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Airborne dust transport to the eastern Pacific Ocean off southern California: Evidence from San Clemente Island

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

James Budahn
U.S. Geological Survey

Marith Reheis
U.S. Geological Survey

Jossh Beann
U.S. Geological Survey

Gary Skipp
U.S. Geological Survey, gskipp@usgs.gov

See next page for additional authors

Authors

Daniel R. Muhs, James Budahn, Marith Reheis, Jossh Beann, Gary Skipp, and Eric Fisher

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Daniel R. Muhs,[1] James Budahn,[1] Marith Reheis,[1] Jossh Beann,[1] Gary Skipp,[1] and Eric Fisher[1]

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[1] Islands are natural dust traps, and San Clemente Island, California, is a good example. Soils on marine terraces cut into Miocene andesite on this island are clay-rich Vertisols or Alfisols with vertic properties. These soils are overlain by silt-rich mantles, 5–20 cm thick, that contrast sharply with the underlying clay-rich subsoils. The silt mantles have a mineralogy that is distinct from the island bedrock. Silt mantles are rich in quartz, which is rare in the island andesite. The clay fraction of the silt mantles is dominated by mica, also absent from local andesite, and contrasts with the subsoils, dominated by smectite. Ternary plots of immobile trace elements (Sc-Th-La and Ta-Nd-Cr) show that the island andesite has a composition intermediate between average upper continental crust and average oceanic crust. In contrast, the silt and, to a lesser extent, clay fractions of the silt mantles have compositions closer to average upper continental crust. The silt mantles have particle size distributions similar to loess and Mojave Desert dust, but are coarser than long-range-transported Asian dust. We infer from these observations that the silt mantles are derived from airborne dust from the North American mainland, probably river valleys in the coastal mountains of southern California and/or the Mojave Desert. Although average winds are from the northwest in coastal California, easterly winds occur numerous times of the year when "Santa Ana" conditions prevail, caused by a high-pressure cell centered over the Great Basin. Examination of satellite imagery shows that easterly Santa Ana winds carry abundant dust to the eastern Pacific Ocean and the California Channel Islands. Airborne dust from mainland North America may be an important component of the offshore sediment budget in the easternmost Pacific Ocean, a finding of potential biogeochemical and climatic significance.

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1. Introduction

[2] Interest in the windblown transport of dust has increased tremendously over the past decade. The new interest is in part a reflection of the recognition that dust plays an important role in many aspects of the Earth's physical systems [*Mahowald et al.*, 1999, 2006; *Kohfeld and Harrison*, 2001]. Dust can travel great distances [*Prospero and Lamb*, 2003; *Prospero et al.*, 2002], thereby influencing radiative transfer in the atmosphere and affecting climate [*Harrison et al.*, 2001; *Tegen*, 2003]. In addition, Fe-rich dust can fertilize the ocean's primary producers [*Jickells et al.*, 2005] and consequently impact the global carbon cycle [*Falkowski et al.*, 1998]. Furthermore, dust may be significant for plant communities in nutrient-limited ecosystems [*Swap et al.*, 1992; *Reynolds et al.*, 2001, 2006; *Muhs and Benedict*, 2006].

[3] Another effect of dust, and one that has received less attention, is that it can form or at least influence the parent material for soils. It is now known, for example, that Asian dust plays a major role in the genesis of soils on many Pacific islands, including the Marianas [*Birkeland*, 1999, pp. 199–200] and Hawaii [*Jackson et al.*, 1971; *Vitousek et al.*, 1997; *Chadwick et al.*, 1999]. Saharan dust influences the development of soils around many parts of the Mediterranean basin [*Yaalon and Ganor*, 1973; *Avila et al.*, 1997]. Detailed measurements of African dust, conducted over four decades, have shown there is a seasonal delivery of clay-rich dust to the Atlantic Ocean [*Prospero and Lamb*, 2003]. Studies conducted on the Canary Islands, composed of basalt, show that soils and sediments there contain abundant quartz and mica, neither of which is found in the basalt bedrock [*Mizota and Matsuhisa*, 1995; *Rognon and Coudé-Gaussen*, 1996; *Zöller et al.*, 2004; *Ortiz et al.*, 2006]. Exotic minerals in Canary Islands soils and sediments are almost certainly derived from African dust, on the basis of examination of satellite imagery [*Criado and Dorta*, 2003]. New geochemical data show that African

[1]U.S. Geological Survey, Denver, Colorado, USA.

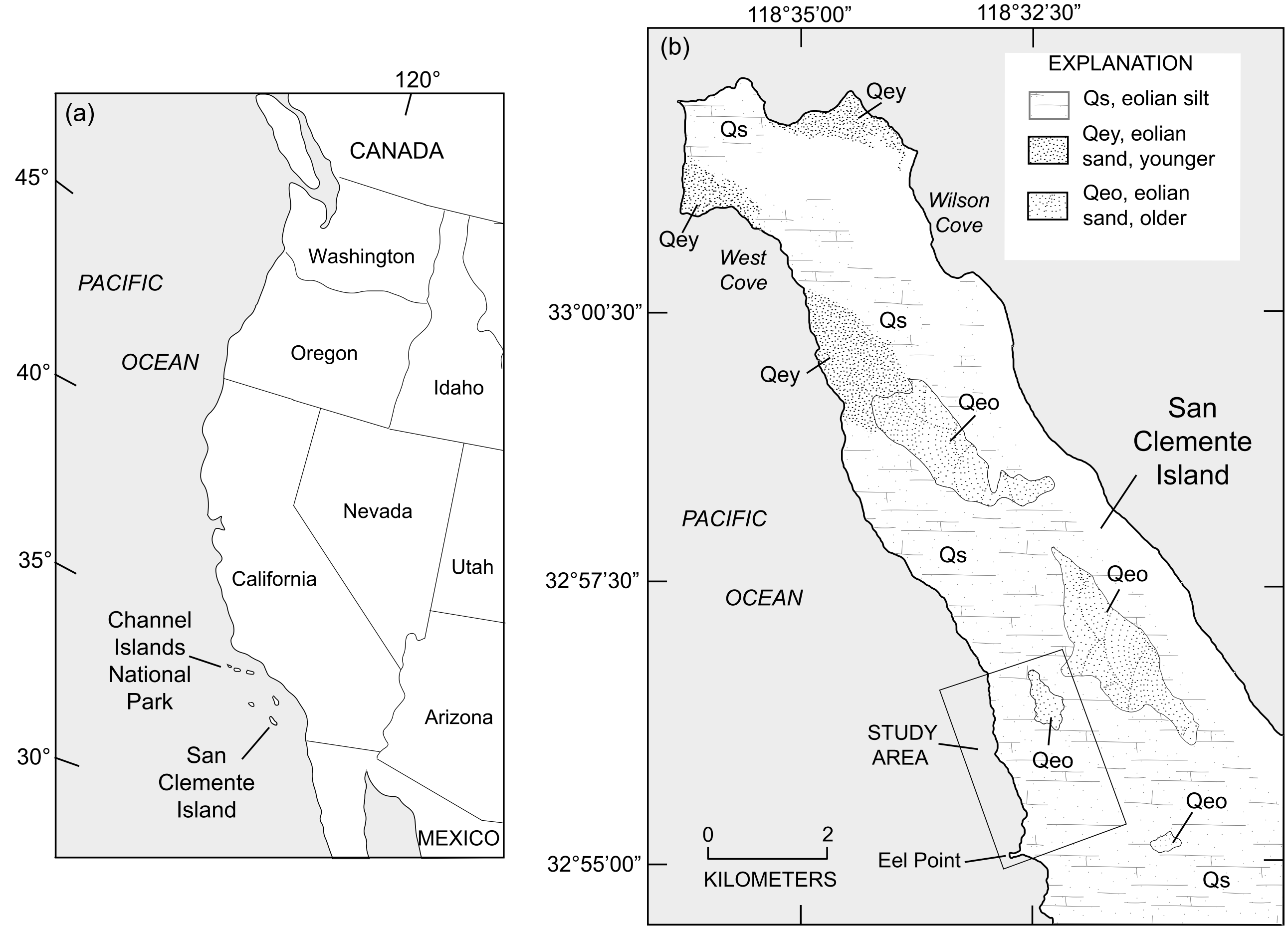

Figure 1. (a) Map of the western United States, showing location of San Clemente Island and Channel Islands National Park. (b) Map of northern San Clemente Island, showing eolian deposits. Eolian sand distributions from *Muhs et al.* [2002]; approximate extent of eolian silt mantles from this study.

dust is a major parent material for soils on islands as distant as the western Atlantic Ocean [*Muhs et al.*, 2007].

[4] The major sources and transport pathways of modern dust, worldwide, have been identified by analysis of data from the total ozone mapping spectrometer (TOMS) on the Nimbus 7 satellite [*Prospero et al.*, 2002], and results are in good agreement with global dust-generation modeling based on climate and vegetation [*Mahowald et al.*, 1999, 2006]. Three of the greatest sources of dust in the world today are North Africa, Central Asia, and the Arabian Peninsula. In North America, the largest dust sources are the deserts of the southwestern United States and northwestern Mexico [*Mahowald et al.*, 1999, 2006; *Prospero et al.*, 2002]. A network of traps in the Mojave and Sonoran Deserts of North America, monitored for two decades, shows that erosion, transportation, and deposition of dust are major processes of sediment exchange across the region [*Reheis and Kihl*, 1995; *Reheis et al.*, 2002; *Reheis*, 2003, 2006].

[5] In this paper, we reexamine a hypothesis presented earlier that some North American dust is delivered to the eastern Pacific Ocean, during easterly "Santa Ana" wind events. Earlier studies report a silt-rich mantle, 5–20 cm thick, in the upper part of soil profiles covering marine terraces of diverse ages on San Clemente Island, California [*Muhs*, 1982, 1983]. This silt mantle has been hypothesized to represent an accumulation of airborne dust from a source or sources external to the island.

2. Study Area and Sources of Dust

2.1. Islands as Dust Traps and San Clemente Island as a Study Area

[6] Islands are natural dust traps, a concept that was recognized by *Darwin* [1846] when he observed African dust on the Cape Verde Islands during his voyage on the *Beagle*. Insular soils provide an ideal setting for identification of eolian inputs to the surrounding oceans because they have limited local sources of sediment. In addition, islands are often composed of rocks whose compositions contrast strongly with dust. Most fine-grained eolian sediments (dust and loess) have an average upper continental crustal composition [*Taylor and McLennan*, 1985, 1995; *McLennan*, 1989; *Gallet et al.*, 1998; *Jahn et al.*, 2001; *Muhs and Budahn*, 2006; *Muhs et al.*, 2007]. Oceanic islands typically are composed of basic volcanic rocks (basalt, if derived from mantle hot spots, or andesite in many subduction zone settings) and (or) relatively pure limestones, if derived from constructional reef growth.

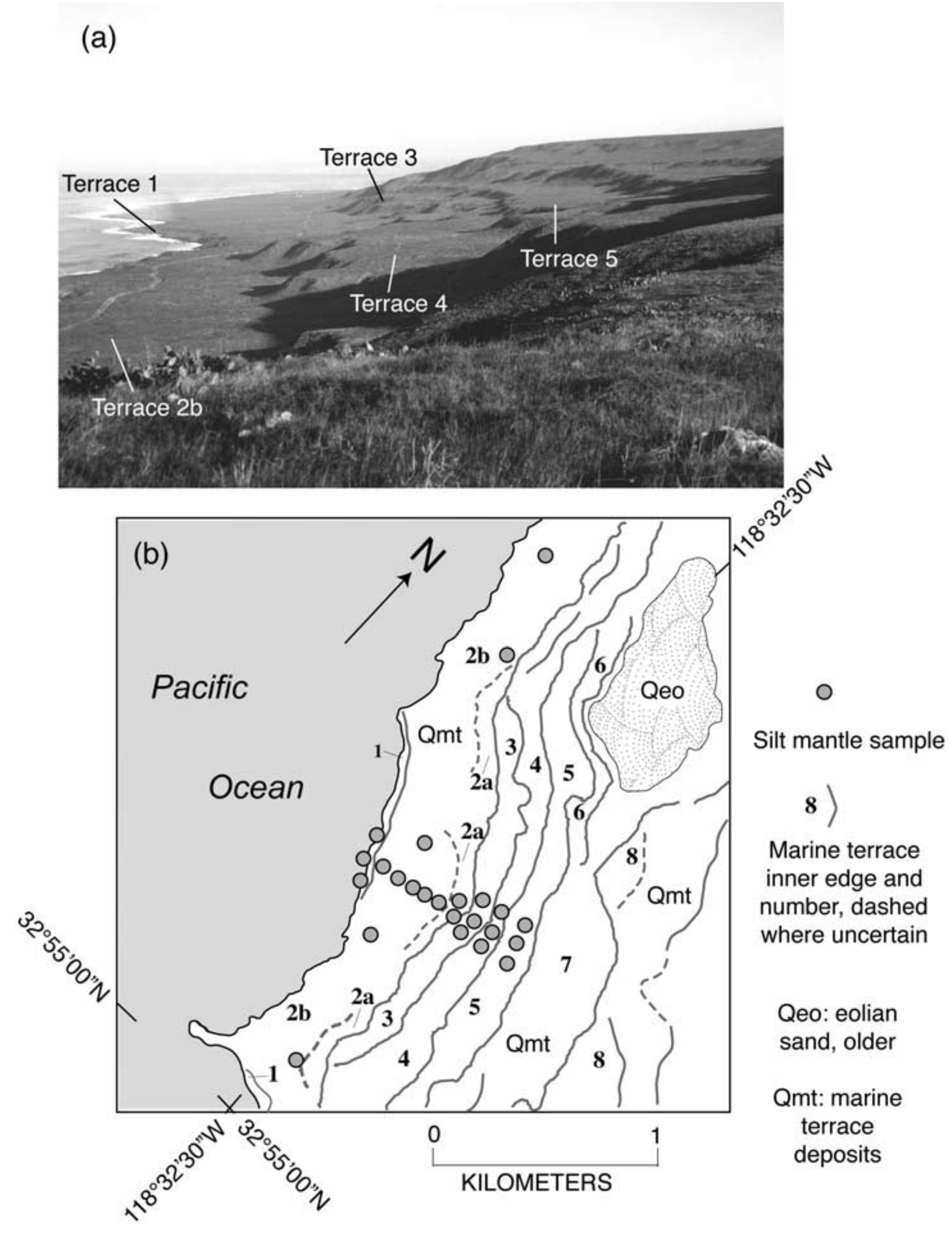

Figure 2. (a) Photograph of lower marine terraces north of Eel Point, looking north; photo by D. R. Muhs. (b) Map of marine terrace inner edges in the Eel Point study area [*Muhs et al.*, 2002] and location of silt mantle sites (circles).

[7] In order to examine possible dust inputs to the eastern Pacific Ocean, we studied soils on San Clemente Island, California. The island is situated ~100 km off the southern California coast (Figure 1) and is composed largely (~95%) of Miocene andesite, with much smaller amounts of dacite and rhyolite [*Olmsted*, 1958]. The geomorphology of the island is dominated by spectacular flights of marine terraces (Figure 2a), formed by Quaternary sea level highstands superimposed on steady tectonic uplift [*Muhs et al.*, 2002]. Fossil corals in the deposits of terrace 2b, with an inner edge of ~25 m elevation, date to ~120 ka [*Muhs et al.*, 2002]. We calculate a long-term average uplift rate of ~0.158 m/ka on the basis of the age, elevation, and paleo-sea level (+6 m) of terrace 2b. Using this uplift rate, inner edge elevations, and an assumption of paleo-sea levels near present at the time of higher terrace formation, yields ages of ~200 ka, ~335 ka, ~430 ka, and ~575 ka, for terraces 2a, 3, 4, and 5, respectively. The first terrace probably dates to the ~80 ka highstand of sea, well dated elsewhere in the region [*Muhs et al.*, 2002].

[8] Soils on the first and second terraces of San Clemente Island are Alfisols with clay-rich B horizons that show some vertic properties (Figure 3a). Soils on higher terraces are even more clay-rich and are classified as fully developed Vertisols. Vertisols contain high amounts of swelling clays (smectites) and develop large desiccation cracks during a dry season, which in California is in summer. Nevertheless, 5-to-20-cm-thick surface horizons of all these soils are light-

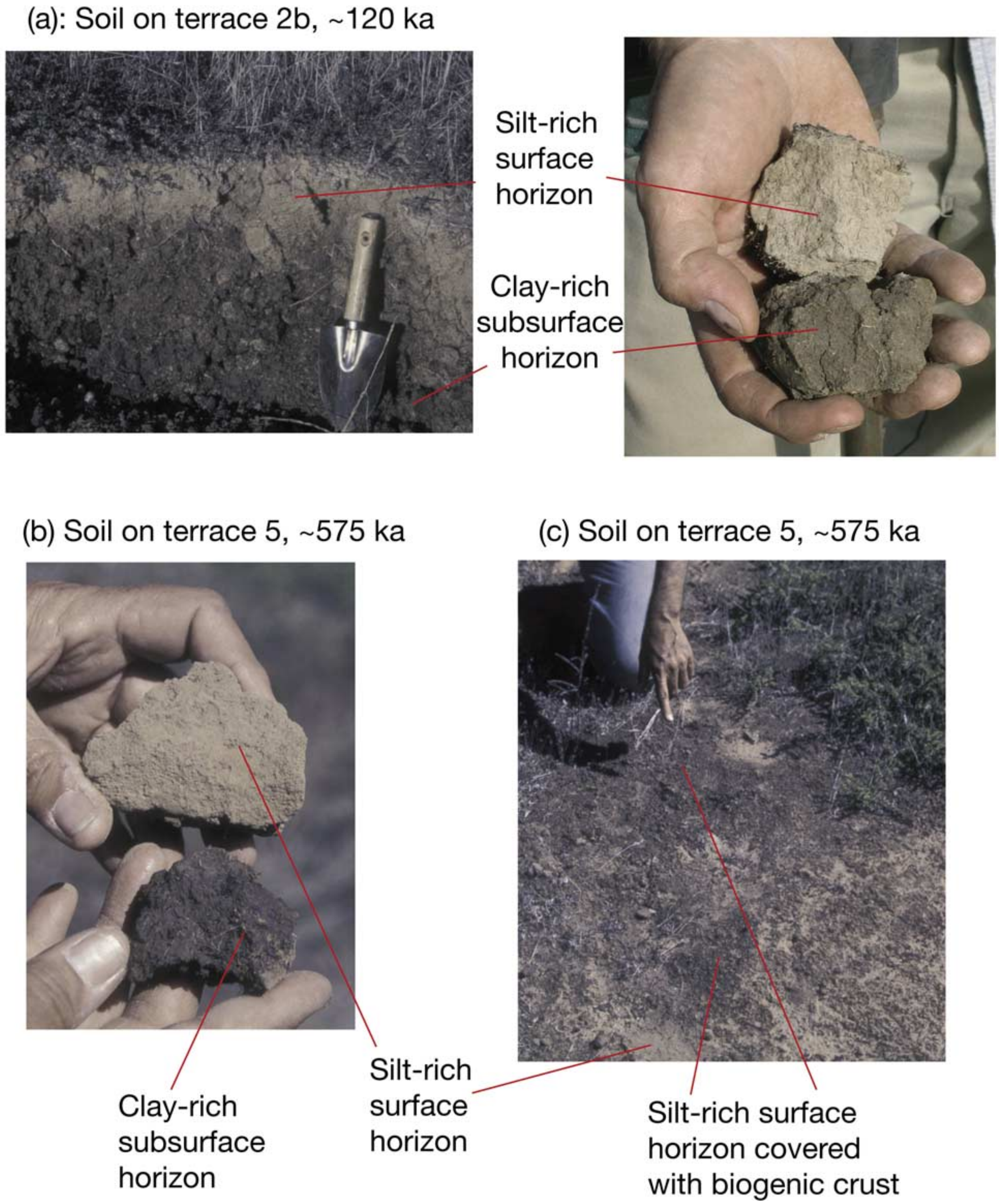

Figure 3. Photographs of silt mantles and associated features on San Clemente Island. (a) Alfisol with silt mantle overlying clay-rich subsoil on terrace 2b, dated to ~120 ka and hand specimens of surface and subsurface horizons. (b) Hand specimens of soils, showing color contrast between silt mantle and clay-rich subsoil of Vertisol on terrace 5, estimated to be ~575 ka. (c) Biological (biogenic) soil crust on surface of silt mantle on Vertisol on terrace 5. Photos by D. R. Muhs.

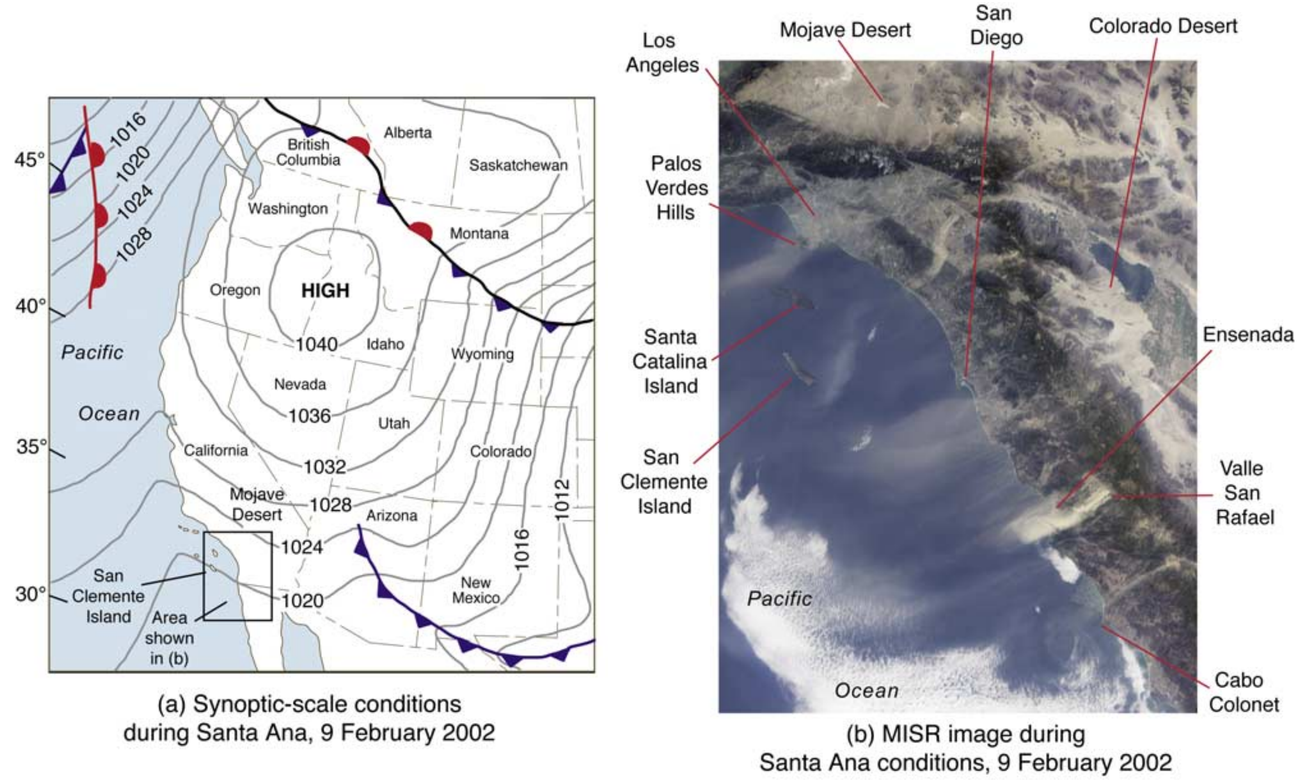

Figure 4. (a) Map of the western United States, showing location of San Clemente Island and positions of air masses, major fronts, and surface pressures (in millibars) during Santa Ana wind conditions of 9 February 2002 (from NOAA archives). (b) Multiangle Imaging SpectroRadiometer (MISR) image from the Terra spacecraft (orbit 11423), 9 February 2002 (courtesy of NASA/GSFC/LaRC/JPL, MISR Team), showing an example of dust transport from mainland California and Baja California to the eastern Pacific Ocean under Santa Ana wind conditions.

colored (10YR 5/3, 6/3, or 7/3, dry), massive, silt-rich zones that resemble loess, or eolian silt [*Muhs*, 1982, 1983]. The silt mantles contrast strongly with the darker, clay-rich subsoils found in both the Alfisols and Vertisols (Figures 3a and 3b). They resemble desert loess mantles found in the Mojave Desert [*McFadden et al.*, 1986]. In places, they are anchored with a biological ("cryptogammic") soil crust (Figure 3c), similar to those described elsewhere [*Belnap and Gillette*, 1998; *Belnap and Lange*, 2001; *Belnap*, 2002; *Eldridge and Leys*, 2003; *Reynolds et al.*, 2001, 2006].

[9] Vertisols (or soils such as Alfisols that have some vertic properties) are common in the western USA, and the U.S. Natural Resources Conservation Service (NRCS) recognizes and maps 86 official soil series (local mapping units) that belong to the Vertisol order in California alone [*Soil Survey Staff*, 2006]. Almost all of these soil series, with the exception of those on San Clemente Island itself (or nearby Santa Cruz Island, in Channel Islands National Park: Figure 1a), have surface horizons with textures that fall into the "clay" or "silty clay" categories, not silt loam as is the case on San Clemente Island. Furthermore, virtually all of the soil series have surface horizons with well-developed angular blocky, subangular blocky, granular, or, less commonly, prismatic structure, in contrast to a massive (structureless) state such as the silt mantles on San Clemente Island. In sum, massive, light-colored, silt-rich surface horizons simply are not characteristic of Vertisols in California. This suggests that the silt mantles have a geologic, rather than pedologic origin.

[10] It is difficult to ascertain the age of the silt mantles on San Clemente Island. They probably were deposited as a sediment blanket at about the same time, on the basis of their similar thickness and composition on terraces of widely varying ages. Thus the silt mantles must be younger than the youngest terrace in the sequence, which is ~80 ka. The silt mantles could even be as young as late Holocene. This age estimate is based on a single radiocarbon age of ~3 ka (cal BP) on midden shells in an alluvial fan that is overlain by a silt mantle [*Muhs*, 1983].

2.2. Sources of Dust Delivered to the Easternmost Pacific Ocean Off Southern California

[11] In the midlatitudes of the Northern Hemisphere, major eolian sediment inputs to the Pacific Ocean are considered to be largely from Asia [*Rea*, 1994]. This view is not surprising because the north Pacific Ocean is dominantly within the zone of the westerlies. *Olivarez et al.* [1991] reported that the grain size of eolian particles from deep-sea cores in the northwestern Pacific Ocean (east of Japan) range from ~2 μm to ~4 μm. Deep-sea sediments in this region of the Pacific Ocean have trace element compositions that indicate they are derived mostly from dust from Asia with a smaller amount of volcanic ash. Fine-grained

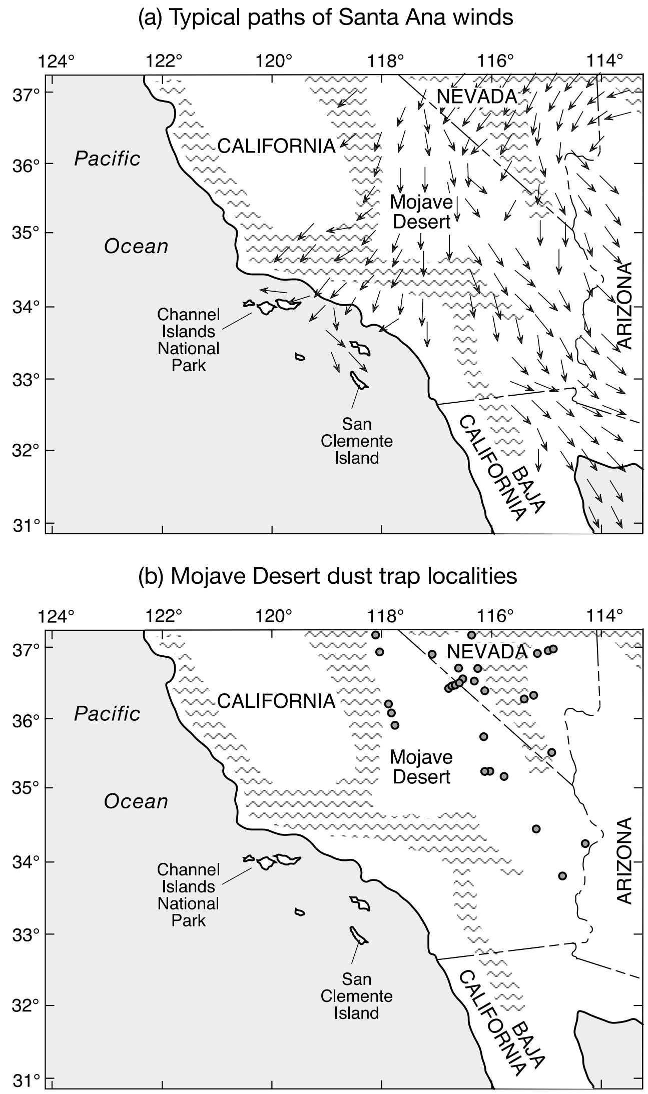

Figure 5. (a) Map of southern California and adjacent areas, showing patterns of wind direction during "Santa Ana" events. Map simplified from model simulations courtesy of Robert Fovell, Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles (http://www.atmos.ucla.edu/~fovell/ASother/mm5/SantaAna/winds.html). (b) Map of southern California and adjacent areas, showing location of San Clemente Island and dust trap localities [*Reheis*, 2003, 2006; *Reheis et al.*, 1995, 2002] in the Mojave Desert.

eolian dust from Asia can travel even farther, as it has been reported from soils on Hawaii, as mentioned above. Indeed, Asian dust has been traced on satellite imagery all the way across the Pacific Ocean to North America during April 1998 [*Husar et al.*, 2001; *Tratt et al.*, 2001], and may be a consistent source of sediment input to western North America in many years [*VanCuren and Cahill*, 2002].

[12] Despite the evidence of long-range transport of dust from Asia to the north Pacific Ocean, North America can also be a source of dust during "Santa Ana" wind conditions, at least to the eastern Pacific Ocean (Figure 4). In contrast to the usual westerly flow of air from the Pacific Ocean to southern California, Santa Ana conditions bring about winds that blow offshore (Figure 5a). These winds develop when there is relatively low pressure over the eastern Pacific Ocean off southern California and a high-pressure cell settles in the Great Basin region of Nevada, Utah, eastern Oregon, and southern Idaho (Figure 4) after the passage of a cold front [*Raphael*, 2003; *Lu et al.*, 2003]. The resulting pressure gradient from the Great Basin to the eastern Pacific Ocean results in strong northerly or north-easterly winds over the Mojave Desert and coastal southern California and Baja California. Santa Ana winds have speeds well in excess of 10 m/s and can have gusts as high as 35 m/s [*Hu and Liu*, 2003]. Examination of images taken by the Multiangle Imaging SpectroRadiometer (MISR) and the Moderate Resolution Imaging Spectroradiometer (MODIS) on the NASA Terra and Aqua spacecraft on 6 January 2002, 7 February 2002, and 27 November 2003 show large fluxes of dust from mainland North America during Santa Ana wind events (Figures 4b and 6). In these images, large dust plumes can be seen moving westward across coastal southern California and northern Baja California to the eastern Pacific Ocean, Santa Catalina Island, and San Clemente Island. Santa Ana winds typically occur several times a year, starting in fall, peaking in winter, and ending in spring [*Raphael*, 2003]. Examination of sediment records from Santa Barbara Basin indicates that Santa Ana winds have been a part of southern California climatology for hundreds of years as a minimum [*Mensing et al.*, 1999].

3. Methods

[13] Our approach in this study is to examine the silt mantles on marine terrace soils of San Clemente Island, previously studied by *Muhs* [1982, 1983], to determine if they have a source other than the local island bedrock, and if so, what that source might be. Eolian sand was previously mapped on the island [*Muhs et al.*, 2002, Figure 1b]. In the present study, we also mapped the approximate distribution of silt-rich mantles (shown as "Qs" on Figure 1b). The silt-rich mantles are found on marine terraces of all ages as well as some bedrock surfaces, and are lacking only on steep slopes, such as sea cliffs, and on stabilized sand dunes, where the silt content is diluted by what we interpret to be recent eolian sand.

[14] Silt mantles were collected from the lower six terraces on San Clemente Island (Figures 2a and 2b). Although the mantles are dominated by silt-sized particles (53–2 μm), they also contain some clay (<2 μm), and sand (2000–53 μm). If some part of these surface mantles is derived from airborne dust, it is most likely the fine-grained components, silts and clays, which can be transported in suspension. Eolian sands are transported dominantly by saltation within the lower ~2 m of the boundary layer. On an island, this precludes anything but a local origin for eolian sand. Thus sands, silts, and clays in the mantles were fractionated and analyzed separately. We used trace element geochemistry to characterize, or "fingerprint," the composition of the local island bedrock (dominantly andesite) and compared this composition to the sand, silt, and clay fractions of the surface soils. Bulk mineralogy of the silt mantles and island bedrock was determined by X-ray

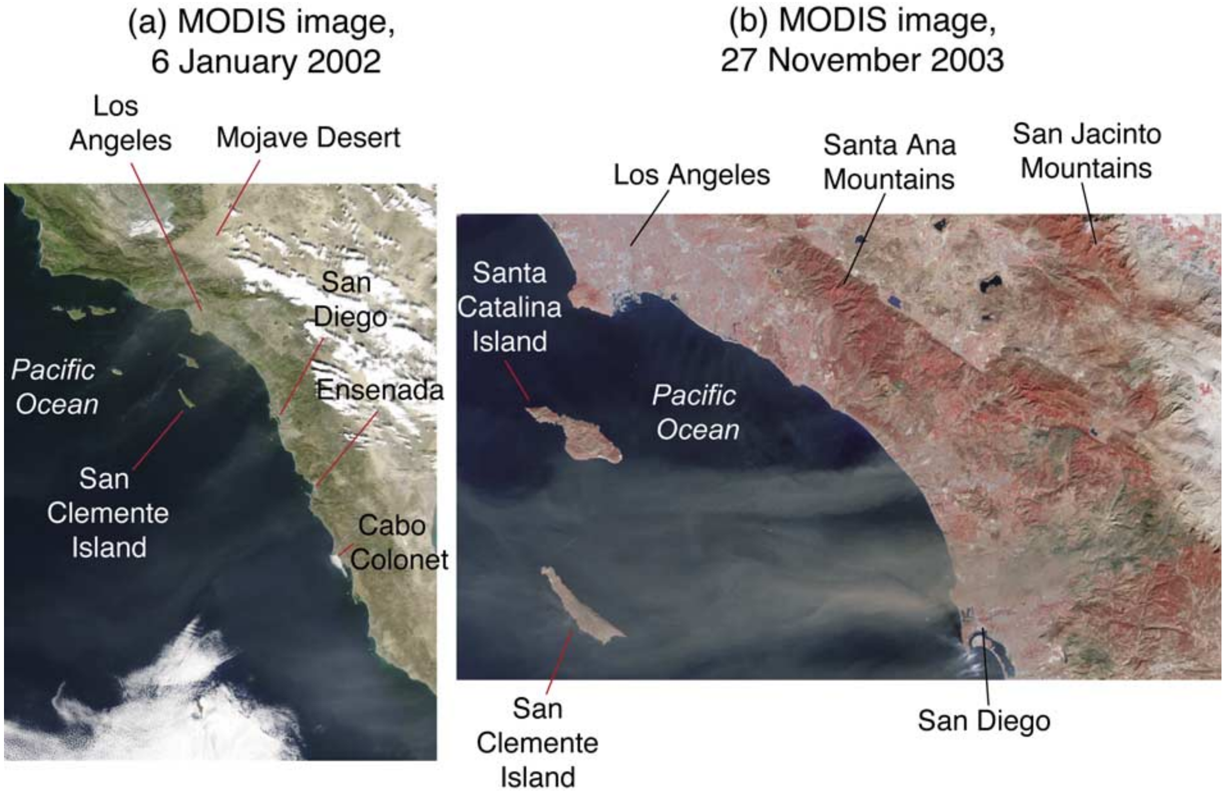

Figure 6. Examples of dust transport from mainland California and Baja California to the eastern Pacific Ocean and the California Channel Islands under recent Santa Ana wind conditions: (a) true-color image from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua spacecraft, 6 January 2002 (courtesy of Jeff Schmaltz, NASA/GSFC/MODIS Rapid Response Team); (b) false-color, nadir image from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua spacecraft, 27 November 2003. Plumes from the mainland to the Channel Islands in this image consist of dust, but also ash from recently burned areas on the mainland (courtesy of Jacques Descloitres, NASA/GSFC/MODIS Rapid Response Team).

diffraction (XRD). In addition, clay mineralogy of the silt mantles was determined by XRD using three treatments, air-dry, glycolated, and heat-treated (550°C).

[15] In order to obtain different size fractions, the surface-mantle soils were first treated with hydrogen peroxide to remove organic matter. Sodium hexametaphosphate was then added as a dispersant and left overnight. Following this procedure, samples were treated by ultrasonic shaking to aid dispersion of clays. Sands were then removed by wet-sieving (53-μm sieve) and clays and silts were segregated by repeated settling and decantation. The same pretreatments were used for particle size distribution analyses of the soils. After pretreatments, volumetric abundances of different size fractions were obtained using a laser particle size analyzer (Table S1[1]).

[16] In order to compare the San Clemente Island samples with the geochemistry of average upper continental crustal material, we used selected samples of Mojave Desert dust, at localities shown in Figure 5b and described by *Reheis and Kihl* [1995], *Reheis et al.* [2002], and *Reheis* [2003, 2006]. Mojave Desert dust trap samples were selected to cover a broad range of landscape settings, local bedrock types, and spatial distribution in order to capture the potential range in compositional variation. Dust traps are ~2 m high, which eliminates or at least minimizes collection of coarse (sand-sized) particles transported by saltation. Geochemistry of Mojave Desert dust trap samples was done on the <50 μm fraction. We emphasize that Mojave Desert dust trap samples were analyzed simply to illustrate the composition of average upper continental crust, although, as we discuss later, this is also a potential source material. In our comparisons, we also plot geochemical data for Chinese loess, derived from *Ding et al.* [2001].

[17] For provenance studies using geochemistry, we utilized only those elements that are considered, on the basis of high ionic potential, to be the least mobile in low-temperature, near-surface environments, similar to the approach we have used in loess provenance studies [*Muhs and Budahn*, 2006]. Concentrations of low-mobility trace elements in both soils and pulverized island bedrock samples were determined by instrumental neutron activation analysis (INAA), as described by *Budahn and Wandless* [2002]. The same method was used in USGS laboratories for samples of Mojave Desert dust [*Reheis et al.* 2002; *Reheis*, 2003], and permits easy comparison with our data

[1]Auxiliary materials are available at ftp://ftp.agu.org/apend/jd/2006jd007577.

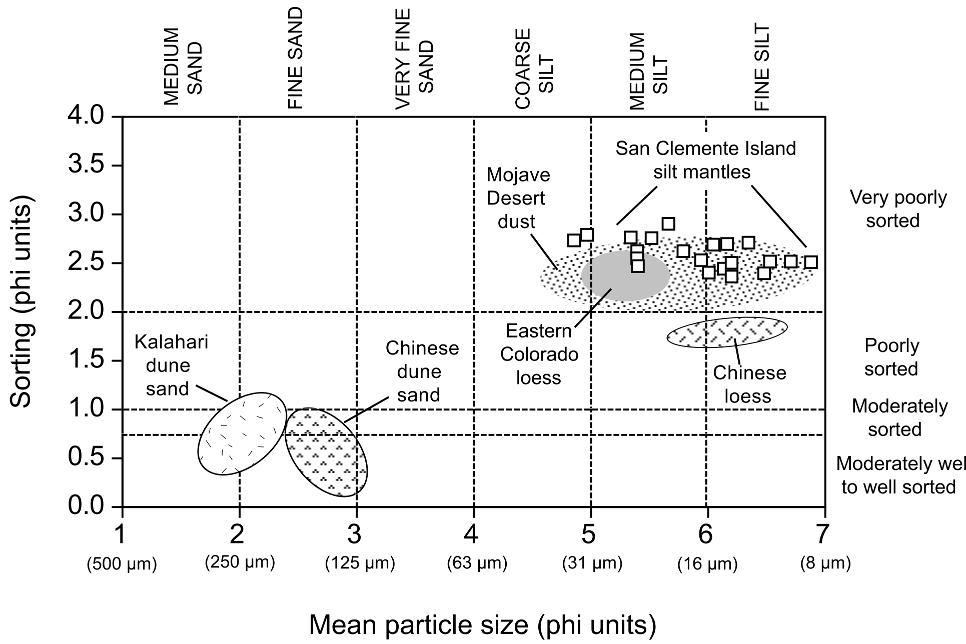

Figure 7. Plot of mean particle size and degree of sorting (standard deviation of the mean particle size) of silt mantles (open squares) from San Clemente Island, California. Also shown for comparison are ranges of mean particle size and degree of sorting of eolian sediments from other areas. Eastern Colorado loess data are from *Muhs and Benedict* [2006]; Chinese loess data are from the Luochuon and Xifeng sections and are from *Lu et al.* [2001]. Mojave Desert dust data are from *Reheis* [2003]. Chinese dune sand data are from the Taklimakan Desert and are from *Wang et al.* [2002]; Kalahari dune sand data are from *Livingstone et al.* [1999]. All analyses are done by laser particle size methods.

(Table S2). The suite of elements chosen includes Sc, Th, La, Ta, Nd, and Cr. The most likely host minerals for Cr and Sc are micas, amphiboles and clay minerals. Th and Ta are found in micas, amphiboles, zircon, sphene and clay minerals; in addition, Ta can be found in magnetite or ilmenite. Two rare earth elements (REE) were also used, La and Nd, and are usually hosted by micas, chlorite, clay minerals, amphiboles, sphene, zircon, monazite, and apatite.

4. Results

4.1. Particle Size Distribution

[18] Particle size analyses indicate that the silt mantles on San Clemente Island resemble some, but not all eolian sediments found in other regions (Figures 7 and 8). In comparisons with other sediments, we use, as much as possible, those samples that have been analyzed by the laser particle size method, similar to that used in our studies. Although they contain between 12% and 36% sand (only two of 21 samples are >40% sand), silt mantles have mean particle sizes that are much finer and more poorly sorted than dune sand in the Kalahari Desert in Africa or the Taklimakan Desert in China (Figure 7). However, the silt mantles have mean particle sizes that overlap the ranges of loess from eastern Colorado and China, although Chinese loess is better sorted than either of the other two sediment groups. San Clemente Island silt mantles are closest in particle-size distribution to Mojave Desert dust, with ranges in mean particle size and degree of sorting that overlap closely.

[19] Detailed particle size distribution plots provide additional information on the possible origins of the silt-rich mantles (Figure 8). The plots show broad primary modes in the range of silt (50–10 μm) and broad secondary modes in the range of medium-to-fine sand (300–200 μm). The primary mode in the silt range falls close to the ranges of Chinese and Colorado loess and very close to the range of dust collected in Los Angeles during a Santa Ana wind event (data from *Emery* [1960]; note, however, that his samples were not analyzed by modern laser methods). In contrast, the secondary mode in the range of sand-sized particles falls close to that of Kalahari Desert dune sand. Asian dust, collected from deep-sea sediments in the northwestern Pacific Ocean, shows particle size ranges of 2–4 μm, much finer than the silt mantles on San Clemente Island. On San Nicolas Island, California, dust was studied during the Asian event of April 1998 by *Tratt et al.* [2001]. Their data show that these far-traveled particles have a mode in the coarse-clay size range (1–2 μm). *Husar et al.* [2001] report that Asian dust that reached other parts of western North America during the April 1998 event had particle sizes of 2–3 μm. The very fine particle size of Asian dust reaching North America is consistent with a long-distance range of transport, similar to that reported for Saharan dust collected in the western Atlantic [*Li-Jones and Prospero*, 1998]. All Asian dust samples, from the northwestern Pacific Ocean to those collected in western North America, have modal particle sizes much finer than San Clemente Island silt mantles.

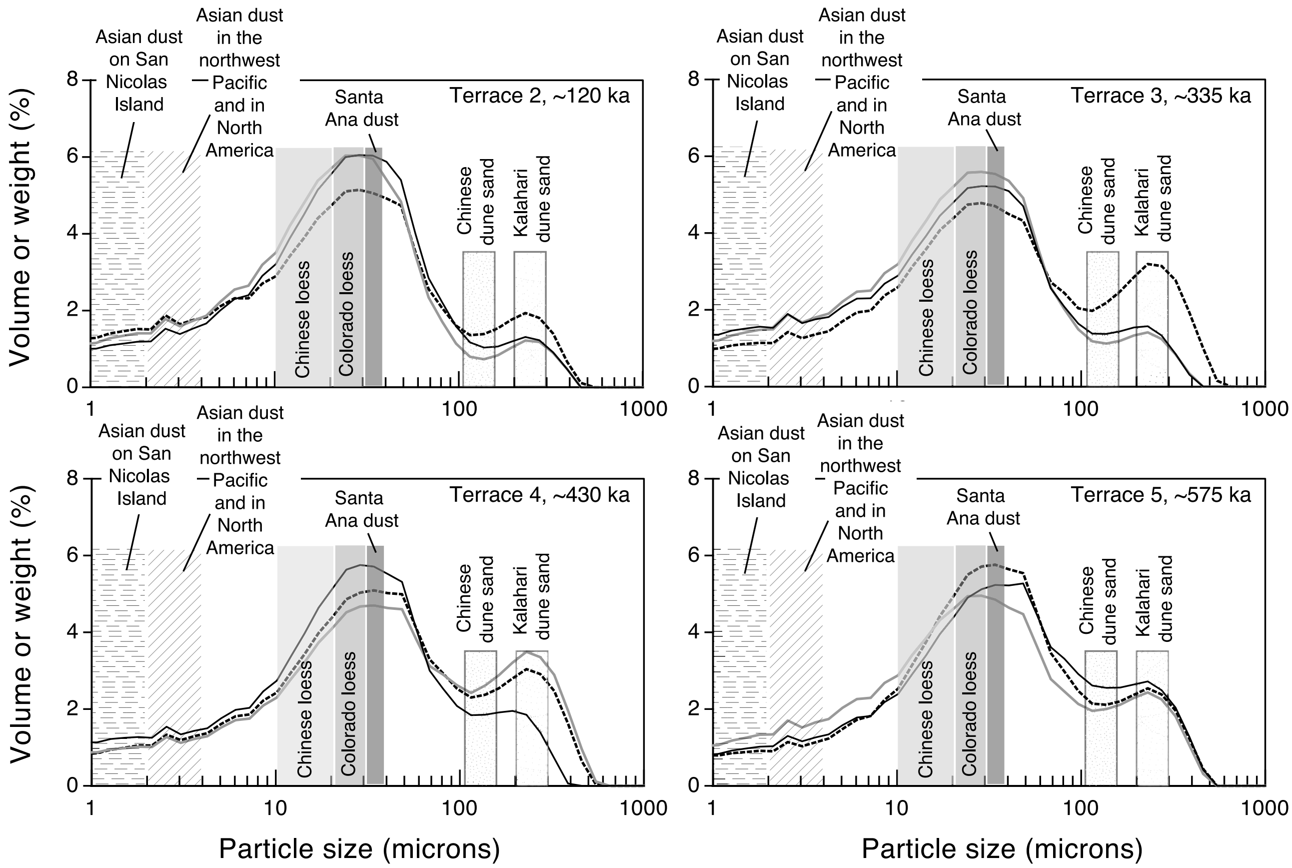

Figure 8. Plots of particle size distributions (volume or weight percent) of silt mantles from terraces of various ages on San Clemente Island compared with ranges of mean or modal size distributions of other eolian sediments from China, Colorado, Asia, and Africa. References for other regions as in Figure 7, except Asian dust that reached San Nicolas Island in April 1998, from *Tratt et al.* [2001]; Asian dust that reached elsewhere in North America in April 1998, from *Husar et al.* [2001]; Asian dust in northwest Pacific Ocean deep-sea sediments, from *Olivarez et al.* [1991]; and Santa Ana dust (collected in Los Angeles), from *Emery* [1960]. For the latter four particle groups, see original references for methods of analysis; all others are done by laser particle size methods.

4.2. Mineralogy and Major Element Geochemistry

[20] We determined the bulk mineralogy of San Clemente Island bedrock using XRD. Bedrock samples included 30 fresh (unweathered) cobbles collected from the modern surf zone in the vicinity of Eel Point (Figures 1b and 2b). Such clasts are probably representative of the marine terrace deposits that covered the wave-cut platforms on this part of the island when they first emerged. Most (90%) clasts are dark-grey, fine-grained volcanic rocks that are 58–62% SiO_2 and are classified as andesite; three samples that are lighter-colored have SiO_2 contents of 70–71% and are classified as rhyolite. The mineralogy and chemistry of San Clemente Island rocks is similar to that of Miocene andesites found elsewhere in southern California [*Weigand et al.*, 2002]. The andesites have abundant plagioclase and common pyroxene; a few samples have sparse amounts of quartz. Some andesite samples have plagioclase phenocrysts. Two of the rhyolite clasts analyzed have quartz and tridymite (SiO_2) in addition to plagioclase, but lack pyroxene. None of the andesite or rhyolite samples analyzed contains detectable mica. These results are consistent with those of *Olmsted* [1958], who studied the mineralogy of the island andesite, dacite, and rhyolite in thin section.

[21] The bulk mineralogy of the silt mantles is similar, regardless of terrace age or topographic position on a single terrace. All samples have common quartz and plagioclase, but only rare pyroxene. The mineralogy of the clay fraction of the silt mantles is also indistinguishable from terrace to terrace, despite an age span of ~500 ka (Figure 9). All silt mantles have a clay mineralogy dominated by mica and quartz, with smaller amounts of kaolinite and feldspar. This mineralogical similarity supports the interpretation that the silt is a thin blanket of sediment draped over landforms of widely differing ages.

4.3. Trace Element Geochemistry

[22] For provenance studies, we chose two suites of immobile elements, Sc-Th-La and Ta-Nd-Cr. We have utilized these elements previously in eolian sediment provenance studies [*Muhs and Budahn*, 2006; *Muhs et al.*, 2007]. These element suites, when arrayed on ternary plots, show clearly separated compositional fields for oceanic crust and upper continental crust [*Taylor and McLennan*,

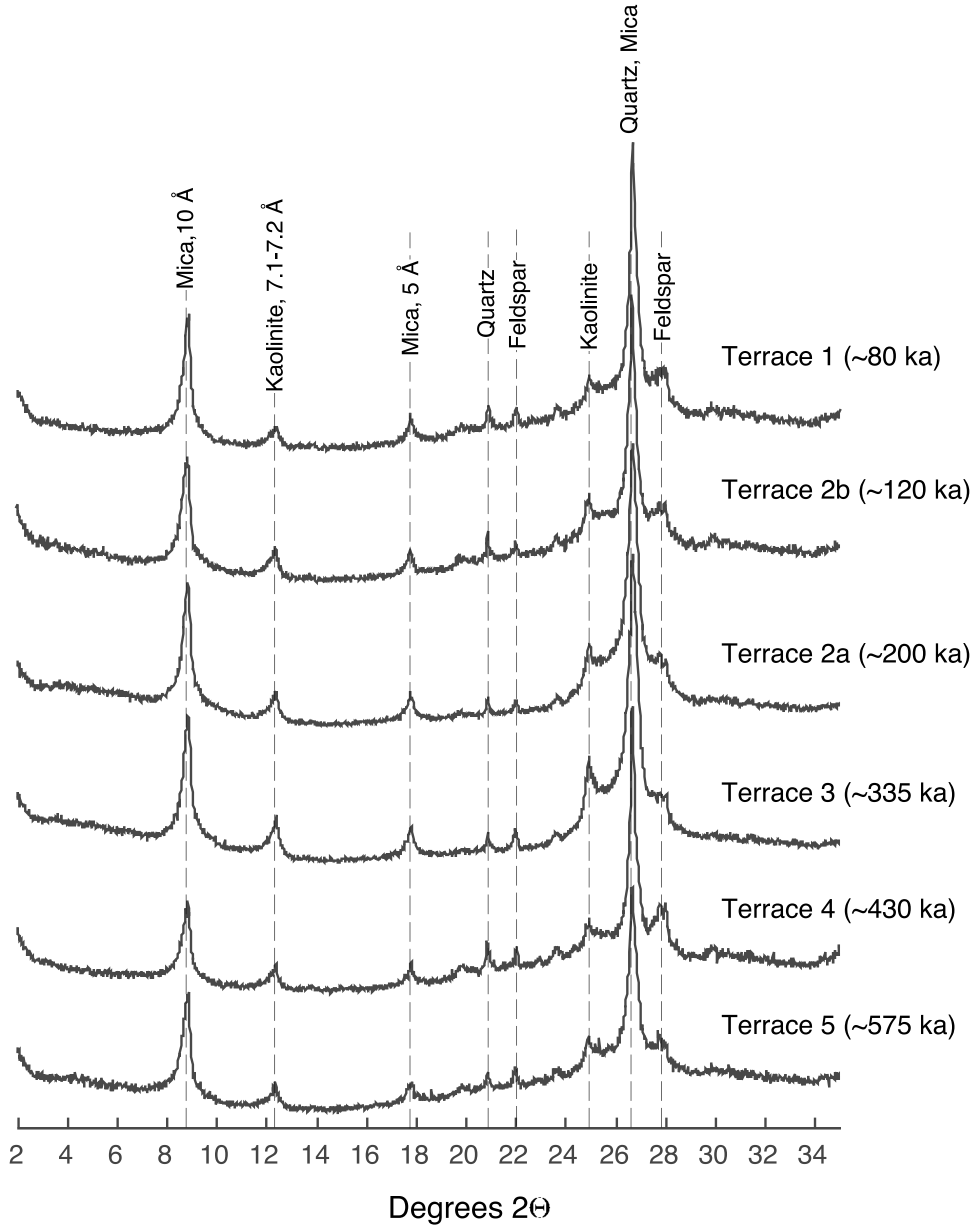

Figure 9. X-ray diffractograms of glycolated clay (<2 μm) fractions of surface mantles on the lowermost six terraces on San Clemente Island, showing similarity of mineralogy regardless of terrace age.

1985; *Olivarez et al.*, 1991]. Although oceanic crust is basalt and bedrock on San Clemente Island is andesite, we expected that andesite trace element geochemistry should show a field distinct from upper continental crust.

[23] Results of the Sc-Th-La analyses show that potential source materials have distinct compositions (Figure 10). Local San Clemente Island andesite plots between average oceanic crust and average upper continental crust, as expected. Chinese loess, Mojave Desert dust and island rhyolite plot near the average for upper continental crust, also expected. Furthermore, compositions of the mantles themselves vary with particle size. Sands (>53 μm), silts (53–2 μm), and clays (<2 μm) have distinctive compositions. Sands, which we interpret to be locally derived from the island bedrock, plot between the compositional fields of San Clemente Island andesite and rhyolite. Clays also plot between the two bedrock types, although most plot closer to the rhyolite/average upper continental crustal fields. Silts, on the other hand, are distinct from island andesite, have only a minimal overlap with a part of the island rhyolite field, and plot well within the fields occupied by Chinese loess and Mojave Desert dust.

[24] The Ta-Nd-Cr analyses are consistent with the Sc-Th-La plots, but Ta-Nd-Cr define compositional fields even more clearly (Figure 11). Again, island andesite occupies a field intermediate between oceanic crust and upper continental crust, and both Mojave Desert dust and island rhyolite are close to average upper continental crust. However, an important difference is that Ta-Nd-Cr compositions are distinct for island rhyolite and Mojave Desert dust.

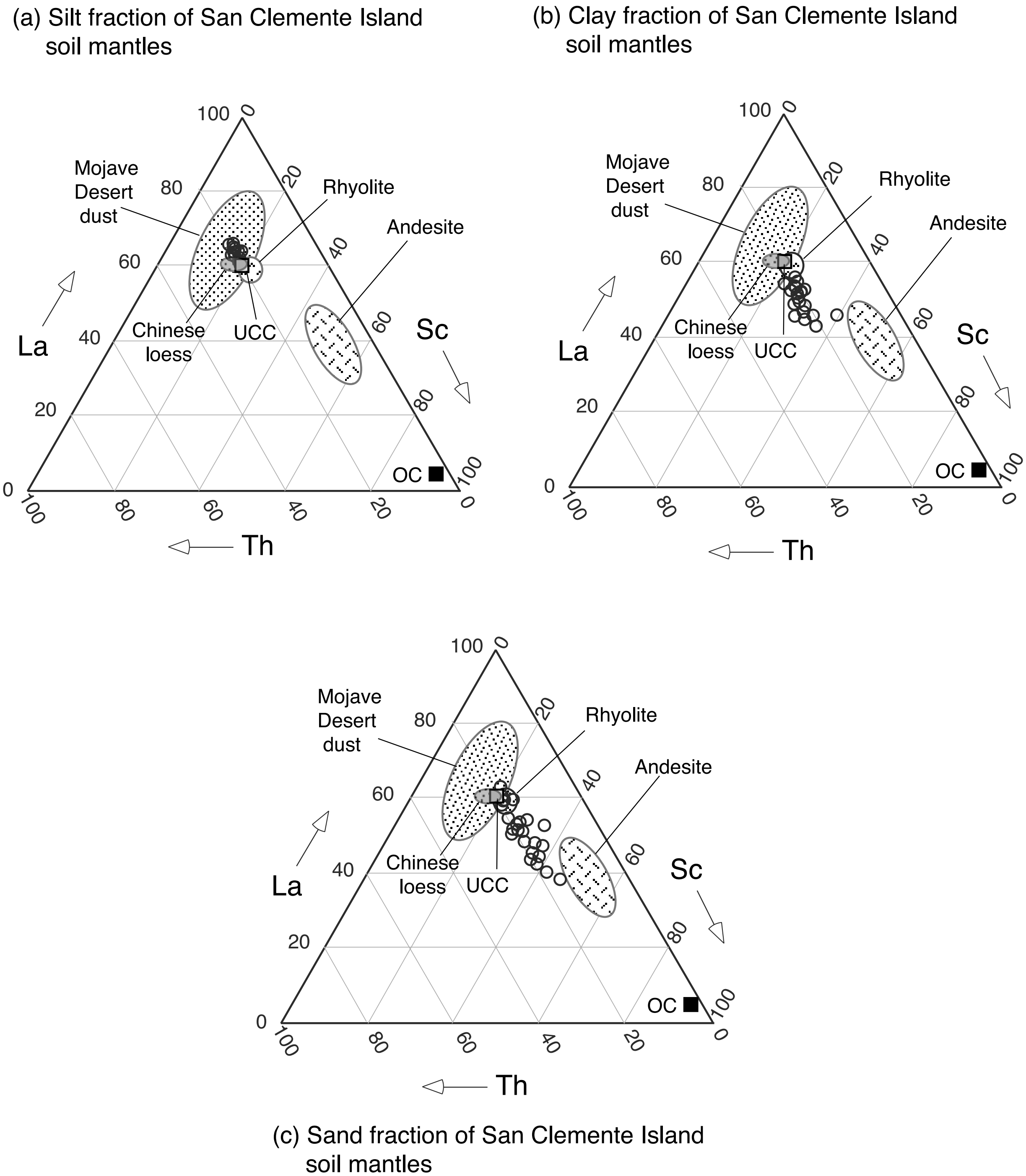

Figure 10. Ternary plots showing relative proportions of immobile elements Sc, Th, and La in (a) silt fractions (53–2 μm), (b) clay fractions (<2 μm), and (c) sand fractions (2000–53 μm) of silt mantles (open circles) on San Clemente Island. Also shown are average values for ocean crust (OC) and upper continental crust (UCC), taken from data in the work by *Taylor and McLennan* [1985]. Field defined by Mojave Desert dust collected in traps is from data in the works by *Reheis* [2003] and *Reheis et al.* [2002]; Chinese loess data are from *Ding et al.* [2001]. Fields defined by San Clemente Island andesite and rhyolite are from this study.

Ta-Nd-Cr compositions are also distinct for the three particle size classes of the silt mantles. Sands are closest to the field defined by andesite. Clays, however, plot mostly within the field defined by Mojave Desert dust and silts plot entirely within the field defined by Mojave Desert dust.

4.4. Soil Chemical Weathering as a Factor in Silt Mantle Mineralogy

[25] On the basis of mineralogy alone, it could be argued that the quartz enrichment in the silt mantles vs. the local bedrock on San Clemente Island is the result of chemical

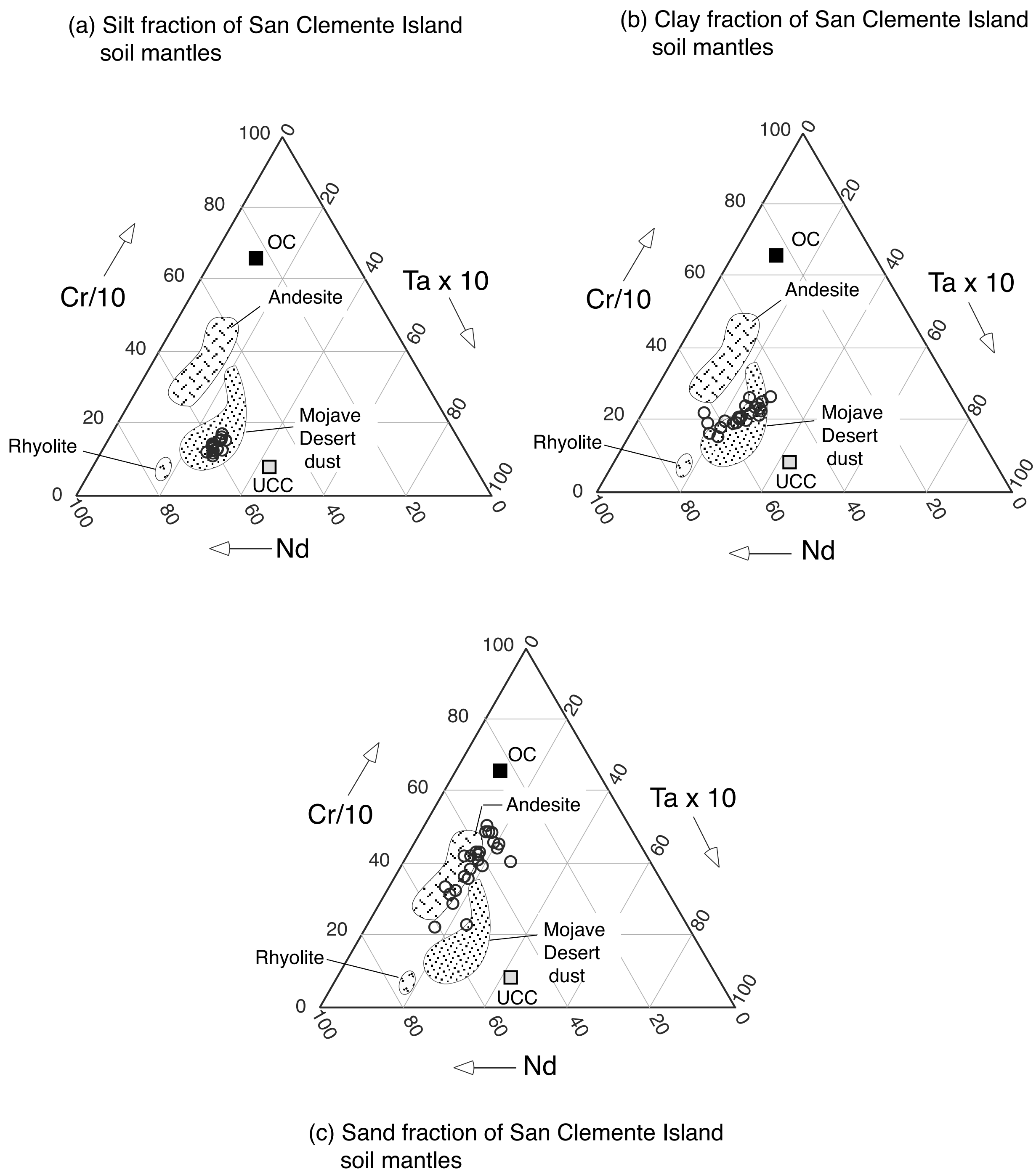

Figure 11. Ternary plots showing relative proportions of immobile elements Ta (x 10), Nd, and Cr (/10) in (a) silt fractions (53–2 μm), (b) clay fractions (<2 μm), and (c) sand fractions (2000–53 μm) of silt mantles (open circles) on San Clemente Island. Also shown are average values for ocean crust (OC) and upper continental crust (UCC), taken from data in the work by *Taylor and McLennan* [1985]. Field defined by Mojave Desert dust collected in traps is from data in the works by *Reheis* [2003] and *Reheis et al.* [2002]; fields defined by San Clemente Island andesite and rhyolite are from this study.

weathering that has depleted less resistant minerals, such as plagioclase and pyroxenes. One way to test this hypothesis is to examine chemical weathering parameters in a soil chronosequence. A soil chronosequence is an array of soils on landforms or deposits of different ages, but with similarities in all other soil-forming factors, which include climate, organisms, topography, and parent material [*Birkeland*, 1999]. The soils on the marine terraces of San Clemente Island form such a chronosequence. In a previous study, soil mineral weathering is reported to be greater on higher terraces, when soil profiles are considered as a whole, including all subsoil horizons [*Muhs*, 1982]. However, this

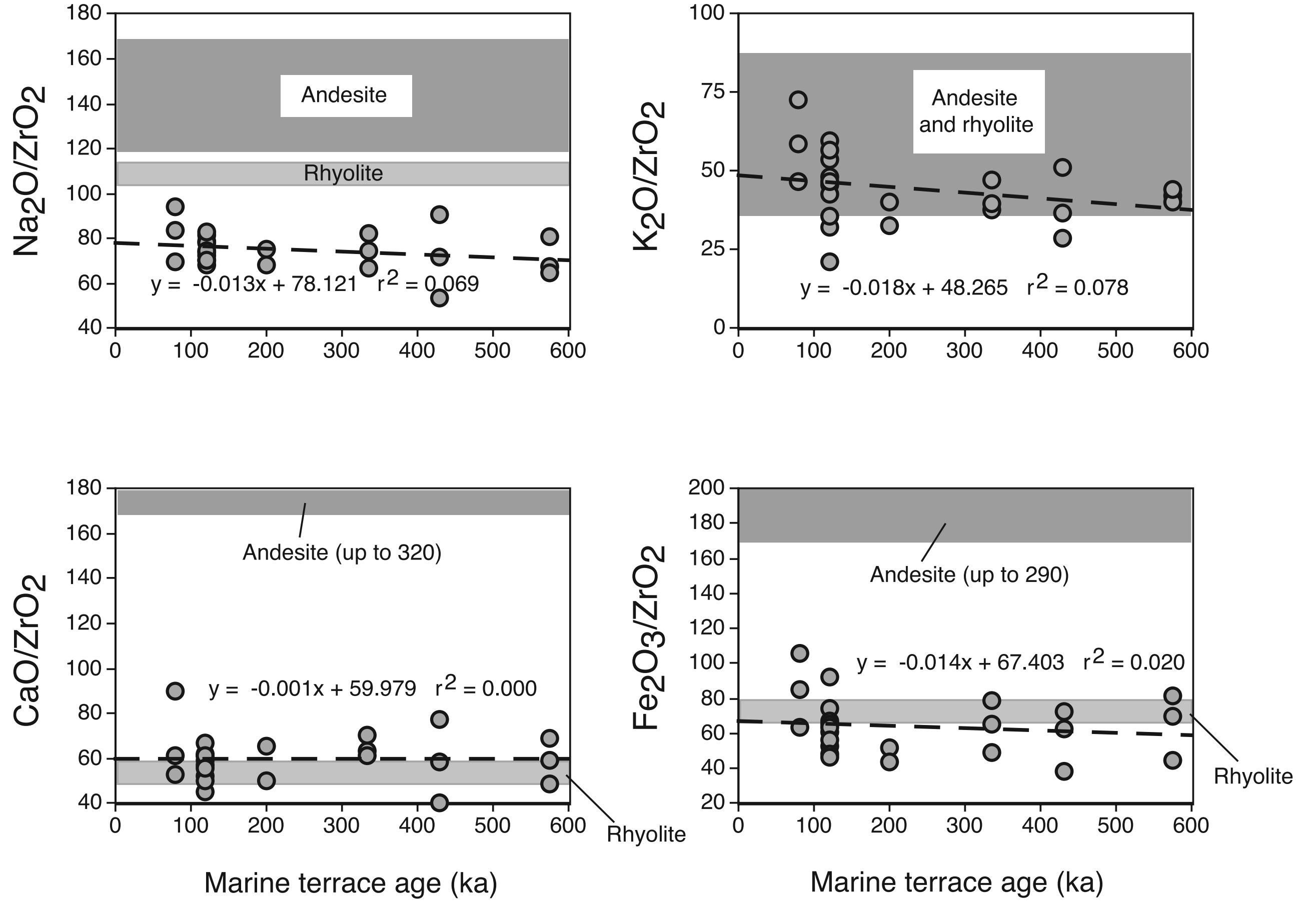

Figure 12. Chronofunctions of mobile-element-to-immobile-element chemical weathering indicators (Na_2O/ZrO_2, CaO/ZrO_2, K_2O/ZrO_2, and Fe_2O_3/ZrO_2) in the silt fractions (53–2 μm) of silt mantles on San Clemente Island as a function of terrace age, showing lack of systematic relations with time (see regression equations and coefficients of determination). Also shown are ranges of these elements in bulk San Clemente Island andesite and rhyolite.

earlier study did not examine silt mantles alone as a function of age for trends in chemical weathering. If the higher quartz concentrations in the silt mantles are a function of a greater amount of mineral weathering due to greater terrace age, then chemical-weathering ratios (mobile to immobile elements) should reflect this. Thus, if quartz enrichment in the silt mantles compared to the island bedrock is due to progressive loss of plagioclase and pyroxene from chemical weathering over time, Na_2O/ZrO_2 (plagioclase) and CaO/ZrO_2 and Fe_2O_3/ZrO_2 (pyroxene) in the silt mantles should all show values lower than the island bedrock and should show decreases with terrace age.

[26] Results indicate that Na_2O/ZrO_2, CaO/ZrO_2, and Fe_2O_3/ZrO_2 in the silt fraction of the silt mantles are lower than the island andesite, but none of these chemical-weathering indicators shows a systematic trend with terrace age (Figure 12). Age, which extends over ~500 ka in this terrace sequence, explains less than 1% of the variability in all chemical weathering indicators. We interpret these results to mean that the composition of the silt mantles, while somewhat variable, is not a function of progressive chemical weathering of silt derived from the island andesite. Although Na_2O/ZrO_2, CaO/ZrO_2, and Fe_2O_3/ZrO_2 in the silt mantles are all lower than the andesite, this is more easily explained as a reflection of the felsic (quartz-rich) composition of an external source.

5. Discussion

5.1. Summary of Evidence for an External, Eolian Origin for Silt Mantles on San Clemente Island

[27] Particle-size data support the interpretation of an external, eolian origin for the surface mantles. Silt contents are high, similar to North American and Chinese loess, Santa Ana dust, and Mojave Desert dust. However, the modal particle size of the silt mantles (20–50 μm) is much greater than that of Asian dust that has been transported to North America (1–3 μm) or even Asian dust in deep-sea sediments of the northwestern Pacific Ocean (2–4 μm). Thus we consider it unlikely that the silt mantles result primarily from long-distance transport of Asian dust, although there may be a small component from this source. The modal 20–50 μm size range suggests a shorter distance of transport and the North American mainland is the only candidate. The secondary mode in the fine-to-medium sand

range suggests that this minor component is locally derived, probably from periodic reactivation of sand dunes (Figure 1b).

[28] The mineralogy of the silt mantles also supports an external origin. Quartz, common in bulk silt mantle samples, is rare or absent altogether in the local island bedrock. In the clay fraction of the silt mantles, quartz is also present and mica is abundant. Because mica is not found in the island bedrock and likely did not form pedogenically [*Fanning and Keramidas*, 1977], it is probable that clay-sized mica is also derived from outside the island.

[29] Immobile trace element geochemistry (Sc-Th-La and Ta-Nd-Cr) indicates that the island andesite has a composition that is intermediate between average oceanic crust and average upper continental crust, as expected. The sand fraction of the silt mantles has compositional similarities to the local island bedrock and this supports our interpretation that the sands are locally derived. The silt fraction, and to a somewhat lesser extent, the clay fraction, however, are very distinct from the local island bedrock, and fall within or near an average upper continental crustal composition, similar to Chinese loess and Mojave Desert dust. We interpret these data to mean that the silts and probably also the clays are derived from an external source or sources. Although San Clemente Island silts are compositionally similar to Asian dust (as represented by Chinese loess), particle size data preclude this as a major source, as discussed above. From the combination of particle size, mineralogical, and geochemical data, we conclude that the silts are derived from a source or sources of upper continental crustal composition on the North American mainland.

5.2. Sediment Availability in Possible Source Areas

[30] The mainland of western North America has a number of possible source sediments for the silt mantles on San Clemente Island. The geochemistry of the silts and clays requires only that the source or sources be derived from sediments or rocks with an average upper continental crustal composition. Identification of specific source areas is beyond the scope of this paper, but interpretation of satellite imagery (Figures 4b and 6) and considerations of geomorphology and sediment availability allow us to hypothesize at least two major dust source regions: (1) canyons draining coastal mountains in southern California and northern Baja California and (2) dry washes, alluvial fans, and playas of the Mojave Desert. These two source regions are not mutually exclusive, and it is likely that both contribute to the dust loads visible in satellite imagery (Figures 4b and 6).

5.2.1. Valleys in Southern California Mountain Ranges as Dust Sources

[31] Mountains in coastal southern California, drained by major rivers that flow to the Pacific Ocean, are composed of a wide variety of rock types. Nevertheless, southern California mountain ranges, including the Peninsular Ranges, San Jacinto Mountains, San Gabriel Mountains, San Bernardino Mountains, Santa Monica Mountains, and Santa Ynez Mountains are composed largely of coarse-grained, felsic igneous rocks, metamorphic rocks, and sedimentary rocks that have the requisite upper crustal composition. Thus rivers draining these mountains transport silt-and-clay-sized sediment that is compositionally similar to San Clemente Island silt mantles. For example, the mineralogical composition of silts in both the Santa Clara River basin (one of the major drainage basins in southern California) and shelf sediments off southern California are very similar to those of the silt mantles on San Clemente Island [*Fan*, 1976]. We have examined modern floodplain sediments in many of these canyons and they are rich in silt-and-clay-sized sediments. Santa Ana winds pass through many of the canyons cut by southern California rivers, such as the Santa Clara River, Ventura River, Cajon Canyon, and Santa Ana River. The winds can entrain unvegetated sediment in the canyons easily, and the canyons themselves often accelerate the winds in the process.

5.2.2. Mojave Desert as a Dust Source

[32] In the Mojave Desert, another possible source region, sediment availability for eolian transport is a function of climate and landscape characteristics, which vary over time. Sediment availability varies significantly over two climatic extremes, full-glacial ($\sim$25 ka to $\sim$10 ka) and full-interglacial (since $\sim$10 ka) times. Shoreline mapping, sediment and stratigraphic studies, and radiocarbon dating indicate that lakes occupied many Mojave Desert basins during full-glacial time. For example, glacial Lake Mojave was present in the Mojave River drainage basin (with a variable size) from before $\sim$24 ka (cal yr BP) to $\sim$9.7 ka (cal yr BP) [*Wells et al.*, 2003]. Thus many basins in the Mojave Desert would not have been sources of sediment when pluvial lakes were in existence. Furthermore, pollen and macrofossils from packrat middens indicate that parts of the Mojave Desert landscape that were not occupied by lakes had a much different vegetation in full-glacial time compared to the present [*Koehler et al.*, 2005]. The vegetation cover was probably greater then than now in a climate that was far less arid than present, consistent with the presence of lakes. With the transition to a more arid Holocene climate at the close of the last glacial period, pluvial lakes disappeared and vegetation shifted, in the next few millennia, to the modern, sparse, creosote-bush-dominated desert vegetation. What were once pluvial lakes are now mostly dry playas that are rich in silt-and-clay-sized sediments.

[33] On the basis of the reconstructions of paleohydrology and past vegetation, we infer that sediment availability for eolian transport of dust from the Mojave Desert would have been greater in the Holocene than during the last glacial period. Other investigators have inferred a similar scenario for eolian dust transport in the Mojave Desert. *Wells et al.* [1985] and *McFadden et al.* [1986] thought that eolian silt mantles on flows of the Cima volcanic field in the Mojave Desert resulted from desiccation of pluvial lakes, reduction of vegetation cover, and greater fine-grained sediment availability during the shift from glacial to interglacial periods, such as the late Pleistocene-Holocene transition. *Reheis et al.* [1995] extended this concept throughout the Mojave Desert and showed that silt-rich surface mantles and even deeper soil horizons had their origins as eolian sediment, on the basis of mineralogy and geochemistry. *McFadden et al.* [1998] pointed out that in the eastern Mojave Desert, fine-grained, eolian-derived vesicular A horizons have similar morphologies on surfaces ranging in age from mid-Pleistocene to mid-Holocene, very similar to San Clemente Island. They attributed this to deposition of

eolian sediment on surfaces of widely varying ages during the Holocene.

[34] Another consideration with regard to sediment availability for eolian transport in the Mojave Desert (and elsewhere on the mainland) is modern human disturbance. *Nakata et al.* [1976] demonstrated that many sources of loose, fine-grained sediment during a Santa Ana dust storm in 1973 were the result of road construction, agriculture, urbanization, stream-channel modification, and off-road vehicle activity. Human disturbance that generates dust is not limited to the Mojave Desert in the USA, either. Some of the most dramatic dust plumes visible on Figure 4b, just south of Ensenada, Baja California, have their origins in the Valle San Rafael-Valle Ojos Negros area. Examination of Landsat imagery shows that this is an area of intense crop cultivation at present. We hypothesize that much of the generation of dust from this valley could have come from recently plowed fields that did not have a crop cover during Santa Ana events.

5.3. Eolian Silt as a Part of the Offshore Southern California Sediment Budget

[35] Delivery of eolian silt and clay to San Clemente Island from mainland North America implies that such sediment is also deposited in the surrounding Pacific Ocean. *Schwalbach and Gorsline* [1985], in their summary of Holocene sediments for offshore southern California, recognized that dust, derived from Santa Ana winds, is a component of the sediment budget. At present, it is not known how much of the overall sediment budget is accounted for by eolian inputs, as opposed to contributions from fluvial and marine erosion processes along the California coast. In areas beyond the continental shelf, and away from submarine canyons that are conduits for continental sediment transport, eolian inputs may play a larger role than previously suspected. *Emery* [1960] estimated dust flux on the basis of measurements made during a single Santa Ana event in Los Angeles. He extrapolated this to an annual flux of 15 g m^{-2} yr^{-1}, assuming 5 Santa Ana events per year (a conservative estimate).

[36] We can estimate rates offshore using data from *Muhs* [1982]. Here, we assume an age of the silt mantles of ~3 ka (based on the single radiocarbon age alluded to earlier), an average silt content of ~65%, thicknesses ranging from 5 to 20 cm, and an average bulk density of 1.6 g cm^{-3}. Using these data, and assuming that ~50% (probably a minimum figure) of the silt is derived from airborne dust, we calculate eolian fluxes ranging from 8.65 g m^{-2} yr^{-1} (thickness of ~5 cm) and 35 g m^{-2} yr^{-1} (thickness of ~20 cm). These estimates bracket that of *Emery* [1960], suggesting that they are at least of the right order of magnitude. The eolian dust fall rates we estimate here also bracket those of Asian dust flux to the northwest Pacific Ocean, mostly east and northeast of Japan, summarized by *Mahowald et al.* [1999].

[37] *Emery and Bray* [1962] and *Schwalbach and Gorsline* [1985] estimate Holocene sedimentation rates for many of the basins offshore southern California and northern Baja California. To the north and close to the coast, where river inputs are high, Santa Barbara Basin (north of Channel Islands National Park; Figure 1) has very high total sedimentation fluxes of 800–1300 g m^{-2} yr^{-1}. However, the basins surrounding San Clemente Island (San Nicolas Basin, to the northwest; Catalina Basin, to the northeast; East Cortes Basin, to the southwest; and San Clemente Basin, to the southeast) are farther offshore and do not have as much fluvial input. Hence they have much lower Holocene sediment fluxes. Those of Catalina Basin and San Nicolas Basin are highest (100–270 g m^{-2} yr^{-1} and 100–210 g m^{-2} yr^{-1}, respectively), while East Cortes and San Clemente Basins are somewhat lower (70–150 g m^{-2} yr^{-1} and ~150 g m^{-2} yr^{-1}, respectively). In all these basins, ~20–25% of the sediment has a biogenic origin, consisting of organic matter, carbonates, and silica [*Schwalbach and Gorsline*, 1985]. Thus the mineral fluxes to the outer basins around San Clemente Island are on the order of 56–216 g m^{-2} yr^{-1}. At the higher end of this range, eolian inputs could amount to only about 4–16% of the total sediment budget for the basins. However, if the lower end of this range is correct, then eolian inputs could constitute ~15–60% of the offshore basin sedimentation. At this point, we have too few reliable data on the ages and rates of dust sedimentation to assess these alternative estimates rigorously, but the initial calculations presented here suggest that further work is potentially fruitful.

6. Summary and Conclusions

[38] We conclude that silt-rich surface horizons of soils on San Clemente Island are eolian, the result of wind transport from mainland North America. Silt mantles on clay-rich Vertisols have not been reported elsewhere in California, despite the ubiquity of this soil type in the western USA. This suggests that the silt mantles have a geologic, rather than a pedologic origin. The mean particle size of the mantles is distinctly finer than eolian sand and coarser than Asian dust, but is similar to loess and Mojave Desert dust. The mineralogy of the silt mantles is dominated by quartz (in bulk samples) and quartz and mica (in the clay fractions). Both quartz and mica are rare or absent altogether from the local andesite, which is the main rock type on San Clemente Island. The relative abundances of Sc-Th-La and Ta-Nd-Cr, all immobile trace elements, show that the silts and clays in the surface mantles are not derived from the local andesite, but from some source or sources of upper continental crustal composition. Collectively, the particle size, mineralogical, and geochemical data support an eolian origin from the North American mainland. Dust can be delivered to the eastern Pacific Ocean from California and Baja California during Santa Ana wind events, after high pressure develops in the Great Basin, following the passage of a cold front. Such conditions occur numerous times each year and satellite imagery demonstrates that Santa Ana winds transport abundant dust from the mainland to the eastern Pacific Ocean. Likely sources include the river valleys draining the coastal mountains of southern California and fluvial and playa sources in the Mojave Desert. If eolian silt is delivered to islands offshore, then it follows that it is also delivered to the surrounding ocean. Thus eolian dust inputs to the eastern Pacific Ocean may be a more significant component of the ocean sediment budget than previously suspected, a finding of potential significance for marine biogeochemistry and effects on climate.

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J. Beann, J. Budahn, E. Fisher, D. R. Muhs, M. Reheis, and G. Skipp, U.S. Geological Survey, MS 980, Box 25046, Federal Center, Denver, CO 80225, USA. (dmuhs@usgs.gov)