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THE ORIGIN AND PALEOCLIMATIC SIGNIFICANCE OF CARBONATE SAND DUNES DEPOSITED ON THE CALIFORNIA CHANNEL ISLANDS DURING THE LAST GLACIAL PERIOD

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Abstract—Most coastal sand dunes, including those on mainland California, have a mineralogy dominated by silicates (quartz and feldspar), delivered to beach sources from rivers. However, carbonate minerals (aragonite and calcite) from marine invertebrates dominate dunes on many tropical and subtropical islands. The Channel Islands of California are the northernmost localities in North America where carbonate-rich coastal dunes occur. Unlike the mainland, a lack of major river inputs of silicates to the island shelves and beaches keeps the carbonate mineral content high. The resulting distinctive white dunes are extensive on San Miguel, Santa Rosa, San Nicolas, and San Clemente islands. Beaches have limited extent on all four of these islands at present, and some dunes abut rocky shores with no sand sources at all. Thus, the origin of many of the dunes is related to the lowering of sea level to ~120 m below present during the last glacial period (~25,000 to 10,000 years ago), when broad insular shelves were subaerially exposed. The exposed island shelves probably hosted abundant sand-sized skeletal debris of marine organisms that accumulated during high sea stands of the previous interglacial periods. The carbonate-rich dunes of the Channel Islands are thus a product of an island setting and dramatic sea-level lowering during the last glacial period.

INTRODUCTION

Sand dunes dominate landscapes over a significant portion of the Earth's surface. Although the Earth's largest dune fields are found in arid and semiarid zones of continental interiors, many dunes are also found along the world's coastlines. River transport and wave erosion of bedrock produce a steady supply of loose, sand-sized particles that are readily deflated from beaches by wind to form dunes. Along the Pacific Coast of North America, from Washington to Baja California, dune fields are an intermittent, but important, component of the coastal geomorphology (Cooper 1958, 1967). Sand dunes are found on a number of the California Channel Islands, covering large portions of San Miguel and San Nicolas islands and smaller parts of the northern or northwestern coasts of Santa Rosa, San Clemente, and Santa Cruz islands. Dunes on the Channel Islands display white or grayish-white colors that are distinct from mainland California dunes, which are typically light brown or tan. In this paper, we present new information on the composition of Channel Islands dunes that explains their white color. We also present new field observations that help explain when dune formation occurred and how this is related to sea level change during the last glacial period.

METHODS

Sand dunes were studied primarily on San Nicolas, San Clemente, and San Miguel islands, and secondarily on Santa Rosa and Santa Cruz islands (Fig. 1). To establish relative ages of surficial deposits, we re-mapped the extent of eolian sand and other Quaternary deposits on western San Nicolas Island, using aerial photographs as a mapping base (Fig. 2). Representative samples of

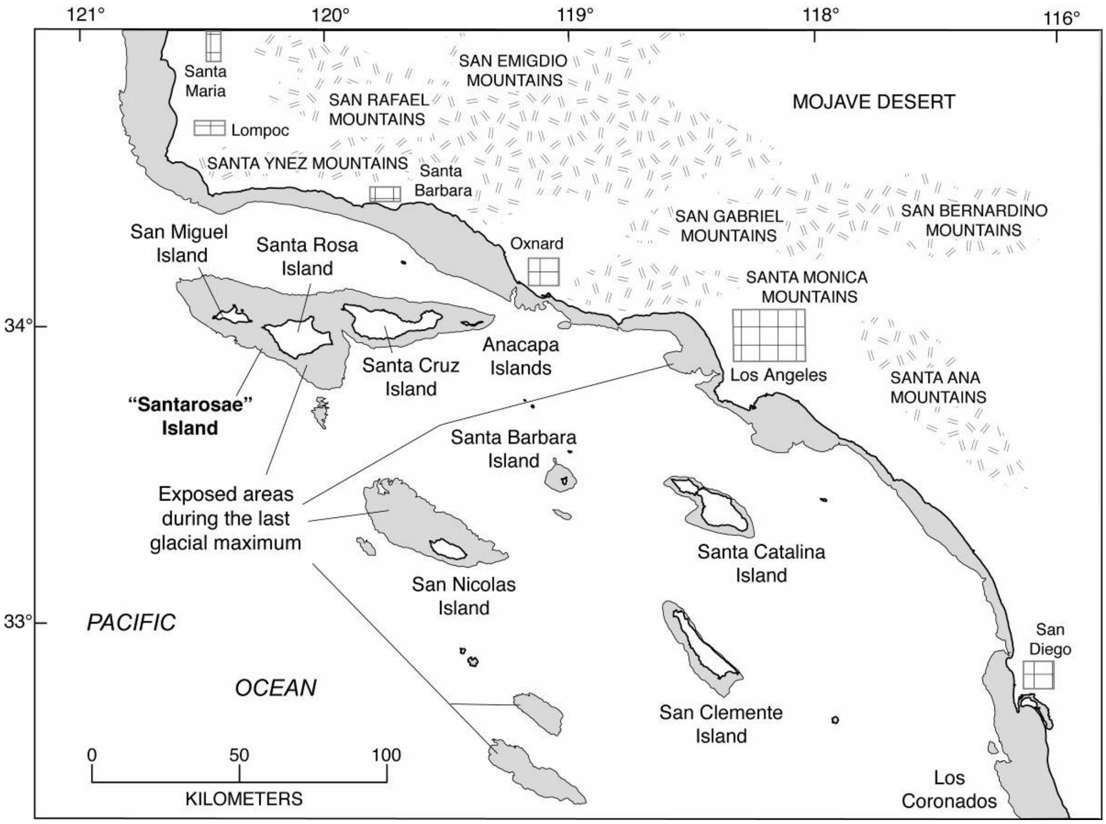

Figure 1. Map of the California Continental Borderland and the Channel Islands. Also shown (gray shading) is the area of now-submerged continental and insular shelves that would have been subaerially exposed during the last glacial maximum, at ~21,000 cal yr BP. Extended land area drawn by the authors using 1:250,000-scale USGS topographic maps, assuming a last-glacial-maximum sea level of ~120 m below present (Fairbanks 1989; Bard et al. 1990).

modern and Pleistocene dunes were collected on San Nicolas Island, as well as samples of modern beaches and Eocene sandstone bedrock. At a particularly complete exposure through a dune sequence at Dizon's Ravine (Fig. 2), we described and sampled eolian sand and buried soils at approximately equal-depth intervals. We also collected samples from Pleistocene dunes on San Clemente Island and modern coastal dunes from mainland California, near the cities of Oxnard, Lompoc, and Guadalupe, west of Santa Maria (Fig. 1).

In the laboratory, we determined the relative proportions of quartz, plagioclase feldspar, calcite, and aragonite for all sand samples using X-ray diffractometry (XRD). Exact percentages of quartz, plagioclase and many other minerals cannot be determined from XRD peak heights, but the ratio of XRD peak heights of these minerals compared to carbonate minerals can be used as a measure of relative mineral abundance. Total $CaCO_3$ (both calcite and aragonite) was measured using a rapid and precise method that utilizes automated coulometric titration (Engleman et al. 1985). Although this method does not distinguish calcite and aragonite, it provides very precise estimates of total carbonate content. To determine whether carbonate minerals were derived from marine or terrestrial sources, we measured concentrations of Sr using X-ray fluorescence. This element has relatively high concentrations in seawater and commonly substitutes for Ca in the skeletal mineralogy of both calcite and aragonite-dominated marine organisms. In contrast, carbonate minerals precipitated from terrestrial waters generally have much lower Sr concentrations. Thus, Sr is a proxy for the presence of marine-derived calcite and aragonite.

The mineralogy of San Nicolas Island dunes was compared to previously published data from

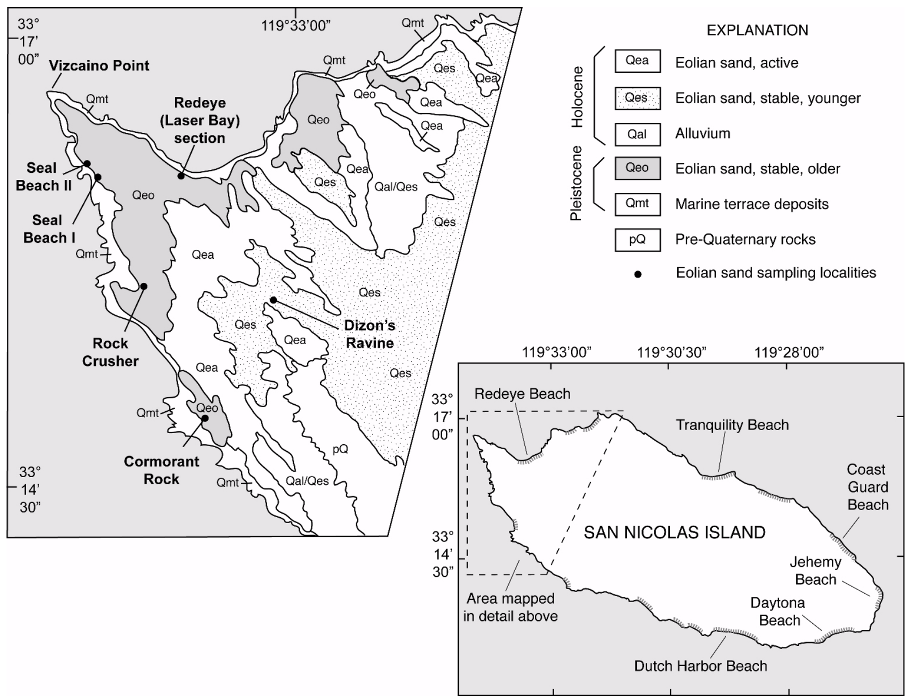

Figure 2: Map showing the distribution of eolian sand and other Quaternary deposits on the western end of San Nicolas Island and localities referred to in the text. Geology by the authors.

desert dunes (Muhs et al. 2003), and to samples collected from mainland California coastal dunes, San Nicolas Island bedrock, and San Nicolas Island beach sand. Ternary diagrams were constructed using the following XRD peaks (all in degrees two-theta): quartz (20.8°), plagioclase (27.8°), aragonite (26.2°), calcite (29.4°). In contrast to the silicate minerals, the separate peaks for calcite and aragonite can be used to determine the proportions of each mineral by measuring peak heights and use of a calibration curve.

RESULTS

Eolian Sand on San Nicolas Island

Eolian (wind-blown) sand is an extensive surficial deposit on San Nicolas Island, particularly in the western part of the island (Vedder and Norris 1963). Although Vedder and Norris (1963) did not distinguish different ages of dunes on their map, they recognized that several ages of eolian sand were present. In our remapping of the island, we recognize three different ages of dunes. The oldest dunes ("Qeo") are found at the surface on the northwest coast and are buried by younger dunes in the interior of the island (Fig. 2). They are commonly weakly cemented into "dune rock" or eolianite, display high-angle cross-bedding, and host well-developed soils. These soils have a reddish-brown, clay-rich Bt horizon in their upper parts and a well-cemented Bk horizon ("calcrete," or "caliche") in their lower parts, although many soils are partially eroded. Based on the degree of soil development, we infer that these dunes are Pleistocene. Younger dunes ("Qes") are stabilized by vegetation, and have minimally developed soil profiles. Commonly, these eolian sands overlie the older deposits, such as in the area around Dizon's Ravine (Fig. 2). These dunes are probably Holocene. The youngest dunes ("Qea") are those that have little or no vegetation, have no soils developed in their upper parts, and experience active transport by wind. Both Pleistocene and stable Holocene dunes host significant numbers of fossil land snails that have been studied in detail by Pearce (1990, 1993). *Micrarionta*, common in the dunes (e.g., Fig. 3), is an island endemic.

Primary and secondary structures in the Pleistocene dunes on San Nicolas Island give

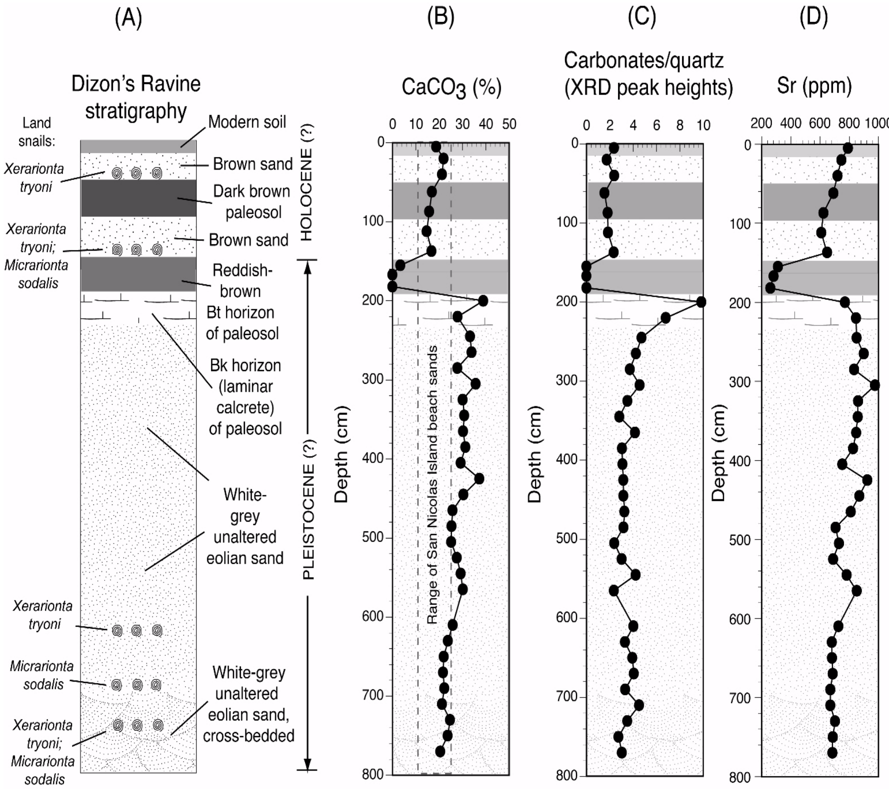

Figure 3. (A) Stratigraphy and land snail species, (B) $CaCO_3$ content, (C) calcite+aragonite/quartz values (based on XRD peak heights), and (D) Sr content of eolian sand and paleosols exposed in Dizon's Ravine, San Nicolas Island (see Figure 2 for location).

important clues about dune history. Exposures of the lowest, older parts of the dunes commonly exhibit high-angle cross-bedding, typically dipping from 25° to 35° to the south, south-southeast, or southeast. The upper parts of many Pleistocene dunes commonly display rhizoliths, or carbonate-filled root, trunk or stem casts of plants. In many exposures, rhizoliths are found in the original plant growth position, but are surrounded and/or buried by eolian sand, indicating deposition was still in progress even when there was at least a minimal plant cover. Eolian sand accretion was likely much slower during this phase of dune deposition, such that vegetation could maintain growth (which in turn probably slowed eolian sand movement). Finally, many exposures of dunes in profile show well-developed soil Bk horizons. Soil Bk horizons do not form when a dune is actively accreting vertically or migrating downwind. Thus, these features represent complete dune stability, colonization by vegetation, and a lengthy period of soil formation.

Composition of Dunes on San Nicolas Island

Microscopic examination of grains in eolian sand from San Nicolas Island shows that although angular-to-subangular quartz is an important mineral, there are large numbers of rounded-to-subrounded skeletal carbonate grains derived from marine organisms. Carbonate grains consist of mollusk shell fragments, sea urchin spines, and other marine skeletal particles. These observations are in broad agreement with more detailed studies conducted by Barron (2003).

Eolian sand exposed in Dizon's Ravine on San Nicolas Island shows how carbonate composition varies in unaltered eolian sand, leached zones of buried soils (paleosols), and enriched secondary calcrete zones of paleosols (Fig. 3). Unaltered eolian sand, whether cross-bedded or unstratified, has between ~20% and ~37% $CaCO_3$. In contrast, horizons of the modern soil and the first buried soil (paleosol) have 15% to 19% $CaCO_3$, and the Bt horizon of the reddish-brown buried soil has only 3% or less $CaCO_3$. The $CaCO_3$ leached from the Bt horizon of the reddish-brown paleosol accumulated in the Bk horizon of the underlying calcrete, where $CaCO_3$ content ranges from 28% to 39%. These changes in $CaCO_3$ content as a function of depth are mirrored by the ratio of XRD peak heights of carbonate-minerals-to-quartz, and by concentrations of Sr, an index of the abundance of marine-derived carbonate minerals. Measurements of XRD peak heights of calcite and aragonite indicate that of the total $CaCO_3$, 25% to 55% is aragonite and 45% to 75% is calcite. The dominance of calcite over aragonite is in good agreement with the generally higher numbers of calcitic marine organisms vs. aragonitic marine organisms in mid-latitude regions of the ocean (Chave 1967; Nelson 1988).

Mineralogy of San Nicolas Island Dunes Compared with Mainland Dunes

The composition of dune sands on the Channel Islands contrasts strongly with that of mainland desert dunes (Fig. 4A). The most common constituents of inland sand dunes worldwide are quartz and feldspars (see examples in Muhs 2004). Dunes near Parker, Arizona, have high quartz, low calcite, and relatively low plagioclase feldspar content. The Parker dunes are derived primarily from mineralogically mature, quartz-rich sediments of the Colorado River, which are in turn derived from old, quartz-rich sandstones drained by this river on the Colorado Plateau (Muhs et al. 2003). Dunes from Rice Valley, California, in the eastern Mojave Desert lack calcite, and have much higher plagioclase feldspar content relative to quartz. These dunes are derived from local, first-cycle alluvium. In contrast to eolian sands in both of these desert dune fields, San Nicolas Island dunes are relatively low in quartz, high in plagioclase feldspar, and high in carbonate minerals.

San Nicolas Island dunes, both modern sands and those of Pleistocene age, also have a composition that differs from mainland California coastal dunes (Fig. 4B). Samples from dunes near Guadalupe and Lompoc have abundant plagioclase feldspar and quartz. The Lompoc dunes contain no aragonite and only small amounts of calcite; the Guadalupe dunes have no calcite or aragonite at all.

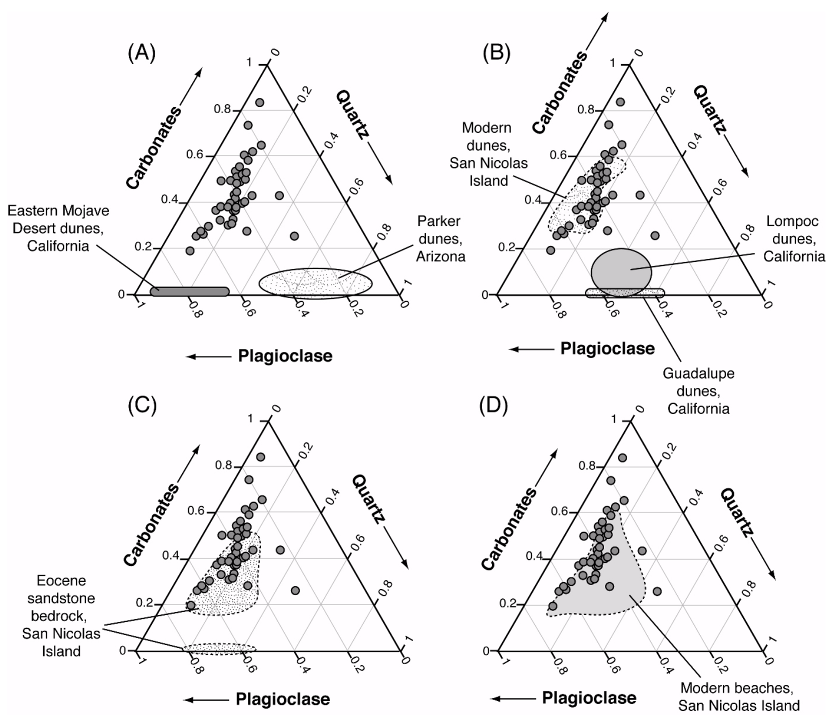

Figure 4. Ternary diagrams comparing relative proportions (*not* percentages) of quartz, plagioclase feldspar, and carbonate minerals (calcite+aragonite) in Pleistocene dunes from San Nicolas Island (filled circles; localities in Fig. 1), with: (A) modern desert dunes (data from Muhs et al. 2003); (B) modern dunes on San Nicolas Island and coastal dunes from mainland California; (C) Eocene sandstone bedrock on San Nicolas Island; and (D) modern beaches on San Nicolas Island.

The actively accreting portions of the mainland California Guadalupe and Lompoc dune fields are derived from nearby beach sediments. These beach sediments are, in turn, derived from sediments delivered to the coast by the Santa Maria and Santa Ynez Rivers (Fig. 5). These rivers drain parts of the southern Coast Ranges (Sierra Madre and San Rafael Mountains) and the western Transverse Ranges (Santa Ynez Mountains). Sandstones and other rocks in these mountain ranges are rich in plagioclase feldspar and quartz (Dibblee 1966; Norris and Webb 1976; Norris 2003) and provide these minerals to the rivers and beaches.

Mineralogy of San Nicolas Island Dunes Compared to Island Bedrock and Beach Sediments

Because San Nicolas Island dunes have much higher calcite and aragonite contents than mainland dunes, it is likely that there is some source of high-carbonate sand that is from the island itself. One possible source of carbonate is the island bedrock. Local bedrock on San Nicolas Island is dominantly Eocene siltstones and sandstones, which contain mostly quartz, plagioclase, and K-feldspar, but also some calcite (Vedder and Norris 1963). Our mineralogical analyses agree with those of Vedder and Norris (1963), with the rocks showing a dominance of quartz and feldspar. Although some of these rocks contain calcite, all lack aragonite and some contain no carbonate minerals at all. A ternary plot comparing the Pleistocene dunes of San Nicolas Island with the Eocene sandstone shows that although there is considerable overlap, most dunes contain a greater abundance of carbonate minerals (Fig. 4C).

In contrast to the Eocene bedrock, San Nicolas Island beach sands have relative abundances of quartz, plagioclase, and carbonate minerals that are

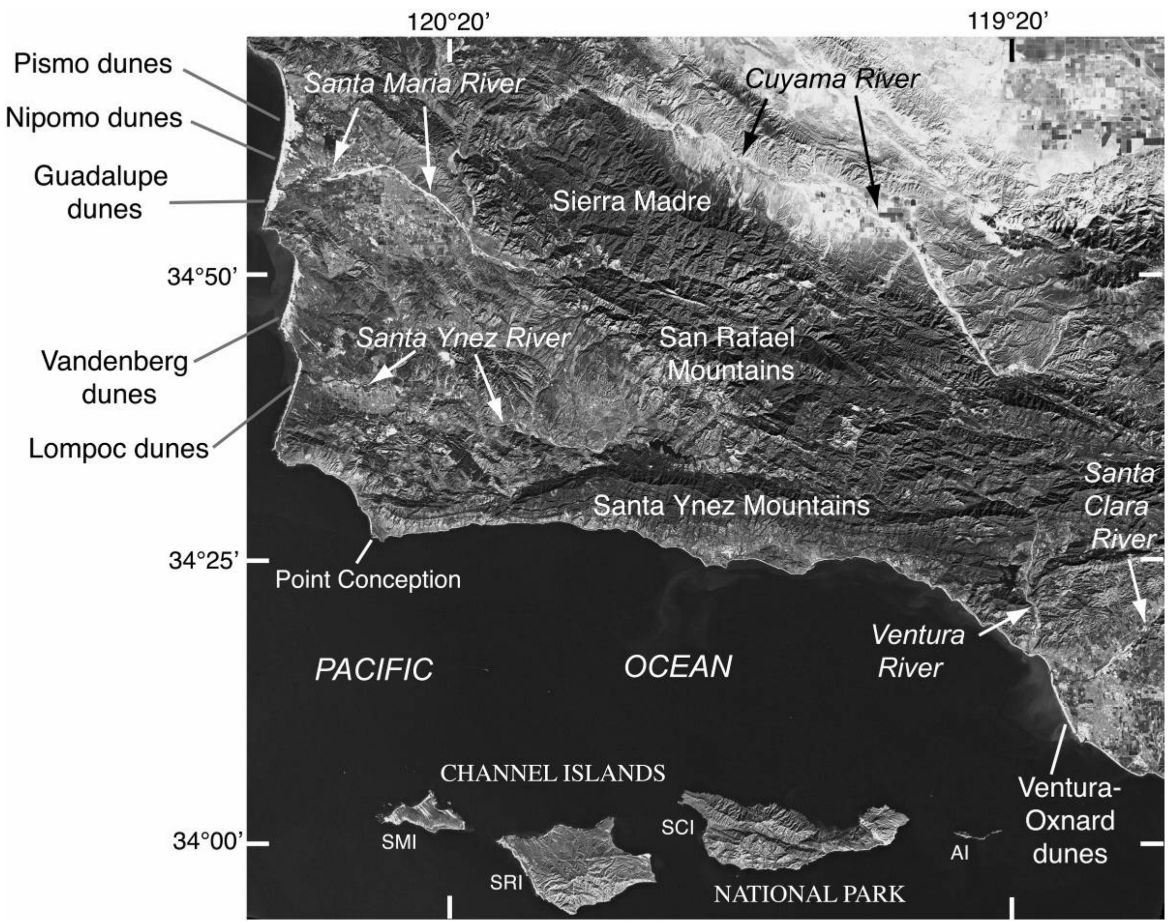

Figure 5. Landsat 7 image (bands 30, 20, and 10) showing the region of coastal southern California from Channel Islands National Park north to the Santa Maria River and coastal mountains. Also shown are the most extensive mainland California coastal dune fields. SMI, San Miguel Island; SRI, Santa Rosa Island; SCI, Santa Cruz Island; AI, Anacapa Islands.

close to those of the Pleistocene dunes (Fig. 4D). Quartz and plagioclase in the beach sediments are probably derived from the local Eocene sandstone bedrock. Unlike the bedrock, however, beach sands on San Nicolas Island contain both calcite and aragonite, which are derived from skeletal particles, in turn derived from marine organisms offshore. Modern beach sands have, overall, higher carbonate mineral content compared to the Eocene bedrock.

Total $CaCO_3$ Content of Channel Islands Dunes, Mainland Dunes, and Source Sediments

We also compared total $CaCO_3$ content, obtained by coulometric titration, in island dunes, mainland dunes, and possible source sediments. Pleistocene dunes on San Nicolas Island have a mean $CaCO_3$ content of 35% (Fig. 6). This value is somewhat lower than what Johnson (1972) reported for eolian sands of various ages on San Miguel Island (mean of ~40%), but somewhat higher than a suite (n=58) of Pleistocene eolian sand samples we analyzed from San Clemente Island (mean of ~32%). Eolian sand exposed in Dizon's Ravine has a mean $CaCO_3$ content of 28%, similar to modern and recently stabilized dunes on San Nicolas Island (Qea and Qes units on Fig. 2), which have a mean $CaCO_3$ content of 27%. In contrast, mainland California dunes from the Guadalupe, Lompoc, and Ventura-Oxnard dunes (Fig. 5) all have $CaCO_3$ contents of <1%.

Possible source sediments for the dunes on San Nicolas Island have highly variable $CaCO_3$ contents. Shelf sands (data from Norris 1951) have $CaCO_3$ contents of just under 20% to as high as 100%, with a mean value of ~48%. Beach sands, sampled at Redeye Beach and Tranquility Beach (Fig. 2), have a mean $CaCO_3$ content of 22%. In contrast, the average $CaCO_3$ content of Eocene sandstone bedrock from Celery Creek Canyon on San Nicolas Island is only 7%.

Timing of Dune Deposition

On the Channel Islands, numerous sea cliff exposures of carbonate eolian sand occur in places where currently no sand source exists. For example, sea cliff exposures of eolian sand commonly abut rocky shores where sandy beaches are absent year-round (Fig. 7). Measurements from ~70 dip azimuths of high-angle (25°-35°) foreset beds from dunes on San Miguel, San Nicolas, and San Clemente islands indicate these beds typically dip to the south, south-southeast, or southeast. This suggests that paleowinds that deposited the dunes were from the north, north-northwest, or northwest, where few or no sand sources exist at present. Thus, dunes in such settings must predate the present (Holocene) interglacial period.

Stratigraphic observations on the Channel Islands support the concept of eolian sand deposition during the last glacial period. Eolian sands exposed on sea cliffs are typically underlain by marine terrace deposits that date to either the early (~120,000 yr BP) or later (~80,000 yr BP) parts of the last interglacial complex (Muhs 1983, 1992; Muhs et al. 2006). This observation constrains the age of the dunes to an interval sometime after the last interglacial period. Well-

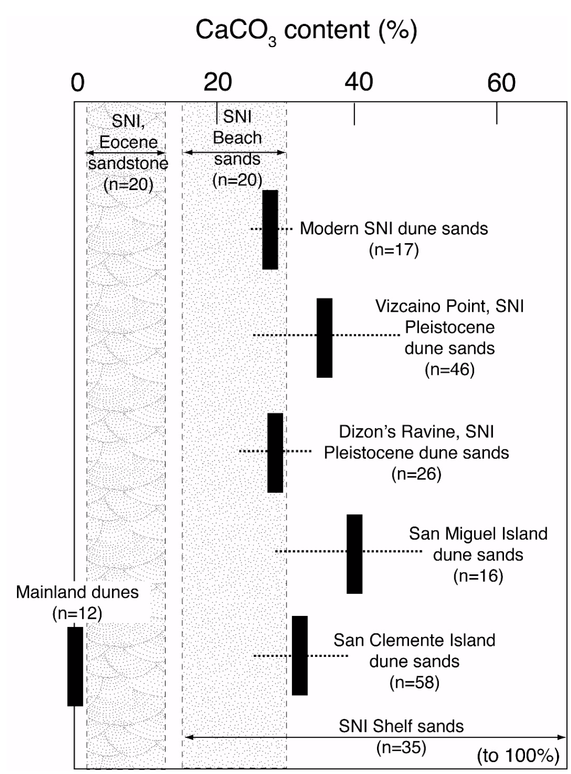

Figure 6. Mean $CaCO_3$ content (thick, black bars; dotted lines are ± 1 standard deviation) of modern and older eolian sands on San Nicolas Island (SNI), and the range of $CaCO_3$ content in various potential source sediments. Also shown is the $CaCO_3$ content of sand dunes on San Miguel Island and San Clemente Island (from locality shown in Fig. 7) and mainland California dunes. All data from this study except those for San Nicolas Island shelf sands, which are from Norris (1951) and San Miguel Island dunes, which are from Johnson (1972).

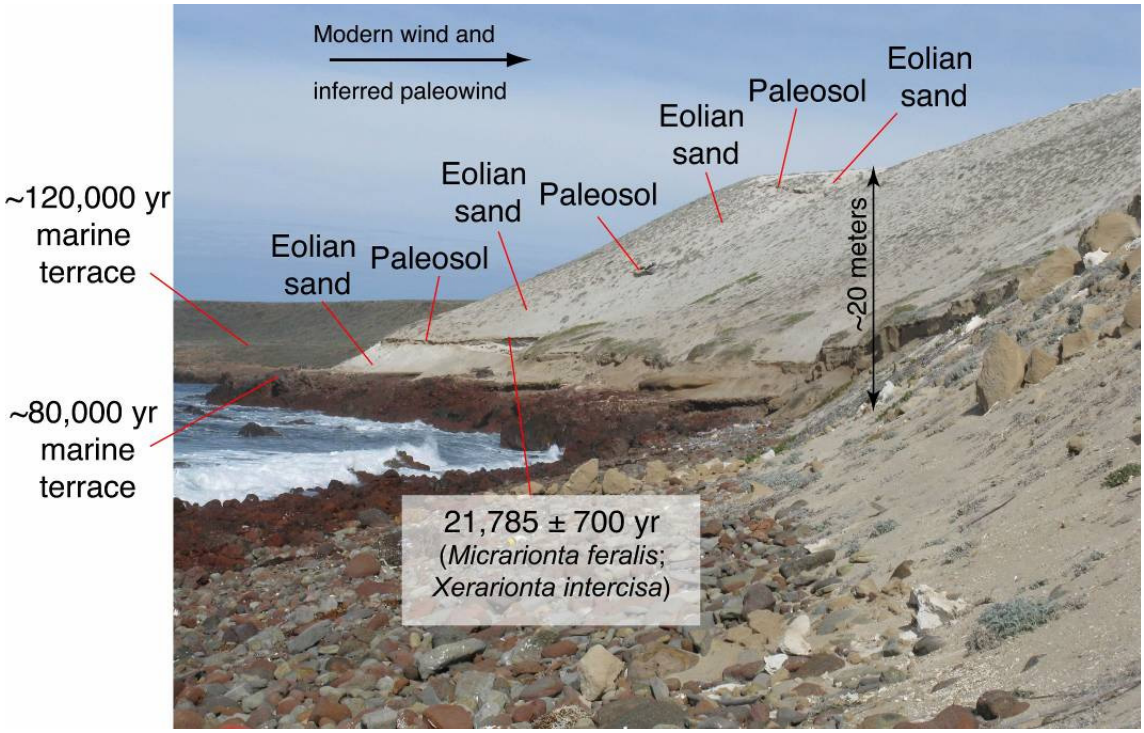

Figure 7. Stratigraphy of eolian sand exposed on the west shore of San Clemente Island (N33°00.046'; W118°34.971'), showing full-glacial age of major carbonate dune package, based on stratigraphic relations and radiocarbon age of land snails (Muhs 1983). Note lack of sand source on present shoreline.

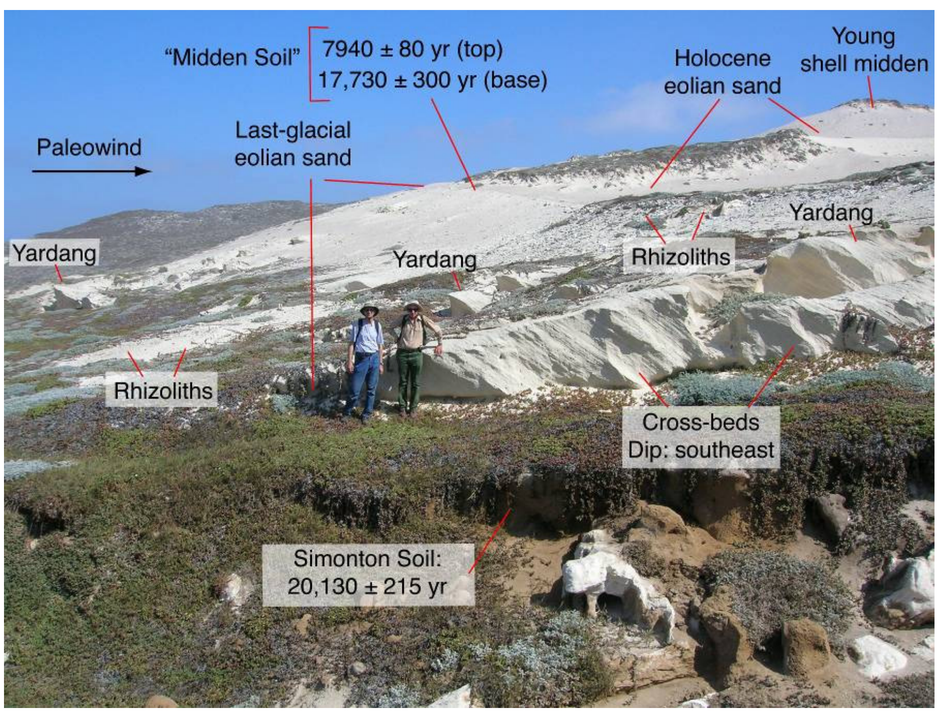

Figure 8. Stratigraphy of eolian sand exposed in Simonton Cove, San Miguel Island, near Yardang Canyon (N34°03.250'; W120°23.083'), showing full-glacial age of major carbonate dune package. "Yardangs" are streamlined landforms carved by the wind and left as erosional remnants. All radiocarbon ages from Johnson (1972, 1977).

developed soils on top of the eolian sands suggest that the dunes did not form during the present (Holocene) interglacial period, narrowing the time period of dune formation to the last glacial period. On San Clemente Island, there is a major dune package, ~20 m thick, that overlies the ~80,000-year-old marine terrace on the west shore (Fig. 7). Land snails (*Micrarionta feralis* and *Xerarionta intercisa*) from a paleosol within this thick dune sequence gave a radiocarbon age of ~22,000 ^{14}C yr BP (Muhs, 1983), very close to full-glacial time. On San Miguel Island, charcoal from a paleosol (the Simonton Soil; Fig. 8) at the base of a thick sequence of eolian sand overlying the lowest (~80,000 yr BP?) marine terrace at Simonton Cove gave a radiocarbon age of ~20,000 ^{14}C yr BP (Johnson 1972, 1977). Another paleosol (the Midden Soil) overlies this dune package, and charcoal from the lower part of this paleosol gave an age of ~17,700 ^{14}C yr BP. These bracketing radiocarbon ages indicate that much of the eolian sand visible in Figure 8 was deposited in just 2000-3000 ^{14}C years during the last glacial period.

DISCUSSION

High Carbonate Production in Waters Outside the Tropics

It is well known that carbonate production along ocean margins is very high in tropical latitudes (James 1997). Hermatypic (reef-building) corals and calcareous green algae dominate carbonate production in warm waters of tropical ocean margins. Consequently, there are many carbonate-rich dunes found along tropical and subtropical coastlines where reefs supply skeletal carbonate sand to beaches and shelves (Gardner 1983; McKee and Ward 1983; Brooke 2001). Nevertheless, there are also areas where carbonate production is significant in higher latitudes, such as the Channel Islands. Thus, the concept of "cool-water carbonates" has arisen within the marine sedimentology community (Chave 1967; Lees and Buller 1972; Nelson 1988; James 1997). Carbonate-producing organisms in cool-water environments include mollusks, foraminifers, echinoderms, bryozoans, barnacles, ostracods, sponges, worms, coralline (red) algae, and ahermatypic corals. All of these marine organisms live off the Channel Islands today and did so in the past as well (for example, see faunal lists in Muhs et al. 2006). Submarine shelves with rich accumulations of cool-water carbonate sediments, similar to the Channel Islands, have been identified off the coasts of New Zealand (Nelson et al. 1988), Vancouver Island (Nelson and Bornhold 1983), and Ireland (Scoffin and Bowes 1988), as well as other localities. Investigators who have studied these environments emphasize that one of the most critical factors in the high carbonate content of the shelves of these non-tropical islands and bank tops is lack of river input from non-carbonate, terrigenous sources. A similar situation exists on the California Channel Islands.

If high carbonate production is not limited to island shelves in tropical waters, a question that arises is why the carbonate dunes on the Channel Islands are so unusual in North America. With high carbonate production found on shelves in mid-latitude and high-latitude waters, at least in those areas where shelf sediments are not diluted by terrigenous silicate particles, it is reasonable to ask why there are not more reports of carbonate dunes on islands outside of the tropics. Gardner (1983) and Brooke (2001) have compiled reports of scattered occurrences of carbonate dunes in England, Ireland, and Scotland. Such dunes are rare, however, and Gardner (1983) speculates that lack of carbonate dunes in high latitudes is likely due to post-depositional dissolution of carbonate grains in climates that are characterized by generally higher precipitation, aided by vegetation that produces

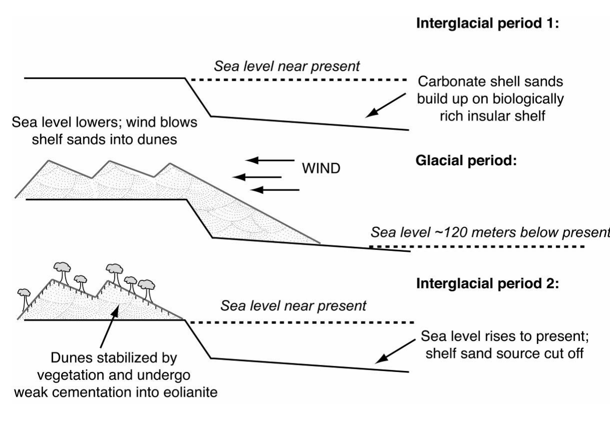

Figure 9. Model of carbonate dune formation as a function of interglacial-glacial cycles and sea-level change on the Channel Islands.

abundant organic acids. The Channel Islands, however, have arid to semiarid climates. Carbonates, though leached to shallow depths in soils and paleosols (Fig. 3), are not completely removed in the dunes.

Carbonates on Mainland vs. Insular Shelves off California

Emery (1960) showed that the $CaCO_3$ contents of shelf sands off the Channel Islands are much higher than those off the mainland California shelf. For example, off the mainland coast near Santa Barbara, $CaCO_3$ contents of shelf sediments range from 1% to 4% and most are only 1% to 2%. In contrast, around Anacapa Island, only 30-40 km to the southeast, $CaCO_3$ contents of shelf sediment range from 10% to 80% (Scholl 1960). The difference in $CaCO_3$ content of sediments on the mainland offshore shelf vs. the island shelves is due primarily to the difference in the relative amounts of delivery of detrital silicate particles vs. production of carbonate skeletal particles (Emery 1960; Johnson 1972). Although skeletal carbonate particle production from marine invertebrate organisms is high adjacent to both the islands and mainland California, in part due to proximity to upwelling cells, mainland shelves receive a greater amount of non-carbonate detrital particles from rivers and streams that drain the coastal mountain ranges (Fig. 5). This detrital silicate (quartz and feldspar) particle input effectively "dilutes" the skeletal carbonate particle input from marine organisms on the mainland California offshore shelf.

In contrast, the Channel Islands have smaller land areas, and, in particular, smaller land areas with any mountainous terrain. Thus, the delivery of detrital silicate particles to island beaches and shelves is commensurately lower. The high carbonate content of insular shelves is well illustrated on San Nicolas Island. Shelf sands off San Nicolas Island have $CaCO_3$ contents that range from 20% to 100% (Norris 1951), far higher than the mean $CaCO_3$ content of sediments on the mainland California shelf, which averages only ~9% (Emery 1960).

Dune Sources During the Last Glacial Period

Eolian sand deposition during the last glacial period was possible because sand sources existed then that are absent now. During the maximum of the last glacial period, ~21,000 yr BP, sea level was ~120 m below present (Fairbanks 1989; Bard et al. 1990). At this time, the northern Channel Islands were connected into a larger, single island called Santarosae (Fig. 1). A particularly large area of now-submerged shelf would have been exposed to the northwest of both San Miguel and Santa Rosa islands. San Nicolas Island would have grown to several times its present areal extent, with the largest expanse of extended subaerial exposure occurring to the northwest (Fig. 1). A sand source to the northwest is consistent with the northwesterly paleowinds estimated from cross-bed dip azimuths.

CONCLUSIONS AND A MODEL FOR GLACIAL-AGE EOLIAN SAND DEPOSITION ON THE CALIFORNIA CHANNEL ISLANDS

The relatively high carbonate content of Channel Islands dunes is rare in North America. Although carbonate-rich dunes, commonly cemented into eolianite, are found on many coastlines, they are unusual outside of tropical and subtropical zones. In North America, excluding Caribbean and western Atlantic islands, carbonate dunes are known to occur only along the Yucatan Peninsula and Baja California, and at one inland locality, Great Salt Lake (McKee and Ward 1983). The high carbonate content of Channel Islands dunes is visually striking to island visitors and often reminds them of tropical islands. The Caliche Ghost Forest of San Miguel Island, a major attraction in Channel Islands National Park, is directly related to the high-carbonate dunes that host it and supplied the carbonate to form the large root and trunk casts (Johnson 1967).

Our findings, and those of Johnson (1972) and Muhs (1992), suggest a three-stage model for carbonate sand accumulation on the California Channel Islands (Fig. 9). During an interglacial period, skeletal carbonate sands build up on biologically rich insular shelves. Lack of terrigenous sediment input from large rivers keeps the carbonate content high. As sea level lowers during the shift into a glacial climate, these shelf sands are exposed and become susceptible to eolian entrainment and transportation. Dunes are built on the subaerially exposed shelf and parts of the islands. New sediment is no longer exposed when the glacial maximum is reached and sea level lowers to its minimum point. As the glacial period ends and sea level rises (sometimes rapidly; see Fairbanks 1989), some dunes are eroded by the rising sea. Those dunes far enough inland to escape marine erosion have no new supplies of sand, and may undergo stabilization by vegetation, weak cementation to eolianite, and pedogenesis. Rhizoliths record this early vegetation colonization, and pedogenic calcretes record long-term dune stability. Many carbonate-rich dunes on the Channel Islands are, therefore, relict features from the ice ages, and reflect the influence of continental ice sheet growth and effects of this growth on global sea level.

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