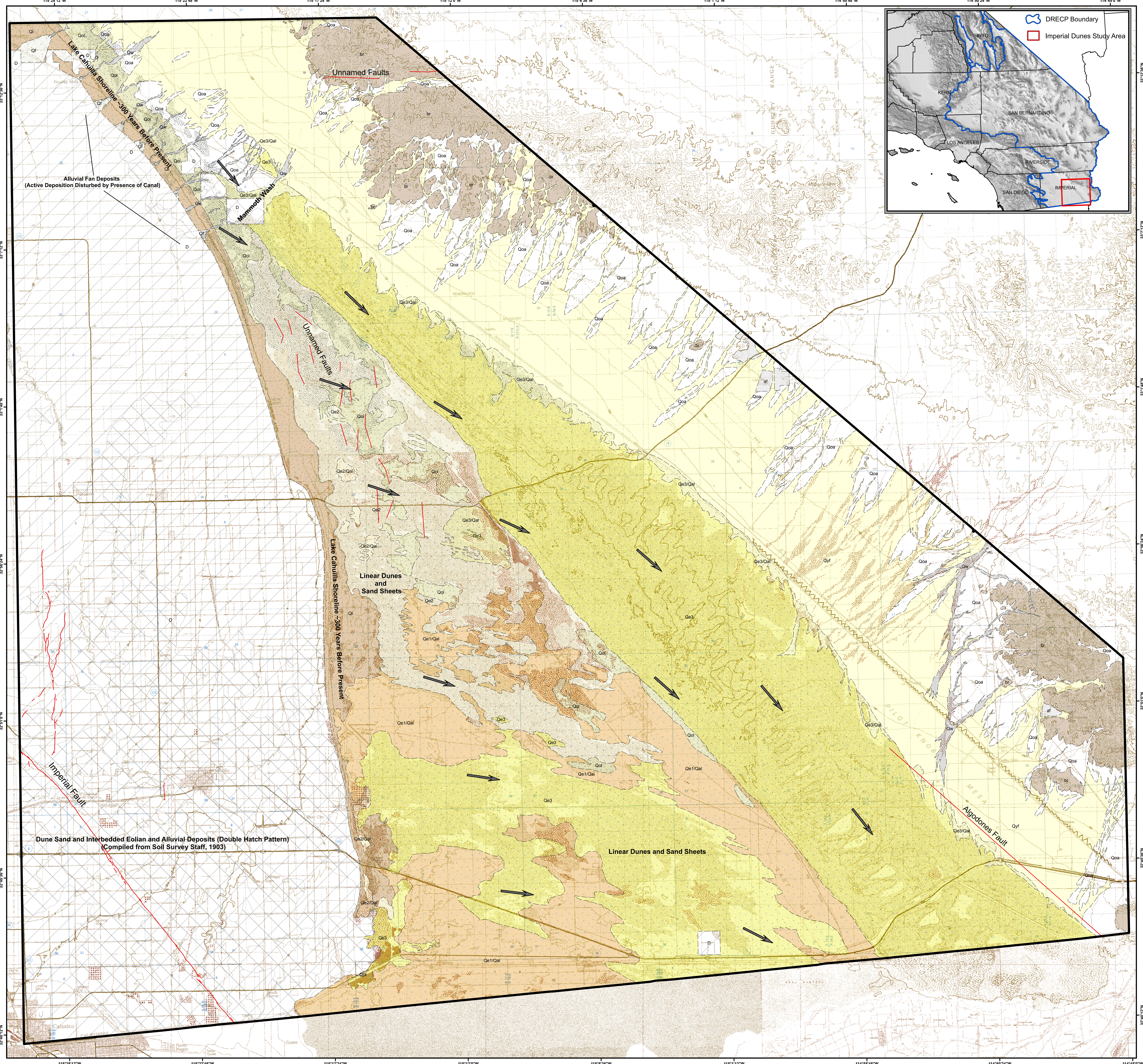
PLATE 4



Projection: Universal Transverse Mercator, Zone 11 North, North American Datum of 1983

Topographic base from U. S. Geological Survey El Centro 30X60 Minute Quadrangle, 1986, Contour Interval 20 Meters; U. S. Geological Survey Salton Sea 30X60 Minute Quadrangle, 1985, Contour Interval 50 Meters; U. S. Geological Survey Trigo Mountains 30X60 Minute Quadrangle, 1986, Contour Interval 50 Meters; U. S. Geological Survey Yuma 30X60 Minute Quadrangle, 1993, Contour Interval 20 Meters.

N

Map Scale: 1:100,000

5 2.5 0 5 Miles

10 5 0 10 Kilometers

EOLIAN SYSTEM MAP OF THE IMPERIAL DUNES AREA

A Project for the California Department of Fish and Wildlife By the California Geological Survey

By: Jeremy T. Lancaster CEG

PROJECT OVERVIEW

Eolian deposits are recognized as areas of higher biological value because they support specific natural communities and wildlife habitats. In response to potential increased land use from renewable energy projects in California where eolian deposits and processes are present, the California Department of Fish and Wildlife (CDFW) and the State and Federal Renewable Energy Action Team have designated sand dunes and their associated processes as areas of higher biological value for inclusion into a Habitat Conservation Plan / Natural Community Conservation Plan. This plan is known as the Desert Renewable Energy Conservation Plan (DRECP, http://www.drecp.org/). The Department of Conservation's California Geological Survey (CGS) provided CDFW with technical assistance on Eolian System Mapping under the Cooperative Endangered Species Conservation Fund (Section 6) Grant Program (Agreement Number P1382002). This project addresses the need for map-based information that identifies the presence of active eolian deposits and their source areas. The Imperial Dunes area is one of several priority areas that are part of the DRECP, identified as Development Focus Areas.

This map of the Imperial Dunes area was developed by CGS to assist in identifying components of the eolian system, including active areas of deposition, source areas, and zones of sand transport. This 100,000 scale map is based on compilation of existing sources and new mapping by CGS of Quaternary age surficial deposits that form the interpretive source in the identification of eolian deposits, sources, and zones of transport for the Imperial Dunes study area. Depending on the geomorphic setting, eolian processes range from primary to secondary (Blair and McPherson, 1994). Within the regional zone of transport, eolian sand accumulates as dunes, sand sheets, and sand ramps. Eolian processes are primary where thick deposits accumulate, develop dune forms, and influence the geomorphology of the landscape. Where these eolian sand accumulations attain sufficient thickness (> 1.5 m) they are typically portrayed as eolian deposits on geologic maps. However, complex interactions occur locally on the landscape between source, and deposition areas. Eolian sand is transported across playa lakes, playa fringe, alluvial fans, alluvial washes, and along bedrock divides. In these geomorphic settings, the primary processes acting on the landscape are gravity-driven flow of water and gravity-induced slope movements (e.g. translational failures and rockfalls). Along playa margins and piedmont landforms, transported eolian sediment interacts with vegetation and topographic irregularities that act as baffles, causing eolian sediment to deposit as thin sand sheets superimposed on these geomorphic surfaces. In the presence of vegetation, sand sheets are typically thin, relatively planar, and lack dune form (Cooke et al., 1993).

To address this complexity, CGS used a hybridized mapping nomenclature that identifies both the primary geomorphic process and the secondary processes superimposed on those features that are specific to eolian systems. Using an original surficial geologic nomenclature of Bedrossian et al. (2012), CGS developed a hybrid geologic nomenclature to identify the presence of eolian veneers. For example, a Holocene to late Pleistocene age alluvial fan (Qyf) within an active eolian transport corridor, may be overlain by a veneer eolian sand. In order to represent the superimposition of this secondary process on the landscape, the map unit is termed Qe/Qal. Conversely, the designation Qe is used singularly when the map unit attained an estimated thickness of > 1.5 m.

In addition to the hybridized mapping nomenclature, CGS used aerial photographic interpretation and field observations of deposit thickness, texture, and soil development in order to attribute map units with their relative state of activity. The relative state of activity is identified by observing the relative degree of soil development, including consolidation and pedogenic horizon development. Where eolian deposits have formed during past episodes of activity (late Quaternary), but have been stabilized by soil development, the land surface may have relatively lower reflectance, or albedo. Active eolian surfaces typically present features that suggest fresh scour of existing soil and vegetation, or deposition of eolian sand over pre-existing land cover. These surfaces have a relatively high albedo. The nomenclature used for this map area is slightly different than the other areas mapped as a part of this project. Where observations suggested a period of stability, eolian deposits are designated as Qe1 (Inactive). Where observations suggest relatively recent activity, eolian deposits are designated as Qe2 and Qe3.

This map, along with others developed as part of this study to address eolian system processes, is regional in nature and should not be used as a substitute for detailed studies in any specific area. It is intended for regional planning efforts and may be used as the framework to identify regional eolian processes and to guide future studies. For additional discussion regarding the Imperial Dunes area and other mapped areas, please refer to the project report (Lancaster and Bedrossian, 2014).

Imperial Dunes Area

The Imperial Dunes area is located entirely within the Colorado Desert geomorphic province, in Imperial County. The Colorado Desert geomporhic province is a low-lying barren desert basin dominated by the Salton Sea. The province is a depressed block between active branches of alluvium-covered San Andreas Fault with the southern extension of the Mojave Desert on the east. The western portion of the map area is characterized by the ancient beach lines and silt deposits of extinct Lake Cahuilla (CGS, 2002). The climate is arid, hot, and dry with average annual temperatures reported for Calexico ranging between 13.3° and 30.1°C (55.9° and 86.2° F) (DRI, 2014). According to the Desert Research Institute (DRI), January mean temperatures range from 3.9° to 19.6°C (39.0° to 67.2°F) and July mean temperatures range from 6.6° to 39.9°C (75.8° and 103.9°F). The average annual rainfall is 68.3 mm/yr (DRI, 2014).

The northwest trending Algodones Dunes form the prominent feature in the map area. As one of the largest active dune fields in the United States, they are up to 11 km wide and roughly 72 km long and extend from Mammoth Wash in the northwest into the northernmost part of Baja California. The Algodones dune field rests on the margin of an ancient lake bed that forms a topographically planar area called the East Mesa. The East Mesa area also contains prominent linear dunes, coppice dunes, and sand sheets. Both the Algodones and East Mesa dunes are dominated by the northwest-trending, fault-bound Salton Trough, which includes the Salton Sea to the northwest and the Imperial Valley, a broad 48 km wide, sparsely populated alluvium-filled valley that lies largely below sea-level to the south of the Salton Sea (Bedrossian, 2011). Below the valley alluvium lie 6100 m of Tertiary and Quaternary sedimentary rocks, predominantly non-marine sandstones, clays, and lacustrine deposits. This thick sequence of sediments is thought to have been derived from the Colorado River during several episodes of prehistoric deposition, i.e., whenever the river shifted its course away from the Gulf of California, where it now flows, to the Salton Trough (Muhs et al., 1995). Numerous active faults within and bordering the Salton Trough suggest it is a depressed block caused by seafloor spreading that is still widening the Gulf of California to the south. South of the Salton Sea, within the Imperial Valley, the western and eastern boundaries of the trough are characterized by ancient beach lines and silt deposits of the now extinct Lake Cahuilla. Late Pleistocene shorelines are thought to underlie the Algodones dune field on East Mesa and the late Holocene lacustrine shorelines of Lake Cahuilla are generally found at elevations of about +12-14 meters above sea level (Muhs et al., 1995). The East Mesa and Algodones dune field are bordered on the east by the Chocolate and Cargo Muchacho mountains. These mountains are composed of Precambrian igneous and metamorphic rocks, Mesozoic granitic and metamorphic rocks, and Tertiary volcanic rocks (Jennings, 1967; Muhs et al., 1995). Holocene alluvial wash and alluvial fan deposits, consisting mostly of gravel and sand, comprise the broad gently sloping piedmont between the mountains to the east and the East Mesa area.

Dune forms in the Algodones Dunes have been well described in studies by numerous authors including 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). Kocurek and Nielson (1986) mapped an east-west transect across the northwestern end of the Algodones Dunes and described the following sequence of dune forms: (1) sand sheet and zibars; (2) linear dunes, with zibars in interdune corridors; (3) compound-complex crescentric ridges or draa (farther to the southeast); and (4) an eastern sand sheet. CGS's current mapping is in general agreement with these four zones. In aerial photographs and on GoogleEarth imagery, coppice dunes, along the eastern and western margins of the sand sheets, and linear dunes and transverse or crescentric ridges are also present throughout the dune field (Muhs et al., 1995). Linear dunes and sand streaks (McKee, 1979) are present and visible on the East Mesa.

Interpretation and Description of Map Units

In this map area, CGS focused preliminary mapping efforts on the identification of Holocene age eolian deposits. Mapping included the identification of features related to primary geomorphic processes (e.g. alluvial fan), followed by interpretation of those deposits related to secondary processes (e.g. eolian sand sheets superimposed on alluvium). CGS made field observations and collected data in March and April 2014. These observations included identification of soil texture and pedogenic development, as well as descriptions of surface cover, including the presence of gravel lag, desert pavement, or the accumulation of freshly deposited eolian sands. Based on field observations, Quaternary alluvial deposits exhibiting soil development and/or having a gravel lag were not retained as map units. These are Pleistocene to mid-Holocene age deposits that have been isolated from deposition for thousands of years. Eolian transport may occur across these surfaces, but thick, laterally continuous deposition of eolian sand is of low potential.

The collection of site-specific wind data was not a part of the project scope, however, CGS used a relatively robust collection of published wind data in analyzing sand transport for the area. Utilizing sand rose data from four weather stations in the vicinity of the Algodones Dunes and one locality at the junction of the All-American and Coachella Canals, immediately west of the southern end of the Algodones Dunes (Sweet et al., 1988), Muhs et al. (1995) determined that: winds form a low energy regime in Indio and are from the northwest all year; winds form an intermediate energy wind regime at El Centro, in which winds are from the west most of the year and sand drift is predominantly west to east; at the junction of Coachella and All-American Canals, the overall drift of sand was from the northwest to southeast. Based on the dune features mapped by Kocurek and Nielson (1986), Muhs et al. (1995) mapped the orientations of linear dune crests, barchanoid ridge (draa) brinks (top of slip face or crest), and transverse ridge (draa) brinks in the Algodones Dunes, and crests of linear dunes and sand streaks on East Mesa, with the following results:

- Active linear dunes (linear sief) in the Algodones Dunes have a mean orientation of N43ºW±12º (n=89), which approximates the dominant dune-forming wind direction.
- Transverse and barcanoid ridges in the Algodones Dunes have a mean brink orientation of N45ºE±16º (n=57), also implying a dominant dune-forming wind direction from the northwest, about N45ºW.
- Linear dunes and streaks on East Mesa have a mean orientation of N71ºW±9º (n=255), although the southernmost dunes on East Mesa have an orientation that is closer to the mean orientation of the Algodones Dunes.
- Because the East Mesa dunes appear to have been stabilized only within the past few hundred years or less, the differences in resultant drift directions on East Mesa may be due to significant differences in resultant drift directions in different parts of the Salton Trough, even over short distances.

To evaluate possible eolian sand sources for the Algodones Dunes and East Mesa, Muhs et al. (1995) performed simple mineralogical studies on a total of 114 samples. Samples were taken from a variety of dune types, sand sheets, alluvial fans, floodplains, and river channels. Semi-quantitative estimates of the relative amounts of quartz, potassium (K)-feldspar, and plagioclase in Algodones and East Mesa eolian sediments were made using x-ray diffractometry (Muhs et al., 1995). Results were then compared with data on the composition of Colorado River sediments previously studied by Van Andel (1964), Olmstead et al. (1973), and Van de Kamp (1973). These studies showed that Colorado River sediments are characterized mostly by quartz (65 to 75%), with lesser amounts of feldspar (10 to 20%), and rock fragments (1 to 8%). Data from Muhs et al. (1995) indicated that Lake Cahuilla sediments have a similar composition to the Colorado River deposits, but contain significantly more quartz and less plagioclase than San Bernardino Mountains-derived alluvium. Muhs et al. also found that Colorado River and Lake Cahuilla sediments are generally higher in quartz than alluvial deposits derived from the Chocolate Mountains. Although their findings differed somewhat from Van de Kamp (1973) who found lower quartz abundances in the Lake Cahuilla sediments than in the Colorado River sediments, Muhs et al. (1995) concluded the Lake Cahuilla sediments were most likely derived from Colorado River, with possibly some contributions from the Chocolate Mountains, but with little or no contribution from the San Bernardino Mountains. Their data also indicated that, since there were no significant differences between eolian sediments in the Algodones Dunes and East Mesa, the two areas appear to have a common origin, i.e., eolian sediments in the Algodones Dunes and in East Mesa were derived from Lake Cahuilla sediments, which in turn were derived mainly from the Colorado River. Based on their wind, mineralogical, and trace element studies, combined with data provided by Havholm and Kocurek (1988), Muhs et al. (1995) concluded that (1) the dominant dune-forming winds are from the northwest on both the Algodones and East Mesa dune fields, (2), that the Lake Cahuilla shoreline deposits both west and northwest of the dunes are the immediate source of the eolian sediments; and (3) that the northwest prevailing winds during fall, winter, and spring are responsible for the movement of eolian sand from the shore line to the dune fields.

Field observations by CGS indicated that while eolian transport occurs across the East Mesa area, between the former Lake Cahuilla deposits and the Algodones dune field, there are local differences in accumulation activity. The northern and central region of East Mesa was perhaps actively accumulating eolian deposits as linear dunes, coppice dunes, and sand sheets after the desiccation of Lake Cahuilla, about 300 years before present (Waters, 1983). However, field observations indicate, that in part, dunes and sand sheets in this area are stabilized by vegetation. These eolian deposits exhibited no soil development (map unit Qe2 and Qe2/Qal) and show locally active accumulations of eolian sand, wind abrasion (erosion), entrainment, and transport. Because the East Mesa dunes appear to have been stabilized only within the past few hundred years or less, Muhs et al. (1995) explored the use of an index of dune mobility (M), originally developed by Lancaster (1988). Using 11 localities in or adjacent to sand dunes or sand sheets in the Colorado Desert, Muhs et al. (1995) found the region should have fully active dunes. The only exception to the predicted and observed degree of activity was the stabilized eolian deposits on East Mesa. Based on various water table elevation studies reported by Loeltz et al. (1975), and the review of aerial photographs, Muhs et al. concluded that stabilization of the East Mesa Dunes and sand sheets may have been caused by recent rises in the water table because of local recharge of ground water from irrigation and canal leakages since 1939. An additional explanation could be that the source of eolian sand in this area has been reduced given the change in land use over the last century to west of the East Mesa area. Conversely, the southern portion of East Mesa has a laterally extensive body of active sand sheets and dunes. CGS reviewed both the most recent USDA soil maps (1981) as well as soil data developed for the Imperial area in 1903. In general, the eolian deposits on the East Mesa align with soils mapped in the Rositas Series (Soil Survey Staff, 1981). Mapping in 1903 of the lowlands to the west of the mesa, indicates that the valley's surficial deposits are comprised of Dune Sand, Imperial Sand, Gila Sandy Loam, Imperial Sandy Loam, Imperial Loam and Imperial Clay. Of these, the sand and sandy loam soils are described as being of eolian source (Soil Survey Staff, 1903). The general locations of these soils have been digitized, grouped, and presented on the map as a cross hatched pattern. While they lie within an area of agricultural land use that is mapped as disturbed (D), they give an indication of potential eolian sources prior to the development of the area for agricultural purposes.

The Algodones dune field is an effective barrier to sediment transport from alluvial wash and alluvial fans onto the East Mesa area. Sediment is impounded on the northern margin of the dune field from Mammoth Wash to the Mexican border. Alluvial embayments occur along the northern margin of the dune field, suggesting that sediment from the Chocolate and Cargo Muchacho mountains is incorporated into the dunes along the northern margin. This observation is consistent with the conclusion by Muhs et al. (1995) that there is some contribution from the Chocolate Mountains. Sand sheets and coppice dunes mantle the surface within the embayments along the northern margin (Map unit Qe3/Qal). Mammoth Wash forms the western boundary of the Algodones Dunes. This wash and many others to the west are incised into older alluvium (Qol and Qoa), becoming distributary alluvial fans (Qf) that prograde onto the younger lake bed deposits of Lake Cahuilla (Ql). Sand transport occurs from the source Lake Cahuilla deposits (Ql) across the surface of the older alluvium and into the western tip of the dune field. Eolian sand accumulations begin to thicken a mile west of Mammoth Wash (Qe3/Qal), transitioning into the thick deposits with dune form to the east of Mammoth Wash (Qe3). The following description of map units summarize CGS' observations.

Active Eolian Deposits

Qe3/Qal Active windblown deposits consisting primarily of sand sheets and coppice dunes superimposed on alluvial deposits typically < 1.5 m in thickness. Sand is predominantly fine- to medium- grained. Dry color is typically very pale brown 10YR 7/4.

Qe3 Active windblown deposits consisting of dunes and sand sheets typically greater than > 1.5 m in thickness. Sand is predominantly fine- to medium- grained. Dry soil color is very pale brown to yellow 10YR 7/4 to 7/6. Dunes include transverse, cresentric, parabolic and barchan forms, as well as coppice dunes and amorphous sand hummocks.

Qe2/Qal Active and partially stabilized windblown deposits consisting of sand sheets and coppice dunes superimposed on alluvial deposits, typically < 1.5 m in thickness. Sand is predominantly fine- to medium- grained. Dry soil color is light brown to pink 7.5YR 6/4 – 6.

Qe2 Active and partially stabilized windblown deposits consisting of dunes and sand sheets typically > 1.5 m in thickness. Sand is predominantly fine- to medium-grained. Dry soil color is light brown to pink 7.5YR 6/4 – 6 and light yellowish brown 10YR 6/4. Dune forms include linear, coppice dunes and amorphous sand hummocks.

Active Eolian Sources

Ql Lacustrine deposits of former Lake Cahuilla. As mapped these deposits are composed of beach ridge gravels and sand deposited on the most recent Lake Cahuilla shore line. To the west of East Mesa these deposits include clay and silt derived from the Colorado River delta.

Qw Alluvial wash deposits consisting of unconsolidated fine - to coarse-grained sand and sandy gravel with subordinate fine sand and silt, bar and swale morphology.

Qf Alluvial fan deposits of latest Holocene age. Unconsolidated to slightly consolidated sand and gravel, poorly to moderately sorted, fine - to coarse-grained; gravel includes pebbles, cobbles, and boulders. Surfaces exhibit bar and swale morphology, locally obscured by eolian deposition, and are traversed by active alluvial washes (Qw).

Qyf Alluvial fan deposits of latest Pleistocene and Holocene age. Unconsolidated to slightly consolidated sand and gravel, poorly to moderately sorted, fine - to coarse-grained; gravel includes pebbles, cobbles, and boulders. As mapped, this unit forms on the bajada between the Imperial Dunes and the Chocolate Mountains. Locally, this map units contains active alluvial fans and washes that cannot be displayed at the map scale.

Qe1/Qal Stabilized windblown deposits consisting of sand sheets superimposed on lacustrine and alluvial deposits of Pleistocene age, typically < 1.5 m in thickness. Surface is typically deflated and mantled by moderately varnished lag consisting of sub- to well-rounded gravels 30 to 50 mm in diameter. Gravel lag is underlain by a silty vesicular horizon to 10 mm.

Potential Eolian Sources

Qol Lacustrine deposits of Pleistocene age. As mapped these deposits underlie the East Mesa area and where exposed are mantled by moderately varnished lag consisting of sub- to well-rounded gravels 30 to 50 mm in diameter. Gravel lag is underlain by a silty vesicular horizon to 10mm developed on silty, very fine sand with abundant tufa nodules. Dry soil color is reddish yellow 7.5YR 6/8.

Other Map Units

Qoa Alluvial deposits of Pleistocene age (undifferentiated). This map unit is comprised of alluvial fan, alluvial valley, and alluvial terrace deposits. In general, these deposits are capped by a gravel lag or desert pavement with moderate to strongly developed desert varnish.

D Areas with in active sand transport/deposition resulting from anthropogenic modification of the land surface. In the map area, these include farms and other land uses larger than 10 acres.

af Artificial fill

br Bedrock (undifferentiated). This map unit is comprised of a variety of Paleozoic sedimentary, Mesozoic granitic, and Tertiary volcanic and sedimentary rocks.

Contact between map units, approximately located. May be gradational where local variations in map unit thickness exist.

Quaternary faults compiled by Bryant (2005)

Predominant transport direction. Inferred from geomorphic interpretation of dune crest migration, sand sheets and streaks, and ventifacts. Active sand transport occurs between mapped source and active eolian deposits.

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