Marine terraces, sea level history and Quaternary tectonics of the San Andreas fault on the coast of California

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TECTONIC SETTING OF NORTHERN CALIFORNIA

The interaction of the Pacific and North American plates has dominated the tectonics of what is now coastal California since the early Miocene (Atwater, 1970). The major plate-boundary structures belong to the San Andreas fault system, a set of northwest-trending, right-lateral, strike-slip faults. In the San Francisco Bay area, the most important faults of this system are the San Andreas, Hayward, Calaveras, and San Gregorio (Fig. 1). The San Andreas fault continues north of San Francisco at least as far as Shelter Cove (Brown, 1995; Prentice et al., 1999; Merritts et al., 2000), but other faults within the San Andreas system accommodate a significant percentage of the plate motion north and east of San Francisco (Argus and Gordon, 2001; Savage et al., 1998; Kelson et al., 1992). This field trip will focus primarily on the San Andreas fault, but also includes one stop along the San Gregorio fault.

Although the Pacific-North American plate boundary is a dominantly right-lateral, transform system, slight variations in plate motion vectors give rise to a small amount of fault-normal compression. This component of compression produces the ongoing uplift of the Coast Ranges that has resulted in the emergence of Quaternary marine terraces along most of the California coast. These marine terraces provide a tool for understanding rates of tectonic uplift and deformation, as well as data that allow a better understanding of climatically driven, eustatic sea level change during the Quaternary.

MARINE TERRACES AND THE NATURE OF THE SEA LEVEL RECORD

The Quaternary geologic record of high sea-stands takes the form of emergent reefs (on tropical shores) or marine terraces (on high-energy, mid-latitude coasts), on either tectonically stable or rising coasts. In contrast to tropical coral reefs, which are constructional landforms, marine terraces are emergent, wave-cut platforms veneered with thin, sometimes fossiliferous, marine sand and gravel. On rising crustal blocks, such as most of coastal California, interglacial high sea-stands leave a stair-step flight of marine terraces (Fig. 2).

Marine terraces have been studied in central California for more than a century, since the pioneering study of Lawson (1893). Alexander (1953), studying the region just south of Santa Cruz, first recognized that California marine terraces are the result of Quaternary sea level high-stands superimposed on a tectonically rising crustal block.

Bradley and Griggs (1976) mapped six prominent terraces along ~40 km of coastline between Santa Cruz and Point Año Nuevo (Fig. 3). The lowest of these, the Santa Cruz terrace, appears...
as a single, relatively flat surface, but Bradley and Griggs (1976) demonstrated it is actually a complex of three platforms, from oldest to youngest the Greyhound, Highway 1, and Davenport platforms. Marine and nonmarine deposits have “smoothed” the surface topographically into a single, broad landform. Most workers agree that the Santa Cruz terrace complex probably represents the last interglacial period, but correlation to specific sea level stands has been a matter of debate (Bradley and Griggs, 1976; Kennedy et al., 1982; Weber, 1990; Lajoie et al., 1991; Anderson and Menking, 1994; Perg et al., 2001, 2002; Brown and Bourles, 2002; Muhs et al., 2002c). Soils on terraces in the Santa Cruz area have been studied by Schulz et al. (2003) in a complimentary field trip (this volume).

**STOP 1. NATURAL BRIDGES STATE BEACH**

At this first stop, some of the best examples of modern coastal landforms in California may be seen at low tide. The bedrock exposed in a well-developed, wave-cut platform along the coast at Natural Bridges State Beach is the Santa Cruz mudstone (Miocene). Although this rock is well cemented, it has thin bedding and is characterized by numerous fractures, which, as pointed out by Bradley and Griggs (1976), can result in easy erosion by waves. The platform is a planar, erosion surface on bedrock that formed by wave erosion through hydraulic impact, abrasion and quarrying, and gravitational collapse by undercutting. Wave erosion is strongest in winter, coastal California’s rainy season, when storms develop in the eastern Pacific Ocean. Griggs and Johnson (1979) showed that the long-term average sea cliff retreat rate in some parts of Santa Cruz County is ~30 cm/yr. However, much cliff retreat takes place episodically during strong winter storms. Accelerated sea-cliff erosion took place during the winters of 1982-1983 and 1997-1998, when large storms related to El Niño conditions dominated the eastern Pacific Ocean (Storlazzi and Griggs, 2000).

**STOP 2. DAVENPORT TERRACE AT POINT SANTA CRUZ**

Much of the city of Santa Cruz, California is built on the Santa Cruz terrace complex (Fig. 3). Looking to the north from many vantage points within the city, the inner edge of the Santa Cruz terrace complex and the sea cliff rising to the next-highest (“Western”) terrace can be seen. Exposures of the Davenport platform are visible in the modern sea cliff, near Point Santa Cruz. The platform, cut into sandstone, is ~6 m above sea level and is overlain by thin (~20 cm), fossiliferous, marine, terrace deposits containing paired valves of *Saxidomus gigantea* and *Protothaca staminea*. At this locality, a single *Balanophyllia elegans* coral, collected and archived by Hoskins (1957), gave a U-series age of 71,500 ± 400 yrs. (Muhs et al., 2002c).

**STOP 3. TERRACE OVERLOOK AT DAVENPORT**

This brief stop provides excellent views of the seaward extent of the Santa Cruz terrace complex. In addition, many of the higher terraces (Cement, Western, Blackrock, and Quarry) mapped by Bradley and Griggs (1976) are visible here.
STOP 4. TERRACE DEPOSITS, FOSSILS, AND FAULTS AT POINT ANO NUEVO

Año Nuevo State Reserve is home to the world’s largest, mainland, elephant seal population, as well as Steller sea lions and harbor seals. The hills above the Reserve are part of Big Basin Redwoods State Park, California’s first state park. The park was established for the occurrence here of the beautiful old-growth coastal redwood (Sequoia sempervirens), a tree found only in a coastal strip from Santa Cruz County, California, to just over the Oregon border.

Near Point Año Nuevo (Figs. 3, 4), fossiliferous, Davenport-platform, terrace deposits are exposed in the modern sea cliff. Note also the presence of both bivalves and gastropods in the Tertiary bedrock here. Quaternary marine deposits that can be observed at this locality are ~0.5 m thick and contain the bivalve Saxidomus gigantea in growth position. The platform has also been bored by pholads, some still in their holes in the platform. The overlying alluvium, which is ~10 m thick, has a well-developed soil (A/E/Bt/C profile) in its upper part. The terrace platform in this area is displaced vertically by at least two northwesterly-striking faults (the Frijoles and Coastways faults) (Fig. 4) that are part of the San Gregorio fault zone (Weber, 1990; Weber et al., 1979). On the uplifted crustal block west of the Frijoles fault, the Davenport platform is ~8-10 m above sea level and can be seen from the modern beach. A sag pond has formed on the downthrown side of the fault (Fig. 4) and is visible from the trail at the top of the terrace. At or near this locality, Hoskins (1957) collected and archived a single individual Balanophyllia elegans coral, which gave a U-series age of 75,800 ± 400 yrs. (Muhs et al., 2002c).

STOP 5. TERRACE AND FOSSILS AT GREEN OAKS CREEK

(Note that this is State Reserve property, so permission is needed for access to this outcrop.)

Figure 4. Aerial photograph of the Point Año Nuevo-Green Oaks Creek area, showing geology (from the present authors), geomorphic features, fossil localities, and faults (from Weber et al., 1979 and Weber, 1990). Qal, alluvium; Qmt, marine terrace deposits; Qes, eolian sand.
One of the richest, marine-terrace, fossil beds in central California is found on the Davenport platform near the mouth of Green Oaks Creek, just north of Point Año Nuevo (Figs. 3, 4). The Davenport platform is ~5 m above sea level and has a fossiliferous basal gravel ~0.5 m thick, overlain by ~4 m of marine (?) sand, capped by ~2 m of eolian sand. A paleosol separates the eolian sand from the underlying marine sediments. The Davenport platform here is bored extensively by pholadid bivalves. Corals are abundant in the terrace deposits at Green Oaks Creek and were collected by Muhs et al. (2002c). U-series ages of 11 individual corals (*Balanophyllia elegans*) from Green Oaks Creek range from 75,800 ± 800 to 84,000 ± 600 yrs. B.P. This age span includes the ~76,000 yrs. B.P. age of the coral from Point Año Nuevo (STOP 1-4) and is close to the ~72,000 yrs. B.P. age of the coral from Point Santa Cruz (STOP 1-2). All fossil corals analyzed from Green Oaks Creek have back-calculated initial 234U/238U values that are in close agreement with those measured for modern seawater (Fig. 5). Therefore, the corals have probably experienced closed-system conditions with respect to U and its daughters, and ages are considered to be reliable.

The coral ages from Green Oaks Creek, Point Año Nuevo, and Point Santa Cruz all indicate that the Davenport platform dates to the ~80,000 yr. B.P. high-stand of the sea. This high-stand is also recorded as marine oxygen isotope substage (OIS) 5a (Martinson et al., 1987), emergent reef terraces on New Guinea (Bloom et al., 1974) and Barbados (Mesolella et al., 1969; Ku et al., 1990; Edwards et al., 1997), and marine deposits on Bermuda (Muhs et al., 2002b). The multiple coral ages from the Green Oaks Creek locality, with their evidence of closed-system histories, give a high degree of confidence that this sea-level high-stand had a duration from ~84,000 to at least 77,000 yrs. B.P., similar to that recorded on Bermuda (Fig. 5).

Coral ages from Green Oaks Creek indicate some differences between the ~80,000-yr.-B.P., high sea stand and the present interglacial high sea stand. The present, relatively high, sea level is the result of melting of the Laurentide and Fennoscandian ice sheets at the end of the last glacial period. Melting of these ice sheets is thought to be the result of relatively high summer insolation in the Northern Hemisphere around 11,000 yrs. B.P. However, sea level did not reach near-present elevations until about 7,000 to 5,000 yrs. B.P., a sea-level lag of 4,000 to 6,000 yrs. In contrast, U-series ages of corals from the Davenport terrace at Green Oaks Creek indicate that sea level must have been relatively high at the time of, or prior to, a previous period of high summer insolation in the Northern Hemisphere (around 82,000 yrs. B.P.; Fig. 5).

The U-series ages for the Davenport terrace differ from the inferred age of this terrace based on cosmogenic isotope dating of higher terraces, reported by Perg et al. (2001). The age of the Davenport terrace, based on Perg et al.'s (2001) data, must be younger than ~65,000 yrs. B.P. Ages reported by these workers may reflect the ages of alluvium that overlies the marine deposits. Our own observations suggest that the terrestrial sedimentary cover in this area is usually much thicker than the marine cover (for example, at Point Año Nuevo), and that marine sediments are rarely, if ever, exposed at the ground surface. One of the implications of the study of Perg et al. (2001) is that uplift rates along this part of the California coast are relatively high, on the order of 1 m/ka. The U-series ages presented here indicate much lower rates of uplift, around 0.20-0.35 m/ka, which are consistent with rates found elsewhere along the coast from Baja California to Oregon (Muhs et al., 1992).

**FAUNAS OF THE MARINE TERRACE DEPOSITS IN CENTRAL CALIFORNIA**

Species that are most important in paleoclimatic interpretation of marine terrace faunas are those with modern geographic distributions of the study of Perg et al. (2001) is that uplift rates along this part of the California coast are relatively high, on the order of 1 m/ka. The U-series ages presented here indicate much lower rates of uplift, around 0.20-0.35 m/ka, which are consistent with rates found elsewhere along the coast from Baja California to Oregon (Muhs et al., 1992).
distributions that extend only to the south ("extralimital southern") or only to the north ("extralimital northern") of a fossil locality. Paleoclimatic inferences can also be made from species that are not strictly extralimital, but whose range endpoints are at or near a given fossil locality. These are referred to herein as "northward ranging" or "southward ranging" species. Our discussion here is based on the faunas, mostly mollusks, reported from the ~80,000-yr-old Davenport terrace by Addicott (1966). We have updated the modern geographic ranges of the species because information now available is better than it was in the 1960s (Fig. 6). Deposits of the Davenport terrace at Green Oaks Creek (USGS loc. M2147) contain three extralimital northern species plus three northward-ranging species whose modern southern ranges terminate at or near Point Año Nuevo. At Point Año Nuevo (USGS loc. M1690), seven extralimital northern species but no extralimital southern or southward-ranging species are found. The Davenport terrace fauna from Point Santa Cruz (USGS loc. M1691) contains three extralimital northern species and five northward-ranging species. As with the other central California localities, it lacks any extralimital southern or southward-ranging species. Based on the combined data from Point Santa Cruz, Point Año Nuevo, and Green Oaks Creek, all localities with extensive cool-water elements in their faunas, we conclude that central California had cooler-than-modern waters at ~80,000 yrs. B.P.

In contrast, during the peak of the last interglacial period at ~120,000 yrs. B.P. (OIS 5e), waters around much of North America, including California, were warmer than present (Muhs et al., 2002a, 2002b). Either the Highway 1 or Greyhound terraces probably date to this high sea stand, but fossils have not been found in the deposits of these terraces. However, an emergent marine deposit called the Millerton Formation, exposed around Tomales Bay north of San Francisco, also probably dates to this high sea-stand, based on both amino acid ratios in mollusks (Kennedy et al., 1982) and thermoluminescence dating of sediments (Grove and Niemi, 1999). The fauna from the Millerton Formation (Johnson, 1962) contains no northern species but has abundant extralimital southern and southward-ranging species (Fig. 6). Other climate proxies agree with the marine faunal data. Alkenone, radiolarian, and pollen data from cores off northern California and southern Oregon indicate cooler-than-present water at ~80,000 yrs. B.P. and warmer-than-present water at ~120,000 yrs. B.P. (Heusser et al., 2000; Herbert et al., 2001; Pisias et al., 2001). Cooler-than-modern waters are probably best
explained by a stronger California Current (subarctic water from the north), whereas warmer-than-modern waters are probably the result of a stronger Davidson Countercurrent (southern water). Mark Twain once said that the coldest winter he ever spent was a summer in San Francisco: during the ~80,000 yrs. B.P. high sea-stand, it would have been even colder!

End of DAY 1: Overnight in Half Moon Bay, CA

DAY 2: HALF MOON BAY TO GUALALA, CA

STOP 6. OVERLOOK OF SAN ANDREAS FAULT FROM VISTA POINT EAST OF HIGHWAY 280

The “rift valley” of the San Andreas fault zone forms a prominent geomorphic feature visible (on a clear day!) from the STOP 6 vista point. The San Francisco earthquake of April 18th, 1906, is the most-recent, large earthquake to rupture the entire northern San Andreas fault (SAF), including the section we see from this vista point. Surface rupture associated with this earthquake was reported along about 435 km of the fault, from near San Juan Bautista to several km NW of Shelter Cove, about 120 km northwest of Point Arena (Fig. 1) (Lawson, 1908; Prentice, 1999). Today, we will stop at several localities to view the active traces of the SAF and to discuss the current understanding of the seismic hazard this fault represents to the San Francisco Bay area.

Crystal Springs Reservoir and San Andreas Lake (Fig. 7) are artificial reservoirs situated in the fault zone, and the active trace of the SAF runs through both. The two dams that impound these reservoirs are San Andreas dam, initially constructed in 1868, and Crystal Springs dam, initially constructed in 1888. Both reservoirs survived the 1906 earthquake, despite their close proximity to the SAF. The brick waste weir tunnel below San Andreas dam was displaced right-laterally 2.7 m (9 ft). The dam embankment did not fail because shearing along the SAF was confined to the bedrock ridge that forms the eastern abutment of the dam (Hall, 1984). The water distribution system, however, was severely damaged (Lawson, 1908; Schussler, 1906), which contributed to the great damage caused by fire in San Francisco after the earthquake.

Due to its proximity to the San Francisco urban area, the San Francisco Peninsula section of the fault is one of the most potentially hazardous segments along the entire length of the SAF. However, it remains one of the most poorly studied in terms of slip rate and earthquake recurrence. Probabilistic earthquake hazard assessments depend largely on recurrence and slip-rate data gathered from analyses of geologic information about prehistoric fault behavior. Recent subsurface investigations at sites along the SAF north of the Golden Gate (Prentice, 1989; Prentice et al., 1991; Niemi and Hall, 1992; Baldwin et al., 2000; Noller et al., 1993; Prentice et al., 2001) have provided some data on pre-1906 earthquakes and the Holocene slip rate, but few successful paleo-seismic sites on the San Francisco Peninsula have been developed. Paleoseismic work at the Filoli site, situated at the southern end of Crystal Springs reservoir (Fig. 7), has yielded a late Holocene slip-rate estimate of 17 ± 4 mm/yr (Hall et al., 1999), similar to slip-rate estimates for the section of the fault north of San Francisco (≤23 ± 2 mm/yr (Prentice, 1989); 24 ± 3 mm/yr (Niemi and Hall, 1992); 18 ± 3 mm/yr (Prentice et al., 2001)). Although these studies have added significantly to the understanding of the recent behavior of the northern SAF, many questions remain, and more work is needed to understand this critical segment of the SAF in the San Francisco area.

STOP 7. OFFSET CYPRESS TREES, FENCE, AND STREAM CHANNEL

(Note that this locality is within the San Francisco watershed, and special permission is needed for access).

The best-surviving cultural features that were offset during the 1906 earthquake on the San Francisco Peninsula are a fence and a row of cypress trees near Crystal Springs Reservoir (Fig. 7). Here, right-lateral displacement of 2.7 m (9 ft) is still clearly visible. This locality was photographed in 1906, and is shown in plate 61B of Lawson (1908) (reproduced here as Fig. 8). Note that the displacement is distributed over a zone sev-
eral meters wide. Note also the excellent preservation of delicate geomorphic features showing the nature and exact location of the surface rupture (seen in Fig. 8 to the right of the person standing in the middle ground of the photograph).

North of the offset fence, the 1906 trace of the SAF lies in a trough and is marked by a small closed depression. The fault trace can be followed to the northwest where prior fault movements have offset an incised stream channel between 52 and 87 m (170 to 285 ft.). This offset represents the sum of 19 to 32 seismic events comparable in slip to that of 1906, suggesting that the active trace has not changed location significantly for thousands of years (Hall, 1984).

STOP 8. URBAN SAN ANDREAS FAULT, CORNER OF WESTBOROUGH BOULEVARD AND FLEETWOOD DRIVE, SAN BRUNO

The urban development in this area (Fig. 9) occurred prior to enactment of the California law that prohibits such construction directly on top of an active fault (Alquist-Priolo Earthquake Fault Zoning Act, 1972). The fault was once well expressed through this area (Fig. 9), but construction has entirely obliterated the geomorphic features, such as sag ponds and shutter ridges, that once marked the active trace. Using photographs taken of the rupture after the earthquake in 1906 and analysis of pre-development aerial photographs, a detailed GIS of the best estimate of precisely where the fault broke in 1906 in this area is being developed by the USGS (Prentice and Hall, 1996). At this location, a fence offset in 1906 was still visible in 1956 when M.G. Bonilla of the USGS took the picture shown in Figure 10A, but was gone by 1962 when he took the photograph shown in Figure 10B. A photograph taken in 1906 (Fig. 10C) at this location shows the offset by three fault strands, a main trace with just under 2 m of right-lateral offset and two smaller, parallel breaks. Our mapping indicates that a number of the houses visible from this location are located directly on top of the 1906 rupture trace.
STOP 9. URBAN SAN ANDREAS FAULT, MYRNA LANE, SOUTH SAN FRANCISCO

This development (Fig. 9) was constructed prior to the Alquist-Priolo Act. The developer in this instance apparently tried to keep homes off the fault by keeping a green belt and a road over the area where they believed the fault came through. However, many of these structures appear to be directly on top of the 1906 fault rupture trace, according to our mapping.

STOP 10. SLIP RATE OF THE SAN ANDREAS FAULT AT MILL GULCH

The Gualala block consists of the area west of the San Andreas fault from south of Fort Ross to north of Point Arena (Fig. 11). Our next stop is just north of where the San Andreas fault comes onshore (Fig. 12). Mill Gulch, a deeply incised stream that is offset 80-100 m across the San Andreas fault, (Fig. 13) is visible from STOP 10. An abandoned channel of Mill Gulch is visible on Fig. 13, north of STOP 10. We excavated trenches in the abandoned channel and collected charcoal samples from pre- and post-abandonment sediments to estimate the age of the 80-100 m offset. Radiocarbon analyses of these samples provide minimum ages that range from 4290–4520 to 4890-5290 cal yrs. B.P., and a single maximum age of 5040–5320 cal yrs. B.P. These data suggest a slip rate of 19 ± 4 mm/yr (best estimate of 18 ± 3 mm/yr) (Prentice et al., 2000, 2001).

STOP 11. OFFSET FENCE AND TERRACE OVERLOOK

From this location (Fig. 12), the view toward the ocean on a clear day shows the flight of Pleistocene marine terraces present along the coast of the Gualala block. A mapping and detailed survey measurement of these terraces is underway to improve understanding of coastal uplift in the region.
At this location, an old picket fence, offset by the 1906 earthquake, is still visible. Although many of the fence posts have fallen, enough remain standing in 2003 to see the offset. The survey of this fence shown in Lawson (1908, p. 64) shows that the total offset of 3.7 m was distributed over a distance of 126 m, with only 2.3 m occurring where the main fault crosses the fence (Fig. 14). Historical research shows that Esper Larsen did the original survey between January 20 and February 3, 1907, about a year after the earthquake (Letters, 20 January 1907, and 3 February, 1907). Resurvey of this fence in 1985 shows virtually no change since the 1907 survey. This indicates that no measurable afterslip occurred on this fault between February 1907 and September 1985, consistent with resurveys of other offset fences along the San Francisco peninsula (R.E. Wallace, USGS, personal communication, 1994).

A few meters south of the fence, the old Russian road leading south from Fort Ross crosses the fault at a low angle. Careful observation shows that this road is displaced about the same amount as the fence suggesting that only one fault movement (1906) has offset this road in the time since the Russians established Fort Ross (1812). Geomorphic features typical of active faults are well displayed in the area south of the fence.

**STOP 12. VIEW OF MARINE TERRACE SHORELINE ANGLE EXPOSED IN SEA CLIFF:**

This is an outstanding (and rare) example of an exposure of a shoreline angle (Fig. 12). The elevation of this feature is 26 m above mean sea level. This is the lowest marine terrace in this area, and our mapping suggests it is correlative with the Point Arena terrace, which is dated to the ~80,000 yrs. B.P. (OIS 5a) sea-level high-stand (Muhs et al., 1994, 2002c).

**End of DAY 2: Overnight in Gualala, CA**

**DAY 3. GUALALA TO POINT ARENA TO MENDOCINO, CA; RETURN TO GUALALA AT END OF DAY**

**STOP 13. POINT ARENA MARINE TERRACE AGES AND FAUNA**

Well-preserved marine terraces are present along much of the coastline of northern California. In the vicinity of Point Arena (Fig. 11), Mendocino County, ~175 km north of San Francisco,
marine terraces were mapped by Prentice (1989) and, over a more limited area, by the present authors (Fig. 15). The three lowest terraces, informally designated Qt1, Qt2, and Qt3 in Fig. 15, have inner edge elevations of ~19-23, ~38-42 and ~56-64 m, respectively. The lowest terrace is called the “Point Arena terrace.” This terrace achieved fame in 1992 when Mel Gibson landed an airplane on it at the end of the movie “Forever Young.”

The Point Arena, or Qt1, terrace is well expressed geomorphically, and the terrace platform has a sharp contact with the overlying marine sediments. On sea-cliff exposures, the platform is typically riddled with pholad-bored holes and has a variable elevation, ranging from ~5 to ~17 m. Terrace deposits are well stratified, and horizontal beds of sand and gravel vary in thickness from ~2 to 7 m. Well-developed soils with A/E/Bw/C or A/E/Bs/C profiles have formed in the upper part of the marine terrace deposits. These soils are interesting in that many of them have a mollic epipedon, developed under the modern coastal prairie vegetation, yet have well-developed E and sometimes Bs horizons, suggesting a former forest cover.

Fossils from the Point Arena terrace deposits (map unit Qt1 on Fig. 15) at Point Arena were studied by Kennedy (1978), Kennedy et al. (1982), Kennedy and Armentrout (1989), and Muhs et al. (1990, 1994) for both their paleozoogeographic aspects and age estimates. Alpha-spectrometric U-series analyses of marine terrace corals from Point Arena (collected before the fossil localities disappeared) has an apparent age of 83,000 ± 800 yrs. B.P. (Muhs et al., 1990, 1994) and is therefore broadly consistent with the earlier ages.

The marine terrace fauna at Point Arena also contains extralimital northern species and lacks any extralimital southern or southward-ranging species. The fauna contains the extralimital northern mollusk *Mya truncata* (Kennedy, 1978; Muhs et al., 1990), which presently ranges only from Barrow, Alaska to Neah Bay, Washington (Coan et al., 2000). A particularly dramatic example of an extralimital northern species is the bivalve *Penitella hopkinsi*, whose modern distribution is limited to the Gulf of Alaska, but is found in the ~80,000-yrs.-B.P.-deposits at Point Arena (Kennedy and Armentrout, 1989). Thus, as with central California, the faunal data indicate cooler-than-modern marine paleotemperatures off the northern California coast at ~80,000 yrs. B.P.

STOP 14. LORAN STATION ON THE POINT ARENA TERRACE:

(Note: This is private property. Permission is needed for access.)

At this location (Fig. 15), the Point Arena terrace is well expressed geomorphically. Sea cliff exposures reveal two Quaternary thrust faults that have been active since the time this terrace formed (Prentice, 1989; Prentice et al., 1991). The first of these...
exposures is illustrated in Fig. 16. Miocene bedrock has been thrust over deposits that overlie the ~80,000 yrs. B.P. wave-cut platform. Several other exposures in this vicinity show similar relationships. Two nearby sea cliff exposures reveal a thrust fault that soles into a bedding plane within the Miocene bedrock. Faulted terrace deposits are also well exposed in a nearby sinkhole. These relations indicate Quaternary compression along the plate boundary in this area.

STOP 15. SAN ANDREAS FAULT AND OFFSET TERRACE RISER VIEW POINT

(Note: This is private property. Permission is needed for access.)

From this location (Fig. 17), we look across the SAF to two marine terrace risers (old sea cliffs) that are truncated on the northeast side of the SAF and see a prominent marine terrace riser on the southwest side of the fault (Fig. 18). Because right-lateral strike slip has occurred across the SAF since the time these terraces formed, the riser southwest of the fault at this location cannot correlate to either of the risers northeast of the fault. The only potential correlative to the risers on the northeast side of the fault is located southwest of the SAF and right-laterally offset 1.3 to 1.8 km (Fig 18, not visible from STOP 15). The prominent riser at this location on the southwest side of the fault at STOP 15 must also have a correlative northeast of the fault. The risers on the northeast side of the fault visible from STOP 15 are both unlikely candidates because right-lateral movement on the SAF would have displaced the correlative feature to the SE. The best candidate for a correlative is located northeast of the fault, right-laterally offset 2.3 to 3.2 km (not visible from this location, and not shown on Fig. 18). Estimates of the ages of these features (~80,000 yr, ~100,000 yr, and ~120,000 yr or substages 5a, 5c, and 5e) suggest average late Pleistocene slip rates of 16 to 24 mm/yr (Prentice, 1989; Prentice et al., 2000), consistent with slip rates estimated from study of Holocene features.

STOP 16. MENDOCINO HEADLANDS

The town of Mendocino (Figs. 1, 19) was founded during the California gold rush in 1852 when San Franciscans came north to recover salvage from the Chinese sailing ship Frolic, which was laden with luxurious goods for the rapidly growing city of San Francisco. Pomo Indians apparently found the wreckage first, but the San Franciscans returned to the city with tales of immense redwood forests, and, soon after, the first successful sawmill was established at the tip of the point. Although the mill now is gone, the New England-style town is a haven for artists and tourists. Our multiple surveys (both real-time, differentially corrected GPS and total station) of flights of broad marine terraces between Mendocino Headlands and the town of Westport, about 30 km to the north (Fig. 19), give consistent altitudes of the shoreline angle/inner edges of the four lowest terraces: 20-24 m, 38-42 m, 58-63 m, and 83-89 m (Fig. 20). At Mendocino Headlands, the 22-m terrace is well exposed, revealing the wave-cut bedrock platform and as much as several meters of stratified near-shore marine deposits.

<table>
<thead>
<tr>
<th>Mendocino Terrace Inner-Edge Elevation (m)</th>
<th>Possible Age By Correlation (ka)</th>
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<tbody>
<tr>
<td>20-24</td>
<td>~80 (OIS 5a)</td>
</tr>
<tr>
<td>38-42</td>
<td>~120 (OIS 5e)</td>
</tr>
<tr>
<td>58-63</td>
<td>~200 (OIS 7)</td>
</tr>
<tr>
<td>83-89</td>
<td>~300 (OIS 9)</td>
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</table>

The correlations given above are tentative, but are based on the following lines of reasoning. The ~22-m terrace at Mendocino has a similar elevation to that of the dated terrace at Point Arena (STOP 13). The ~42-m terrace is correlated with the ~120,000-yr-B.P.-high-sea stand (OIS 5e) because the elevation difference between this terrace and the ~22-m-high terrace is similar to that seen for terraces of these ages elsewhere in California (Muhs et
The ~60-m terrace is correlated with the penultimate interglacial period, when sea level was near or above present at ~200,000 yrs. B.P. (OIS 7; see Muhs et al., 2002b). Finally, the ~86-m terrace is correlated with the long interglacial at ~310,000-330,000 yrs. B.P. (OIS 9) when sea level was also near or above present (Stirling et al., 2001). If these correlations are correct, then the rate of uplift for this part of the coastline is ~0.3 m/ka (Figure 20). Note that these terrace correlations differ slightly from those reported by Merritts and Bull (1989) for this segment of coastline. Between Mendocino and the San Andreas fault near Alder Creek, correlation of these four low terraces is more difficult than it is to the north, between Mendocino and Westport. We have completed seven GPS surveys of terraces along this coastal stretch, and, apparently, terraces rise to the south from Mendocino to Alder Creek, where the San Andreas fault crosses the coastline and extends offshore. Planned work in 2003 will help resolve the terrace correlations in this area.

**STOP 17. POINT CABRILLO LIGHTHOUSE**

Point Cabrillo Preserve was protected as of 1992 when the Coastal Conservancy acquired it. Its 300 acres are prime habitat
for raptors and other birds, deer, wildflowers, and river otters. The lighthouse, still operating today, was established in 1909 and is open for tours. We will hike seaward across the three lowest marine terraces (going down in elevation from the 60-m to the 42-m to the 22-m terraces) until we reach the sea cliff. In the wall of the sea cliff, a low platform notch at about 10 m elevation lies below an unusual weathered zone that resembles marine-gravel cover sediments from a distance. Up close, however, the orange-colored zone is actually weathered bedrock of the next higher (22-m) terrace platform. The weathered zone generally has a uniform thickness of 2-3 m. In some places, small springs of groundwater seep from the base of the zone, suggesting that the weathering is associated with a fluctuating groundwater table. Because the weathered bedrock has little resistance to wave attack, it recedes more quickly than the underlying bedrock, resulting in a morphology that resembles a shoreline angle and paleo-sea-cliff. The same feature occurs at numerous sites along the coast between Mendocino and Westport and is consistently at an altitude of about 10 m. This feature was considered to represent a marine terrace shoreline angle at a height of 10 m and was correlated to the 80,000 yrs. B.P. sea level high-stand by Merritts and Bull (1989). However, our subsequent work suggests that the 20-24-m-high shoreline angle, and not the 10-m-high feature, was cut by the 80,000 yrs. B.P. high-stand. Kennedy (1978) and Kennedy et al. (1982) sampled mollusk shells from a low terrace at Laguna Point in MacKerricher State Park, midway between Mendocino and
Westport (see Figure 19). Amino acid ratios in the shells plus the cool-water aspect of the fauna allowed Kennedy et al. (1982) to correlate the terrace with either the ~80,000 or ~100,000 yrs. B.P. high sea-stands. Because the elevation of the terrace sampled by Kennedy (1978) and Kennedy et al. (1982) is not reported, we are unsure if it is the 10-m-high platform notch or the 20-24-m-high terrace that we correlate with the ~80,000 yrs. B.P. high-stand.

At Cabrillo Point, we will examine the possible paleo-sea cliff at 10 m and discuss whether or not it might be a lower terrace associated with an interstadial sea-level high-stand that post-dates the 80,000 yrs. B.P. high-stand.

**STOP 18. JUGHANDLE ECOLOGICAL STAIRCASE**

The headland area around the mouth of Jughandle Creek is part of the Jughandle State Reserve that includes the famous...
Jughandle Ecological Staircase Trail. This ~5-mile (~8 km) trail traverses the three lowest marine terraces of the flight that is nearly continuous from Mendocino Headlands (STOP 16) and Cabrillo Point (STOP 17) to the town of Westport (Merritts and Bull, 1989). We will begin the trail on the lowest terrace, then hike across the second terrace and end at the outer edge of the third and oldest terrace. If our age estimates are correct (see STOP 16), the three terraces are ~80,000, ~120,000 and ~200,000 yrs B.P. Each older terrace has a better-developed soil profile, and hence, a different suite of biota. The two lowest terraces are covered with coastal prairie bunchgrasses and scrubs, and Bishop pines are found along the walls of ravines incised into the terraces. The third (and higher) terrace(s) has a unique botanical habitat called the Pygmy Forest, which includes mature Mendocino cypress, Bolander and Bishop pines, and redwood trees over 100 years old that are less than 1-2 m high. The flat terrain of the terrace landform, combined with sandy (marine nearshore and eolian) parent material and poor drainage at the platform-sand interface has resulted in extremely acidic, nutrient-deficient soils.

Gently sloping marine terraces in northern California provide excellent conditions for minimizing variations in non-temporal, soil-forming factors and for preserving the chronological record of soil properties that vary as a function of time. Jenny et al. (1969) recognized the value of the elevated northern California marine terraces for soil chronosequence studies, noting especially the "remarkable and fortunate mineralogical uniformity in the soil parent materials [that] are either weathering greywacke sandstone or sandstone-derived [Franciscan Assemblage] beach materials and dunes" (p. 62). Climatic conditions also are similar along much of the northern California coast between Mendocino and Westport, with cool, foggy, and dry summers; mean annual temperatures of 12-14° C; mean monthly temperatures that vary less than 6° C throughout the year; mean annual precipitation of 100-102 cm; and more than 90% of mean annual precipitation as rain during mild winters.

In places where the soil profiles include a silica-and-iron-rich hardpan (illuvial horizon), pockets of Pygmy Forest habitat are most well developed. At these locations, dark, organic-rich, upper A horizons rest on a leached, light-colored, thixotropic (i.e., can become liquid when shaken) horizon. Below the eluvial horizon are illuvial (B) horizons that are rich in clay, very sticky, hard when dry, buff-to-orange colored, mottled, and abundant in iron concretions and iron and manganese streaks (Figure 22). Maximum clay

![Aerial view looking east and south along the Point Cabrillo to Mendocino coastline. Dashed lines indicate inner edges (IE) of tread surfaces of two lowest terraces. Road in the distance, just west of the forested area, is California HWY 1. [From Figure 2 of Merritts et al., 1991.](Figure 21)

![Depth profiles of five pedons from the Mendocino to Westport area. Pedon site numbers and inferred terrace ages are indicated on the right. Pedon 6 is on the 20-24 m terrace, inferred to be ~80,000 yr old. Pedon 7 is on the 38-42 m terrace, inferred to be ~120,000 yr old. Pedon 8 is on the 58-63 m terrace, inferred to be ~200,000 yr B.P. Pedon 9 is on the 83-89 m terrace, inferred to be ~310,000-330,000 yr old. The soil properties diagrammed are percent clay and Fe_d. [From Figure 8 in Merritts et al., 1991.](Figure 22)
content in the B-horizons varies from 30 to 52%, maximum iron from 2.6 to 5.9 %, and maximum B-horizon thickness from 152 to 178 cm on the second and third terraces (Merritts et al., 1991, 1992).

End of DAY 3: Overnight in Gualala, CA

DAY 4: End of trip—thank you for joining us! Return to San Francisco International Airport

ACKNOWLEDGMENTS

We dedicate this field trip to the pioneers of marine terrace geology of the central and northern California coast: Warren Addicott, Charles S. Alexander, William C. Bradley, Hans Jenny and Andrew C. Lawson. Muhs’ work was supported by the USGS Earth Surface Dynamics Program and is a contribution to the LITE (Last Interglacial: Timing and Environment) project. Prentice’s work was supported by the USGS National Earthquake Hazards Reduction Program. Merritt’s work was supported by the Keck Geology Consortium (awards in 1995-96 and 1999-2000) and the National Science Foundation (grants EAR-8405360 and EAR-9418682). We thank John Sisto (Point Arena lighthouse curator) and Jim Riley (Mendocino College) for granting access that enabled us to map the deposits at Point Arena, and Gary Strachan (Supervising Ranger at Año Nuevo State Reserve) for allowing access to exposures near Green Oaks Creek and Point Año Nuevo. Many thanks go to Josh Been (USGS, Denver) for help in organizing and carrying out the trip and Kathleen Simmons (USGS, Denver) who dated all of the corals. Thanks also go to Ken Ludwig (Berkeley Geochronology Center) who helped collect the corals and George Kennedy (Brian F. Smith and Associates) for helpful discussions of fossil mollusks. Oliver Chadwick (University of California, Santa Barbara) and David Hendricks (University of Arizona) contributed significantly to the field and laboratory work for the soil analyses in the Mendocino-Westport area. William Bull (University of Arizona) assisted with the interpretation of marine terrace ages at Mendocino and Cabrillo Point. Jorie Schulz and Marith Reheis (USGS) provided helpful reviews of an earlier version of the manuscript, and we thank Don Easterbrook for careful editing.

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