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A Late Holocene Paleoecological Record from Torrey Pines State Reserve, California

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Paleoenvironments of the Torrey Pines State Reserve were reconstructed from a 3600-yr core from Los Peñasquitos Lagoon using fossil pollen, spores, charcoal, chemical stratigraphy, particle size, and magnetic susceptibility. Late Holocene sediments were radiocarbon dated, while the historical sediments were dated using sediment chemistry, fossil pollen, and historical records. At 3600 yr B.P., the estuary was a brackish-water lagoon. By 2800 yr B.P., Poaceae (grass) pollen increased to high levels, suggesting that the rising level of the core site led to its colonization by *Spartina foliosa* **(cord-grass), the lowest-elevation plant type within regional estuaries. An increase in pollen and spores of moisture-dependent species suggests a climate with more available moisture after 2600 yr B.P. This change is similar to that found 280 km to the north at 3250 yr B.P., implying that regional climate changes were time-transgressive from north to south. Increased postsettlement sediment input resulted from nineteenth-century land disturbances caused by grazing and fire. Sedimentation rates increased further in the twentieth century due to closure of the estuarine mouth. The endemic** *Pinus torreyana* **(Torrey pine) was present at the site throughout this 3600-yr interval but was less numerous prior to 2100 yr B.P. This history may have contributed to the low genetic diversity of this species.**

Key Words: **late Holocene; Los Peñasquitos Lagoon; pollen; charcoal;** *Pinus torreyana;* **chemical stratigraphy; estuarine marsh; sedimentation rates.**

INTRODUCTION

Los Peñasquitos Lagoon is one of 24 medium-to-large estuaries in southern California (Macdonald, 1977). These estuaries contain detailed stratigraphic records of past environments and events (Mudie and Byrne, 1980; Davis, 1992; Cole and Liu, 1994). Los Peñasquitos Lagoon supports a unique salt-tolerant plant community and is surrounded by distinctive plant communities of grassland, coastal sage scrub, and chaparral, as well as a stand of *Pinus torreyana* (Torrey pine) (Munz, 1974), and it lies within Torrey Pines State Reserve in San Diego, California (Figs. 1 and 2).

The reserve encompasses one of two naturally occurring stands of *P. torreyana.* The other stand is located 280 km to the northwest on Santa Rosa Island (Fig. 1C). *Pinus torreyana* has the smallest natural population of any known *Pinus* species and has little genetic diversity (Ledig and Conkle, 1983; Waters and Schaal, 1991). The lack of variability within the population has been proposed to result from low population levels during the dry, middle Holocene (Ledig and Conkle, 1983). Fossils of *P. torreyana* are unknown (Haller, 1967), except for the 5400-yr palynological record from near the Santa Rosa Island population (Cole and Liu, 1994) and the data presented here. The mainland and island *Pinus torreyana* populations differ somewhat, although not enough to be considered separate species (Haller, 1986). Both populations are located along the tops of steep coastal cliffs where summer fogs are frequent.

METHODS

Palynological Analysis

Several sites were sampled from Los Peñasquitos drainage and lagoon (Cole and Wahl, 1997). Only the most complete record, a 2.5-m core taken with a Livingston piston corer, is reported here. Pollen and spores were extracted and counted using standard methods (Faegri and Iversen, 1989), and pollen concentration was estimated using measured amounts of spores of *Lycopodium clavatum.* High intensity scans for trace amounts of *Erodium* sp. (storksbill) were made on extra slides containing from 1500 to 3000 pollen grains for samples immediately below its first recorded presence.

Because of the importance of *P. torreyana* in this study,

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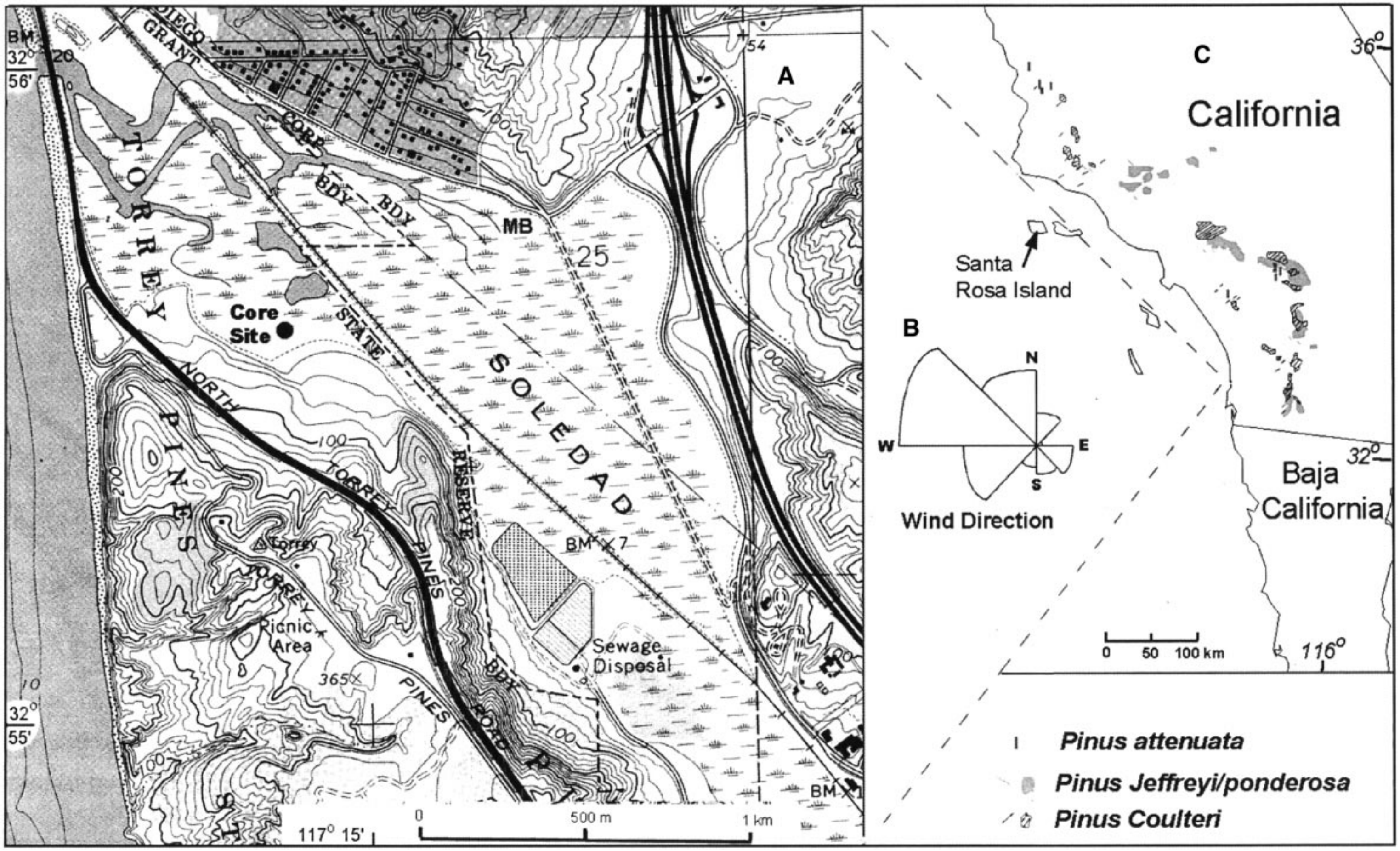

FIG. 1. Maps of the study area, including: (A) Topographic map showing the core site (USGS 7.5-minute map of Del Mar, CA). "MB" marks the location of the Mudie and Byrne (1980) core (from Scott *et al.*, 1976). (B) Wind rose showing wind direction from January to May, 1995 (*Pinus* pollination season), weighted for wind speed (Sugita *et al.*, 1997), recorded at the Scripps Pier, 6 km south of the core site. (C) Map of southern California showing the locations of Los Peñasquitos Lagoon and Santa Rosa Island. The distributions of several *Pinus* species with pollen similar to that of *P. torreyana* are taken from Griffin and Critchfield (1972).

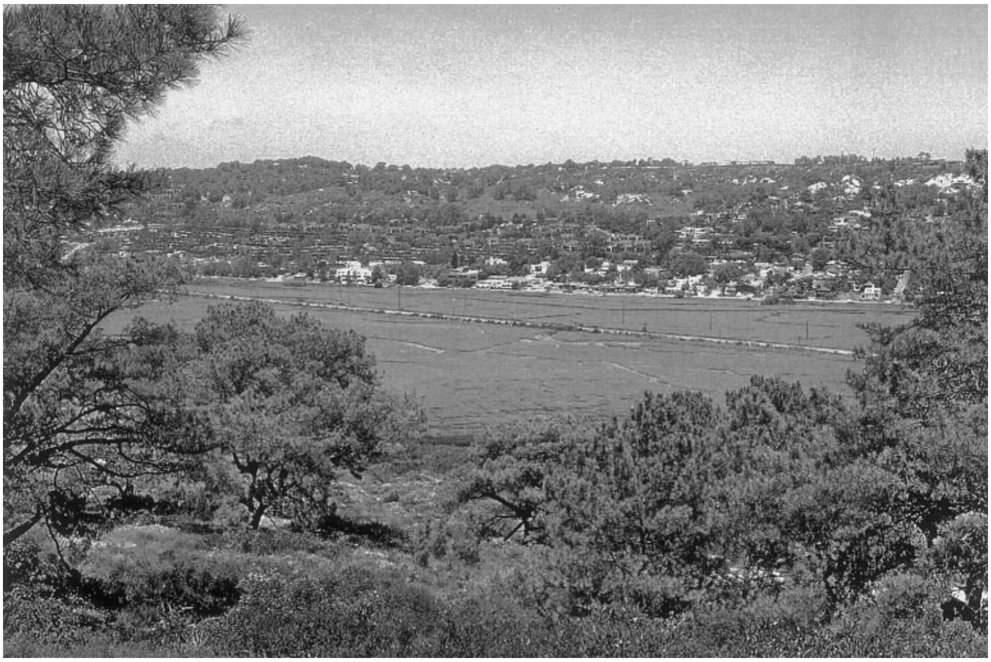

FIG. 2. Coring site in the estuary viewed from the stand of *P. torreyana.*

special attention was focused on *Pinus* pollen identification. *Pinus torreyana* and five other *Pinus* species native to southern California, *P. sabiniana* (digger pine), *P. coulteri* (Coulter pine), *P. jeffreyi* (Jeffrey pine), *P. ponderosa* (ponderosa pine), and *P. attenuata* (knobcone pine), have pollen of similar size ($\geq$78 μm total grain length; Kapp, 1969) and morphology (without distal verrucae). All of these other species now grow in distant mountainous habitats, the closest of which are downwind (east) from the lagoon (Fig. 1C). By 3600 yr ago, most North American plant species had reached their approximate modern distributional limits (Davis, 1983; Thompson, 1988), and it is unlikely that plant species now restricted to mountain habitats would have been present along the California coast during the late Holocene.

Undoubtedly, some *P. torreyana*-type pollen deposited in Los Peñasquitos Lagoon comes from long-distance transport. However, the regional wind patterns diminish the likelihood of this dispersal from the east. After weighting wind measurements for speed (Sugita *et al.*, 1997), winds measured near Los Peñasquitos Lagoon during the season of *Pinus* pollen production (January to May) are largely from the WNW (Fig. 1B). The surface concentration of *P. torreyana*-type pollen at the east edge of the lagoon is only half the amount deposited nearer the *Pinus* stand. Surface samples from sites in the region with no nearby upwind *Pinus* have less *P. torreyana*-type pollen than the lowest value in the lagoon record (E. Wahl, unpublished data). These data indicate the pollen signal from the *P. torreyana* stand is relatively local in extent and suggest that it exceeded "background" levels of similar pollen throughout the last 3600 yr.

Charcoal and Chemical Stratigraphy

The planar areas of microscopic charcoal particles, $>$0.0001 to $<$0.01 mm^2, were measured and counted from the fossil palynological preparations using a digital imaging system. Larger, macroscopic charcoal particles, $>$0.125 mm along their largest dimension, were counted after hand-sieving 8-cc samples of the sediment through graduated sieves.

Chemical analyses of major elements were completed at the University of Minnesota Research Analytical Laboratory using inductively coupled plasma spectrography (ICP), following a microwave/nitric acid digestion (US EPA, 1987; method 3051). Particle-size analysis was done at the University of Minnesota Soil Characterization Laboratory using the pipette method. Bulk magnetic susceptibility was measured at the University of Minnesota Limnological Research Center. Loss-on-ignition analysis of organic and carbonate material was done using a muffle furnace at the University of Minnesota Department of Forest Resources. Radiocarbon dates were obtained from Woods Hole Oceanographic Institution and the University of Arizona using the AMS method.

RESULTS

Physical and Chemical Stratigraphy

Results from the loss-on-ignition analysis (Fig. 4) demonstrate that the sediments are mostly inorganic with slightly more organic matter near the surface. The particle-size analysis shows that the sediments are sandy at the base of the core and clay-rich near the surface. Phosphorus is concentrated in the upper meter of the core, possibly due to recent phosphate pollutants from the sewage treatment plant within the estuary (Mudie *et al.,* 1974); some phosphorus compounds are water soluable and may have translocated down the core. Calcium reaches high concentrations between 83 and 53 cm, and sodium increases above 32 cm. Magnetic susceptibility, magnesium, and manganese all increase just above 65 cm. Iron and zinc concentrations are highest in the top 32 cm, and lead is highest in the top 12 cm.

Palynological and Charcoal Record

Pollen concentrations averaged about 30,000 grains/cc for most samples but were much higher (115,000 grains/cc) between 175 and 130 cm (Fig. 5). The entire core is dominated by pollen of the *Chenopodium/Amaranthus*-type (Cheno/Ams-type) which averages 68% of the pollen counted (Fig. 5). This Cheno/Ams-type pollen most likely represents the nearly monospecific cover of *Salicornia* spp. (glasswort), which now surrounds the core site to a distance of >100 m. Because this pollen is so dominant and is primarily aquatic, Cheno/Ams-type was eliminated from the terrestrial pollen total in Fig. 5, allowing a clearer representation of the other palynological taxa.

Potamogeton sp. (pondweed) is only found below 165 cm depth. High levels of Poaceae pollen are recorded between 175 and 130 cm. Pollen of the *P. torreyana*-type (*Pinus,* diploxylon, >78 microns) occurs throughout the core. Several palynological taxa that could indicate greater wet season (November–April) moisture, such as *Populus* sp. (cottonwood), *Cheilanthes* sp. (lip fern), *Ophioglossum* sp. (adder's tongue fern), and *Selaginella* sp. (little club-moss), all increase at about 130 cm depth. Pollen of *Erodium* sp. (storksbill), *Tamarix* (tamarisk), Cupressaceae (cypress family), and *Anemopsis* sp. (yerba mansa) are only found in the uppermost portions of the core.

High levels of microscopic charcoal occur at 130 and 60 cm with generally higher levels between those depths (Fig. 5). Macroscopic charcoal reaches very high values below 220 cm and high values at 65 and 5 cm.

Radiocarbon Dating

Two samples from the base of this core produced nearly identical dates of 3625 ± 190 (wood chip) and 3610 ± 35 yr B.P. (bulk sediment) (Table 1, Fig. 3). Two more comparisons between plant and bulk sediment samples, one from the core reported here (Core 2b) and the other from another part of the lagoon (Trench Face 2), resulted in bulk sediment samples dating 1190 and 1490 ^{14}C yr older than the samples of plant parts or charcoal (Cole and Wahl, 1997). These age disparities are commensurate with the ~1200-yr error reported by Cole and Liu (1994) for bulk sediment dates from another California estuary. A "dead carbon" error apparently affects some bulk-sediment radiocarbon ages from these deposits (Cole and Liu, 1994). The sediment cores can be most reliably radiocarbon-dated by using charcoal or fragments of plant or shell, which are infrequent within these deposits.

DATING THE HISTORIC PERIOD

An historical chronology for the core is suggested by the events listed in Table 2 and shown in Fig. 3. Although any single variable is not definitive, the series of multiple variables correlating with historical events produces a consistent sequence.

The European settlement horizon is placed at 65 cm because of numerous sedimentological changes in samples between 60 and 70 cm depth. First, the magnetic susceptibility rises dramatically between 68 and 64 cm, and manganese doubles in concentration at 63 cm (Fig. 4). These unique changes reflect human and herbivore disturbances on the adjacent mesas, which are capped by the Linda Vista Formation (Inman, 1983). This sandstone is uniquely rich in both magnetite (Emery, 1950) and manganese (Elenora Robbins, written communication, 1998). Second, pollen of the introduced European plant *Erodium* was found in trace amounts at 60 cm, but not at 70 cm or below. Several *Erodium* species are known to have invaded California during the earliest parts of the Spanish colonial period (West, 1989), and possibly even 10 to 20 years before it (Mensing and Byrne, 1998). Mission San Diego, 25 km south of Los Peñasquitos Lagoon, was founded in 1769. Thus, the absence of *Erodium* at 70 cm suggests an age prior to ca. 1760, and its presence at 60 cm dates to somewhat after that time. Third, both macro-charcoal (at 65 cm) and micro-charcoal (at 60 cm) reach high values during this period (Fig. 5). One of the first acts of ranchers in chaparral areas is to burn the chaparral in order to improve the palatability of the browse by stimulating the production of young tender shoots from older woody vegetation (Evarts, 1994; Cole and Liu, 1994).

The earliest historical records of settlement in the Peñasquitos drainage date from 1823 when the Ruiz-Alvarado land grant established a ranch within this watershed (San Diego Historical Society, 1996). The presence of cattle and "other stock" is documented for the site somewhat after this date (Kerr Collection, 1951). We assume that impacts of settlement became evident in the sediment core about 1830. Because the changes recorded within the core at ca. 65 cm depth involve several variables, the impacts recorded are likely the result of significant modifications to the landscape rather than incidental changes.

Evidence of even-larger-scale impacts of settlement should be seen in the sediment record by ca. 1850. Historical data record that in December, 1846, the United States Army of the West collected "some 100 head of cattle [and]· · ·about 100 head of sheep" at the Ruiz-Alvarado rancho (a few km upstream from the core site) and that by 1850, "large scale" cattle raising had begun in the area (Kerr Collection, 1951).

At 35 cm depth in the core, a shift toward fine-grained

TABLE 1
Radiocarbon Dates from Core 2b, Los Peñasquitos Lagoon

Depth below surface (cm)	Lab number	Age (^{14}C yr B.P.)	Age range (cal yr @ 1 δ)[a]	∂^{13}C	Material dated
132–136	OS-19842	2600 ± 40	814–592 B.C.	−21.48	plant parts
133–135	OS-15528	3790 ± 30	2276–2073 B.C.	−23.29	bulk sediment
171–174	OS-9159	2810 ± 30	1006–899 B.C.	−23.25	charcoal and plant parts
245	AA-19539	3625 ± 190	2269–1693 B.C.	−27.6	wood chip
246–249	OS-5310	3610 ± 35	2012–1884 B.C.	−28.09	bulk sediment

[a] Based upon Stuiver and Reimer (1993).

sediments coincides with higher concentrations of sodium (Fig. 4). This change likely reflects the weakening of tidal flushing as the accumulating sediments diminished the tidal prism. The mouth of the estuary was constricted by a road constructed over it in 1909, and it was closed entirely after the construction of a railroad in 1925 (Hubbs *et al.,* 1991) and Highway 101 in 1933. Salinity in the estuary reached high levels after the closure (Mudie *et al.,* 1974).

Pollen of the Cheno/Ams-type reaches a minimum at 30 cm, while Asteraceae (Composite family) pollen reaches a maximum at this level. This minimum in Cheno/Ams-type probably occurred as the fine-grained clayey sediments filled the estuary, covering much of the *Salicornia* habitat. An aerial photograph from 1928 shows that the core site was in the middle of a bare mud flat, devoid of *Salicornia* (Fig. 6). By 1953, much of the *Salicornia* had grown back, and by 1964 it covered the core site.

Pinus torreyana-type pollen declines between 50 and 30 cm. This decrease likely reflects burning and cutting of the trees between about 1870 and 1920. By 1885, San Diego officials had become concerned about harvesting of *Pinus* for wood and posted signs to prevent it (Evarts, 1994). In 1890, the city

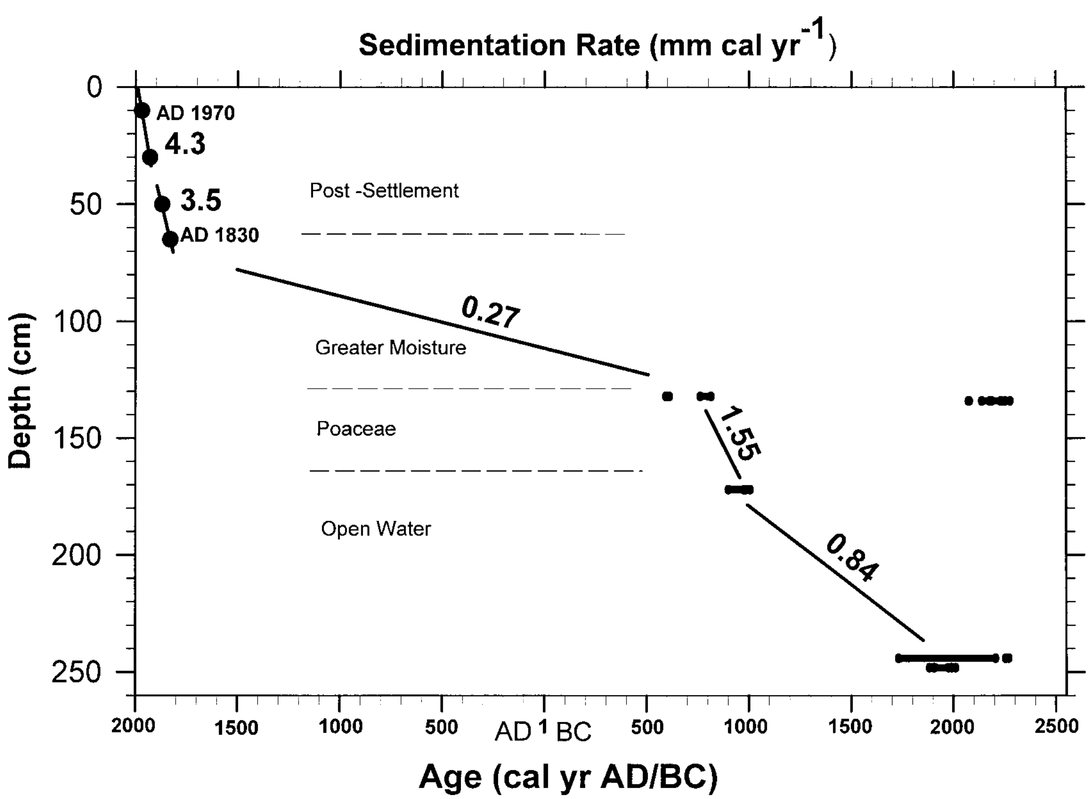

FIG. 3. Graph of sediment depth versus sediment age. Sediment ages are shown as lines representing 95% confidence limits in cal yr (Stuiver and Reimer, 1993) for radiocarbon dates and as solid dots for recent ages (Table 2). Sedimentation rates are shown above each trend line. Horizontal zones are described in text.

TABLE 2
Pollen and Chemical Stratigraphic Indicators Used to Date Historical Sections of the Core

Depth (cm)	Proposed date (A.D.)	Sedimentation rate (mm/yr)	Pollen or sediment data	Probable cause
10	1965–1975	4.1	—first *Tamarix* pollen	—expansion of *Tamarix* in watershed
			—increase in *Salix* pollen	—expansion of *Salix* in watershed
			—first *Picea* pollen	—ornamental *Picea* planted in adjacent developments
			—increase in Pb deposition	—rise in automobile traffic using leaded gasoline (Interstate 5 built nearby)
30	1925–1935	5.0	—minimum of *Chenopodium/ Amaranthus*-type (probably *Salicornia*)	—bare mud flats of fresh sediment fill estuary (seen on 1928 aerial photo; Fig. 6)
			—lowest levels of *Pinus* pollen	—*Pinus torreyana* cut for fuel over previous 50 yr
			—maximum in Tubliflorae pollen	—weeds propagate in agricultural fields north of lagoon
35	1910–1925	4.0	—shift toward finer-grained sediments	—mouth of estuary closed by accumulating sediments, road construction (1909), and railroad berm (1925)
50	1860–1880	3.2	—*Erodium* pollen rises	—intensive grazing era and consequent increase of *Erodium* and decline of grass forage
			—Poaceae pollen drops	
65	1820–1840	3.8	—magnetic susceptibility rises	—disturbance of magnetite and manganese bearing sandstones on uplands
			—Mn concentration rises	
			—high charcoal values	—fire used to increase palatability of chaparral forage
			—trace of *Erodium* pollen	—*Erodium* already present in watershed
70	1650–1760	0.23 to 0.29	—absence of settlement indicators	—uncertain age due to large differential between pre- and post-settlement sedimentation rates

leased the land occupied by the *P. torreyana* for sheep and cattle grazing. Cattlemen further cut and burned the chaparral, probably including some *P. torreyana,* to improve the forage (Evarts, 1994). By 1916, the trees were still being cut for firewood, and it was estimated that only about 200 remained (Evarts, 1994).

Pollen from the exotic *Tamarix pentandra* is first recorded at 10 cm depth, dating to between 1965 and 1975 using our chronology. These numbers are consistent with its growth in the watershed late in this century (Mike Wells, California Department of Parks and Recreation, personal communication, 1998). *Salix* sp. (willow) pollen also increases significantly in this 10-cm sample. Aerial photographs show an expansion of *Salix* in the Peñasquitos drainage over the last 40 yr. *Picea* sp. (spruce) and Cupressaceae pollen also are found only in this most recent sample and probably were produced by cultivated taxa planted in nearby residential developments.

Lead (Pb) increases dramatically at 12 cm depth. Construction began on Interstate 5 in 1964, 1 km east of the core site (Fig. 1A). The increase in Pb may be related to increasing automobile traffic using leaded gasoline (Cole *et al.*, 1990). Another possible cause was the presence of a sewage plant within the estuary beginning in 1962 (Fig. 1A).

DISCUSSION

Sedimentation Rates and Geomorphic History

During and following the settlement period, sedimentation rates in the lagoon increased by approximately an order of magnitude. Presettlement sedimentation rates averaged 0.5 mm cal yr^{-1} between A.D. 1830 and 1848 B.C., but the average twentieth century sedimentation rate was 4.3 mm cal yr^{-1}. The twentieth century rate derived from this study is almost identical to the 4.6 mm cal yr^{-1} reported in an earlier study (Mudie and Byrne, 1980). The average nineteenth century postsettlement sedimentation rate from the present study was 3.5 mm cal yr^{-1} (Table 2).

Coastal salt marshes, such as Los Peñasquitos Lagoon, were far below their modern levels near the close of the Pleistocene (Fairbanks, 1989). The rapid postglacial rise in sea level then inundated Los Peñasquitos Lagoon, forming an open bay with rocky, cobbly beaches before 6000 yr B.P. (Inman, 1983). By 4000 yr B.P., sea-level rise had slowed and sandy beaches began to form, as indicated by a shift from rocky-coast Molluscan species to sandy-beach species in coastal archaeological middens (Masters and Gallegos, 1997). Thus, the sandy sediments at the base of this core formed at the time when lagoonal infilling and tectonic uplift were catching up with the preceding rise in sea level.

During and following European settlement, disturbances on the landscape caused sediments to be eroded from the uplands and deposited within the estuary. This larger sediment load decreased the volume of water entering and leaving the estuary with every tide, thus reducing the effectiveness of tidal flushing. Later, the roads and railroads obstructing the drainage channel further decreased and eventually stopped tidal flushing of the estuary. As a result, the lagoon now contains 50 to 55 cm

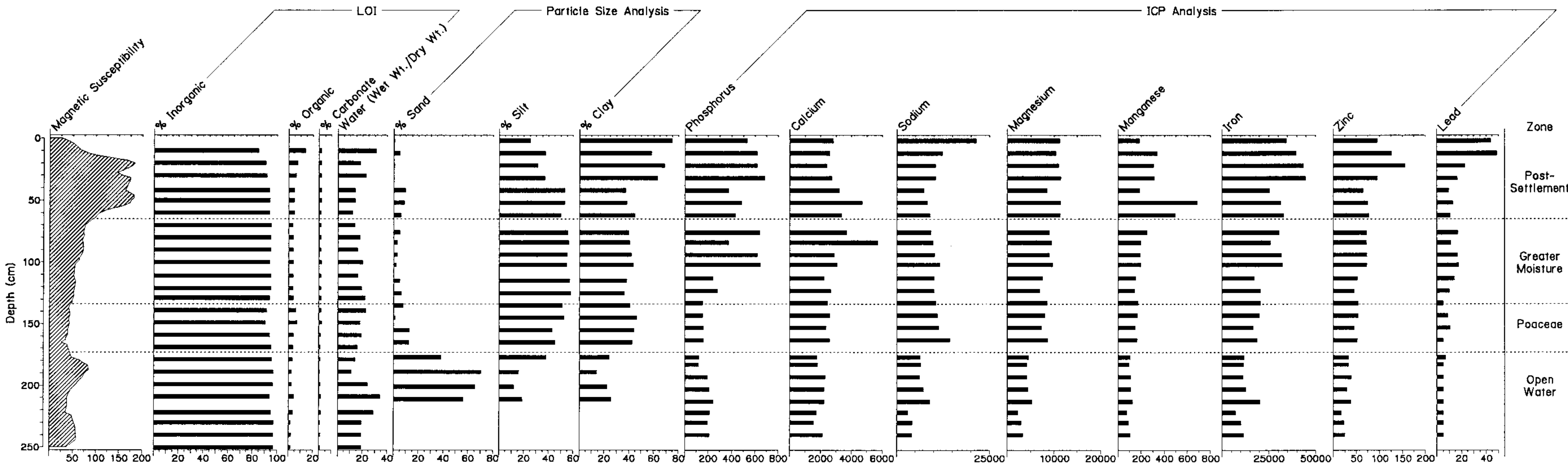

FIG. 4. Physical and chemical stratigraphy from Los Peñasquitos Lagoon. Magnetic susceptibility measures are in SI units. Loss-on-ignition (LOI) analysis shows the percentages of the sediments which are inorganic, organic, or carbonate. Water values are the percentages of original sample water weights. Particle size results are in percentages. Inductively coupled plasma spectroscopy (ICP) data are all in parts per million (mg kg^{-1}).

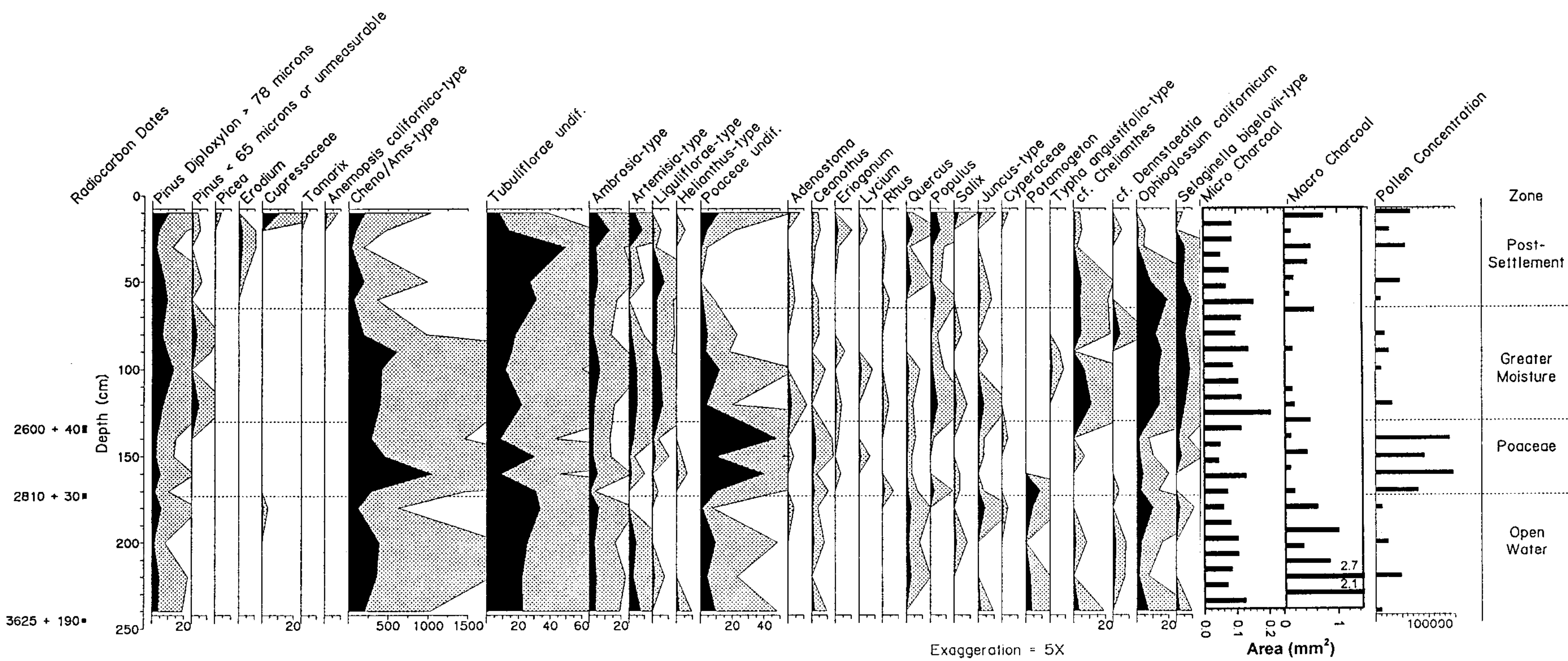

FIG. 5. Fossil pollen and charcoal from Los Peñasquitos Lagoon. All taxa are expressed as percentages of total terrestrial pollen, except for Cheno/Ams-type, which is expressed as percentages of total pollen. Micro-charcoal and macro-charcoal are expressed in surface area cc^{-1}. Measurements of *Pinus* pollen are in total grain length as defined by Kapp (1969).

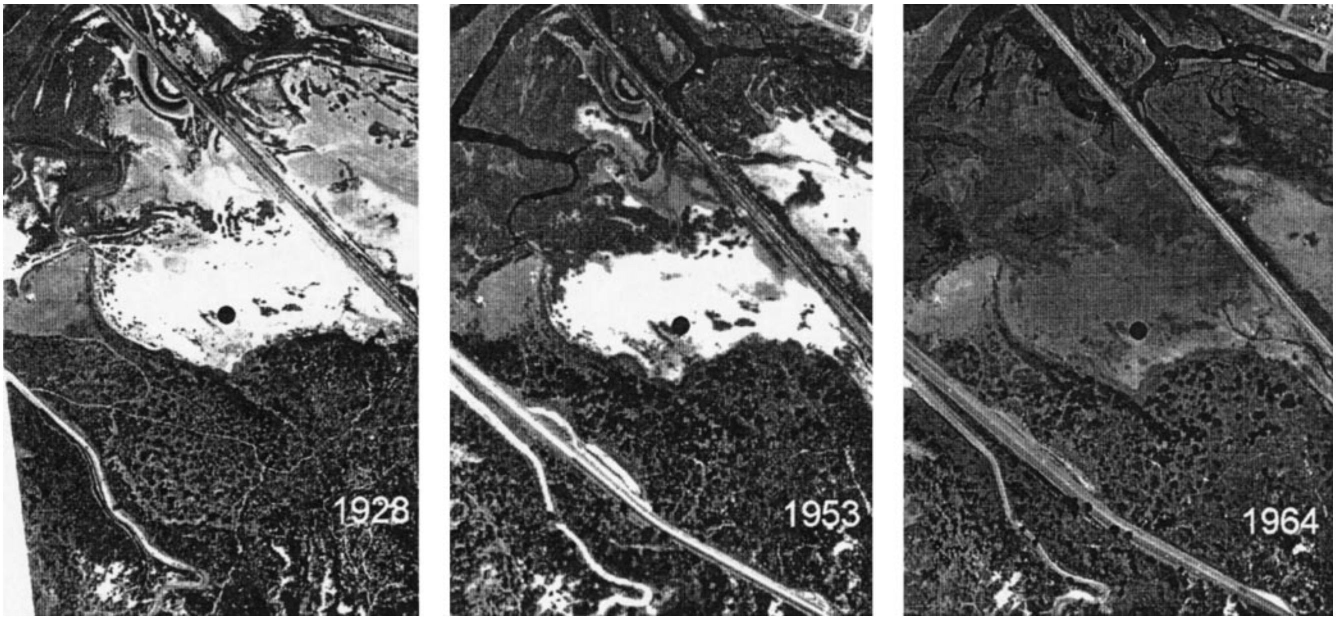

FIG. 6. Three historical aerial photographs of the core site (black dots) in Los Peñasquitos Lagoon. The 1928 photo shows broad mud-flats within the lagoon. By 1953, *Salicornia* had expanded into many of the bare areas, and it covered almost the entire lagoon by 1964 (Fig. 2). The *P. torreyana* stand is in the lower left of each photo. Photo credit: Aerial Fotobank, Inc./Landiscor, 858-455-0780.

of excess sediment above its presettlement elevation relative to sea level. The results obtained here are similar to those from other studies of southern California salt marshes for the settlement era (Mudie and Byrne, 1980; Davis, 1992; Cole and Liu, 1994).

Paleovegetation and Paleoclimate

Potomogeton sp. (pondweed) pollen is found in the lowest levels of the core (Fig. 5), which are largely composed of sandy sediments (Fig. 4). At least one local *Potomogeton* species (*P. foliosus*) currently grows in brackish pools within the study area. The presence of *Potomogeton* and dominance of sandy sediments suggest the persistence of open water until about 2750 yr B.P. After that time, *Potomogeton* pollen disappears, and the sand fraction drops dramatically.

Poaceae (grass family) pollen and total pollen concentration greatly increase as *Potomogeton* and sand decline. High percentages of Poaceae pollen are recorded between about 2850 and 2600 yr B.P. This increase could indicate an expansion of *Spartina foliosa* (cord-grass) at the core site. Although currently extirpated, *S. foliosa* historically occurred within Los Peñasquitos Lagoon (Purer, 1942), where it formed the lowest vegetation zone (Macdonald, 1977). If the sediment surface was slowly rising relative to sea level, *S. foliosa* would likely be the first colonizer. Also, the high sedimentation rate during this period (Fig. 3) and high pollen accumulation rate (Fig. 5) could result from sediment trapping within the grassy vegetation.

Alternatively, the high levels of Poaceae pollen could indicate an expansion of upland grasslands surrounding the lagoon at the expense of woody chaparral. The microscopic charcoal record (see below) and the concurrent decline of *Quercus* (oak) pollen give some support for this interpretation. Modern surface samples taken in southern California coastal sage scrub and chaparral have far lower levels of Poaceae pollen, usually $<3\%$ (E. Wahl, unpublished data). Comparison of modern pollen percentages in California grasslands is problematic, for these areas are now dominated by introduced European grasses. It is also possible that *Spartina* colonized the core site at the same time that terrestrial grasslands were expanding.

Several terrestrial taxa suggest that moister conditions prevailed after about 2600 yr B.P. An increase in *Populus* sp. (cottonwood) pollen may indicate a more-consistent freshwater flow into the lagoon. Increases in *P. torreyana*-type pollen and spores of *Cheilanthes* sp. (lip fern), *Ophioglossum californicum* (adder's tongue fern), and *Selaginella bigelovii*-type (spike moss) suggest greater winter/spring moisture availability. Microscopic charcoal also increases at this time, possibly suggesting greater continuity between fire fuels (Cole and Liu, 1994).

Ophioglossum californicum is infrequent today in San Diego County (Beauchamp, 1986). Its abundance in this record, along with its presence in the record of Anderson and Byrd (1998), suggests that this species was formerly much more common.

The suggested increase in late Holocene moisture is similar to, but slightly later than, that of other southern California records. On Santa Rosa Island, Cole and Liu (1994) interpreted a rise in *Selaginella bigelovii*-type and microscopic charcoal, similar to this record, as indicating greater moisture after 3250 yr B.P. The difference between the onset of these late Holocene moister conditions, 3250 yr B.P. in the north and 2600 yr B.P. in the south, could represent a time-transgressive strengthening of the winter precipitation regime. Present winter/spring precipitation greatly increases from south to north. A gradual southerly shift of the modern gradient could produce the observed pattern. Anderson and Byrd (1998) report a radiocarbon-dated sequence of alluvial pollen and spores 50 km north of Los Peñasquitos Lagoon. Their record suggests that more effective moisture was present at Las Floras Creek ca. 3800 yr B.P. They also interpret a significant change at 2600 yr B.P., representing the establishment of the modern vegetation mosaic around their site.

Most coastal southern California palynological records indicate that available winter/spring moisture increased during the late Holocene, but the timing of this change differs somewhat from study to study. Because radiocarbon dating is problematic in many of these records, future studies are needed to clarify whether the moisture shifts were synchronous or time-transgressive as this study suggests.

Charcoal and Fire History

Beginning ca. 2800 yr B.P., macroscopic charcoal decreases, whereas microscopic charcoal reaches a peak and Poaceae pollen greatly increases. This change in charcoal size could be caused by a conversion of woody plant communities to grassland within the drainage. Burning grasslands could produce microscopic charcoal but might also produce less macroscopic charcoal. Such a relationship between plant-community type and charcoal size has been recognized in the Holocene conversion of prairie to oak savanna in eastern Minnesota (Lease, 1998). The simultaneous decline in *Quercus* pollen further supports this interpretation.

Between ca. 2600 yr B.P. and the settlement period, microscopic charcoal reaches its highest levels, while macroscopic charcoal is at its lowest levels (Fig. 5). This zone could represent a period of more-frequent fires. Microscopic charcoal could be produced by burning grassland and other less woody vegetation, such as coastal sage scrub. The dominant sage scrub species, *Artemisia californica* (California sagebrush) and Liguliflorae-type Asteraceae, have higher pollen percentages during this period. Frequent fires would suppress the growth of woody chaparral species (Zedler, 1995) and thus produce fewer large charcoal particles. In addition, this period represents the wettest interval. Wet winter/spring periods can produce abundant grassy and herbaceous fuels, leading to summer or fall fires encompassing larger areas.

Fire frequency also was likely affected by aboriginal populations living near the estuary (Christenson, 1990). Although there are few hard data, fire probably was used for landscape management by native Americans throughout this period. Aboriginal fire use is historically documented for the late eighteenth century (Timbrook *et al.*, 1982) and is suggested by early Spanish accounts from the mid-sixteenth century (Bean and Lawton, 1973).

The high levels of microscopic and macroscopic charcoal marking the start of the settlement period (Fig. 5) probably result from burning around ranches to clear older woody vegetation. Lower levels of microscopic charcoal occur during the period of historic fire suppression. Higher values for the final samples in both the microscopic and macroscopic charcoal probably result from one of the recent small fires that burned chaparral and sage scrub close to the core site in 1972, 1984, 1985, and 1992 (Mike Wells, oral communication, 1999).

Recent and Past Pinus torreyana Populations

Pollen of the *P. torreyana*-type occurs throughout the 3600-yr record from this core and is also present in 4200-yr-old samples from the eastern edge of the estuary (Cole and Wahl, 1997). *Pinus torreyana*-type pollen averaged 8.0% of the terrestrial pollen since 2100 yr B.P. but only 3.6% before then. Over the last 2100 yr, the *P. torreyana* population may have been ca. two to three times as large as it was about 3000 yr ago. This interpretation is consistent with a reduction in the *P. torreyana* population during the warm/dry middle Holocene as suggested by Ledig and Conkle (1983), and this reduction could be responsible for its present extremely low heterozygosity (Waters and Schaal, 1991). Relatively high *P. torreyana*-type pollen percentages during the last 30 yr suggest that the *P. torreyana* population may now be at its highest level since settlement. The aerial photographs and pollen accumulation rate values corroborate this inference. In the photographs, canopy *P. torreyana* increased 2.8 times between 1928 and 1964 (Cole and Wahl, 1997), correlating positively with an increase of 1.9 times in the accumulation rate of *P. torreyana*-type pollen over a similar period (ca. 1930 to 1970). An increase in canopy trees also corresponds with the age structure of the stand (McMaster, 1980). The parallel movement of pollen percentage, number of mature trees, and pollen accumulation rate in the twentieth century support the estimates of past relative population sizes based upon *Pinus* pollen percentages.

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REFERENCES

Anderson, R. S., and Byrd, B. F. (1998). Late-Holocene vegetation changes from the Las Flores Creek Coastal Lowlands, San Diego County, California. *Madrono* **45,** 171–182.

Bean, L. J., and Lawton, H. W. (1973). "Some Explanations of the Rise of Cultural Complexity in Native California with Comments on Proto-agriculture and Agriculture." Ballena Press Anthropological Papers 1, Ballena Press, Menlo Park, CA.

Beauchamp, R. M. (1986). "A Flora of San Diego County, California." Sweetwater River Press, National City, CA.

Christenson, L. E. (1990). "The Late Prehistoric Human People of San Diego County, California: Their Settlement and Subsistence System." Unpublished Ph.D. dissertation, Arizona State University.

Cole, K. L., and Liu, G. (1994). Holocene paleoecology of an estuary on Santa Rosa Island, California. *Quaternary Research* **41,** 326–335.

Cole, K. L., and Wahl, E. (1997). "The Late Holocene Vegetation and Fire History of Torrey Pines State Reserve." Unpublished Technical Report to Torrey Pines State Reserve.

Cole, K. L., Engstrom, D., Futyma, R., and Stottlemyer, R. (1990). Atmospheric deposition of metals in northern Indiana measured using a peat core from Cowles Bog. *Environmental Science and Technology* **24,** 543–548.

Davis, M. B. (1983). Holocene vegetational history of the eastern United States. *In* "Late Quaternary Environments of the United States" (H. Wright, Ed.), pp. 166–180. University of Minnesota Press, Minneapolis.

Davis, O. K. (1992). Rapid climatic change in coastal southern California inferred from pollen analysis of San Joaquin Marsh. *Quaternary Research* **37,** 89–100.

Emery, K. O. (1950). Ironstone concretions and beach ridges of San Diego County, California. *California Journal of Mines and Geology* **46,** 213–221.

Evarts, B. (1994). "Torrey Pines: Landscape and Legacy." Torrey Pines Association, La Jolla, CA.

Faegri, K., and Iversen, J. (1989). "Textbook of Pollen Analysis." Wiley, New York.

Fairbanks, R. G. (1989). A 17,000-year glacio-eustatic sea level record: Influence of glacial melting rates on Younger Dryas event and deep-ocean circulation. *Nature* **342,** 637–642.

Griffin, J. R., and Critchfield, W. B. (1972). "The Distribution of Forest Trees of California." USDA Forest Service Research Paper PSW-82/1972.

Haller, J. R. (1967). A comparison of the mainland and island populations of Torrey pine. *In* "Proceedings of the Symposium on the Biology of the California Islands" (R. Philbrick, Ed.), pp. 79–88. Santa Barbara Botanic Garden, Santa Barbara, CA.

Haller, J. R. (1986). Taxonomy and relationships of the mainland and island populations of *Pinus torreyana* (Pinaceae). *Systematic Botany* **11,** 39–50.

Inman, D. L. (1983). Application of coastal dynamics to the reconstruction of paleocoastlines in the vicinity of La Jolla, California. *In* "Quaternary Coastlines and Marine Archaeology" (P. M. Masters and N. C. Flemming, Eds.), pp. 1–49. Academic Press, London.

Kapp, R. O. (1969). "How to Know Pollen and Spores." W. C. Brown, Dubuque.

Kerr Collection (1951). Collection of California Land Title Notes received by San Diego Historical Society in 1951.

Lease, K. (1998). "Paleoecology of Some Plant Taxa Uncommon on the Anoka Sand Plain." Unpublished masters thesis, University of Minnesota.

Ledig, F. T., and Conkle, M. T. (1983). Gene diversity and genetic structure in a narrow endemic, Torrey pine (*Pinus torreyana* Parry ex. Carr.). *Evolution* **37,** 79–85.

Macdonald, K. B. (1977). Coastal salt marsh. *In* "Terrestrial Vegetation of California" (M. Barbour and J. Major, Eds.), pp. 263–294. Wiley, New York.

McMaster, G. S. (1980). "Patterns of Reproduction in Torrey Pine (*Pinus torreyana*)." Unpublished masters thesis, San Diego State University.

Masters, P. M., and Gallegos, D. R. (1997). Environmental change and coastal adaptations in San Diego County during the middle Holocene. *In* "Archaeology of the California Coast during the Middle Holocene, Volume 4," pp. 11–21. University of California, Los Angeles, Institute of Archaeology, Perspectives in California Archaeology, Los Angeles.

Mensing, S., and Byrne, R. (1998). Pre-mission invasion of *Erodium cicutarium* in California. *Journal of Biogeography* **25,** 757–762.

Mudie, P. J., Browning, B., and Speth, J. (1974). "The Natural Resources of Los Peñasquitos Lagoon and Recommendations for Use and Development." Coastal Wetlands Series 7, California Department of Fish and Game, Sacramento.

Mudie, P. J., and Byrne, R. (1980). Pollen evidence for historic sedimentation rates in California coastal marshes. *Estuarine and Coastal Marsh Science.* **10,** 305–316.

Munz, P. A. (1974). "A Flora of Southern California." University of California Press, Berkeley.

Purer, E. A. (1942). Plant ecology of the coastal salt marshlands of San Diego County. *Ecological Monographs* **12,** 82–111.

Stuiver, M., and Reimer, P. J. (1993). A radiocarbon calibration program. *Radiocarbon* **35,** 215–230.

Scott, David B., Mudie, P., and Bradshaw, J. (1976). Bethonic foraminifera of three southern California lagoons: Ecology and recent stratigraphy. *Journal of Foraminiferal Research* **6,** 59–75.

Sugita, S., MacDonald, G. M., and Larsen, C. P. S. (1997). Reconstruction of fire disturbance and forest succession from fossil pollen in lake sediments: Potential and limitations. *In* "Sediment Records of Biomass Burning and Global Change" (J. Clark, H. Cachier, J. Goldammer, and B. Stocks, Eds.), NATO AS1 Series, Vol. 151, pp. 387–411. Springer-Verlag, Berlin/New York.

Thompson, R. S. (1988). Vegetational dynamics in the western United States: Modes of response to climatic fluctuations. *In* "Vegetation History" (B. Huntley, and T. Webb III, Eds.), pp. 415–454. Kluwer Academic, Dordrecht/Norwell, MA.

Timbrook, J., Johnson, J. R., and Earle, D. D. (1982). Vegetation burning by the Chumash. *Journal of California and Great Basin Anthropology* **4,** 163–186.

Waters, E., and Schaal, B. A. (1991). No variation is detected in the chloroplast genome of *Pinus torreyana. Canadian Journal of Forest Research* **21,** 1832–1835.

West, G. J. (1989). Early historic vegetation change in Alta California—The fossil evidence. *In* "Columbian Consequences: Archaeological and Historic Perspectives on the Spanish Borderlands West" (D. H. Thomas, Ed.), pp. 333–348. Smithsonian Press, Washington, DC.

U.S. Environmental Protection Agency (1987). "Test Methods for Evaluating Solid Waste: Physical/Chemical Methods," 3rd ed. USEPA, Washington, DC.

Zedler, P. H. (1995). Fire frequency in Southern California shrublands: Biological effects and management options. *In* "Brushfires in California Wildlands" (J. E. Keeley and T. Scott, Eds.), pp. 102–112. International Association of Wildland Fire, Fairfield, Australia.