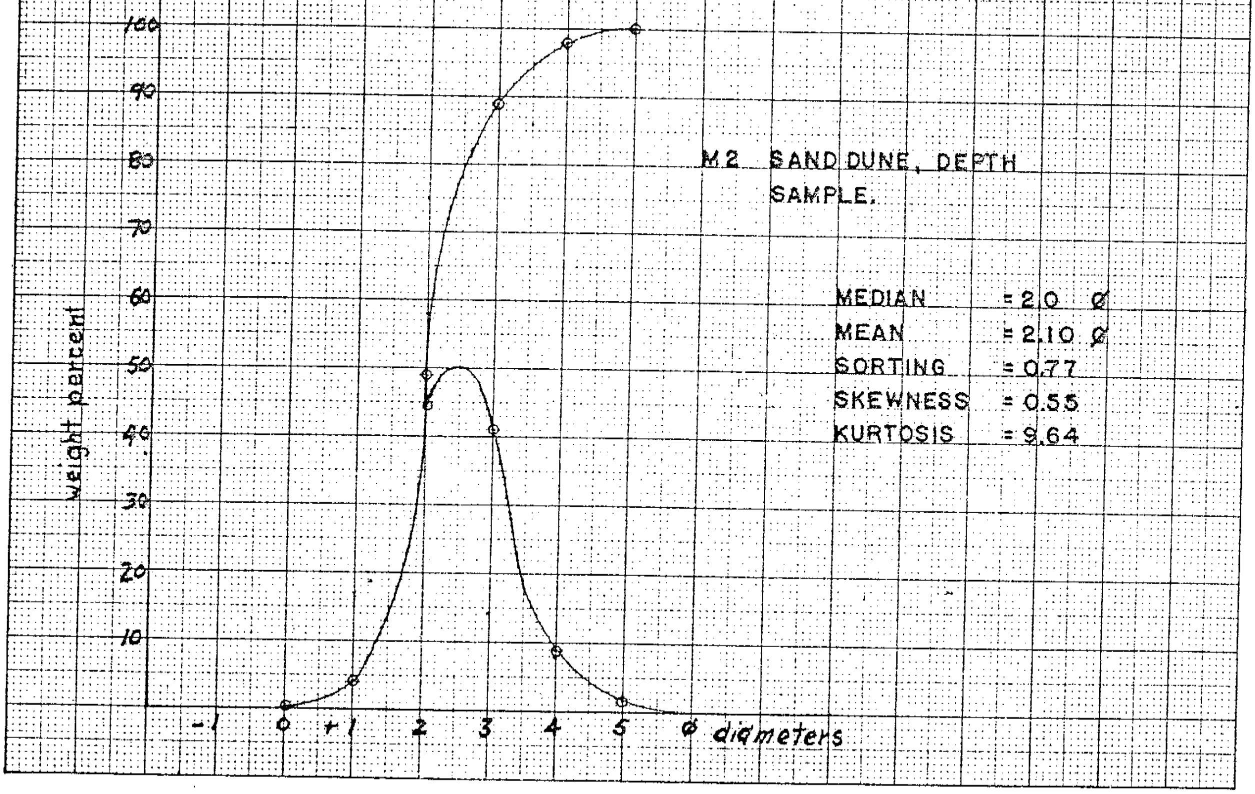
Plates 24 - 38. Graphs of weight-percent against Phi (ϕ) diameters for sands in the vicinity of the lower Rio Salado. The curve that rises to 100% at + 5 ϕ is the cumulative-percent curve. The curve which branches from the cumulative percent curve and falls to + 5 ϕ is the weight-percent frequency curve. The sample classifications and statistical parameters are defined in Mechanical Analysis section. Sample locations are shown on Plate 23 and Figure 2.

PL. 24



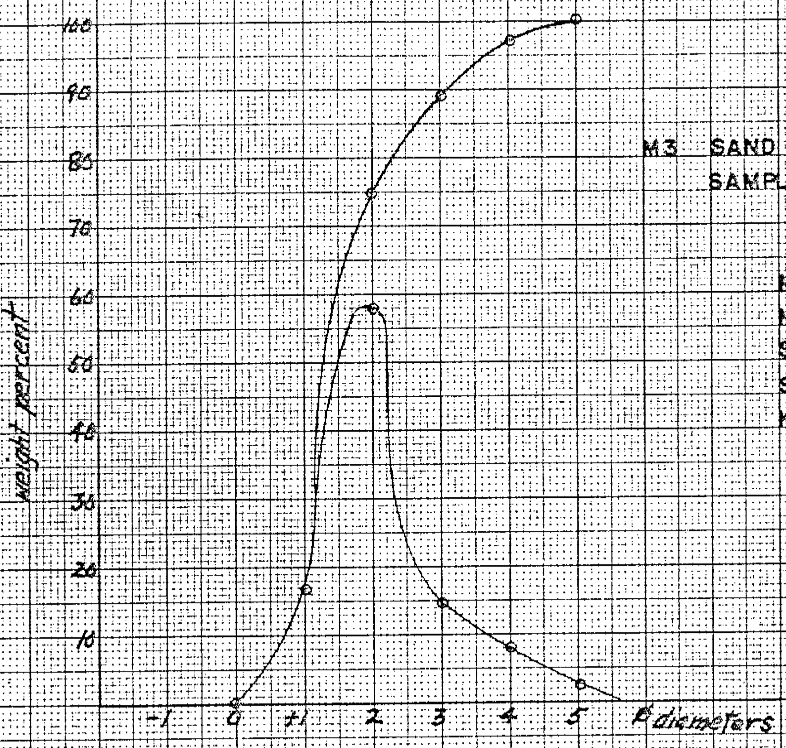
M 1 SAND DUNE, SURFACE SAMPLE.

MEDIAN = 1.4 ø
MEAN = 1.53 ø
SORTING = 0.93
SKEWNESS = 0.85
KURTOSIS = 2.06



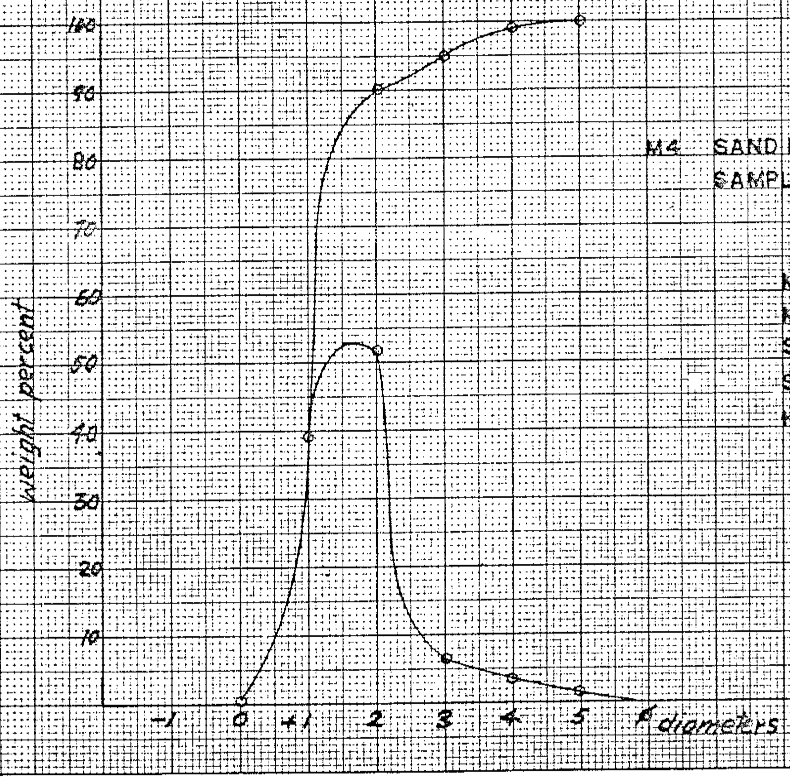
M 2 SAND DUNE, DEPTH SAMPLE.

MEDIAN = 2.0 ø
MEAN = 2.10 ø
SORTING = 0.77
SKEWNESS = 0.55
KURTOSIS = 9.64



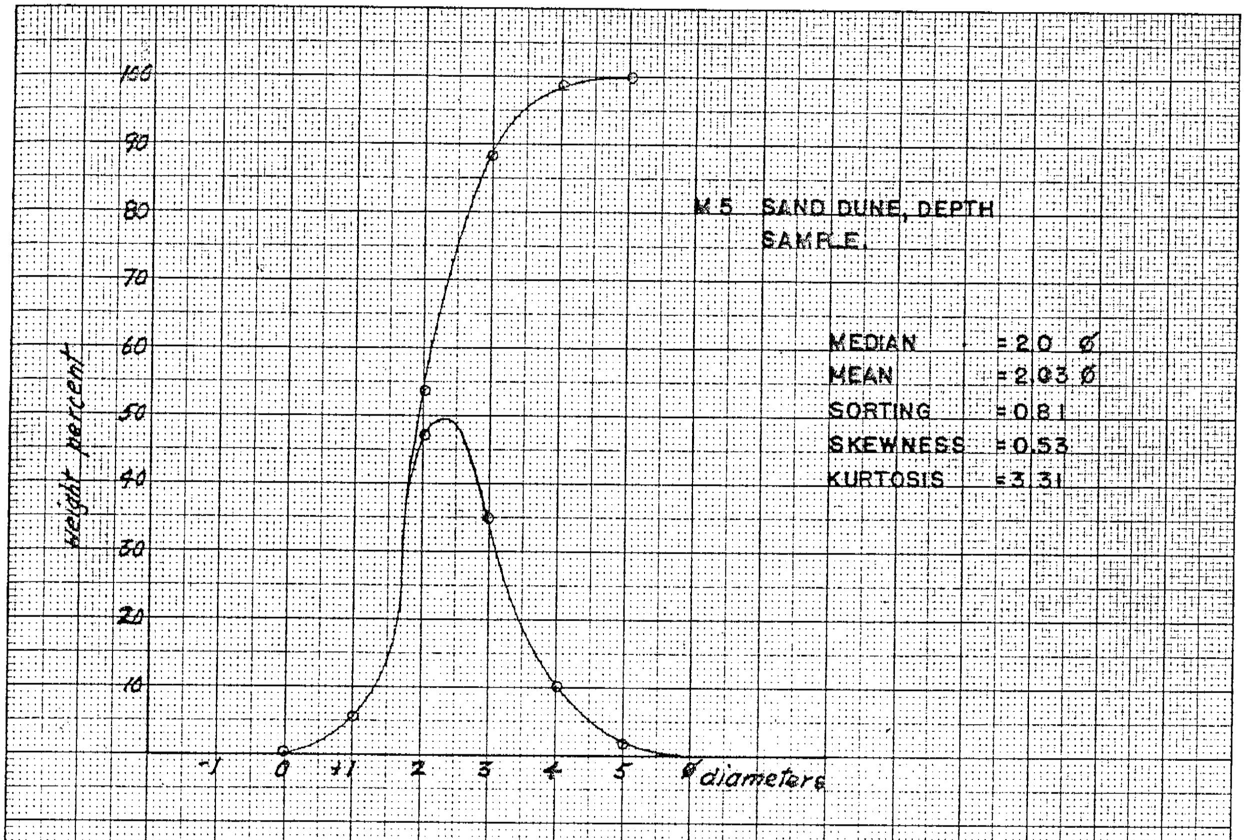
M3 SAND DUNE, SURFACE
SAMPLE.

MEDIAN = 1.5 φ
MEAN = 1.72 φ
SORTING = 0.91
SKEWNESS = 1.05
KURTOSIS = 4.12



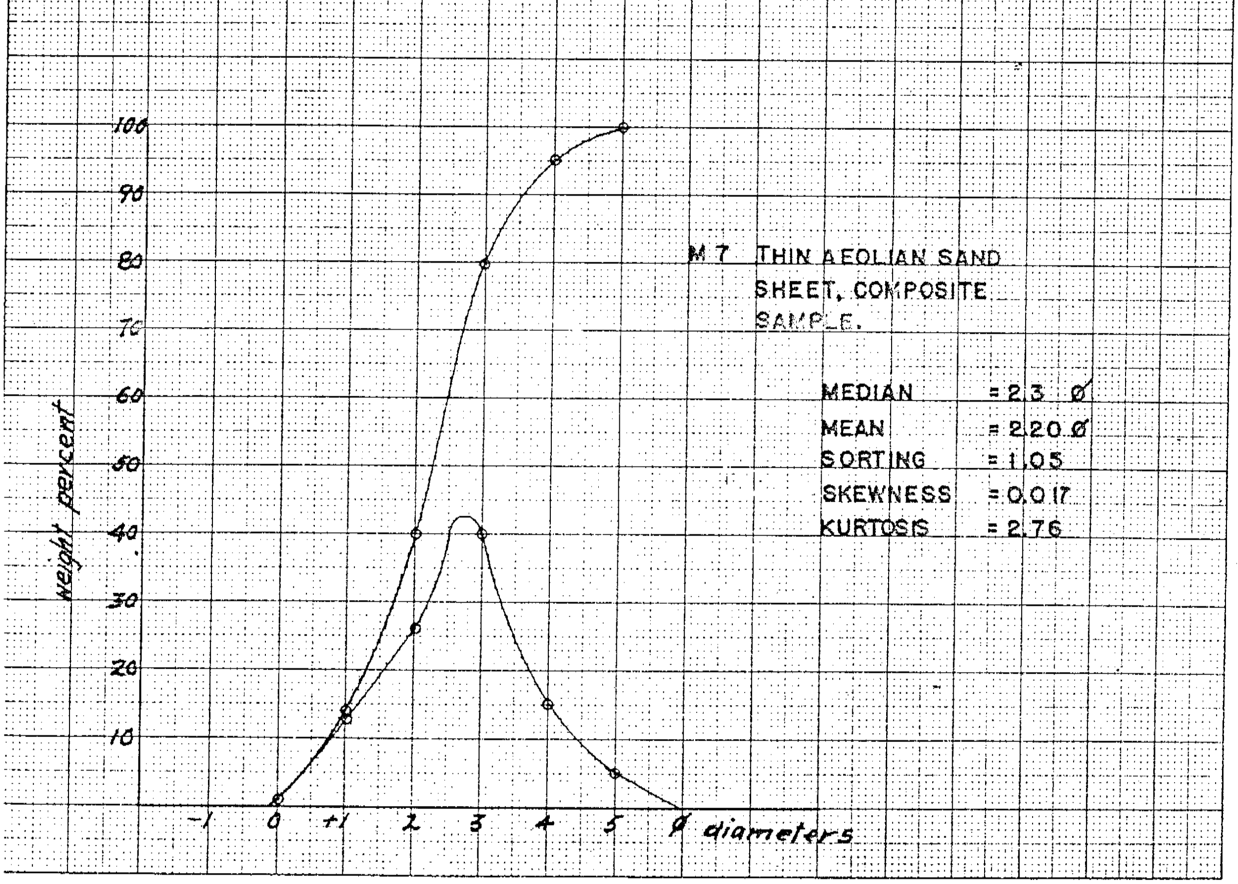
M4 SAND DUNE, SURFACE
SAMPLE.

MEDIAN = 1.3 φ
MEAN = 1.27 φ
SORTING = 1.18
SKEWNESS = 0.98
KURTOSIS = 1.75



M 5 SAND DUNE, DEPTH SAMPLE.

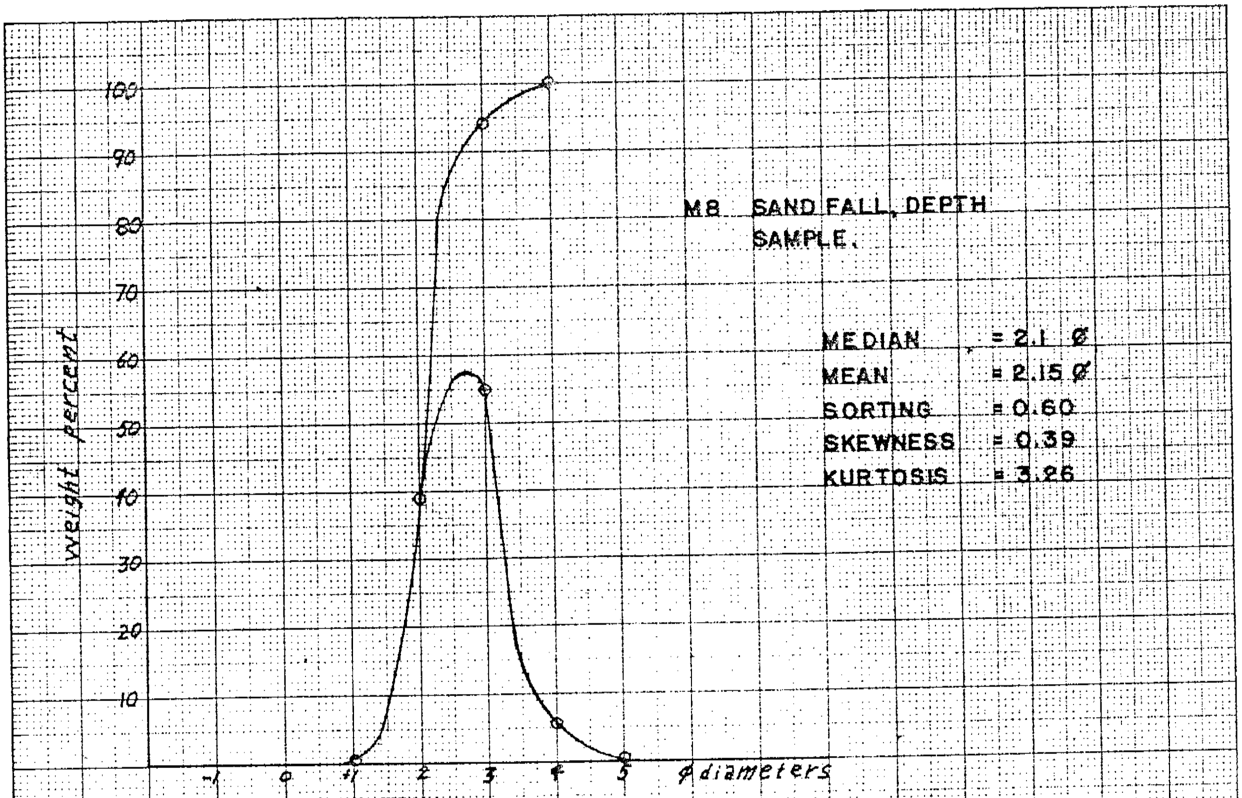
MEDIAN = 2.0 Ø
MEAN = 2.03 Ø
SORTING = 0.81
SKEWNESS = 0.53
KURTOSIS = 3.31



M 7 THIN AEOLIAN SAND SHEET, COMPOSITE SAMPLE.

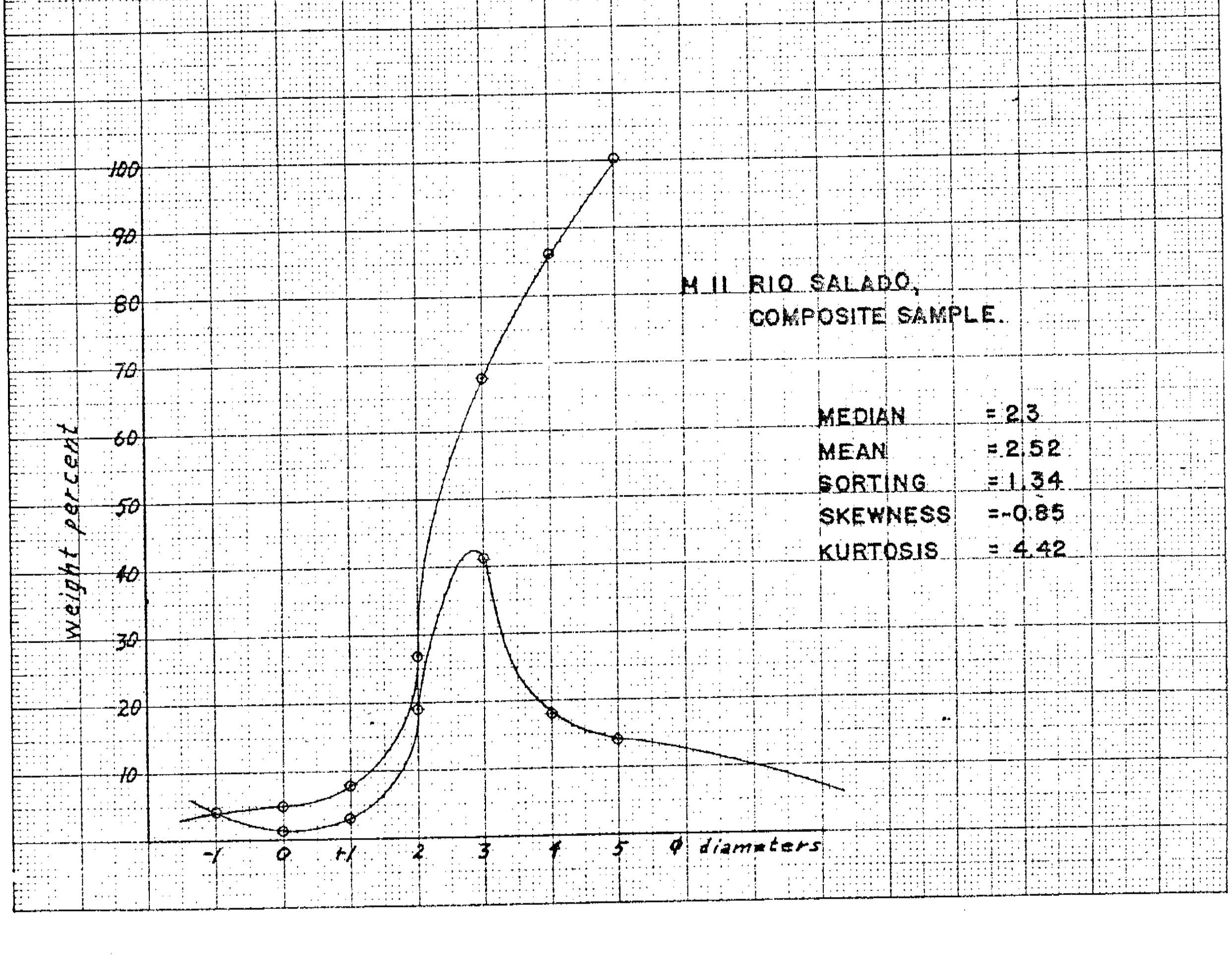
MEDIAN = 2.3 Ø
MEAN = 2.20 Ø
SORTING = 1.05
SKEWNESS = 0.017
KURTOSIS = 2.76

PL. 27



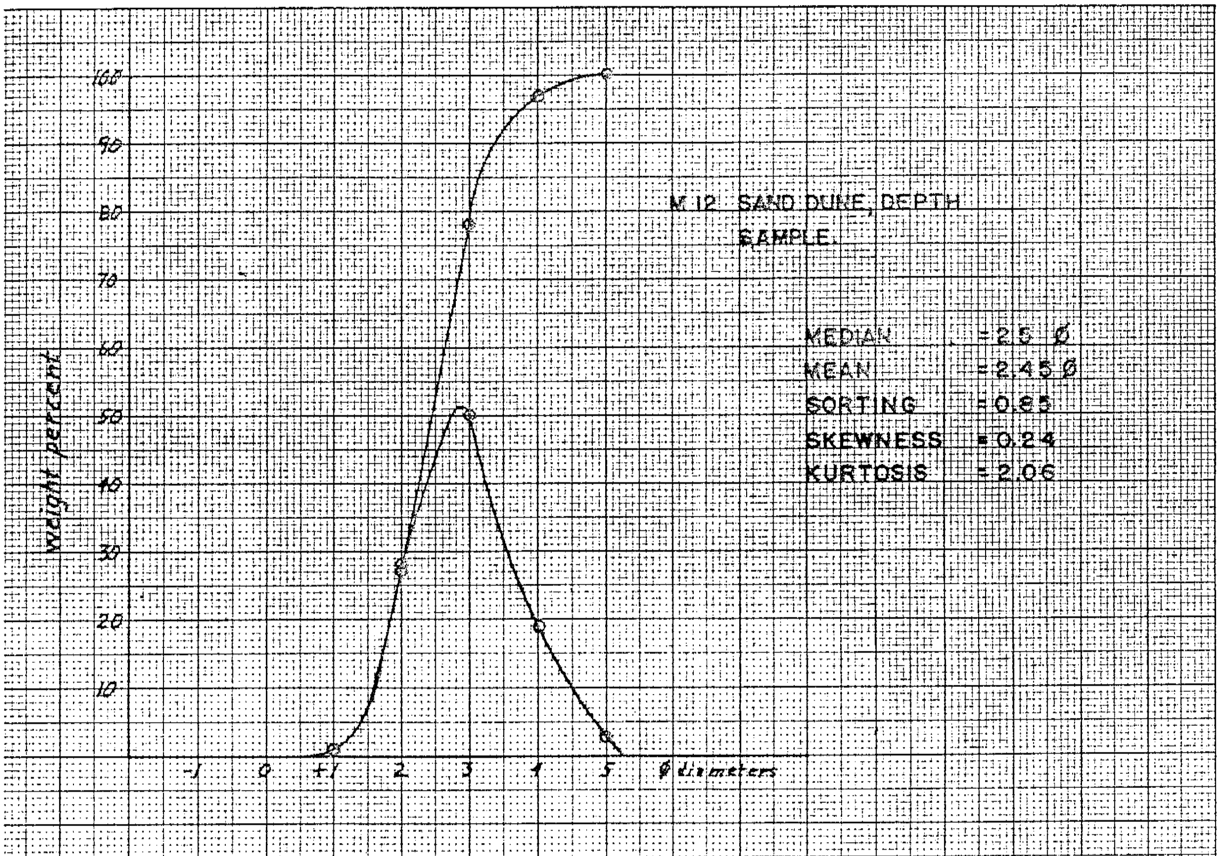
M8 SAND FALL, DEPTH SAMPLE.

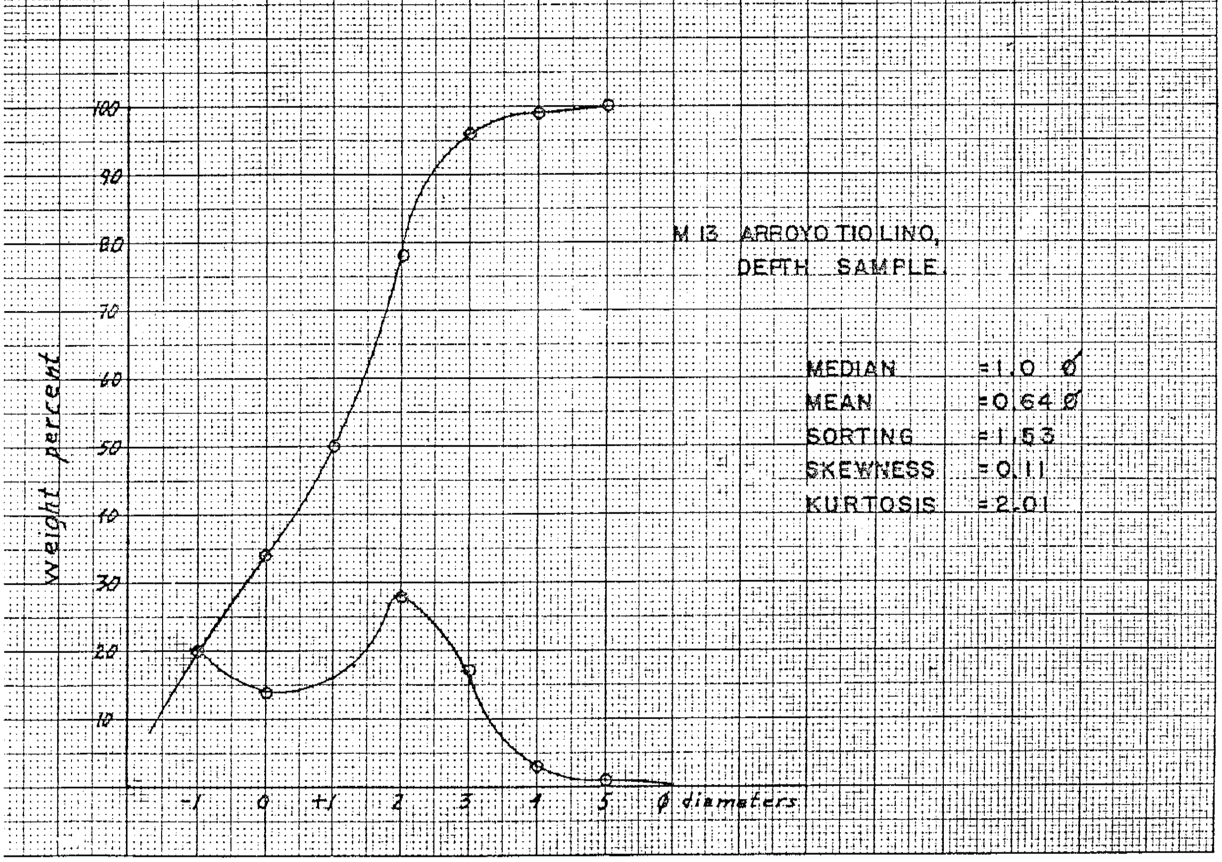
MEDIAN = 2.1 φ
MEAN = 2.15 φ
SORTING = 0.60
SKEWNESS = 0.39
KURTOSIS = 3.26

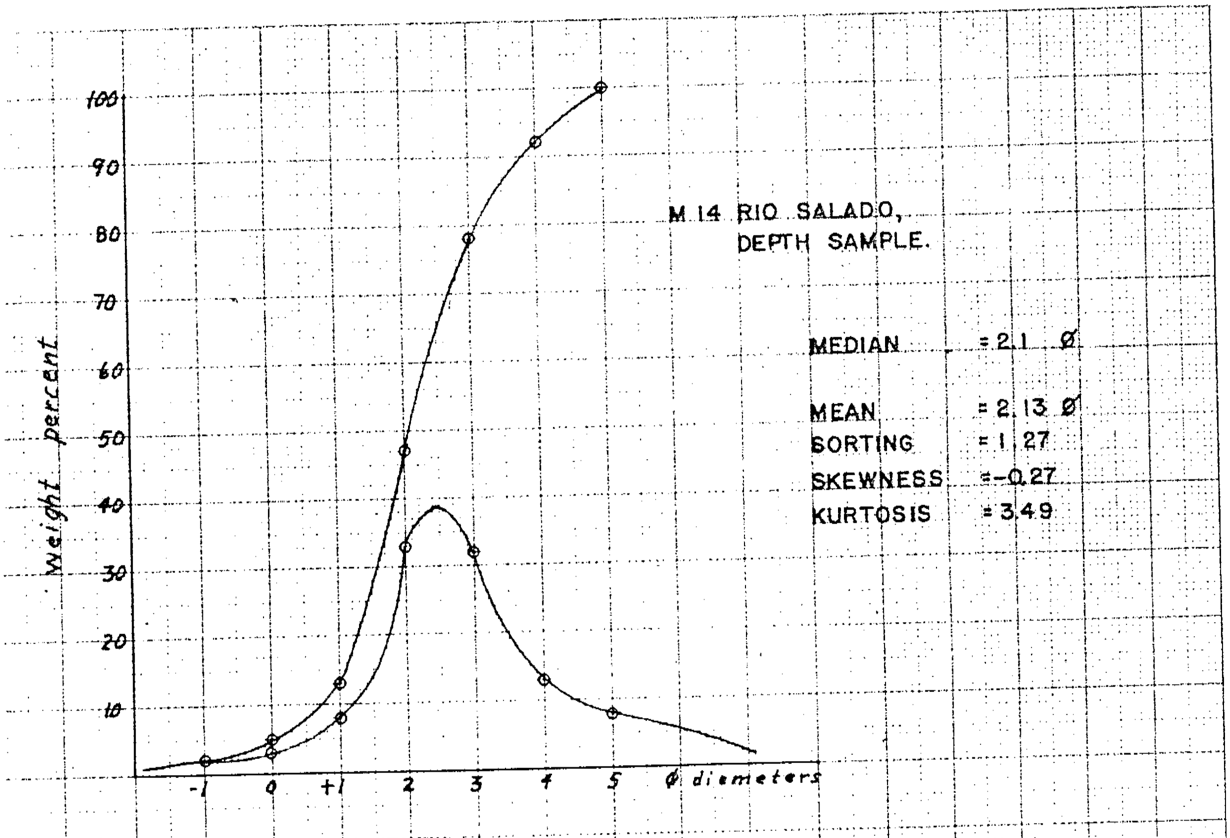


M 11 RIO SALADO, COMPOSITE SAMPLE.

MEDIAN = 2.3
MEAN = 2.52
SORTING = 1.34
SKEWNESS = -0.85
KURTOSIS = 4.42


100
90
80
70
60
50
40
30
20
10
weight percent
-1
0
+1
2
3
4
5
φ diameters
M 12 SAND DUNE, DEPTH SAMPLE.
MEDIAN =2.5 φ
MEAN =2.45 φ
SORTING =0.85
SKEWNESS =0.24
KURTOSIS =2.06

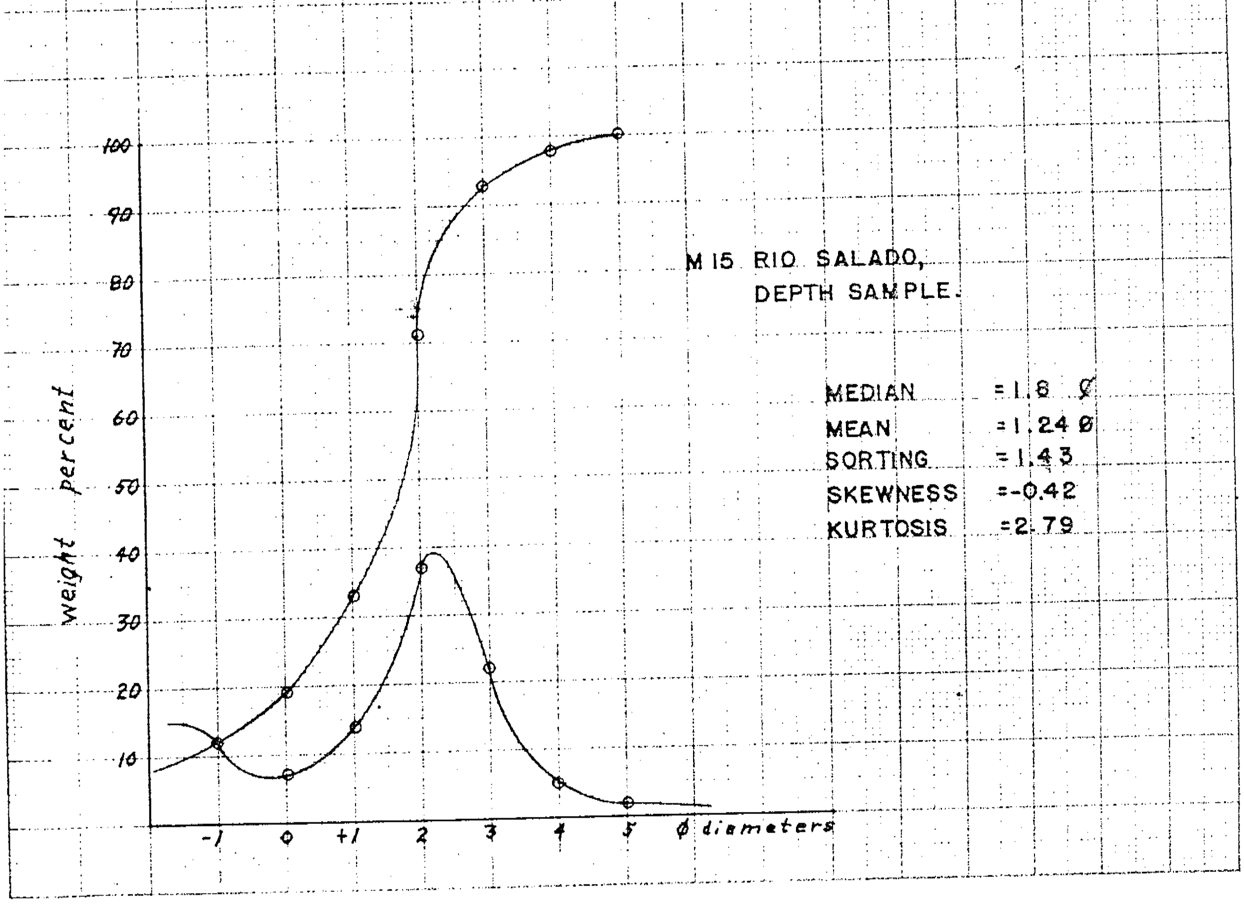

100
90
80
70
60
50
40
30
20
10
weight percent
-1
0
+1
2
3
4
5
φ diameters
M 13 ARROYO TIO LINO, DEPTH SAMPLE.
MEDIAN =1.0 φ
MEAN =0.64 φ
SORTING =1.53
SKEWNESS =0.11
KURTOSIS =2.01



M 14 RIO SALADO,
DEPTH SAMPLE.

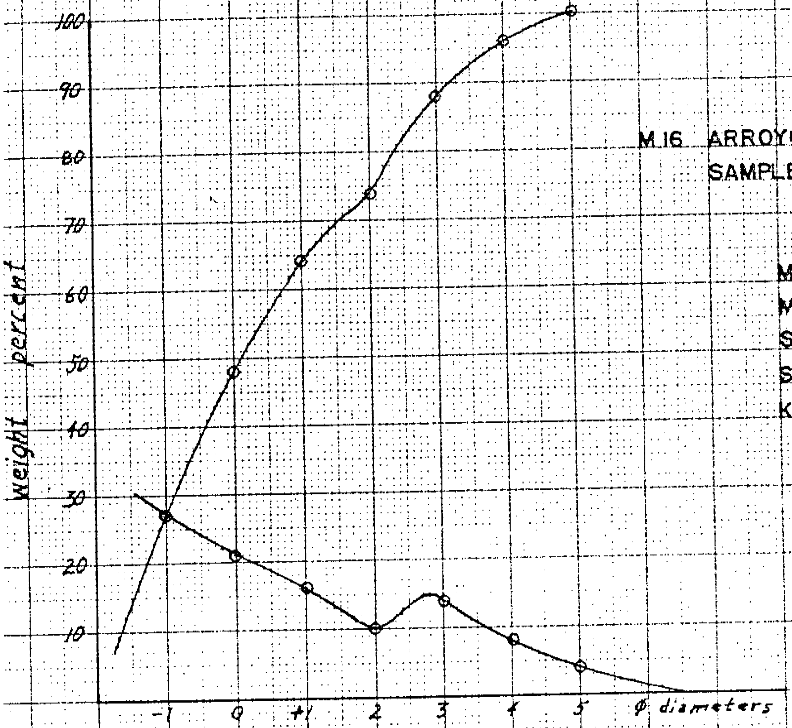
MEDIAN = 2.1 φ

MEAN = 2.13 φ
SORTING = 1.27
SKEWNESS = -0.27
KURTOSIS = 3.49



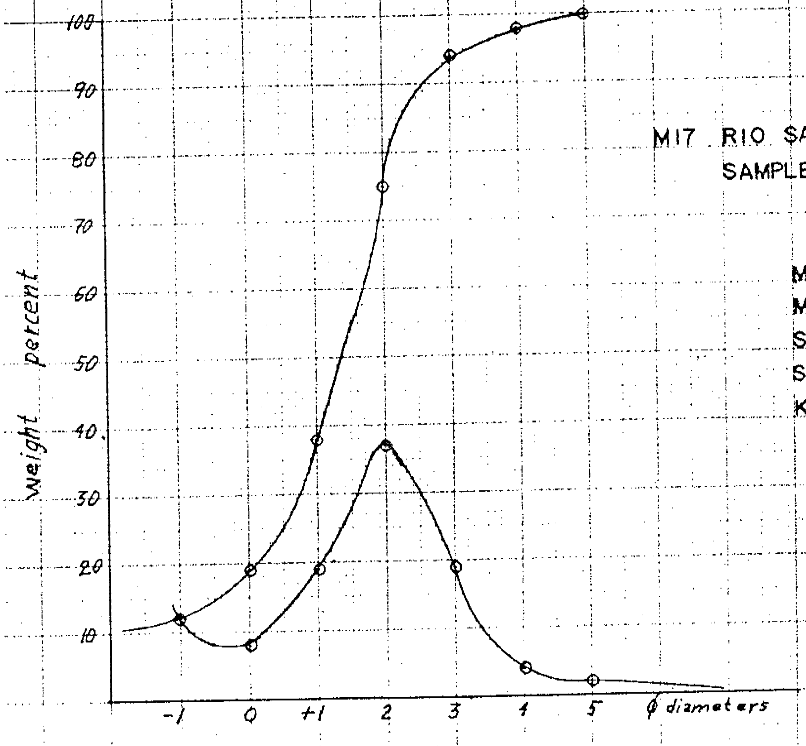
M 15 RIO SALADO,
DEPTH SAMPLE.

MEDIAN = 1.8 φ
MEAN = 1.24 φ
SORTING = 1.43
SKEWNESS = -0.42
KURTOSIS = 2.79



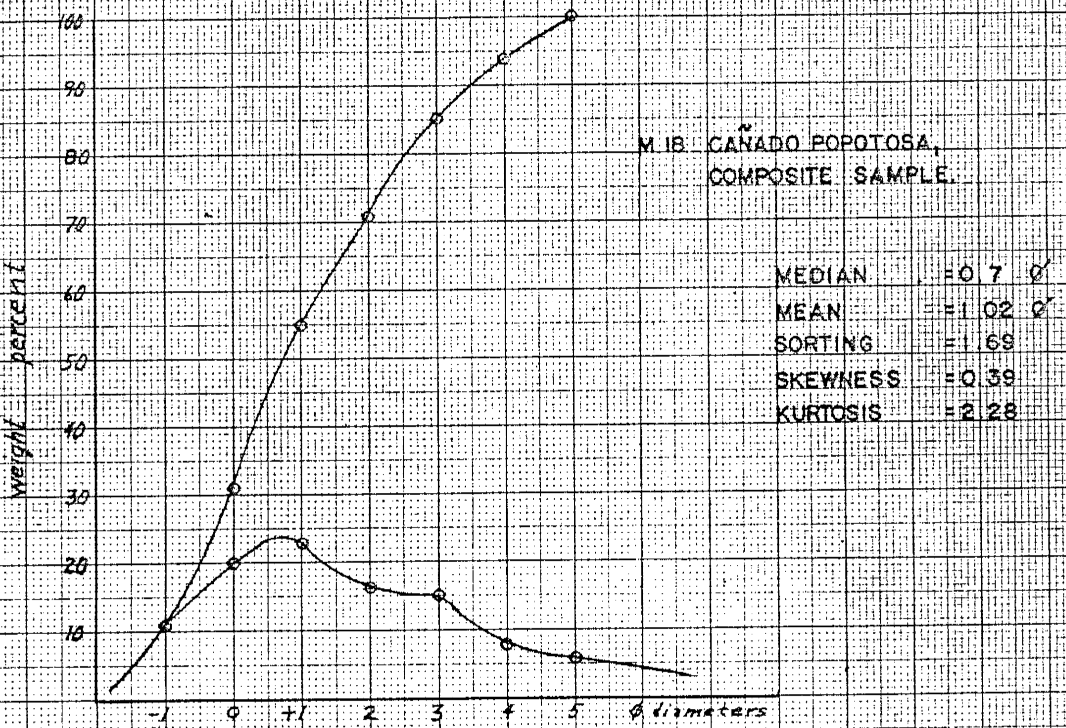
M16 ARROYO, COMPOSITE SAMPLE.

MEDIAN = 0.1 Ø
MEAN = 0.54 Ø
SORTING = 1.82
SKEWNESS = 0.55
KURTOSIS = 2.14



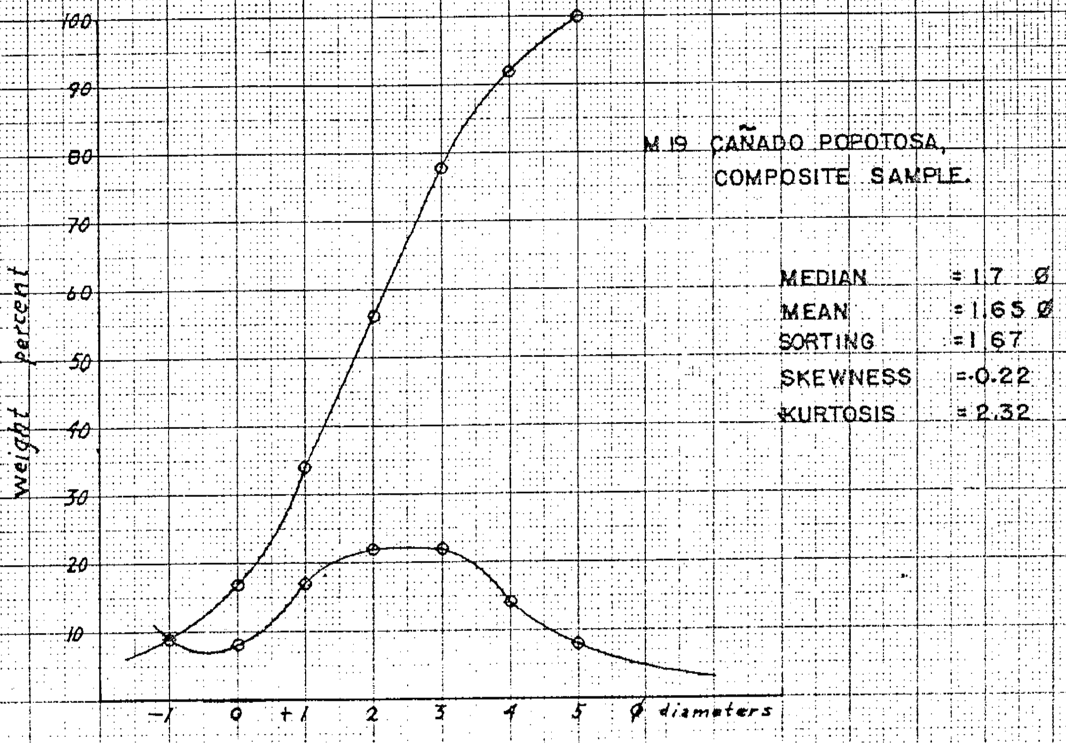
M17 RIO SALADO, DEPTH SAMPLE.

MEDIAN = 1.4 Ø
MEAN = 1.14 Ø
SORTING = 1.39
SKEWNESS = -0.32
KURTOSIS = 2.75



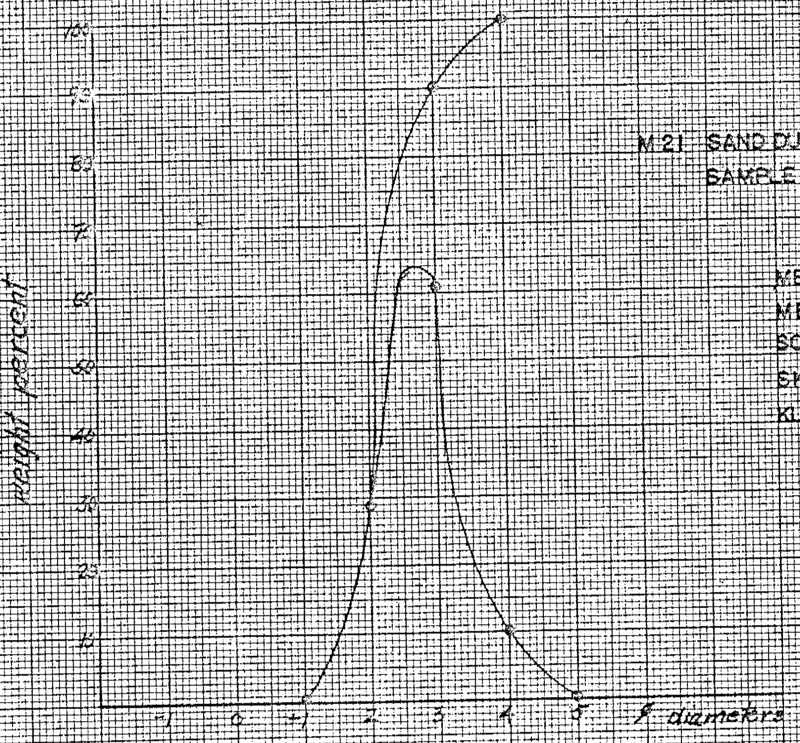
M 18 CAÑADO POPOTOSA,
COMPOSITE SAMPLE.

MEDIAN = 0.7 φ
MEAN = 1.02 φ
SORTING = 1.69
SKEWNESS = 0.39
KURTOSIS = 2.28



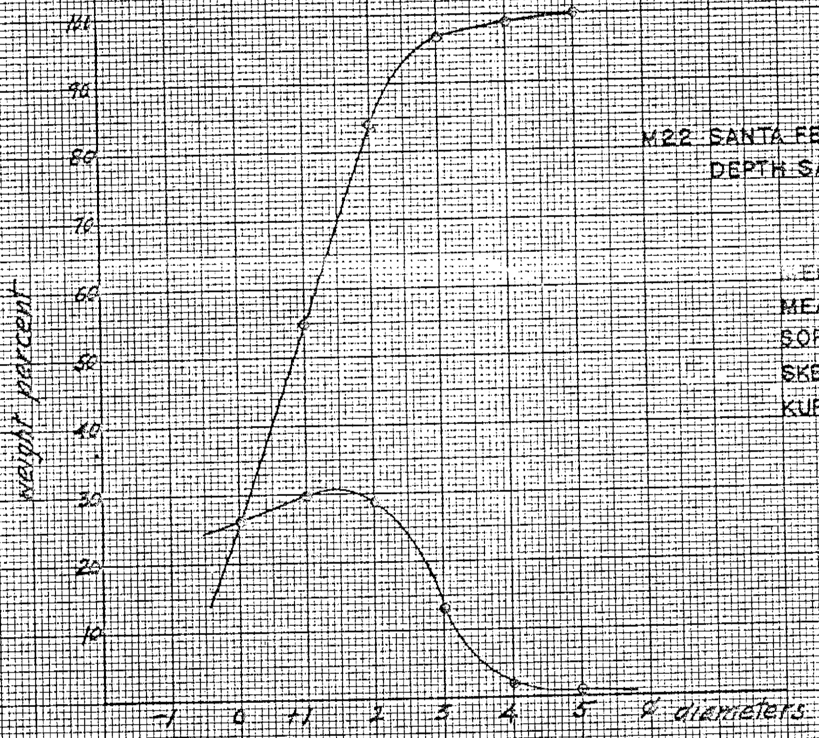
M 19 CAÑADO POPOTOSA,
COMPOSITE SAMPLE.

MEDIAN = 1.7 φ
MEAN = 1.65 φ
SORTING = 1.67
SKEWNESS = -0.22
KURTOSIS = 2.32



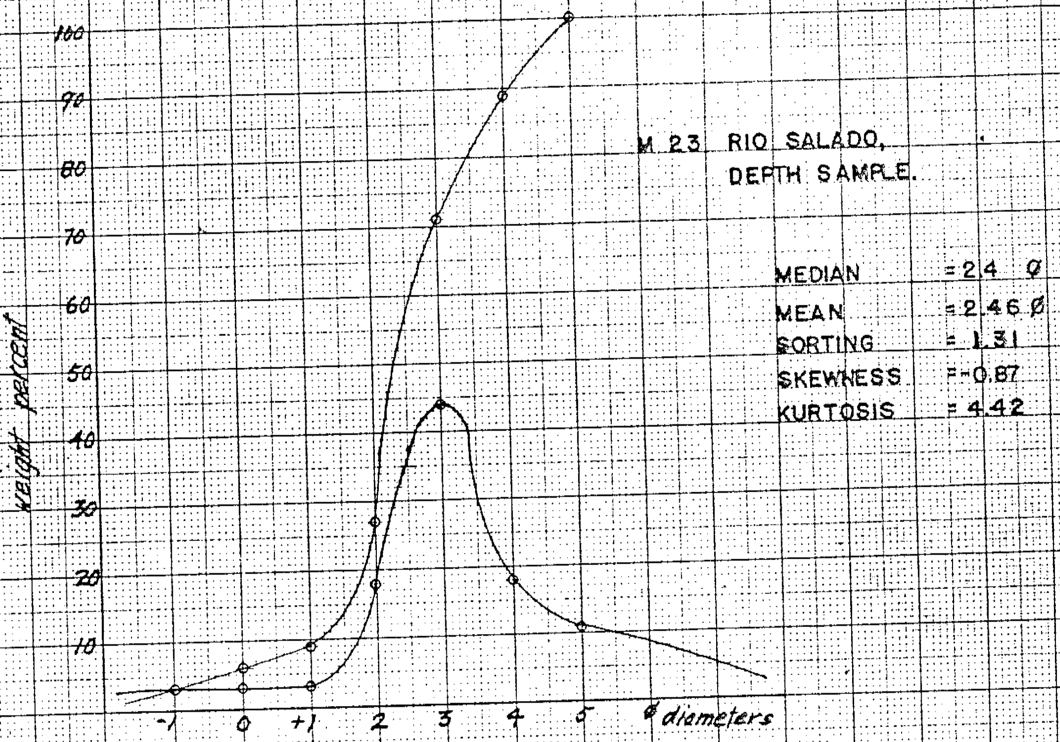
M21 SAND DUNE, DEPTH
SAMPLE.

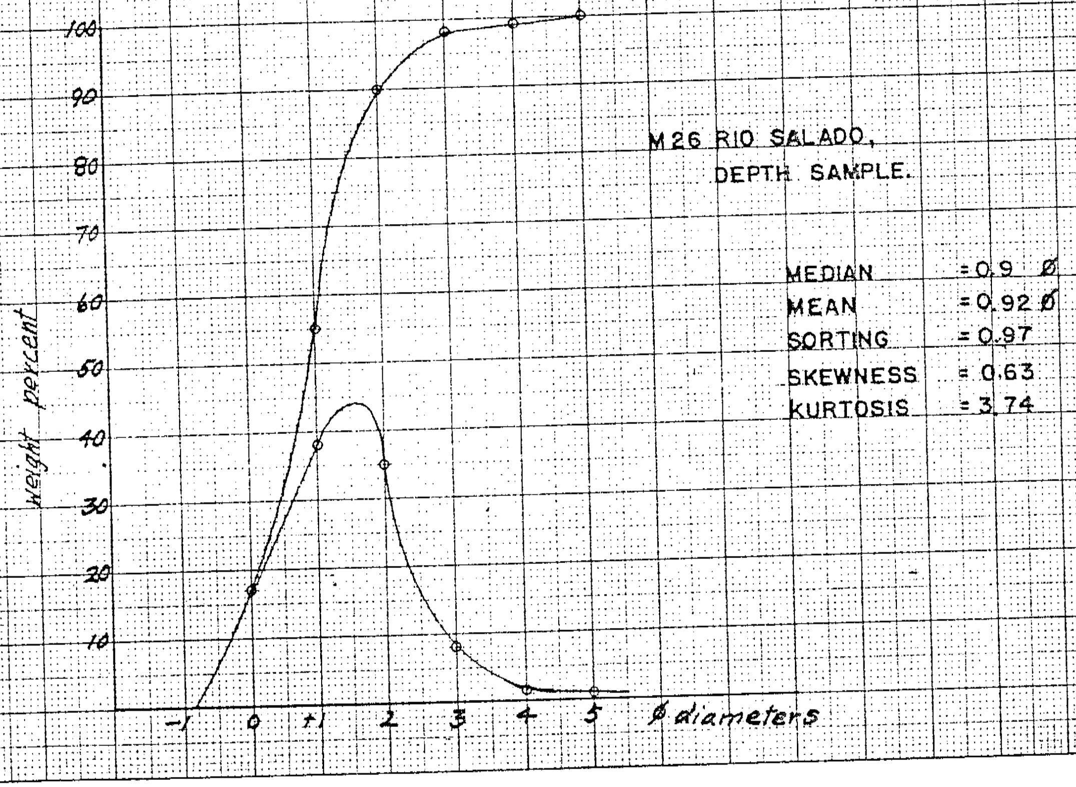
MEDIAN = 2.1 Ø
MEAN = 2.30 Ø
SORTING = 0.61
SKEWNESS = 0.09
KURTOSIS = 2.94

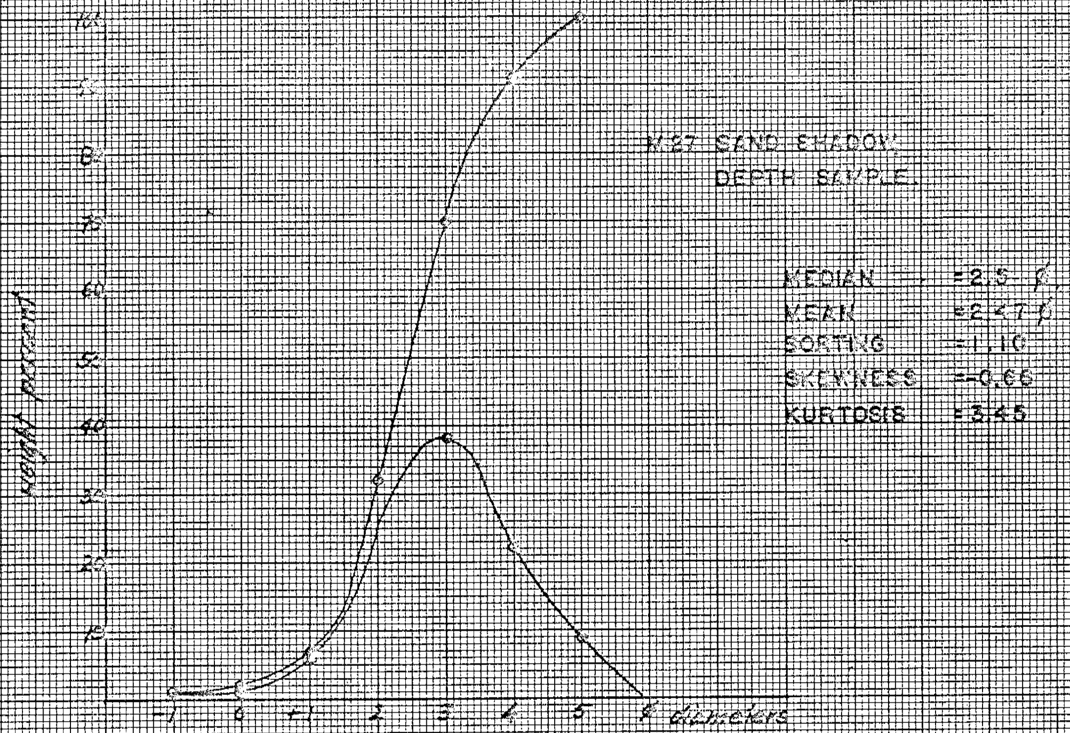


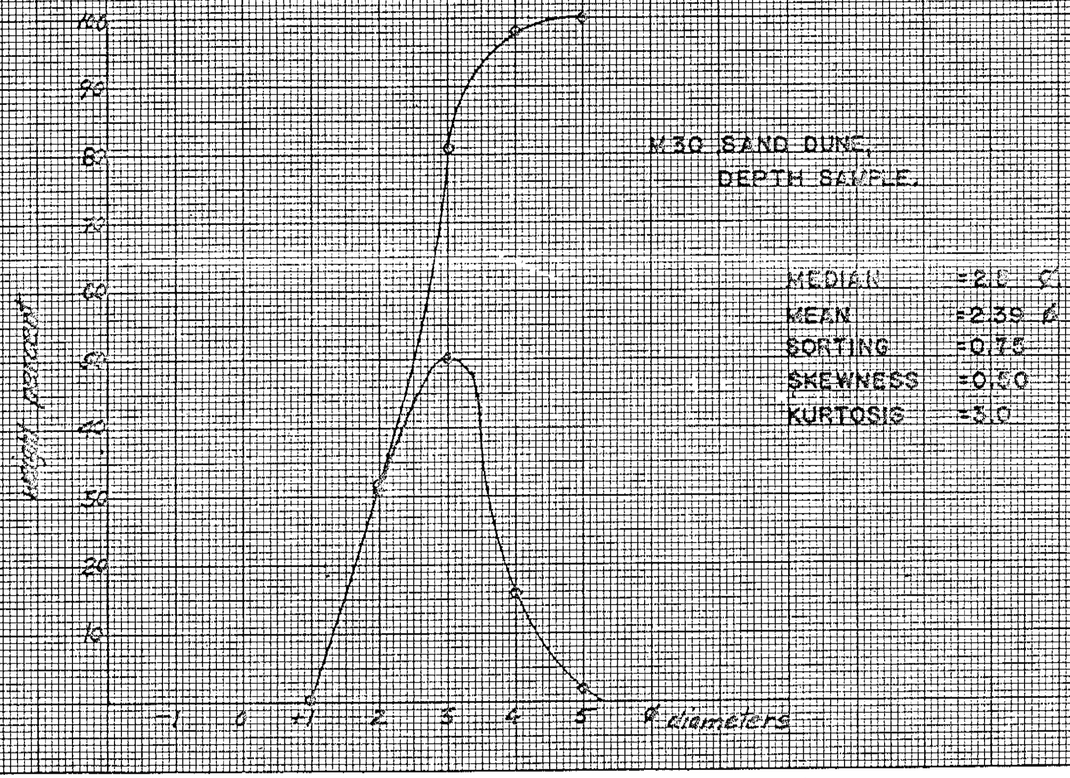
M22 SANTA FE GROUP, UPPER FACIES
DEPTH SAMPLE.

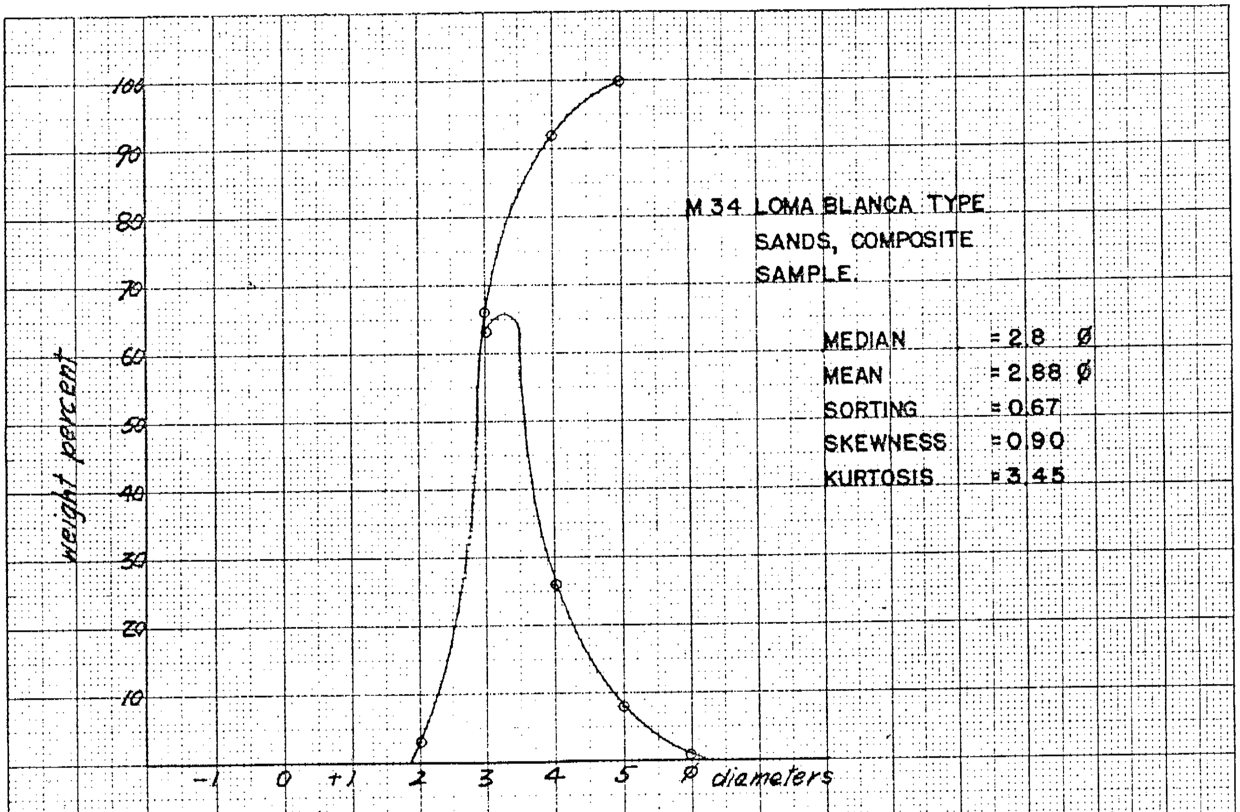
MEDIAN = 0.5 Ø
MEAN = 0.85 Ø
SORTING = 1.11
SKEWNESS = 0.50
KURTOSIS = 2.84


M 23 RIO SALADO,
DEPTH SAMPLE.
MEDIAN = 2.4 Ø
MEAN = 2.46 Ø
SORTING = 1.31
SKEWNESS = -0.87
KURTOSIS = 4.42
weight percent
100
90
80
70
60
50
40
30
20
10
-1
0
+1
2
3
4
5
Ø diameters


M26 RIO SALADO,
DEPTH SAMPLE.
MEDIAN = 0.9 Ø
MEAN = 0.92 Ø
SORTING = 0.97
SKEWNESS = 0.63
KURTOSIS = 3.74
weight percent
100
90
80
70
60
50
40
30
20
10
-1
0
+1
2
3
4
5
Ø diameters

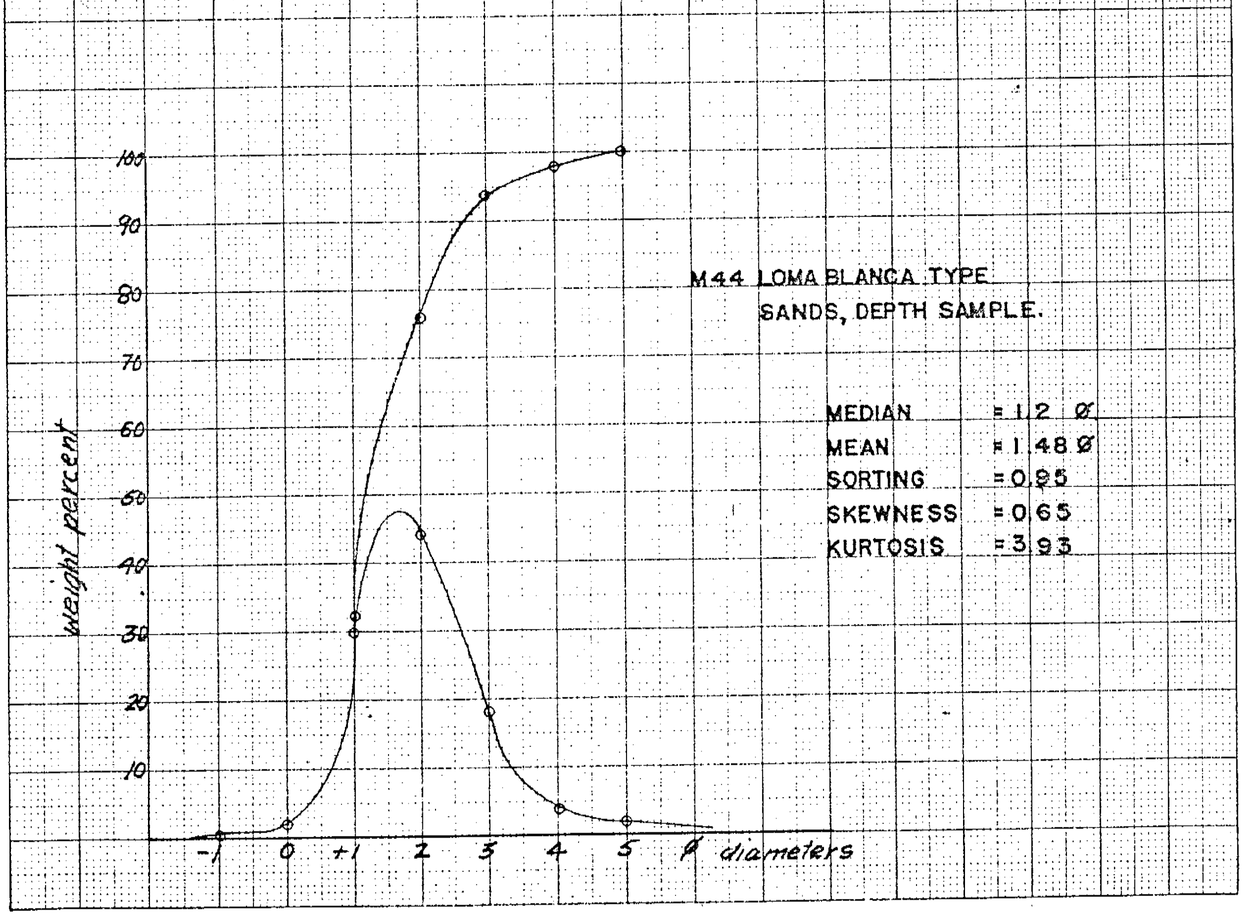

M27 SAND SHADOW
DEPTH SAMPLE.
MEDIAN =2.5 ϕ
MEAN =2.47 ϕ
SORTING =1.10
SKEWNESS =-0.66
KURTOSIS =3.45
Weight percent
10
20
30
40
50
60
70
80
90
100
-1
0
+1
2
3
4
5
ϕ diameters


M30 SAND DUNE,
DEPTH SAMPLE.
MEDIAN =2.8 ϕ
MEAN =2.39 ϕ
SORTING =0.75
SKEWNESS =0.50
KURTOSIS =3.0
Weight percent
10
20
30
40
50
60
70
80
90
100
-1
0
+1
2
3
4
5
ϕ diameters



M 34 LOMA BLANCA TYPE SANDS, COMPOSITE SAMPLE.

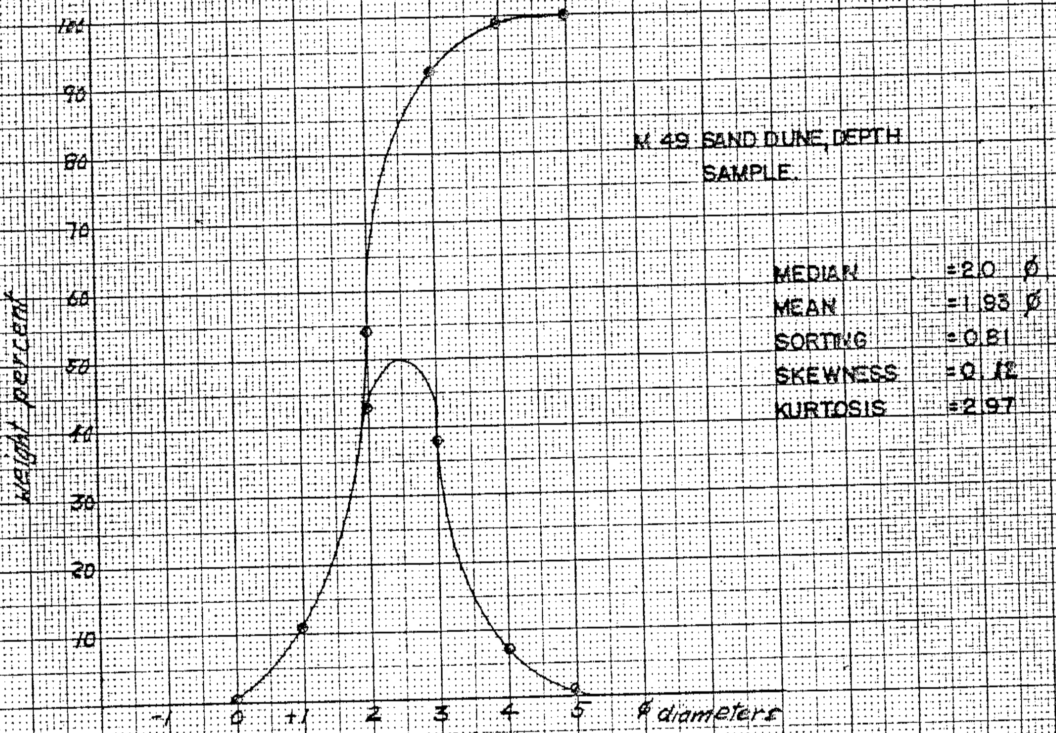
MEDIAN = 2.8 ø
MEAN = 2.88 ø
SORTING = 0.67
SKEWNESS = 0.90
KURTOSIS = 3.45

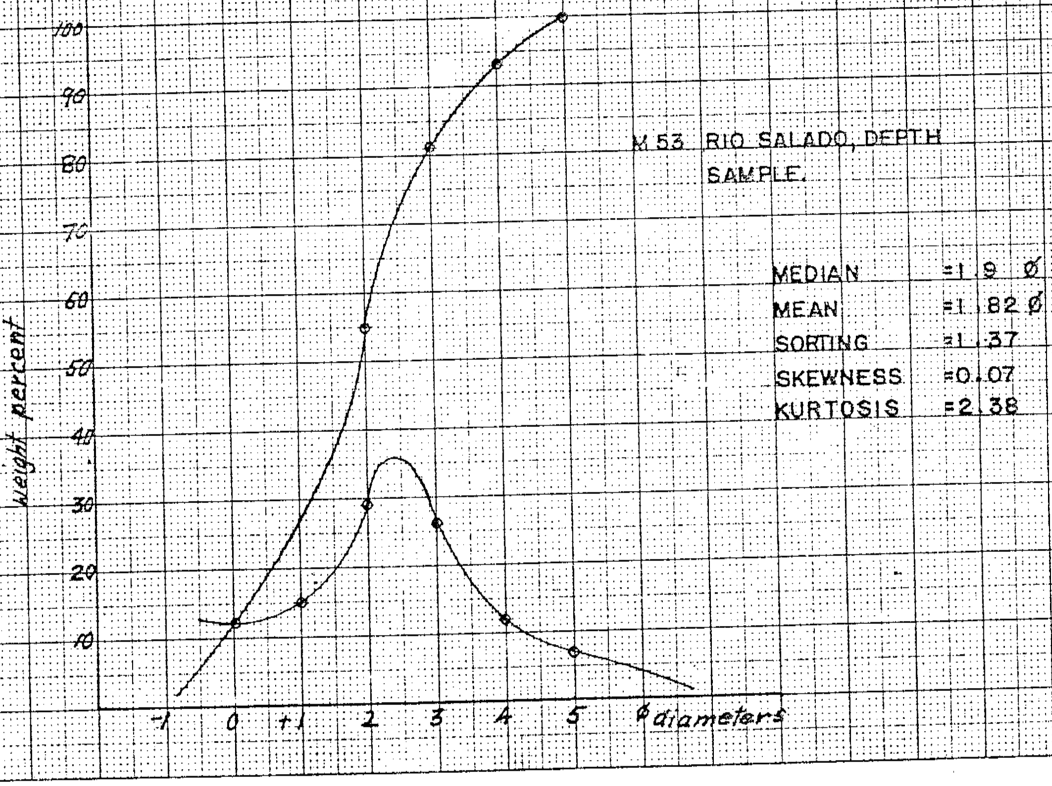


M44 LOMA BLANCA TYPE SANDS, DEPTH SAMPLE.

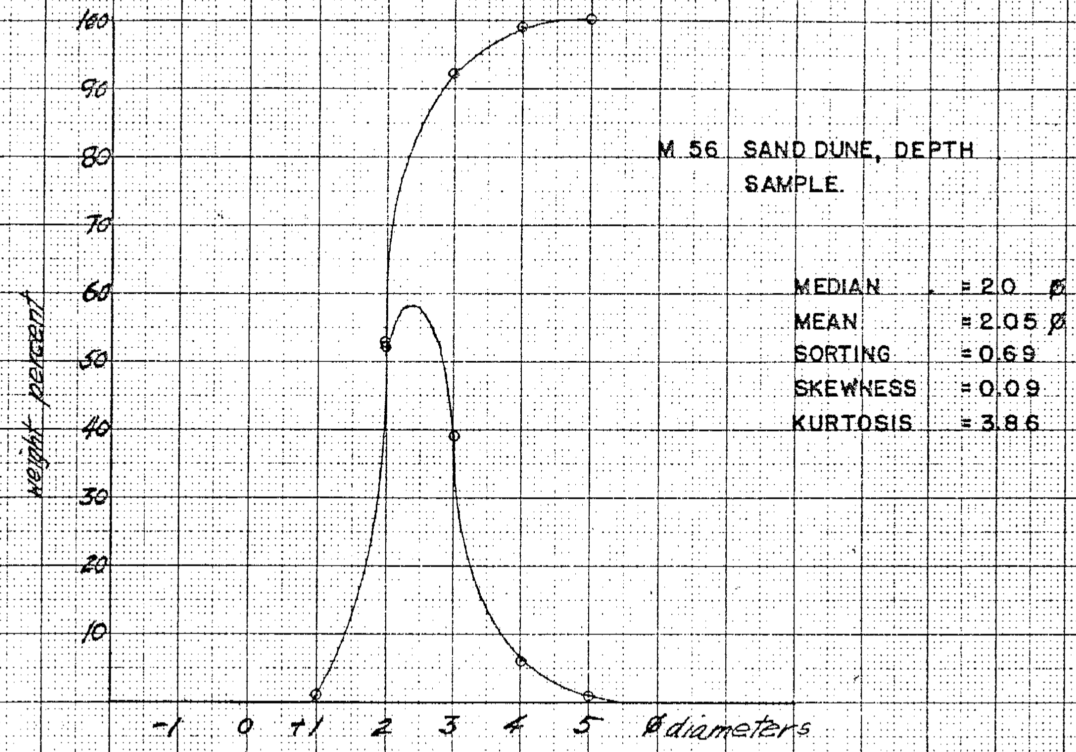
MEDIAN = 1.2 ø
MEAN = 1.48 ø
SORTING = 0.95
SKEWNESS = 0.65
KURTOSIS = 3.93

PL. 36


M 49 SAND DUNE, DEPTH SAMPLE.
MEDIAN =2.0 ø
MEAN =1.93 ø
SORTING =0.81
SKEWNESS =0.12
KURTOSIS =2.97
weight percent
100
90
80
70
60
50
40
30
20
10
-1
0
+1
2
3
4
5
ø diameters

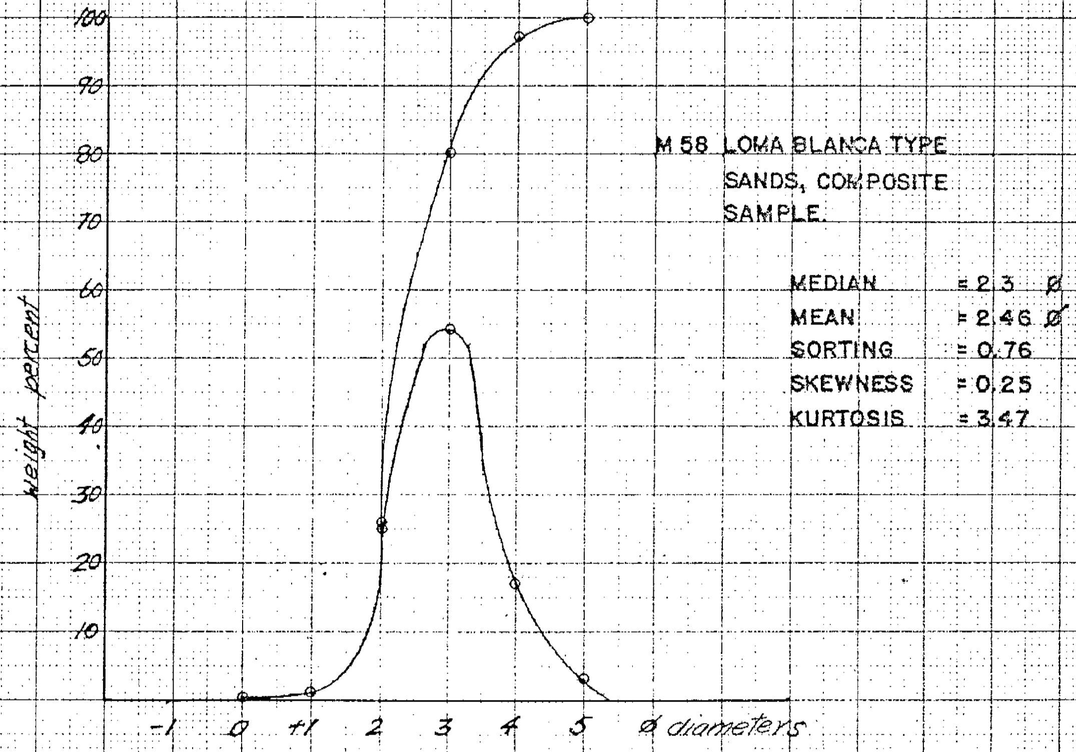

M 53 RIO SALADO, DEPTH SAMPLE.
MEDIAN =1.9 ø
MEAN =1.82 ø
SORTING =1.37
SKEWNESS =0.07
KURTOSIS =2.38
weight percent
100
90
80
70
60
50
40
30
20
10
-1
0
+1
2
3
4
5
ø diameters

PL. 37



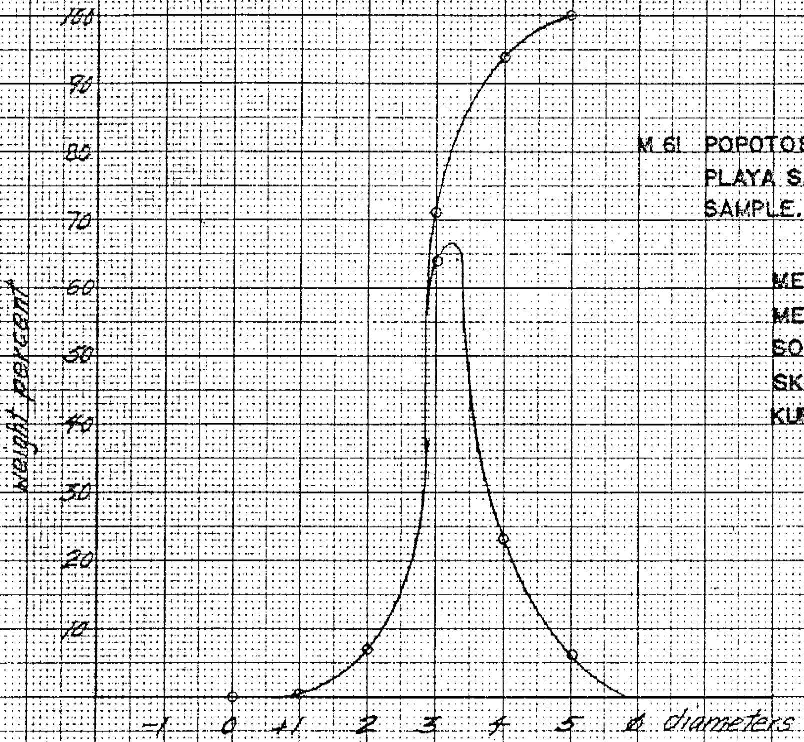
M 56 SAND DUNE, DEPTH SAMPLE.

MEDIAN = 2.0 ø
MEAN = 2.05 ø
SORTING = 0.69
SKEWNESS = 0.09
KURTOSIS = 3.86



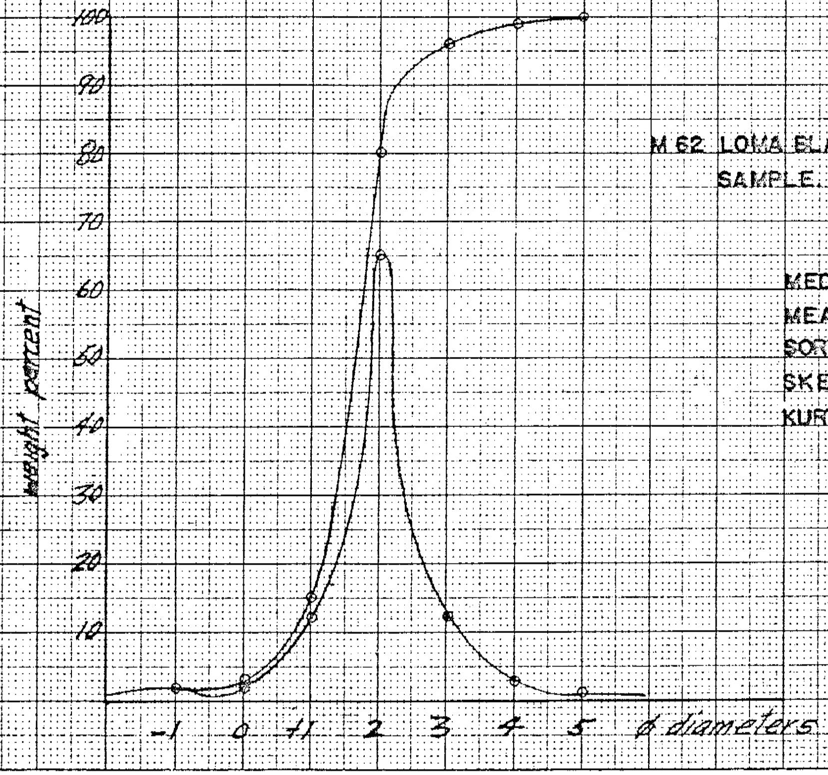
M 58 LOMA BLANCA TYPE SANDS, COMPOSITE SAMPLE.

MEDIAN = 2.3 ø
MEAN = 2.46 ø
SORTING = 0.76
SKEWNESS = 0.25
KURTOSIS = 3.47



M 61 POPOTOSA UNCEMENTED
PLAYA SANDS, COMPOSITE
SAMPLE.

MEDIAN = 2.8 Ø
MEAN = 2.78 Ø
SORTING = 0.70
SKEWNESS = 0.60
KURTOSIS = 3.98



M 62 LOMA BLANCA TYPE SANDS, DEF'Y
SAMPLE.

MEDIAN = 1.6 Ø
MEAN = 1.43 Ø
SORTING = 0.81
SKEWNESS = 0.24
KURTOSIS = 7.29

This thesis is accepted on behalf of the faculty of the Institute by the following committee:

Allan R. Sanford

Clay T. Smith

Max E. Willard

Robert H. Weber

Date: May 1, 1963