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Geomorphic and Geochemical Evidence for the Source of Sand in the Algodones Dunes, Colorado Desert, Southeastern California

Daniel R. Muhs
U.S. Geological Survey, dmuhs@usgs.gov

Charles A. Bush
U.S. Geological Survey

Scott D. Cowherd
U.S. Geological Survey

Shannon Mahan
U.S. Geological Survey

3 GEOMORPHIC AND GEOCHEMICAL EVIDENCE FOR THE SOURCE OF SAND IN THE ALGODONES DUNES, COLORADO DESERT, SOUTHEASTERN CALIFORNIA

Daniel R. Muhs, Charles A. Bush, Scott D. Cowherd, and Shannon Mahan
U.S. Geological Survey, Denver

ABSTRACT

The Algodones dunes of southeastern California comprise one of the largest active dune fields in the United States. The source of sand of the Algodones dunes is controversial, and the source of stabilized aeolian sand in the adjacent East Mesa area has not been investigated at all. We used mineralogical compositions and trace element concentrations to ascertain the most likely source of sand for these active and stabilized dunes. Results indicate that alluvium derived from the San Bernardino Mountains, which enters the Salton trough to the northwest of the dune fields, and alluvium derived from the Chocolate Mountains, which is deposited immediately to the northeast of the dunes, do not appear to be significant sources of sediment for the Algodones and East Mesa dunes. Both active aeolian sand from the Algodones dunes and stabilized aeolian sand on East Mesa are probably derived from sediments of ancient Lake Cahuilla, which formerly occupied part of the Salton Trough and left sandy shoreline sediments to the west and northwest of where the dune fields are now found. Lake Cahuilla sediments, in turn, were apparently derived from the Colorado River, when the river shifted its course and emptied into the Salton Trough, rather than the Gulf of California.

INTRODUCTION

The Algodones dunes are one of the largest active dune fields in the United States and are found in the Colorado Desert portion of southernmost California and northernmost Baja California Norte (Figures 1 and 2). Because the dunes are currently active, they have been studied by numerous researchers interested in understanding the processes of dune formation and sand sea evolution (Norris and Norris 1961, McCoy et al. 1967, Sharp 1979, Smith 1982, Nielson and Kocurek 1986, Kocurek and Nielson 1986, Havholm and Kocurek 1988, Sweet et al. 1988, 1991, Lee 1991). They have also been compared to dunes in the Hellespontus region of Mars, based on geomorphic similarities (Cutts and Smith 1973, Breed 1977). Study of active dune fields is important because sand seas that are presently inactive may have paleoclimatic significance (Fryberger and Ahlbrandt 1979, Lancaster 1990, Pye and Tsoar 1990, Thomas and Shaw 1991). In addition, stabilized dune fields may become active in the future with a change in climatic conditions, such as those predicted by models of a 21st century greenhouse climate (Muhs and Maat 1993). Thus, understanding of the dynamics of active dune fields is critical for interpretations of

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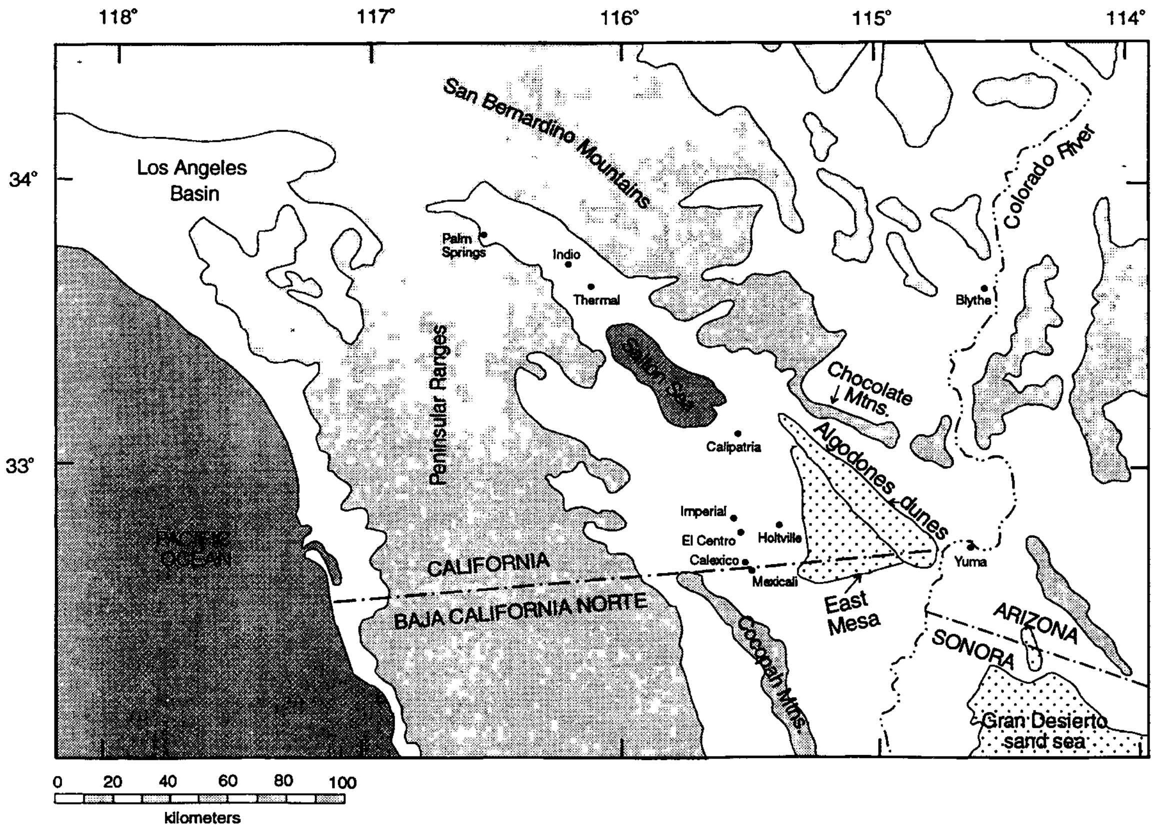

Figure 1. Map showing the localtion of the Algodones dunes and East Mesa in the Salton trough area and localities referred to in the text. Stippled areas are aeolian sand, light-shaded areas are mountain ranges, and dark-shaded areas are water bodies.

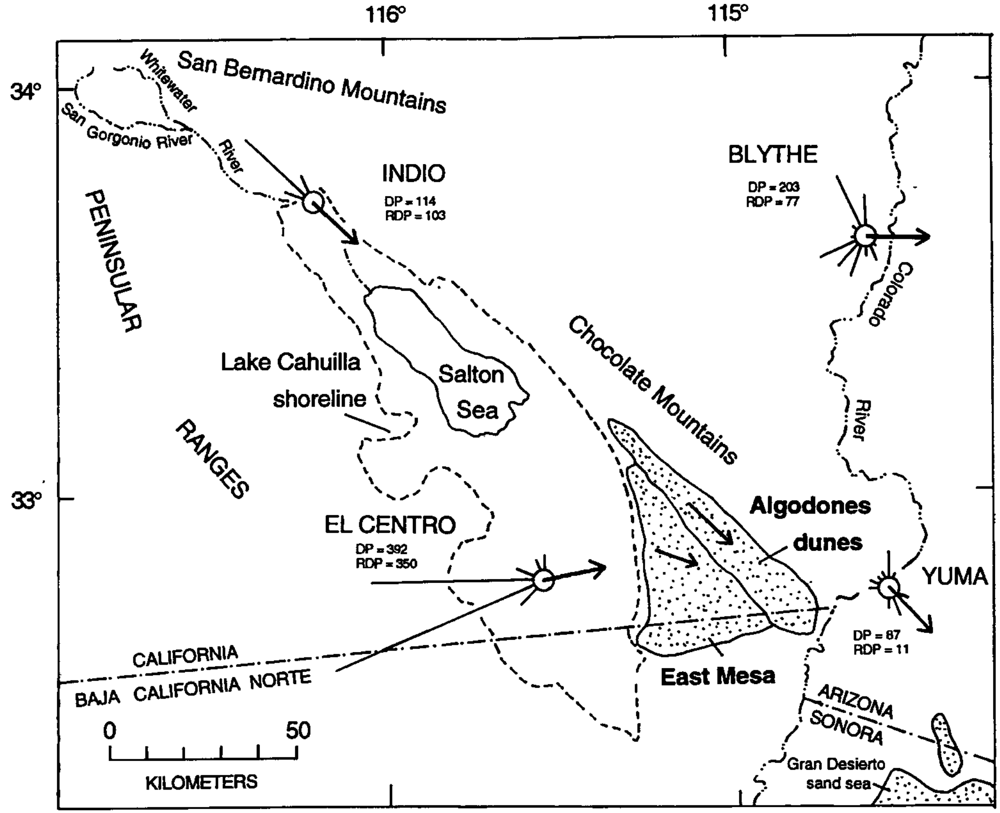

Figure 2. Location of Lake Cahuilla shoreline (dashed line) taken from Waters (1983), sand roses for various localities near the Algodones dunes and East Mesa, and arrows showing the mean direction of sand movement in the dune fields, inferred from dune orientations. Stippled areas are aeolian sand.

present-day processes, interpretation of extraterrestrial geologic processes, past events, and predictions of future activity.

An important part of understanding the dynamics of sand seas is identification of the source sediments for dunes. In some cases, this can be observed directly if source sands are actively feeding a dynamic dune field. In most cases, however, the source of aeolian sediments must be inferred either from the geologic and geomorphic setting, from the direction of prevailing strong winds, or from sedimentologic and mineralogic data which can effectively "fingerprint" the source. The source of aeolian sediments in the Algodones dunes is controversial. In this study, we report new geochemical and mineralogical data for the Algodones dunes, stabilized aeolian sediments of adjacent East Mesa, and the most reasonable candidate sediments that have been cited by previous workers as sources. These data allow us to test the hypothesized sources that previous workers have identified for this important dune field.

REGIONAL GEOLOGIC SETTING AND PREVIOUS STUDIES OF THE ORIGIN OF THE ALGODONES DUNES

Regional Geologic Setting

The Algodones dunes are in the Salton Trough, a fault-bounded, structural basin that is the landward extension of the Gulf of California. A good summary of the geology of the basin can be found in Dohrenwend and Smith (1991). The Salton Trough is bordered on the east by the Orocopia, Chocolate, and Cargo Muchacho Mountains, on the west by the Peninsular Ranges, and on the north by the San Bernardino Mountains (Figures 1 and 2). The Orocopia, Chocolate, and Cargo Muchacho Mountains are composed of Precambrian igneous and metamorphic rocks, Mesozoic granitic and metamorphic rocks, and Tertiary volcanic rocks (Jennings 1967, Haxel et al. 1987). The Peninsular Ranges are a batholith composed largely of Mesozoic granitic rocks and a variety of other pre-Cenozoic granitic and metamorphic rocks (Strand 1962). The San Bernardino Mountains in this area are composed mostly of Mesozoic plutonic rocks and Precambrian metamorphic rocks (Dibblee 1964, Morton et al. 1980).

The Salton Trough itself is filled with upper Cenozoic sediments that were derived from the Colorado River (Muffler and Doe 1968, Van de Kamp 1973, Dohrenwend and Smith 1991). These sediments were deposited in the basin whenever the Colorado River shifted its course away from the Gulf of California, where it now flows, to the Salton Trough. A modern analog to this change in course of the river occurred in the years 1905-1907, when a combination of floods and canal construction diverted the Colorado River away from its usual course to the Gulf of California into the Salton Trough, and created the present-day Salton Sea (Sykes 1937).

The most recent prehistoric episodes of Colorado River flow to the Salton Trough are recorded as abandoned shorelines and beach deposits of late Holocene lakes that occupied the basin (Waters 1983, Dohrenwend and Smith

1991). The late Holocene lacustrine shorelines are found at an elevation of about +12-14 m above sea level; collectively, the paleolakes represented by these shorelines are referred to as Lake Cahuilla (Figure 2). Radiocarbon dating of mollusks, charcoal, and peats associated with these shoreline deposits has shown that there have been several distinct high stands of Lake Cahuilla in the late Holocene at ~2300, ~1300-1200, ~900-600, and ~500-400 yr B.P. (Waters 1983, Rockwell and Gurrola 1993). With the exception of short-lived flood events such as the 1905-1907 diversion, however, the Colorado River has been flowing into the Gulf of California at least since the years 1539-1540 A.D., based on accounts of early Spanish explorers (Sykes 1937, Waters 1983).

Previous Studies of Algodones Dunes Source Sediments

Hypotheses of the origin of the Algodones dunes can be found as far back as the mid-19th century. Blake (1857) thought that Algodones dune sand was "derived from the surface of the upper gravelly plain of the Desert by the continued action of the northerly winds." Brown (1923) thought that beach sediments from ancient Lake Cahuilla (Figure 2) were the source of the Algodones dune sands. Norris and Norris (1961) proposed that most sediment entering the Salton Trough is derived from the San Bernardino Mountains via the San Gorgonio and Whitewater Rivers from the north, and from the Peninsular Ranges via San Felipe Creek from the west (Figure 2). They felt that little sediment was contributed to the basin by small streams draining the Chocolate Mountains to the east, or from the Colorado River (Figures 1 and 2). Mineralogical studies conducted by Norris and Norris (1961) did not allow them to differentiate between fluvial sediments, Lake Cahuilla sediments, and Algodones dunes sediments. They ultimately concluded, however, that the primary source of the dunes was Lake Cahuilla sediments that were in turn derived from fluvial sediments of the Whitewater River, with alluvial fan sediments derived from the Chocolate Mountains being a secondary source. McCoy et al. (1967) accepted the general model of Norris and Norris (1961) in their calculations of the volume of sediment moving through the Algodones dunes. Merriam and Bandy (1965) did not study the Algodones dunes, but conducted detailed mineralogical studies of other upper Cenozoic sediments in the Salton Trough and concluded that they were derived from the Colorado River. Similar conclusions were also reached by Muffler and Doe (1968), on the basis of mineralogical and Pb-isotope studies of late Cenozoic sediments in the Salton Trough, although they also did not specifically study the Algodones dunes. Merriam (1969) conducted mineralogical studies of the Algodones dunes and the Gran Desierto sand sea (Figures 1 and 2) and compared the data to the mineralogical composition of Colorado River sediments and sediments derived from the mountains bordering the Salton Trough. He concluded, in part on the basis of high quartz-to-feldspar ratios, that aeolian sediments in both the Algodones dunes and the Gran Desierto sand sea were derived primarily from Colorado River sediments; he did not, however, study the composition of Lake Cahuilla beach sediments. Van de Kamp (1973) reached conclusions similar to those of Merriam (1969) on the basis of mineralogical data and in addition analyzed Lake Cahuilla sediments. Van de Kamp (1973) reported that Lake Cahuilla sediments have lower quartz and higher volcanic rock fragments compared to Colorado River and Algodones dunes sediments. He inferred that deflation of Colorado River-derived sediments in the southern part of the Salton Trough was the source of the Algodones dunes and implied that Lake Cahuilla sediments were not an important source. Loeltz et al. (1975) thought that a higher shoreline, older than the Lake Cahuilla shorelines, was the source of sand for the dunes, but that these sediments were ultimately derived from the Colorado River, which originally deposited the sand on East Mesa. The Colorado River was also identified as the source of sediment for part of the nearby Gran Desierto sand sea (Figures 1 and 2) on the basis of textural, mineralogical, and Landsat TM spectral data by Blount and Lancaster (1990) and Lancaster (1993), although these workers did not study the Algodones dunes. Smith (1982) and Sweet et al. (1988, 1991) presented no new data on the source sediments for the Algodones dunes, but generally accepted the concept that Lake Cahuilla sediments were the source. Dohrenwend and Smith (1991) thought that the Colorado River was the ultimate source of the Algodones dunes and speculated that these sediments may have been reworked by Lake Cahuilla before accumulation into dunes; however, they pointed out that the exact mechanism for accumulation of aeolian sediments in the Algodones dunes is not known.

REGIONAL CLIMATIC SETTING

Synoptic Climatic Controls in the Colorado Desert

The Salton Trough is in the low-elevation (below ~300 m) portion of southeastern California called the Colorado Desert (also sometimes referred to as the "low desert" in contrast to the "high desert," which is the Mojave Desert to the north). It is a hot desert, classified as BWh in the Köppen system. Climatically, the Colorado Desert is an extension of the Sonoran Desert of Mexico and Arizona, if the climatic criteria of Schmidt (1989) are applied. Ezcurra and Rodrigues (1986) and Schmidt (1989) provide summaries of the synoptic climatic controls on the region. Pacific frontal systems derived from the Aleutian low pressure cell bring rain to the area in winter, and for most Colorado Desert localities, this is the time of maximum precipitation. In late winter, spring, and early summer, the region is under the influence of the eastern edge of the Pacific high pressure cell and there is little or no precipitation. In mid-summer, the Pacific high pressure cell migrates to the northwest, and the Colorado Desert comes under the influence of the western edge of the Bermuda high pressure cell. Combined with the thermally generated continental interior low pressure cell that develops in the southwestern United States in the summer, the presence of the Bermuda high sets up a monsoonal flow of air that results in summer thunderstorms, but precipitation during this season is much lower than during the winter. Overall precipitation ranges from 46 to 140 mm/yr, but most localities within the basin have mean annual totals of 60-80 mm/yr. January mean temperatures range from about 11°-13°C, and July mean temperatures range from about 32°-34°C. Potential evapotranspiration is thus very high, and ranges from about 1190-1275 mm/yr.

Sand-Moving Potential of Winds and Predicted Directions of Sand Drift
Particularly critical to a study of the Algodones dunes is an understanding of the climatic controls on wind regimes. Brazel and Nickling (1986) and MacKinnon et al. (1990) discuss the synoptic weather conditions that are capable of generating dust storms in Arizona, including the Yuma area, which is near the Algodones dunes (Figure 2). The two most important weather conditions for generating dust storms in the Yuma area are Pacific frontal systems that develop in winter, and convective storms (thunderstorms) that develop in the summer monsoon season. Pacific frontal systems in the Yuma area result in strong winds from the north and northwest, whereas convective storms generate strong winds with much more directional variability, and are of shorter duration. However, the majority of long-duration, high-intensity convective storms generate winds from the southwest and southeast (Brazel and Nickling 1986).

Wind regimes as they apply to the formation of sand dunes and sand sheets can be quantified in terms of sand-moving potential. Fryberger and Dean (1979) developed a method for graphic presentation of sand-moving potential called sand roses, which are circular histograms showing weighted magnitudes and directional variability of winds for a given station. The arms in a sand rose are weighted sums of the amount of time that the wind is above the threshold velocity for sand from a given direction; weights are applied to higher velocity winds because the sand-moving ability of wind is a function of the cube of wind speed. Fryberger and Dean (1979) define several parameters from sand rose data: drift potential (DP), which is the scalar sum of all sand-moving winds, regardless of direction; resultant drift potential (RDP), which is the vector sum of all sand-moving winds and will always be less than or equal to DP; and resultant drift direction (RDD), which is the net direction of sand movement. It should be noted, however, that some experimental data suggest that in wind regimes that are not unidirectional, bedform trends are not necessarily predicted correctly by RDD values (Rubin and Hunter 1987). Nevertheless, good agreement between RDD values and dune orientations from many parts of the world suggest that it is a valuable parameter in studying dune forms and their relations to winds (Fryberger and Dean 1979, Breed et al. 1979, Ahlbrandt and Fryberger 1980, Muhs 1985, Lancaster et al. 1987, Lancaster 1988, Wells et al. 1990). The ratio of RDP to DP is also a useful measure; this value decreases with greater directional variability. Calculation of DP, RDP, and RDD requires fairly detailed wind data, and we were able to find sufficient data for only four weather stations which surround the Algodones dunes (Figure 2), three of which have relatively short periods of record: Indio, California (1948-1950);

Blythe, California (1948-1954); El Centro, California (1950-1957); and Yuma, Arizona (1948-1988). In addition, Sweet et al. (1988) present sand rose data for a locality called Drop 1, at the junction of the All-American and Coachella Canals, immediately to the west of the southern edge of the Algodones dunes. In the classification scheme of Fryberger and Dean (1979), DP values for Yuma (87) and Indio (114) put them into "low-energy" wind regimes, and DP values for El Centro (392) and Blythe (203) put them into "intermediate-energy" wind regimes (Figure 2). RDP values for Yuma and Blythe are significantly lower than DP values because of directional variability (Figure 2). In contrast, Indio has winds that are from the northwest all year, and El Centro has winds mostly from the west all year (Figures 3a, 3b, 3c). The shift in wind direction at Yuma and Blythe is because of the change from a wintertime regime of predominantly Pacific-derived frontal systems to a summertime regime of convective storm systems owing to the summer monsoonal flow of air from south to north. The RDD values indicate a predominantly northwest-to-southeast drift of sand for Indio and Yuma, and an east-to-west drift of sand for El Centro and Blythe (Figure 2). Sweet et al. (1988) report that wind data derived from Drop 1 indicate an overall northwest to southeast drift of sand, in broad agreement with Indio and Yuma.

GEOMORPHOLOGY OF THE ALGODONES DUNES AND EAST MESA AEOLIAN DEPOSITS

Surficial Deposits

Using 1:80,000 black-and-white, stereo aerial photographs (Figure 4) as a base, we constructed a generalized surficial geologic map of the Algodones dunes, East Mesa, and the surrounding area (Figure 5). Our unit Qe consists of active sand in the Algodones dunes. Unit Qes includes all of the deposits of East Mesa, and includes sediments of stabilized linear dunes, coppice dunes, sand sheets and sand streaks; alluvial deposits that are apparently older based on the degree of soil development observed by us and by Zimmerman (1981) are included within this unit. Unit Qal includes alluvial and lacustrine deposits of the Imperial Valley; the youngest sediments of this unit were laid down by the last high stand of Lake Cahuilla (Waters 1983, Rockwell and Gurrola 1993). Alluvial fan deposits that are derived from the Chocolate and Cargo Muchacho Mountains were subdivided into two units: (1) Qafo, which consists of older fan deposits that are close to the mountain front, dissected, and covered with rock varnish, which gives them a dark tone on aerial photographs; and (2) Qaf, which consists of alluvial fan deposits found in modern washes and in younger fans that are inset against the older Qafo fan deposits. Small areas of pre-Quaternary bedrock, of too-limited extent to map separately, are included within unit Qafo. Although mapped independently, our Qafo and Qaf units correspond closely to Loeltz et al.'s (1975) "older alluvium" and "alluvium," respectively, that they mapped along the Chocolate Mountains range front. Bull (1991) has recently

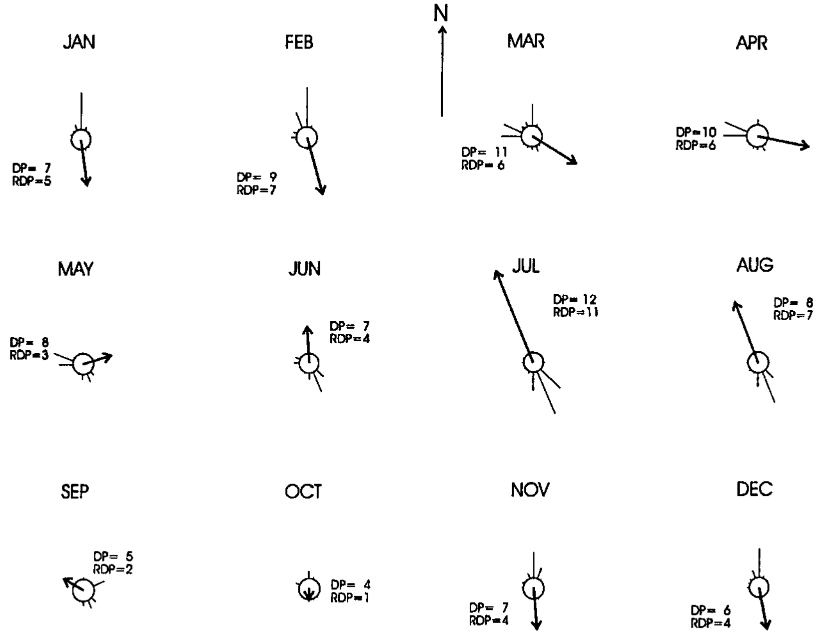

Figure 3a. Monthly sand roses for (a) Yuma, AZ, (b) Indio, CA, and (c) El Centro, CA, using the format of Fryberger and Dean (1979). DP, drift potential in vector units; RDP, resultant drift potential in vector units.

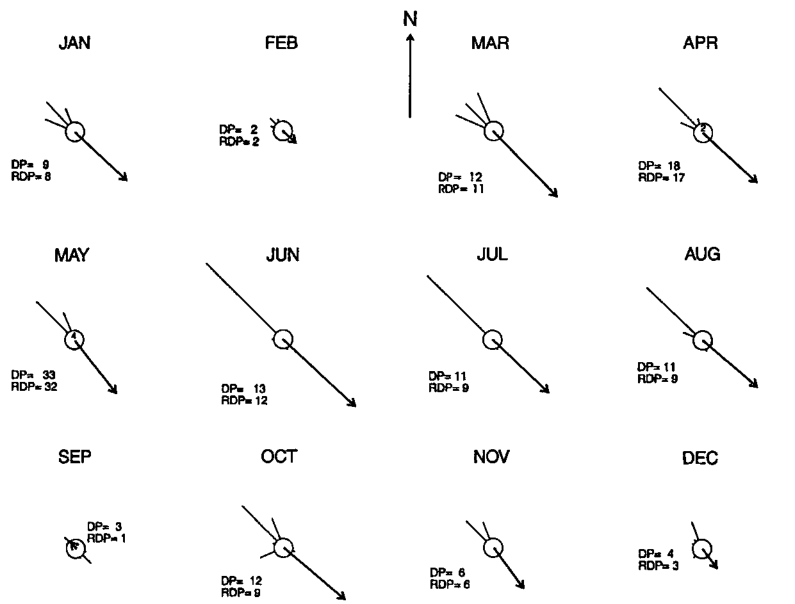

Figure 3b. Monthly sand roses for (a) Yuma, AZ, (b) Indio, CA, and (c) El Centro, CA, using the format of Fryberger and Dean (1979). DP, drift potential in vector units; RDP, resultant drift potential in vector units.

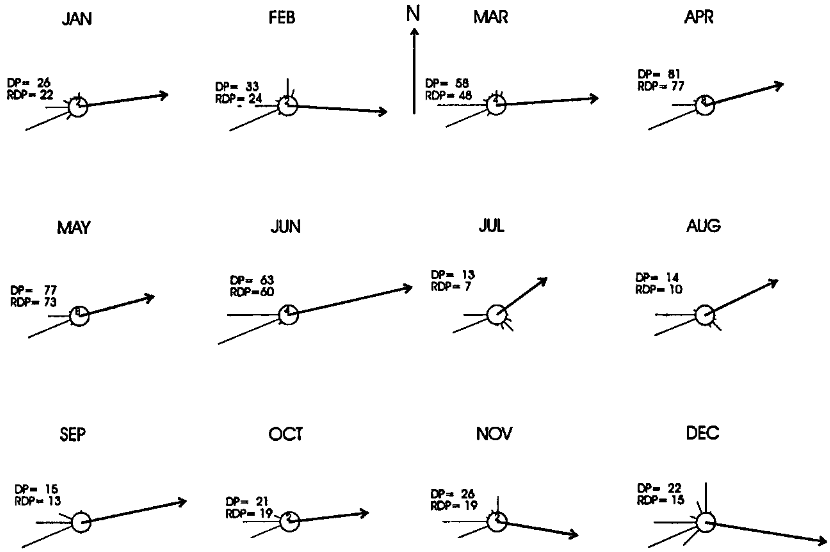

Figure 3c. Monthly sand roses for (a) Yuma, AZ, (b) Indio, CA, and (c) El Centro, CA, using the format of Fryberger and Dean (1979). DP, drift potential in vector units; RDP, resultant drift potential in vector units.

summarized the alluvial fan stratigraphy of the lower Colorado River region. Our Qafo unit probably correlates with Bull's Q1, Q2, and older Q3 deposits; our Qaf unit probably correlates with his Q4 and younger Q3 deposits. Of the alluvial fan deposits, the younger Qaf unit is the most likely candidate to have been a source of sand for the Algodones dunes, because these sediments are not armored by desert pavement or cemented by pedogenic carbonate.

Landforms of the Algodones Dunes and East Mesa

The geomorphology of the Algodones dunes has been well described by Norris and Norris (1961), Olmsted et al. (1973), Sharp (1979), Smith (1982), Kocurek and Nielson (1986), Nielson and Kocurek (1986), Havholm and Kocurek (1988), Sweet et al. (1988), and Dohrenwend and Smith (1991). In an east-west transect across the northwestern end of the dune field, Kocurek and Nielson (1986) report the following sequence of bedforms: (1) sand sheet and zibars, (2) linear dunes (with zibars in interdune corriders) and crescentic dunes, (3) compound-complex crescentic dunes or draa (farther to the southeast), and (4) an eastern sand sheet. In the field, we also observed coppice dunes in various places, particularly on the eastern and western margins of the dune field, where the sand sheets are the dominant landforms. On aerial photographs, linear dunes and transverse and crescentic ridges are prominent features in the Algodones dune field, and linear dunes and sand streaks (as defined by McKee,

1979) are visible on East Mesa (Figure 4). We mapped orientations of crests of linear dunes and sand streaks on East Mesa and linear dune crests, barchanoid ridge (draa) brinks, and transverse ridge (draa) brinks in the Algodones dunes on aerial photographs (Figure 5). Between the active linear and barchanoid/transverse ridge dunes in the Algodones dunes there are smaller, transitional crescentic ridges whose orientations we did not measure. Results indicate that active linear dunes in the Algodones dune field have a mean orientation of N43°W ± 12° (n = 89), which approximates the dominant dune-forming wind direction. Transverse and barchanoid ridge draas in the Algodones dune field have a mean brink orientation of N45°E ± 16° (n = 57), also implying a dominant dune-forming wind direction from the northwest, about N45°W. Our measurements of the transverse and barchanoid ridges are in agreement with those reported by Havholm and Kocurek (1988). The inferred winds of formation based on dune orientations are nearly identical to the RDDs for Indio and Yuma (Figure 2), but imply a general drift of sand that is somewhat more easterly than the RDD for Drop 1 near the southern end of the dune field reported by Sweet et al. (1988). Havholm and Kocurek (1988) reported that superimposed features on the transverse ridge draas are the result of a secondary air flow that is the result of modification of the primary air flow by the draas themselves.

East Mesa dunes and sand sheets are presently stabilized by vegetation, mostly creosote (*Larrea divaricata*). The winds that formed the aeolian landforms on East Mesa had a more westerly component than the winds that formed the linear and transverse ridge dunes of the Algodones dune field. Linear dunes and sand streaks on East Mesa have a mean orientation of N71°W ± 9° (n = 255), although the southernmost dunes on East Mesa have an orientation that is closer to the mean orientation of the Algodones dunes. One explanation for the difference in mean orientations of East Mesa and Algodones dunes is that the East Mesa dunes were formed by winds different from those of today. However, the East Mesa dunes and sand sheets do not appear to be very old. We dug pits in aeolian deposits of East Mesa at several localities and found that there is no evidence of soil formation, consistent with the observations of Zimmerman (1981). Even minimal accumulations of organic matter to form simple A horizons, such as those that characterize the youngest (<2 ka) Holocene aeolian sands on the Great Plains and the Colorado Plateau (cf. Muhs 1985, Wells et al. 1990, Jorgensen 1992, Madole 1992) are absent in aeolian deposits of East Mesa. Thus, it appears that these deposits have only recently (i.e., within the past few hundred years or less) been stabilized by vegetation, and it is improbable that wind directions have been greatly different from the present in the past few hundred years. A more likely explanation is that there are significant differences in resultant drift directions in different parts of the Salton Trough, even over short distances. The resultant drift direction for El Centro, immediately west of East Mesa, is west-to-east, whereas that of Yuma is northwest-to-southeast (Figure 2).

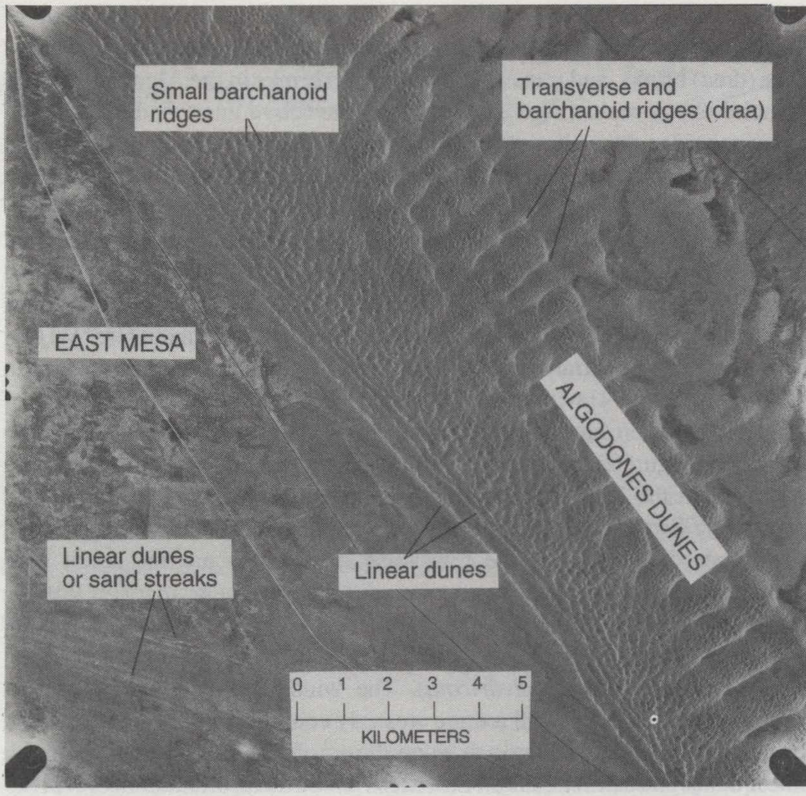

Figure 4. Vertical aerial photograph of the central portion of the Algodones dune field and a part of East Mesa, showing types of aeolian landforms.

Cause of Stability of East Mesa Aeolian Deposits

The relative stability of East Mesa aeolian sands contrasts sharply with the active Algodones dunes (Figure 4). It is possible that local climatic factors could be responsible for the relative stability of the East Mesa dunes. Lancaster (1988) has shown from studies in the Namib and Kalahari deserts in southern Africa that degree of dune activity is a function of the balance between the amount of time (W) that wind is above the threshold velocity for sand, and the precipitation-to-potential evapotranspiration ratio (P/PE). He generated an index of dune mobility (M) that is computed from these data as W/(P/PE). Higher values of M correspond to greater degrees of dune activity. Lancaster recognized, from field studies in southern Africa, four classes of dune activity: (1) inactive dunes, M values <50; (2) dunes with active crests only, M values between 50 and 100; (3) dunes that are fully active except for plinths and interdune areas, M values between 100 and 200; and (4) fully active dunes, M values >200. Muhs and Maat (1993) applied Lancaster's index to localities near dune fields in the Great Plains and found good agreement between predicted and actual degrees of dune activity.

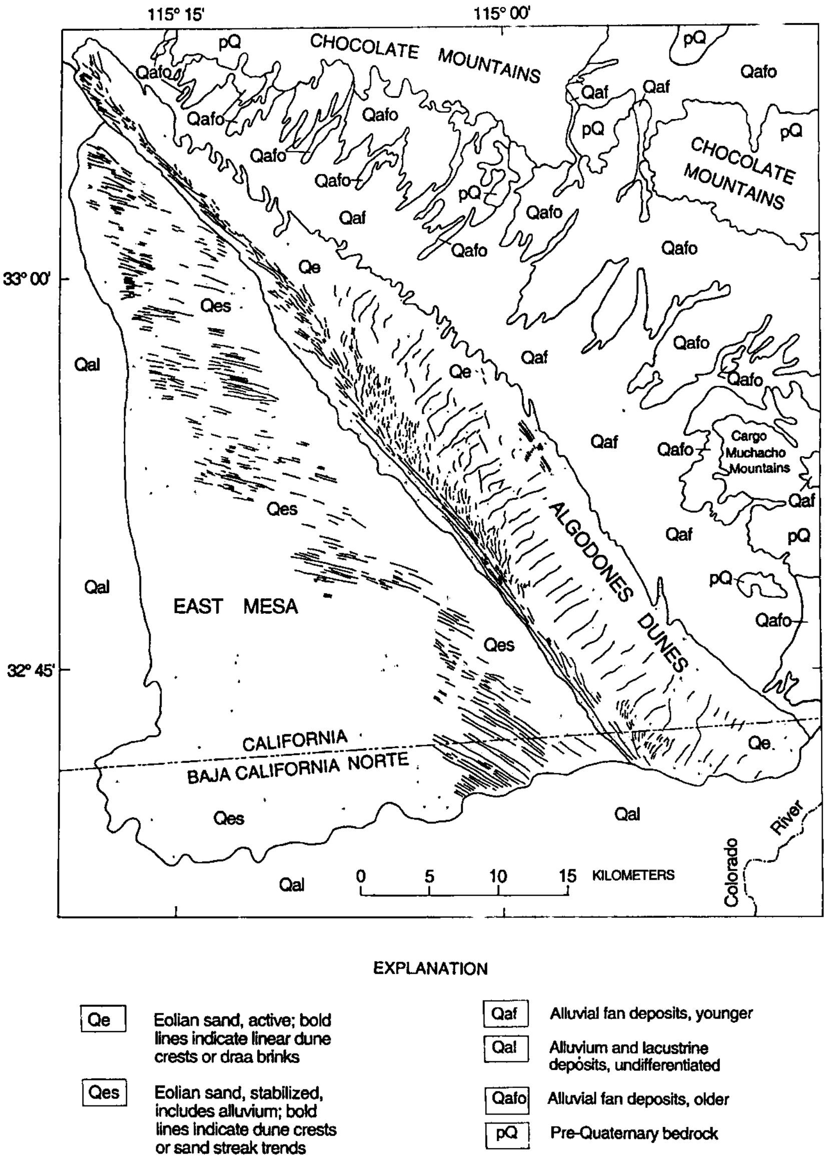

Figure 5. Generalized surficial geologic map of the Algodones dunes, East Mesa, and surrounding areas.

Using modern wind speed, P, and PE data, calculated by the method of Thornthwaite and Mather (1957), we computed M values for eleven localities in or adjacent to sand dunes or sand sheet areas in the Colorado Desert. Weather stations record wind data with anemometers at different heights; for most stations in the Colorado Desert, no anemometer heights are given and we assumed a standard 10 m height for these localities, and used a threshold velocity of 5 m/s. Results indicate that the Lancaster index predicts that most of the region should have fully active dunes (Figure 6). All but the two northernmost localities (Palm Springs, CA, 187; and Indio, CA, 202) have M values significantly greater than 200, and one (Calipatria, CA) has an extremely high value of 776. The field evidence supports the predictions of active sand by the mobility index. In the area just northwest of Palm Springs and continuing south to Indio (Figure 1), there are limited areas of active sand, but also significant tracts of aeolian sand sheets, coppice dunes, and barchanoid dunes that are at least partially stabilized by vegetation (Beheiry 1967, Shelton et al. 1978). However, farther south, in the areas where localities have M values significantly greater than 200, aeolian sand is active. West of the Salton Sea and Calipatria, active barchan dunes are found whose rates of movement have been documented by Rempel (1936), Long and Sharp (1964), Norris (1966), and Shelton et al. (1978). Southwest of Calipatria and northwest of Imperial there are longitudinal dunes that feed into active barchan dunes whose rates of movement are given by Smith (1982). The active Algodones dunes themselves are closest to the localities of El Centro, Holtville, and Calexico, CA, Yuma, AZ, and Mexicali, Mexico, where M values range from 274 to 469. The only major exception to the predicted and observed degrees of activity are the stabilized aeolian deposits on East Mesa (Figures 1 and 2), near localities where M values range from 274 to 469. We conclude, therefore, that local climatic factors are not responsible for the stability of the East Mesa dunes.

Stabilization of the East Mesa dunes and sand sheets may have been caused by recent rises in the water table that have helped to establish vegetation. Loeltz et al. (1975) reported that ground water levels rose from 0 to 18 m in the period 1939-1960 because of local recharge from irrigation canal leakages. Based on their data showing the elevation of the water table in 1960 and land surface elevations, we estimate that the water table under East Mesa was within 5-18 m of the surface in 1960. It is possible that the water table is closer to the surface at the present time, although we do not have, at present, any modern water table depth data. Whether or not the recent rise in ground water level since 1939 was sufficient to stabilize the dunes of East Mesa can be answered by examination of aerial photographs from the 1930s, before significant canal leakage had recharged the local ground water. A comparison of 1954 and 1979 aerial photographs of East Mesa by G. Kocurek (written communication, 1993) seems to indicate that there was less vegetation in the area in the 1950s, and a systematic study using older aerial photographs would be a worthwhile effort.

Possible Source Sediments

The observations of dune orientations and resultant drift directions from wind data help to constrain possible source sediments for the Algodones dunes and East Mesa aeolian sediments. Fluvial deposits of the San Gorgonio and

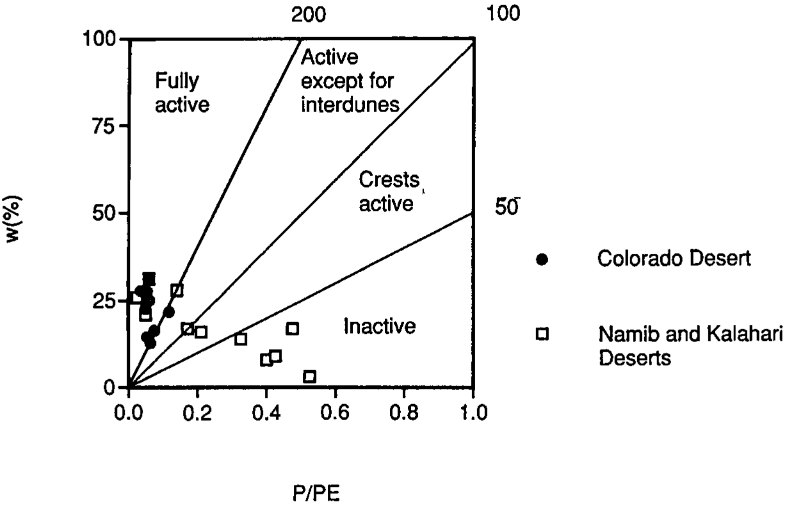

Figure 6. Plot of data from weather stations (localities shown in Figure 1) in or near bodies of aeolian sand in the Colorado Desert (solid circles) showing amount of time that wind is above the threshold velocity for sand (W) vs. ratio of mean annual precipitation to potential evapotranspiration (P/PE). Similar data for localities in the Namib and Kalahari Deserts (open squares), taken from Lancaster (1988) are also plotted for comparison. Bold numbers (50, 100, 200) are threshold values of M (W/[P/PE]) that separate dune activity classes.

Whitewater Rivers, which drain the San Bernardino Mountains, occur in dry, sandy washes to the northwest of the dune fields, and are thus potential sources of sand (Figure 2). We witnessed dramatic aeolian movement of sand from these river beds to the southeast after passage of a Pacific frontal system in March, 1993. Visibility was so poor because of blowing sand that numerous roads in the area had to be closed. Sand-rich Lake Cahuilla shoreline sediments occur to the west and northwest of the dune fields and are also likely candidates for source sands (Figure 2). Alluvial fan deposits of the Chocolate and Cargo Muchacho Mountains occur mostly to the northeast of the dune fields (Figure 5) and would seem to be a less likely source based on drift potentials, but active washes carry abundant sand from these mountains and terminate at the northeastern side of the Algodones dunes. Therefore, the hypothesized source sediments sampled include: (1) modern alluvium collected from active channels of the Whitewater and San Gorgonio Rivers, which drain the San Bernardino Mountains; (2) modern sediments from active channels incised into alluvial fans that are derived from the Chocolate and Cargo Muchacho Mountains; (3) beach sediments of the shoreline of Lake Cahuilla that occur at about +12-14 m above sea level, as mapped by Waters (1983); and (4) Colorado River sediments, collected from the modern floodplain in the vicinity of Yuma, Arizona, and from deposits of Yuma Mesa, which is thought to be an old terrace of the Colorado River, possibly of last-interglacial age (Olmsted et al. 1973, Dohrenwend and Smith 1991). Aeolian sediments from the Algodones dunes and East Mesa include samples from barchanoid-ridge, barchan, linear, and coppice dunes, as well as aeolian sand sheet deposits (Table 1).

MINERALOGY AND TRACE ELEMENT GEOCHEMISTRY

Mineralogy

We conducted simple mineralogical studies in our efforts to identify the source sediments of the Algodones and East Mesa aeolian sands. All source-sediment samples were sieved to include only the fine sand fraction, which is the modal particle size for aeolian sediments in the Algodones dune field (Sweet et al. 1988). Silts and clays were removed by wet-sieving after dispersion with Na-pyrophosphate.

Semiquantitative estimates of the relative amounts of quartz, K-feldspar, and plagioclase in the fine sand fractions of the Algodones dunes, East Mesa aeolian sediments, and hypothesized source sediments were made using X-ray diffractometry. Mineral peak heights were measured for the 20.8° (quartz), 27.4° (K-feldspar: microcline and sanidine), and 27.8° (plagioclase) peaks. These values were summed for each sample and relative proportions were calculated using the peak height of each mineral as a fraction of the sum. The data are presented in the form of ternary diagrams (Figures 7, 8, and 9), but are not intended to be interpreted as precise quantification of mineral content.

Van Andel (1964) and Olmsted et al. (1973) give data on the composition of modern and ancient Colorado River alluvium, respectively; their results are similar to each other and indicate that this alluvium is mineralogically quite mature. Colorado River sediments are characterized mostly by quartz (65%-75%), with lesser amounts of feldspar (10%-20%), and rock fragments (1%-8%). Our data support these earlier observations, and also indicate that Lake Cahuilla sediments have a composition that is not significantly different from Colorado River sediments, but is significantly more quartz-rich and lower in plagioclase than San Bernardino Mountains-derived alluvium (Figures 7a and 8b). Our observations differ from those of Van de Kamp (1973), who found that quartz abundances in Lake Cahuilla sediments are lower than in Colorado River sediments. Lake Cahuilla and Colorado River sediments are also generally higher in quartz than Chocolate Mountains-derived alluvium, although there is considerable overlap between these sediment groups (Figure 7b). Thus, Lake Cahuilla sediments are most likely derived from the Colorado River, as inferred by most previous workers (other than Van de Kamp, 1973), with possibly some contributions from the Chocolate Mountains, but little or no contribution from the San Bernardino Mountains. The higher quartz and lower plagioclase contents in Colorado River sediments compared to sediments derived from the local basin-bounding mountain ranges may be explained by the fact that Colorado River sediments have been derived from numerous rocks in the river's drainage basin, many of which have undergone several cycles of

Table 1
Elemental concentrations in Algodones and East Mesa aeolian sediments, Colorado River sands, Lake Cahuilla sands, Chocolate and Cargo Muchacho Mountain alluvial fan sands, and sands from rivers draining the San Bernardino Mountains

ID#	K (%)	Ca (%)	Ti	Rb	Sr	Y	Zr (ppm)	Nb	Ba	La	Ce	Geomorphology**
Algodones aeolian sediments												
ALG-1	2.08	1.58	903	52	144	8	49	2	514	14	29	C
ALG-2	1.90	1.40	858	54	137	7	46	1	486	10	26	B
ALG-3	2.04	1.86	834	49	133	7	46	1	486	12	28	BR
ALG-4	1.74	1.57	798	47	129	7	56	2	447	21	28	B
ALG-5	2.07	1.89	864	48	128	7	47		451	13	16	B
ALG-6	1.90	2.36	1433	51	164	9	70	4	529	18	28	L
ALG-7	1.56	1.59	1099	48	143	9	61	1	457	7	24	S
ALG-8	1.96	1.59	959	48	131	7	52	2	465	10	26	C
ALG-9	1.74	1.47	883	48	40	7	49		482	14	28	S
ALG-10	1.67	1.48	987	49	141	8	56	2	482	17	20	C
ALG-11	1.66	2.23	1487	47	152	10	71	5	438	14	31	L
ALG-12	1.64	2.93	1965	46	163	13	90	7	436	21	33	L
ALG-13	2.08	3.24	1535	47	157	10	58	5	454	18	29	L
ALG-14	1.53	2.24	1673	47	154	11	93	6	437	18	32	L
ALG-15	1.57	1.88	1236	50	151	8	71	4	460	7	35	S
ALG-16	1.80	2.48	1296	48	151	9	71	2	457	17	36	S
ALG-17	1.69	1.93	1146	48	148	8	60	3	468	6	24	L
ALG-18	1.83	1.76	1076	51	148	7	58	2	486	8	21	L
ALG-19	1.85	1.97	1084	51	150	9	55	1	477		25	L
ALG-20	2.27	2.15	1140	48	136	8	50	1	471	16	35	BR
ALG-21	1.63	1.25	858	56	147	6	55	2	490	11	12	BR
ALG-22	2.10	2.76	1266	49	145	8	68	3	439	16	31	BR
East Mesa aeolian sediments												
EM-1	1.90	2.41	1322	50	167	10	76	2	567	7	29	S
EM-2	1.84	2.09	1388	50	163	9	81	3	580	7	23	C
EM-3	2.19	2.56	1654	55	162	11	117	2	548	16	30	C
EM-4	1.63	2.64	1597	49	178	12	86	5	531	16	30	S/C
EM-5	1.74	2.44	980	46	152	6	53	3	450	10	22	S/C
EM-6	1.56	1.70	1022	48	138	9	62	2	445	7	13	S/C
EM-7	1.88	2.31	1397	51	163	9	70	2	522	18	28	S/C
EM-8	2.03	2.30	1262	49	154	8	59	3	512	13	31	S/C
EM-9	1.99	2.27	1131	56	148	8	62	2	496	9	8	S
EM-10	1.66	2.62	1168	34	124	8	47	3	383	19	44	S
EM-11	1.83	1.75	887	49	134	7	54	3	477	4	14	C
EM-12	2.01	2.21	1193	50	138	8	68	3	472	14	24	C
EM-13	2.01	1.80	952	51	136	7	62	2	480	12	32	C
EM-14	1.70	1.97	963	48	132	8	53	2	446	5	16	B

Colorado River sediments

CO-1	1.32	1.70	1635	36	131	10	113	5	370	15	30	YM
CO-2	1.88	1.80	1148	50	119	9	72	1	479	11	18	YM
CO-3	2.14	2.80	1978	52	168	9	89	5	470	15	48	YM
CO-4	1.87	1.65	1028	42	96	7	76	3	416	9	22	YM
CO-5	1.92	2.20	1064	49	106	11	87	2	437	10	24	YM
CO-6	1.92	1.97	996	50	332	8	67	2	676	23	35	YM
CO-7	1.66	1.39	968	46	108	9	65	2	470	7	13	YM
CO-8	2.18	1.96	994	51	113	7	76	2	485	7	33	YM
CO-9	2.37	1.51	2548	73	196	13	98	7	582	22	42	YM
CO-10	2.35	1.39	2940	73	196	15	102	8	578	16	38	YM
CO-11	2.29	1.31	3074	78	212	17	95	10	602	10	38	YM
CO-13	2.01	2.30	1784	50	138	9	98	2	468	17	33	FP
CO-14	1.86	2.52	1208	50	128	10	116	1	465	5	19	FP
CO-15	2.20	3.19	1546	58	152	10	101	2	530	13	22	FP
CO-16	2.11	3.69	1717	56	197	11	136	2	500	8	35	FP
CO-17	2.26	3.72	1661	59	150	12	110	3	548	19	26	FP
CO-18	2.13	3.90	1544	52	151	9	130	3	493	8	13	FP
CO-19	1.86	2.80	1759	50	147	12	184	3	467	14	22	FP
CO-20	1.79	2.86	2422	50	153	15	286	5	469	16	18	FP
CO-20A	2.14	3.31	1769	57	137	13	103	4	504	14	25	FP
CO-21	1.87	2.72	1651	52	158	9	167	4	480	11	28	FP

Lake Cahuilla sediments

LC-1	1.46	1.87	842	48	160	5	52		462	10	15
LC-2	1.75	3.58	1659	43	168	10	93	2	437	20	37
LC-3	1.67	3.21	1552	52	181	12	89	5	480	18	32
LC-4	2.05	3.10	1423	50	169	9	73	3	499	16	28
LC-5	2.22	3.63	1360	54	171	9	60	4	533	14	34
LC-6*	0.69	1.58	25229	21	105	85	1626	63	251	115	205
LC-7	1.33	2.91	3579	39	150	17	142	10	400	26	47
LC-8*	0.91	2.47	15539	26	122	50	580	46	319	84	148
LC-9	1.58	2.24	1771	46	152	9	80	4	446	12	39
LC-10	1.56	2.11	2709	40	140	14	87	7	424	21	47
LC-11	2.07	2.97	1381	54	172	8	68	2	543	11	24
LC-11A	2.44	2.87	1708	68	195	9	91	4	578	10	36
LC-12	1.88	1.64	824	58	169	7	62	1	598	14	28
LC-13	1.92	1.75	931	54	57	7	55	2	558	12	21
LC-14	1.77	2.64	1488	41	149	10	74	4	434	20	37
LC-15	1.65	2.07	1074	50	134	9	59	2	444	13	25
LC-16	1.41	1.98	1654	40	145	11	83	6	374	11	27
LC-17	1.96	2.47	1849	48	155	10	73	3	461	12	24

Alluvial fan sediments from the Chocolate and Cargo Muchacho Mountains

CM-1	1.78	2.42	1811	56	195	15	214	4	638	22	47	CA
CM-2	1.96	2.71	3101	56	208	38	589	15	834	63	110	CA
CM-3	2.34	2.70	2653	69	229	25	318	13	786	36	68	CA
CM-4	2.72	2.51	1698	84	244	18	161	8	893	12	30	CA
CM-5	2.86	2.23	2382	92	243	28	338	13	782	36	71	CA
CM-6	2.37	2.12	2189	76	198	21	294	8	634	23	43	CA
CM-7	2.68	2.52	2779	100	249	29	354	12	735	34	71	CA

CM-8	2.18	2.42	2559	82	201	21	312	10	580	20	42	CA
CM-9	2.33	2.73	3153	92	225	36	385	18	603	41	84	CA
CM-10	3.42	2.18	1860	121	299	19	195	9	843	8	30	CA
CM-11	2.69	2.06	2583	99	257	24	264	11	661	28	57	CA
CM-11A	2.36	2.04	2200	73	197	18	332	6	594	29	54	CH
CM-12	2.66	2.14	1846	93	272	16	109	6	740	21	35	CH
CM-14	2.38	2.68	2488	73	243	16	170	7	680	19	45	CH
CM-15	2.29	2.42	2294	74	297	14	126	8	779	5	39	CH
CM-16	2.40	2.99	2809	69	235	17	242	7	679	15	36	CH
CM-17	2.13	2.64	2858	64	195	18	299	7	586	18	42	CH
CM-18	2.48	2.81	2682	84	232	18	229	8	756	16	40	CH
CM-19	2.22	2.18	2966	73	192	20	391	7	626	24	52	CH
CM-20	2.72	2.19	2316	106	214	16	123	6	715	13	40	CH
CM-21	2.26	2.70	2608	69	213	16	235	6	639	23	37	CH
Sediments from rivers draining the San Bernardino Mountains												
SB-1	2.10	2.35	4722	70	333	40	321	9	767	64	120	SG
SB-2	2.08	2.39	4946	67	336	40	307	12	749	55	119	SG
SB-3	2.30	2.51	4030	72	390	36	197	13	856	71	142	SG
SB-4	2.23	2.31	3722	71	381	32	266	10	836	40	92	SG
SB-5	1.94	3.20	4770	67	519	19	201	11	718	21	53	SG
SB-6	2.33	2.44	3975	81	399	35	271	11	852	43	98	SG
SB-7	2.66	2.61	3136	109	440	20	143	6	966	22	60	SG
SB-8	2.40	2.50	3940	88	399	34	350	12	862	42	101	SG
SB-9	2.54	2.17	2880	89	409	18	129	7	925	22	58	SG
SB-10	2.45	2.27	3647	87	388	26	249	9	860	33	79	SG
SB-11	2.87	2.05	3428	104	387	22	180	9	959	29	61	W
SB-12	2.63	2.14	3324	91	391	28	271	10	960	46	92	W
SB-13	2.59	2.49	3991	96	384	39	357	11	868	43	95	W
SB-14	2.80	2.07	3523	102	402	30	288	10	964	48	103	W
SB-15	2.63	2.20	3567	96	413	35	265	13	913	66	112	W
SB-16	2.85	1.94	3466	102	402	34	277	11	930	73	141	W
SB-17	2.77	1.88	3025	100	404	29	236	11	986	55	102	W
SB-18	2.57	2.01	4000	94	383	42	433	14	892	90	166	W
SB-19	2.95	1.84	3185	112	389	30	289	11	1010	45	105	W

* Not included in element concentration plots because of unusually high concentrations of heavy minerals.

** Abbreviations for landforms: C, coppice dune; B, barchan dune; BR, barchanoid-ridge; L, linear dune; S, sand sheet; YM, Yuma Mesa; FP, modern floodplain of Colorado River; CA, modern fan channel sediments of Cargo Muchacho Mountains; CH, modern fan channel sediments of Chocolate Mountains; SG, modern channel sediments of San Gorgonio River; W, modern channel sediments of Whitewater River.

(a)

(b)

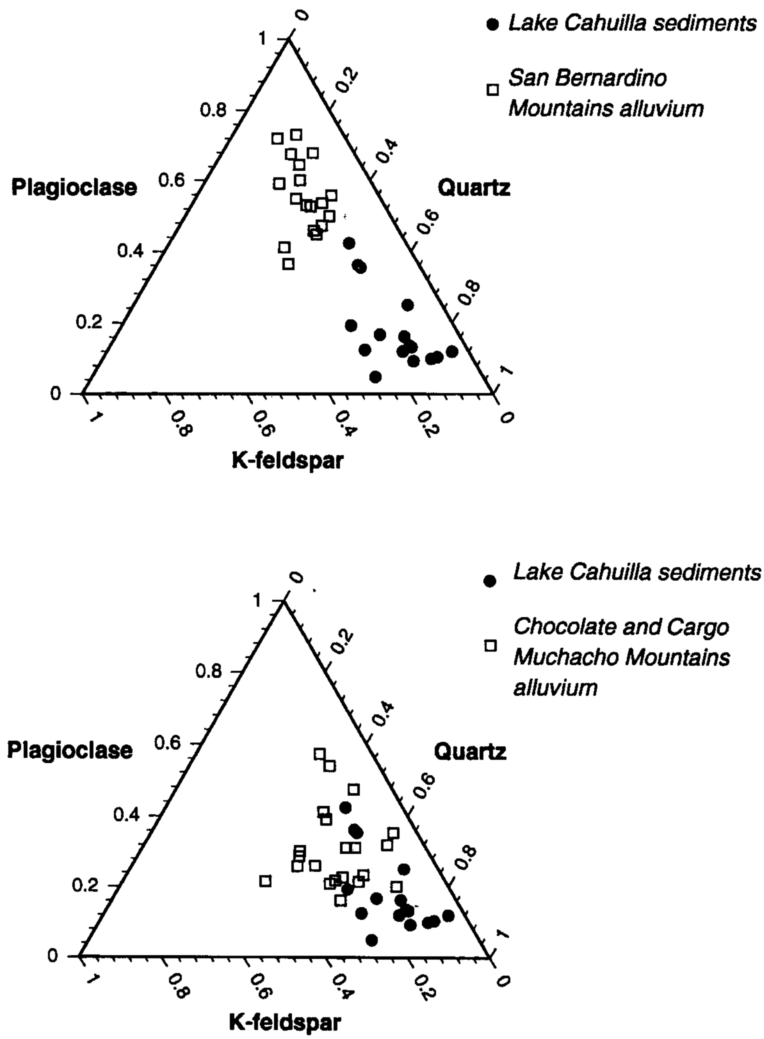

Figure 7. Ternary diagram comparing relative abundances of quartz, K-feldspar, and plagioclase in sediments from Lake Cahuilla, the San Bernardino Mountains, and the Chocolate and Cargo Muchacho Mountains.

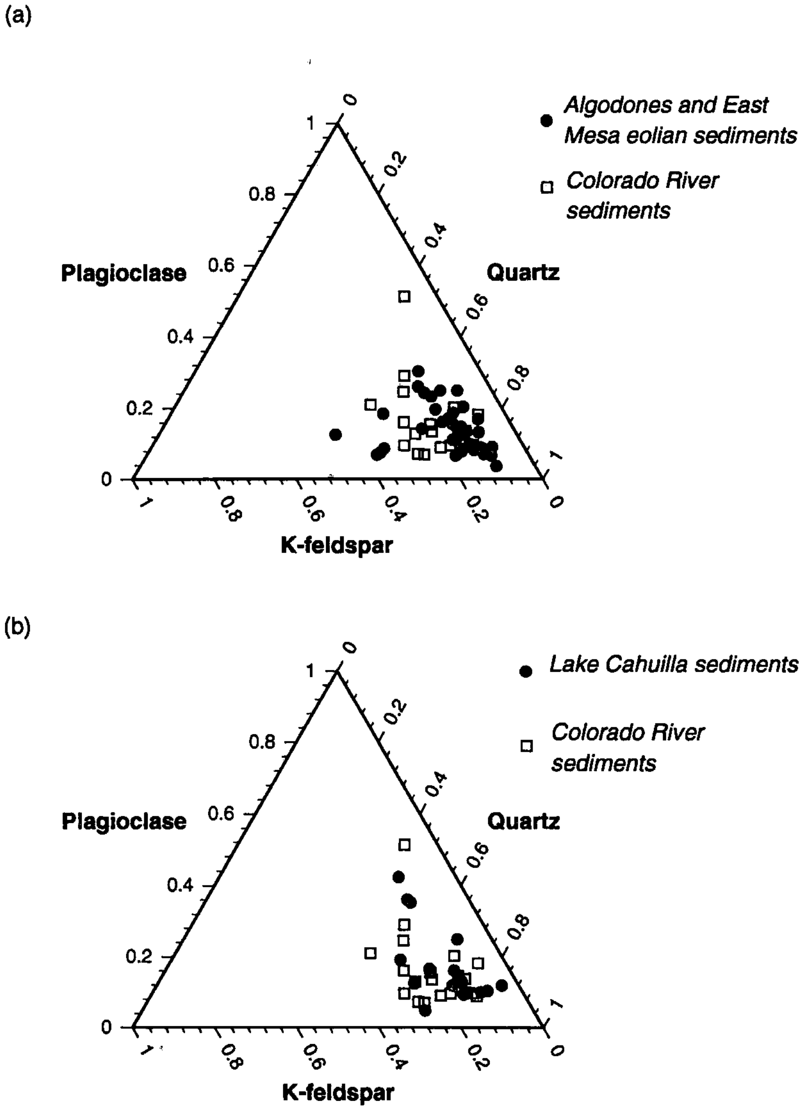

Figure 8. Ternary diagram comparing relative abundances of quartz, K-feldspar, and plagioclase in sediments from the Colorado River and Lake Cahuilla, and aeolian sediments from the Algodones dunes and East Mesa.

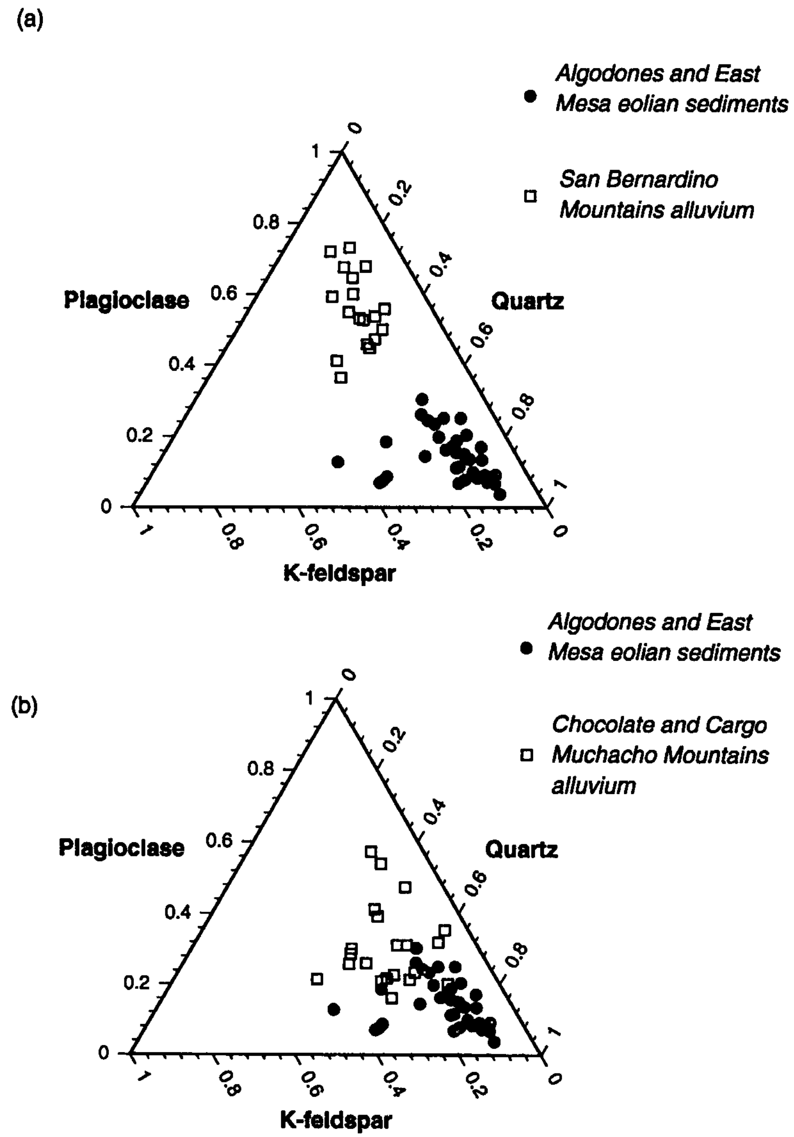

Figure 9. Ternary diagram comparing relative abundances of quartz, K-feldspar, and plagioclase in aeolian sediments from the Algodones dunes and East Mesa, and alluvial sediments derived from the San Bernardino Mountains and Chocolate and Cargo Muchacho Mountains.

Table 2
Mean values and standard deviations for USGS rock standard GSP-1 (n = 15 runs) and published values (Govindaraju 1989) for GSP-1.

Element	Mean value	Standard deviation	Standard deviation (%)	Published value
K (%)	4.86	0.04	0.9	4.57
Ca (%)	1.47	0.02	1.4	1.48
Ti (ppm)	3806	82	2.2	3897
Rb (ppm)	255	3	1.2	254
Sr (ppm)	237	3	1.3	234
Y (ppm)	34	3	8.8	26
Zr (ppm)	513	12	2.3	530
Nb (ppm)	28	1	3.6	28
Ba (ppm)	1320	10	0.8	1310
La (ppm)	181	9	5.0	184
Ce (ppm)	407	8	2.0	399

weathering, erosion, and sedimentation, and are thus mineralogically more mature.

Mineralogical data indicate that there is no significant difference between aeolian sediments of the Algodones dunes and East Mesa. Therefore, on subsequent ternary diagrams, we combine these two sediment groups because they appear to have had a common origin. Aeolian sediments of East Mesa and the Algodones dunes are enriched in quartz and depleted in plagioclase when compared to alluvium derived from the San Bernardino Mountains, which suggests that sediments of the Whitewater and San Gorgonio Rivers are not important sources of the aeolian sediments (Figure 9a). The same conclusion can be inferred from a comparison of aeolian sediments with Chocolate Mountains alluvium, although there is a slight amount of overlap between the sediment groups (Figure 9b). The greatest similarities are seen in a comparison of aeolian sediments of East Mesa and the Algodones dunes with a pooled sediment group that consists of Colorado River alluvium and Lake Cahuilla sediments (Figure 8a). From this comparison and those made above, we conclude that the best candidate for a source of the aeolian sediments is Lake Cahuilla sediments, which in turn appear to be derived mainly from the Colorado River (Figures 8a, 8b).

Geochemical Methods

We used trace element concentrations, measured by energy-dispersive X-ray fluorescence spectrometry, to "fingerprint" the potential source sediments and compare them to aeolian sands from the two dune fields. A similar approach, using ratios of trace element concentrations, was employed by Muhs et al.

(1990) in determining the source of clay-rich soils on Quaternary limestones on Caribbean and western Atlantic islands, and has been commonly used by petrologists studying the origins of volcanic and metavolcanic rocks (Pearce and Cann 1973, Brooks and Coles 1980). As with the mineralogical determinations, only the fine sand fraction was used for analyses. Concentrations of most trace elements can be measured with relatively high precision and accuracy with the exceptions of Y (low precision and uncertain accuracy) and Nb and La, which show relatively low precision (Table 2). However, concentrations of Y, Nb, and La are still useful for semiquantitative discrimination. The trace elements studied occur in a variety of mineral phases. In aeolian and alluvial sands derived from granitic rocks, the most common constituents are quartz, K-feldspar, plagioclase, rock fragments, and minor amounts of heavy minerals. Rb substitutes for K and is therefore found in K-feldspar and biotite. Sr substitutes for Ca, and is present in plagioclase, but can be found in some potassium minerals as well. La and Ce are light rare earths, and Y has behavior similar to the heavy rare earths. The rare earth elements are found in a wide variety of minerals, but on an overall basis, most of the rare earth abundances in these samples are probably accounted for by the feldspars. Zr is present almost exclusively in zircon. Ti is found mainly in ilmenite, anatase, rutile, titanomagnetite, and sphene. Nb is present in sphene and ilmenite, and to a lesser extent in biotite; Nb concentrations are often highly correlated with concentrations of Ti.

Trace Element Concentrations

Concentrations of Sr, Rb, Ti, Zr, Y, Nb, La, and Ce are not significantly different in aeolian sediments of East Mesa and the Algodones dunes, which suggests a common origin, consistent with the mineralogical data discussed above (Figure 10). In further discussions, therefore, we combine the East Mesa and Algodones dunes geochemical data, and consider them as one sediment population. Comparison of Lake Cahuilla beach sands with San Bernardino Mountains-derived alluvial sands shows that the former are significantly lower in concentrations of all trace elements, which is consistent with the mineralogical data discussed above. Relatively high concentrations of Sr, La, Ce, and Y in San Bernardino Mountains-derived alluvium are consistent with relatively high amounts of plagioclase in these sediments; high Rb also indicates relatively high amounts of K-feldspar. Concentrations of heavy minerals, as shown by the Ti, Zr, and Nb data, are also much higher in alluvium derived from the San Bernardino Mountains (Figure 11). Lake Cahuilla sediments do not appear to have a significant component of alluvial sands derived from the Chocolate Mountains and the Cargo Muchacho Mountains. Although the mineralogical data discussed above show that some component of alluvium derived from these mountains could be present in Lake Cahuilla sediments, data for Sr, Rb, Ti, and Zr show that Lake Cahuilla sediments all have much lower concentrations of these elements (Figure 12). Concentrations of La and Ce, and to a lesser degree, Y and Nb, show some overlap between alluvium

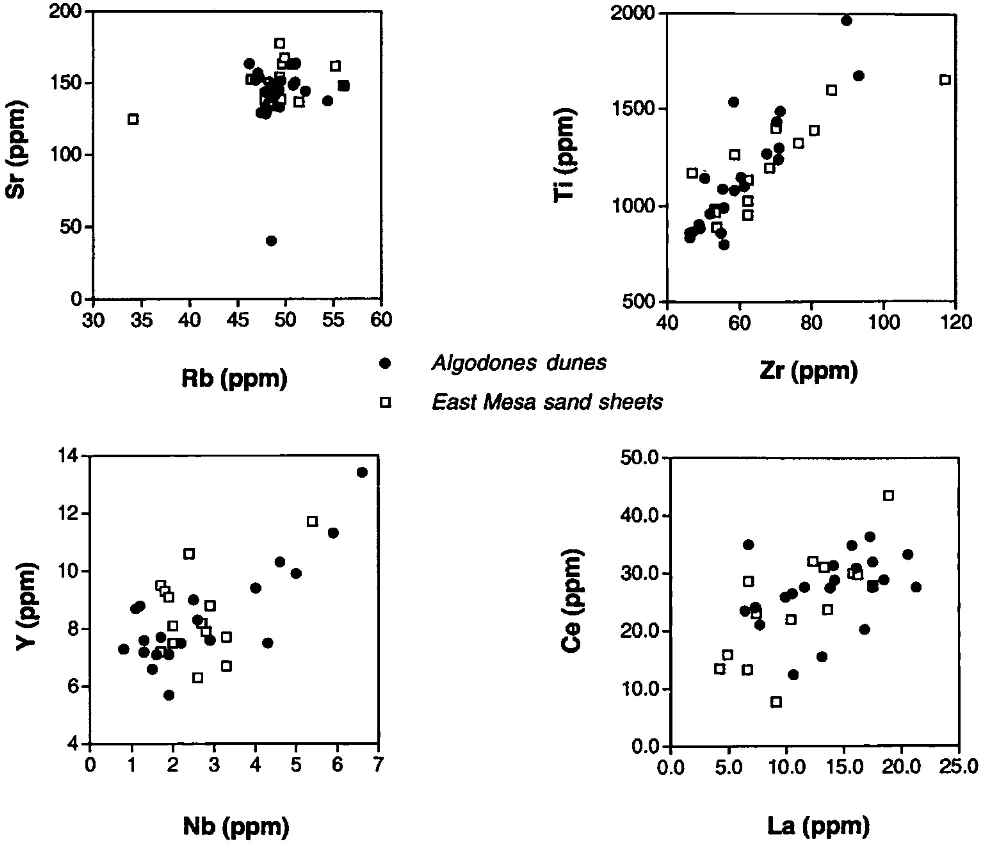

Figure 10. Comparison of trace element concentrations in sediments from the Algodones dunes and East Mesa.

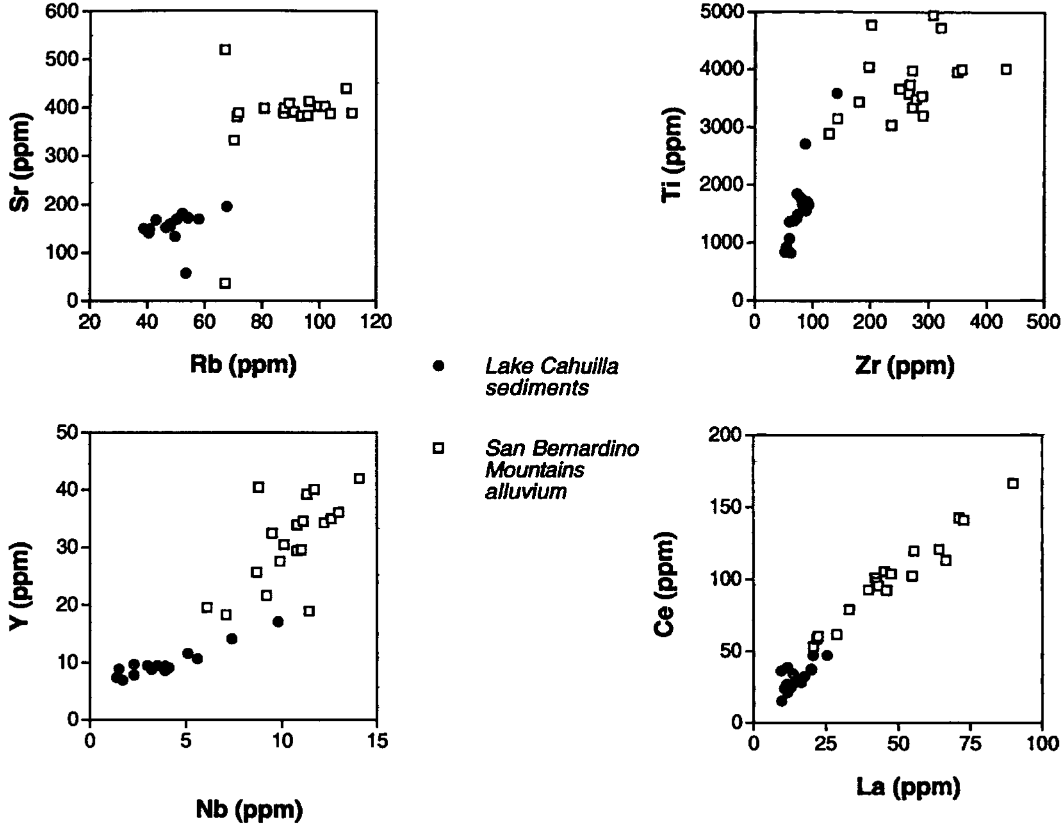

Figure 11. Comparison of trace element concentrations in sediments from Lake Cahuilla and the San Bernardino Mountains.

from the Chocolate and Cargo Muchacho Mountains and Lake Cahuilla sediments. Thus, both mineralogical and geochemical data suggest that alluvium derived from the Chocolate and Cargo Muchacho Mountains could be a minor, but not significant, component of Lake Cahuilla sediments. Overall, the best geochemical match is between Lake Cahuilla sediments and Colorado River sediments, which is consistent with the mineralogical data. Concentrations of Sr, Rb, Ti, Zr, Y, Nb, Ce, and La are not significantly different between Lake Cahuilla and Colorado River sediments, although it appears that the Ti/Zr value is somewhat higher in Lake Cahuilla sediments (Figure 13). Based on these data, and the geochemical comparisons between Lake Cahuilla sediments and alluvium derived from the basin-bounding mountain ranges, we conclude that the lake sediments were derived primarily from Colorado River sediments. Hence, in further geochemical discussions, we combine the Lake Cahuilla and Colorado River data and consider them as one sediment group.

The trace element concentrations of the combined East Mesa and Algodones dunes sediment group can be compared to the three other sediment groups of San Bernardino Mountains alluvium, Chocolate and Cargo Muchacho Mountains alluvium, and Lake Cahuilla/Colorado River sediments. The East Mesa and Algodones dunes all have significantly lower concentrations of all trace elements when compared to San Bernardino Mountains alluvium, consistent with the mineralogical data (Figure 14). There is a slight amount of overlap in the concentrations of Nb, Ce, and La between East Mesa and Algodones dunes and alluvium derived from the Chocolate and Cargo Muchacho Mountains, but concentrations of Rb, Sr, Ti, Zr, and Y are all significantly higher in the alluvial sediments (Figure 15). However, concentrations of all trace elements in East Mesa and Algodones dunes are not significantly different from those found in Lake Cahuilla/Colorado River sediments (Figure 16). Combined with the mineralogical data, these observations lead us to conclude that both East Mesa and Algodones dunes are derived from Lake Cahuilla beach sediments, and the beach sediments in turn are ultimately derived from Colorado River sediments. Geochemical and mineralogical data *permit* the interpretation that alluvial fan sediments from the Chocolate and Cargo Muchacho Mountains could have made minor contributions to both Lake Cahuilla sediments and East Mesa and Algodones dunes, but it is unlikely that the bulk of the aeolian sediments are derived from this source.

It can be inferred from Van de Kamp's (1973, p. 841) studies that the Algodones dunes were derived from Colorado River sediments in the southern part of the basin, based on his mineralogical data showing the similarities of these two sediment groups, and his observed differences with Lake Cahuilla sediments. In such an interpretation, sediments of the Algodones dunes would have to have been derived from the Colorado River floodplain during the summer, because this is the only time of the year that the monsoonal flow of air would generate winds from the south, based on the sand rose data presented earlier (Figures 2 and 3a). Although sand rose data show that drift potentials are relatively high for the Yuma area during this period, the geomorphic data

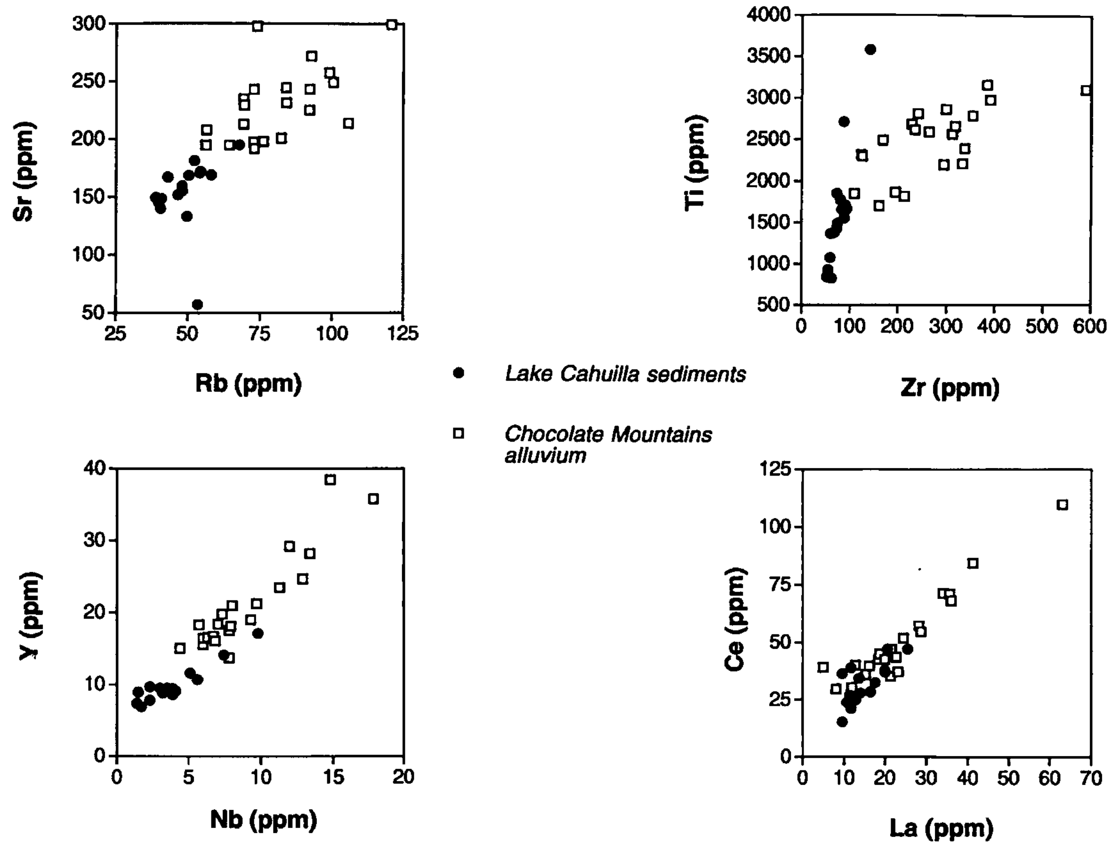

Figure 12. Comparison of trace element concentrations in sediments from Lake Cahuilla and the Chocolate Mountains.

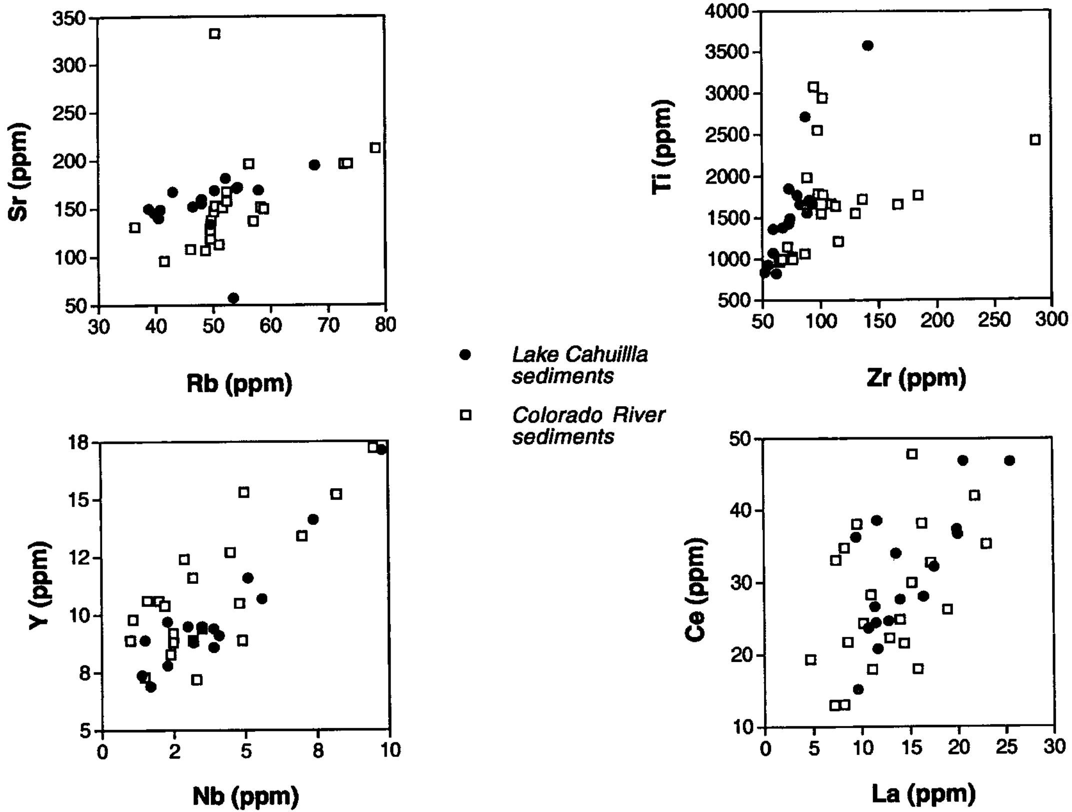

Figure 13. Comparison of trace element concentrations in sediments from Lake Cahuilla and the Colorado River.

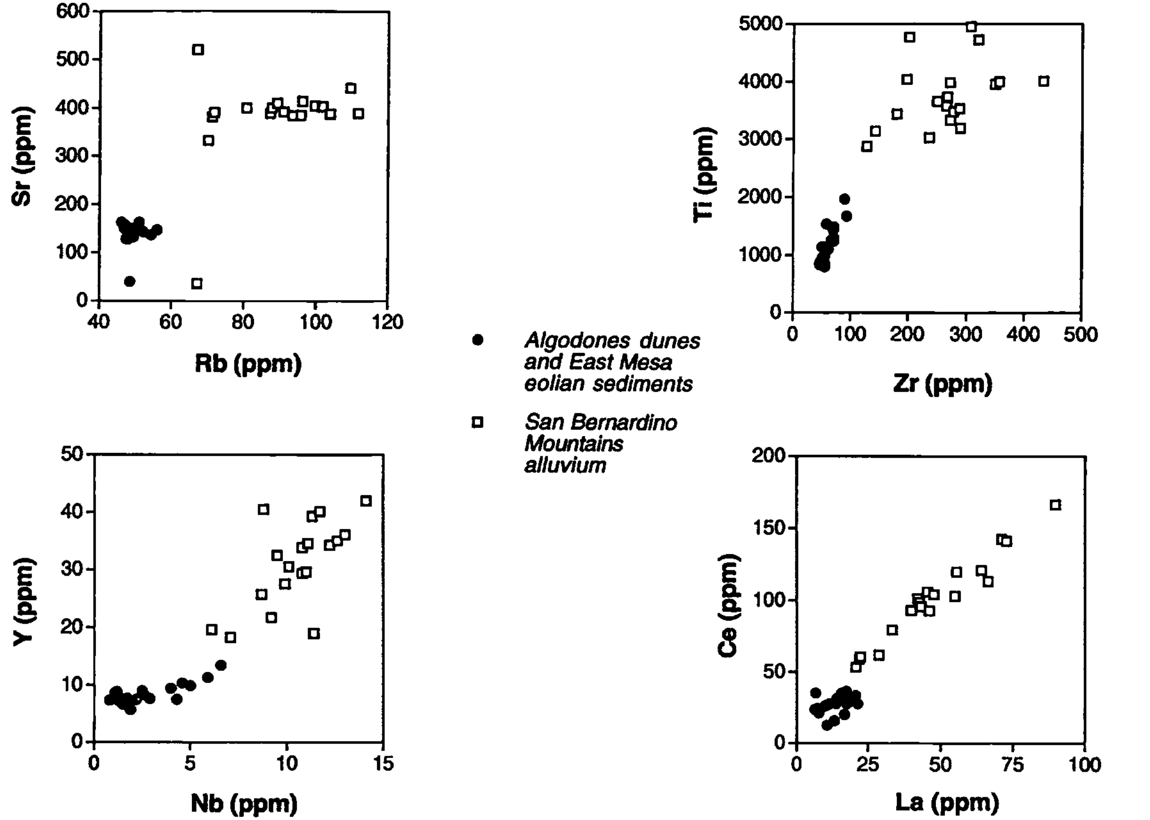

Figure 14. Comparison of trace element concentrations in sediments from the Algodones dunes, East Mesa, and the San Bernardino Mountains.

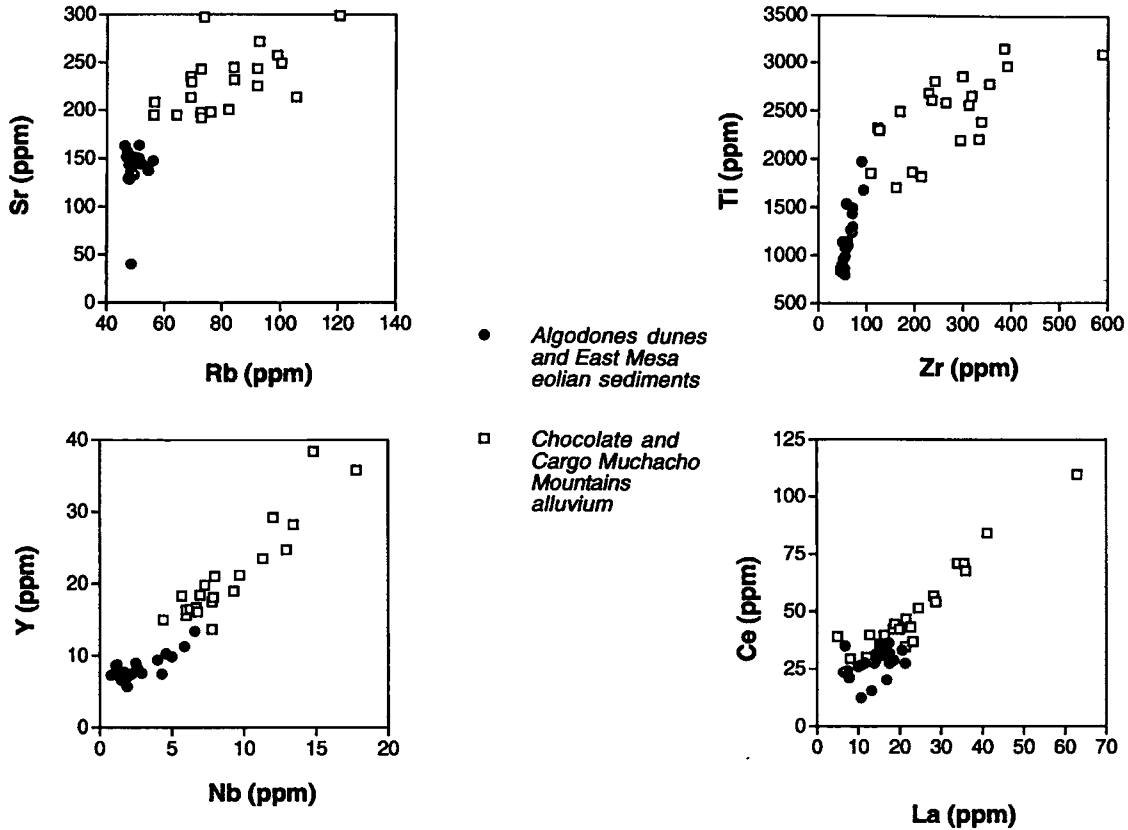

Figure 15. Comparison of trace element concentrations in sediments from the Algodones dunes, East Mesa, and the Chocolate and Cargo Muchacho Mountains.

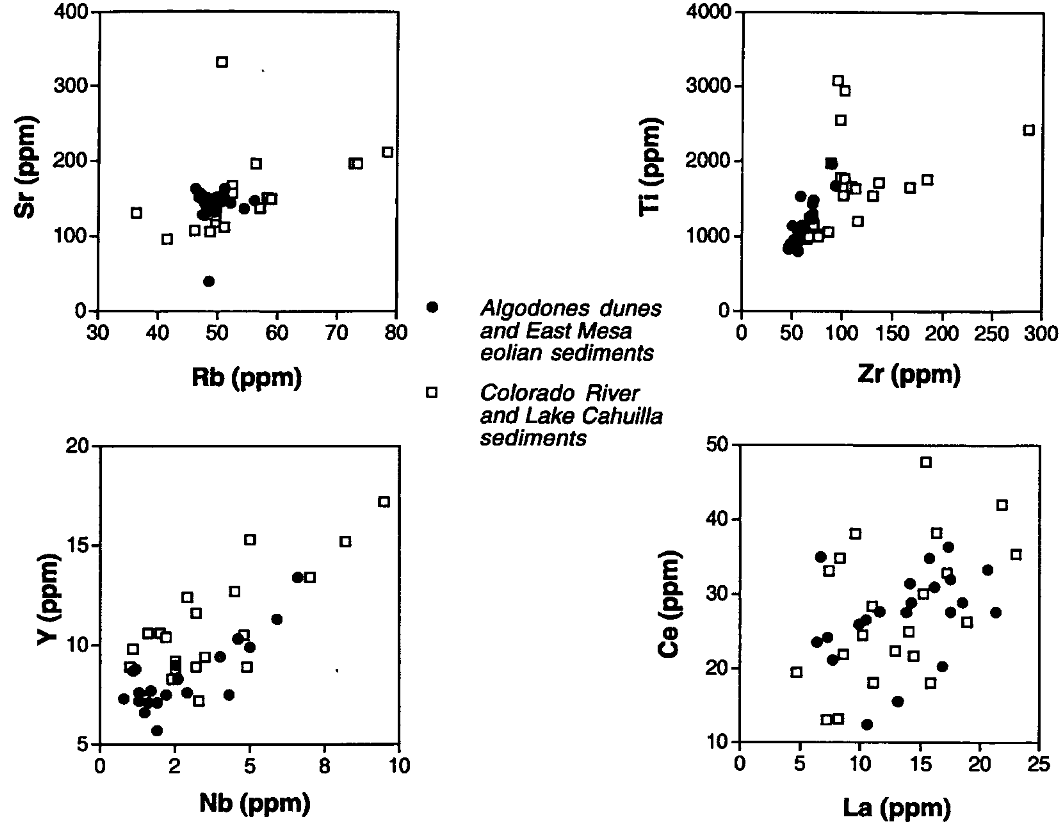

Figure 16. Comparison of trace element concentrations in sediments from the Algodones dunes, East Mesa, Lake Cahuilla, and the Colorado River.

presented by Havholm and Kocurek (1988) and in Figures 4 and 5 show that the dominant dune-forming winds have been from the northwest, both on East Mesa and in the Algodones dune field. It does not seem likely that all of the aeolian sand in the two areas was derived directly from the Colorado River during southerly, monsoonal flows of air in the summer and then simply reworked by northwesterly winds during the fall, winter, and spring. Given the geochemical and mineralogical data which show that Lake Cahuilla sediments are not significantly different from the aeolian sediments, and given that the late Holocene Lake Cahuilla shorelines are to the west and northwest of the dunes, we conclude that the immediate source of the aeolian sediments was the Lake Cahuilla shoreline deposits, and that northwesterly winds during the fall, winter, and spring were responsible for the movement of aeolian sand from the shoreline to the dune fields.

SUMMARY AND CONCLUSIONS

Climatic data indicate that winds in the Colorado Desert of southeastern California have low-to-intermediate drift potential for aeolian sand, but because of low precipitation and high evapotranspiration, a dune mobility index predicts that most aeolian sand in the area should be active, and this is supported by field observations. The major exceptions to predicted degree of activity are the aeolian deposits of East Mesa, which may have been recently stabilized by vegetation owing to human-caused rises in the ground water. This hypothesis requires testing by examination of older aerial photographs, however.

Orientations of the Algodones dunes indicate that the dominant winds of formation are from the northwest, which is consistent with resultant drift directions at Indio, to the northwest of the dune field, and Yuma, to the southeast of the dune field. Orientations of dunes and sand streaks on East Mesa also indicate winds of formation from the northwest, but with a more westerly component, which is consistent with resultant drift directions at El Centro, immediately to the west of East Mesa.

The various potential source sediments for the Algodones dunes vary in their degree of mineralogical maturity, and thus can be easily differentiated from one another. Colorado River sediments are high in quartz and relatively low in plagioclase because of the incorporation of grains from rocks that have undergone many cycles of weathering, erosion, and deposition. In contrast, sands from the local mountain ranges that surround the Salton Trough are mostly first-cycle sediments, and have high feldspar and heavy mineral contents, and relatively low quartz contents. Mineralogical data indicate that the Algodones dunes, East Mesa aeolian sediments, Lake Cahuilla sediments, and Colorado River sediments are indistinguishable from one another. In contrast, alluvium derived from the San Bernardino Mountains is significantly lower in quartz and higher in plagioclase than aeolian sediments from the Algodones dunes and East Mesa. Alluvium from the Chocolate Mountains is closer in composition to the aeolian sediments than is alluvium from the San Bernardino Mountains, but does not have the similarities to them that sediments from the Colorado River and Lake Cahuilla have.

Trace element concentrations (Rb, Sr, Ti, Zr, Y, Nb, La, and Ce) in the sediments studied support the conclusions drawn from the mineralogical data. With the exception of La and Ce concentrations from the Chocolate Mountains, concentrations of all trace elements from the Chocolate and San Bernardino Mountains are significantly higher than those in sediments from the Algodones and East Mesa dunes, and Lake Cahuilla and Colorado River sediments. In contrast, Algodones and East Mesa dunes, Lake Cahuilla sediments, and Colorado River sediments have trace element concentrations that are not significantly different from one another, indicating similar feldspar contents (based on Rb, Sr, La, Ce, and Y concentrations) and similar heavy mineral contents (based on Ti, Zr, and Nb concentrations). We conclude from the combined mineralogical and geochemical data that Lake Cahuilla sediments were the immediate source of sand for both the East Mesa and Algodones dunes. Lake Cahuilla sediments, in turn, were ultimately derived from the Colorado River, when its course shifted at times in the past and emptied into the Salton Trough rather than the Gulf of California.

Many additional questions about the origin of the Algodones dunes are raised by our results. It is not known if shoreline sand was deflated from beaches to the dunes while Lake Cahuilla was present or after the lake waters receded. In addition, it is not clear whether aeolian sediment inputs to the dune fields were associated with each lake stand; stratigraphic and radiocarbon data in Waters (1983) and Rockwell and Gurrola (1993) indicate that there were several late Holocene high stands. Given that the overall volume of sediment in the Algodones dunes is high (McCoy et al. 1967) and the present surface area of the late Holocene Lake Cahuilla shorelines is limited, we hypothesize that the present volume of sediment in the Algodones dunes is probably the result of multiple episodes of aeolian deflation from beach sources. If this is the case, there may be stratigraphic evidence of multiple episodes of aeolian sediment accumulation in the form of buried soils between dune or sand sheet deposits in the Algodones or East Mesa, similar to what Lancaster (1993, and this volume) has described from the Gran Desierto sand sea to the south. Future studies of the history of the Algodones dunes and East Mesa could explore the possibility of a stratigraphic record of multiple episodes of aeolian sand accumulation.

Our results indicate that trace element geochemistry is a promising technique for provenance studies of aeolian sand. The best results should be obtained in areas where hypothesized source sediments have very different geochemical signatures such as silicic vs. mafic sediments or mineralogically mature vs. mineralogically immature sediments. Many other dune fields and sand sheets whose source sediments are uncertain, controversial, or of multiple origins could be studied using trace element geochemistry, such as those in the Mojave Desert (Smith 1984), the Colorado Plateau (Price et al. 1988, Wells et al. 1990), the Great Plains (Ahlbrandt and Fryberger 1980, Muhs 1985), and Alaska (Lea and Waythomas 1990).

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