The Geology from Santa Cruz to Point Año Nuevo— The San Gregorio Fault Zone and Pleistocene Marine Terraces

Gerald E. Weber
University of California, Santa Cruz, Calif.

Alan O. Allwardt
Geologic Consultant, Santa Cruz, Calif.

Introduction

On this field trip, we will illustrate two aspects of the tectonic unrest along the coastline between Santa Cruz and Point Año Nuevo: (1) late Quaternary activity in the San Gregorio Fault Zone at Año Nuevo State Reserve and (2) Pleistocene marine terraces in the vicinity of Wilder Ranch State Park, formed in response to regional uplift and fluctuating sea level. Among the topics of discussion will be rates of soil development on the terrace surfaces, techniques for dating terrace sequences and determining rates of uplift, and problems in using offset Pleistocene strandlines to estimate slip rates across the fault zone.

Our goal in scheduling only two field trip stops is to maximize the time spent outside the bus. For much of the day we will be walking and examining outcrops on State Parks land, where sample collecting is prohibited. However, the quality of the exposures will more than compensate for this handicap. Time permitting, we may also visit some of the optional field-trip stops described in the road log, which will provide additional background on the geology and cultural history of this stretch of coastline.

The San Gregorio Fault Zone (SGFZ) is the principal fault west of the San Andreas Fault Zone (SAFZ) in central California and is part of the larger San Andreas Fault system, representing the active tectonic boundary between the Pacific and North American lithospheric plates (fig. 1.1). At its type locality at Point Año Nuevo, the SGFZ is 2 to 3 km wide and includes seven fault strands with late Quaternary activity. From here, the SGFZ has been traced northward to its juncture with the SAFZ near Bolinas Lagoon in Marin County and southward across Monterey Bay, a cumulative length approaching 200 km (125 miles). Based on its dimensions and late Quaternary activity, this fault zone appears to be a potential source of significant earthquakes and has been assigned a 7.3 M_{max} (Petersen and others, 1996).

Based on cross-fault matches, Clark (1998) infers 150 to 160 km of cumulative dextral (right-lateral) slip on the SGFZ, whereas Burnham (1998) postulates between 150 to 185 km of dextral slip. Sedlock and Hamilton (1991) suggest 150 km of dextral slip between the early Paleocene and Miocene, but only 5 km of dextral slip during the late Cenozoic (Neogene). Clark (1997), on the other hand, suggests that slip on the SGFZ was initiated about 10 Ma (late Miocene) with the following rates:

Time Interval	Displacement	Slip Rate
10 to 8 Ma (late Miocene)	50 to 60 km	25 to 30 mm/yr
8 to 3 Ma (late Miocene-late Pliocene)	81 km	16 mm/yr
3 to 0 Ma (late Pliocene-Holocene)	19 km	6 mm/yr

The post-late Pliocene slip rate of 6 mm per year falls within the slip-rate estimates for late Quaternary of Weber and others (1995): 5 to 9 mm per year, based on offset marine terraces and offset streams on alluvial fans at Point Año Nuevo. Exploratory trenching of the eastern, onland trace of the SGFZ at Seal Cove indicates a post-late Pleistocene slip rate of 3.5 to 4.5 mm per year for the SGFZ (Simpson and others, 1997). This is a minimum rate because it does not include the western, offshore strand of the SGFZ. The addition of dextral slip from the SGFZ to the SAFZ may also explain why the present-day slip rate along the SAFZ northwest of their juncture in Marin County appears to be greater than that on the San Francisco Peninsula segment of the SAFZ.

A major unresolved question for seismic hazard analysis is the location of the southern terminus of the SGFZ in central coastal California and its postulated continuity with the Hosgri Fault Zone (HFZ). Most workers have followed Silver (1978) and Graham and Dickinson (1978), who postulated that the SGFZ is linked, via a segment of the Sur Fault Zone, with the HFZ (fig. 1.1). Greene and others (1973), alternatively, have suggested that the

SGFZ curves inland south of Monterey Bay to join the Palo Colorado Fault in the northern Santa Lucia Range.

A related problem is the apparent discrepancy between recent estimates of cumulative offsets on the SGFZ and the HFZ. For example, Dickinson's (1996) reconstruction infers 156±8 km of dextral slip on the SGFZ and 110±5 km of slip on the HFZ. One hypothesis explaining this discrepancy is that the shear to the south is distributed along en echelon faults within the Santa Lucia Range, rather than being restricted to a continuous, offshore HFZ.

This trip will examine some of the field evidence for recent faulting along the SGFZ at its type locality near Point Año Nuevo, in western San Mateo County. The bus will pass through Santa Cruz and, after stopping near the western boundary of Wilder Ranch State Park, follow the coastline northward to Año Nuevo State Reserve (fig. 1.2). We will discuss recent (and not so recent) onshore work relating to problems of the SGFZ, including (1) marine terrace stratigraphy, ages, and cross-fault correlation, (2) Neogene stratigraphic contrasts across the SGFZ in the central Santa Cruz Mountains, including the postulated offset of a thick upper Miocene unit (Santa Cruz Mudstone), and (3) late Pleistocene and Holocene deformation along the SGFZ at Point Año Nuevo.

Approaching Santa Cruz by Highway 17

As we approach Santa Cruz on Highway 17, the bus will take the Highway 1 off-ramp and head through town. About a quarter-mile to the west, we will cross the San Lorenzo River bridge.

San Lorenzo River. To the left (south) is downtown Santa Cruz. The downtown area is built on the floodplain of the San Lorenzo River, underlain by soft, unconsolidated Holocene sediments that back-filled the ancestral San Lorenzo Valley during the rise in sea level associated with the end of the Wisconsin glaciation. During the Wisconsin glaciation, the San Lorenzo River channel had become incised about 20 to 30 meters (or more) below its current elevation in this area, in response to a sea level that was about 100 meters lower than present.

During both the April 18, 1906, and October 17, 1989, earthquakes downtown Santa Cruz suffered partial to nearly complete collapse of many older, unreinforced brick and masonry buildings. The higher intensity shaking in the downtown area resulted from the unconsolidated substrate. Ground cracking related to lateral spreading, along with other liquefaction phenomena, occurred in this area during both earthquakes.

At the intersection of Highway 1 and Highway 9/River Street (first traffic light), the bus will continue straight ahead.

Mission Street intersection with Highway 1 (second traffic light). The bus will turn right and continue west on Mission Street/Highway 1. We have now climbed above the floodplain of the San Lorenzo River to the Santa Cruz terrace. Most of the city of Santa Cruz is built on this terrace, both east and west of the San Lorenzo River floodplain. The geologic setting of the terrace—a thin layer of well-drained sands and silts overlying firm to hard bedrock—resulted in a reduced level of seismic shaking in 1989, when compared to the floodplain of the San Lorenzo. Although numerous chimneys were knocked down, most buildings on the terrace sustained only minor damage during the Loma Prieta earthquake.

From this point north to Waddell Creek, Highway 1 lies near the back edge of the Santa Cruz terrace of Bradley and Griggs (1976), the first (lowest) of five prominent marine terraces cut into the southwestern flank of Ben Lomond Mountain (fig. 1.3). The modern seacliff, the first emergent terrace, and also most of the older, higher terraces from here north to Point Año Nuevo are cut into a single rock type—the Santa Cruz Mudstone, a hard, blocky fracturing, siliceous mudstone of Delmontian age (late Miocene). The marine terraces are essentially undeformed from Santa Cruz to Point Año Nuevo, except for some minor warping, tilting and fault offset near Greyhound Rock. Two terraces (the Wilder and Cement terraces) are discontinuous and are not present along the entire coastline (fig. 1.3).

Bay Street. The University of California Santa Cruz campus lies about 1 mile to the north (right), on one of the few well-developed karst landscapes in California. Between here and Almar Street we will cross the surface trace of the Ben Lomond Fault, the structural element that bounds Ben Lomond Mountain on the north and east. The late Tertiary through middle Pleistocene vertical slip on this fault (west side up, east side down) is between 300 and 600 meters; however, there is no evidence of offset in the marine terrace deposits or the wave-cut platform (wcp) of the Santa Cruz terrace, as exposed in the seacliff near Almar Street. Stanley and McCaffrey (1983) argue that the wcp is offset about 2 to 3 cm, but they agree that the terrace deposits are not offset. Consequently, the Ben Lomond Fault may display movement since the formation of the abrasional platform but no movement since the deposition of the shallow marine sands; these observations suggest the possibility of a brief episode of minor movement approximately 80,000 years ago (see discussion of terrace ages, below).

Road Log: Santa Cruz to Point Año Nuevo

For this field trip our mileage log will begin at the intersection of Highway 1 and Almar Street in westside Santa Cruz.

Mileage/Notes

0.0 **Almar Street.** Highway 1 bends to the right at the three-way traffic light. Safeway lies to the southwest (left) of Highway 1. As we head north, note the steep slope on the right (northeast), which is the erosionally modified, ancient seacliff at the back edge of the Santa Cruz terrace (see figure 1.4 for an explanation of terrace terminology). Two wave-cut platforms have been tentatively identified within the Santa Cruz terrace in this area (fig. 1.5). Fossil mollusks exposed in the seacliff at Point Santa Cruz have yielded an average U-series age of 86,500 years B.P. (Bradley and Addicott, 1968) and an amino-acid racemization age of about 85 ka for the lower, Davenport platform. These dates on fossil material suggest that the Davenport platform was created during the sea-level high stand corresponding to oxygen isotope stage 5a, dated 80 to 83 ka by most workers (see discussion of Stop 1, below). In contrast, shell fragments from a basal lag recovered in a boring near the inner edge of the terrace displayed a cold water fauna and an amino-acid racemization age estimate of 103 ka. This suggests that, in west Santa Cruz, the upper wave-cut platform within the Santa Cruz terrace is the so-called Highway 1 platform, created during the sea-level high stand corresponding to oxygen isotope stage 5c (103 to 105 ka). The two wave-cut platforms within the Santa Cruz terrace are apparently separated by a 1-to-2 meter seacliff, which is buried by the continuous alluvial apron that forms the topographic surface of the terrace.

Because the Cement terrace is absent in the Santa Cruz area, the next highest terrace surface here is the Western terrace of Bradley and Griggs (1976), visible northeast of Highway 1 as a series of erosionally dissected topographic flats above the 103 to 105 ka seacliff. The age of the Western terrace is estimated to be approximately 213 ka (oxygen isotope stage 7). Between Santa Cruz and Point Año Nuevo, the marine terraces of Ben Lomond Mountain lie within a single structural block, the Santa Cruz Mountains structural block (Weber and Lajoie, 1979; Weber, 1980), which lies east of the San Gregorio Fault Zone. Marine terraces within this structural block are undeformed except for a broad, shallow anticlinal flexure in the terrace near Greyhound Rock.

1.0 **Moore Creek.** This creek and other large streams along this segment of the Santa Cruz County coast eroded their bedrock canyons to the Wisconsin low stand of sea level, 100 to 115 meters (300 to 350 feet) below present sea level. The Holocene rise in sea level flooded the lower reaches of these streams, resulting in alluviation of the stream valleys. Small lagoons formed at the mouths of these streams as they became dammed by a combination of storm berms and small aeolian dunes.

Coastal Erosion Rates. Measured rates of cliff retreat along this section of coast are generally less than 1 foot per year (Griggs, 1979). Along the Santa Cruz County coast from Almar Street north to the San Gregorio Fault Zone at Point Año Nuevo, the modern seacliff has formed in the late Miocene Santa Cruz Mudstone. Consequently, the rock type under wave attack in the surf zone is essentially uniform along this entire stretch of coastline, except for a few scattered sandstone dikes.

2.7 **Sandy Flat Gulch.** Late Miocene Santa Margarita Sandstone is quarried for construction sand on the northeast (right) side of the road. The roadcut exposes Quaternary colluvium overlying Santa Cruz Mudstone, as Highway 1 is built just above the Santa Cruz terrace on the colluvial wedge at the base of the 103 to 105 ka seacliff. Between here and Davenport the first three marine terraces and occasionally the fourth terrace are visible from the highway.

5.3 Stop 1—Ben Lomond Mountain Marine Terraces

Information on Stop 1

Introduction

We will be walking up the road beyond the gate to examine the Western, Wilder, and Blackrock terraces. Upon reaching the Wilder terrace, take the right fork in the road and note the intricate flow structures in the asphalt: this is one of the oldest paved roads in Santa Cruz County, utilizing locally quarried bituminous sandstone. For a brief history of these asphalt quarries, which date back to the late 1880’s, see the discussion below on Majors Creek (milepost 5.8 on the road log).

Since the initial study of Rode (1930), the exceptionally well-preserved Ben Lomond Mountain marine terrace sequence has been the subject of numerous studies and reinterpretations. These include Bradley (1957, 1958), Bradley and Griggs (1976), Lajoie and others (1979), Hanks and others (1984), Lajoie (1986), Weber (1990a, b), Anderson (1990, 1994), Anderson and Menking (1994), Anderson and Weber (1990), Lajoie and others (1991), and Weber and others (1995).

To summarize briefly, the terrace sequence consists of six marine terraces cut into the slowly rising coastline by successive high stands of sea level during the Pleistocene. Terrace names, elevations, estimated ages and estimated uplift rates for the Davenport area are shown in table 1.1.

Table 1.1. Marine terraces on Ben Lomond Mountain (Santa Cruz Mountains structural block)—elevations, estimated ages and estimated uplift rates.

Marine terrace	Elevation (m)	Estimated age (ka)	Paleosea level (m)	Tectonic uplift (m)	Uplift rate (m/k.y.)
Santa Cruz					
DAV	17	80	-19	36	0.45
Hy 1	32	105	-9	41	0.39
GRX	40	sp			
Cement	58	125	+ 6	52	0.42
Western	92	213	- 5	97	0.46
Wilder (p)	140	320	0	140	0.44
Blackrock	190	430	0	190	0.44
Quarry	240	545 ?	0	240	0.44

DAV, Davenport wave-cut platform;
Hy 1, Highway 1 wave-cut platform;
GRX, Greyhound rock wave-cut platform;
p, shoreline angle elevation projected

Bradley and Griggs (1976) describe the lowest emergent terrace (Santa Cruz terrace) as containing three separate wave-cut platforms and shoreline angles named, from youngest to oldest, the Davenport, Highway 1, and Greyhound Rock wave-cut platforms (note: only one terrace, but three abrasional surfaces). Although not specifically stated, Bradley and Griggs (1976) imply that each of these platforms was formed by surf erosion during a separate sea-level high stand. More recent investigators have concluded that the Greyhound Rock abrasional surface is simply a localized shore platform associated with the Highway 1 wave-cut platform (Weber and others, 1995).

The areal extent of the terraces on the flank of Ben Lomond Mountain is shown in figure 1.3. The Santa Cruz terrace forms the broad, extensively cultivated bench closest to the ocean. Highway 1 lies along the back edge of this terrace between Santa Cruz and Waddell Creek. The Santa Cruz terrace is late Pleistocene in age, probably having formed during the Sangamon interglacial (oxygen isotope stage 5). The higher terraces are all older, ranging in age from about 213 ka for the Western terrace to possibly 545 ka for the Quarry terrace. The older terraces are not continuous along the entire coastline and show successively greater erosional modification and dissection with age and elevation. Note that the Wilder terrace is not preserved north of Laguna Creek, and the Cement terrace is restricted to the immediate vicinity of Davenport.

Determination of Marine Terrace Ages

Despite their excellent geomorphic expression and preservation, there are no indisputable absolute age determinations for any of the terraces (the previously cited dates on fossil material notwithstanding). We know that each terrace must have formed in response to a period of sea-level rise culminating in an interglacial high stand, but we cannot unambiguously correlate this particular sequence of terraces with the known high stands in sea level. Traditionally, any attempt to date a succession of marine terraces has required an assumed age for at least one terrace in the sequence, coupled with an unknown but *constant* rate of uplift throughout the late Quaternary. These assumptions allow the researcher to match, by trial and error, the spatial sequence of the terraces with the independently derived, temporal sequence of sea-level high stands. The best fit yields both the ages of the terraces and an estimate of the uplift rate. This procedure is analogous to the way magnetic stripes on the sea floor could be correlated with the known sequence of geomagnetic polarity reversals, thus providing an estimate of the spreading rate (see Glen, 1982).

Accordingly, we have estimated the ages of the terraces by comparing their shoreline angle elevations to the known high stands of sea level in the Pleistocene, using the method described by Lajoie (1986). Because each episode of terrace cutting must be linked with a period of rising sea level, each shoreline angle must be associated with a high stand (strandline). Consequently, dating a particular strandline is reduced to correlating it with a peak in an established sea-level curve (fig. 1.6). In our analysis, we have used what is probably the most detailed datum from which to determine terrace ages, the sea-level curve obtained by subtracting tectonic uplift from the record of emergent coral-reef strandlines (terraces) on the Huon Peninsula of Papua, New Guinea. This terrace sequence, accurately dated using U-series techniques on corals, provides a reliable estimate of global sea-level fluctuations back to about 340 ka (Bloom and others, 1974; Chappell, 1983).

We approximated the ages of terraces on Ben Lomond Mountain using the simple graphic technique of Lajoie (1986) and the New Guinea sea-level curve. Shoreline angle elevations are plotted on the vertical axis, and lines are drawn between the shoreline angle elevations and the sea-level high stands. If uplift rates have been constant, all the lines connecting shoreline angle elevations to sea-level high stands will be parallel (see fig. 1.6). If uplift has not been constant during the late Pleistocene (the last 0.5 to 1.0 m.y.), the lines should diverge and not be parallel.

Discussion: Terrace Ages and Uplift Rates

The graphic technique described above does not produce a unique solution for terrace ages and uplift rates on Ben Lomond Mountain. This stems from the absence of an indisputable, independently determined age date for at least one of the terraces. Two contrasting interpretations of terrace ages and uplift rates are shown in table 1.2. A low uplift rate (0.21 m/k.y.) is envisioned by Lajoie and others (1991), whereas both Hanks and others (1984) and Weber and others (1995) suggest a higher uplift rate, 0.41 to 0.44 m/k.y. The Lajoie and others (1991) assignment of terrace ages is similar to that of Bradley and Griggs (1976), with the Highway 1 platform 125 ka in age and the Western terrace about 430 to 450 ka in age. (The Greyhound Rock wave-cut platform would represent the 213 ka strandline in their scheme.) Anderson and Menking (1994), using a more formal analysis, indicate that either of the uplift rates can be used to explain the coast-parallel pattern of shoreline angle elevations for the terraces. We prefer the higher uplift rate interpretation, because it appears that the Greyhound Rock wave-cut platform is a shore platform and not a paleo-strandline as envisioned by Lajoie and others (1991).

Table 1.2. Marine terraces of Ben Lomond Mountain—alternative interpretations of terrace ages and uplift rates in the Davenport area.

Marine terrace	Hanks and others, 1984 Uplift rate: 0.41 m/k.y.	Lajoie and others, 1991 Uplift rate: 0.21 m/k.y.	Weber and others, 1995 Uplift rate: 0.42 to 0.44 m/k.y.
Santa Cruz Hy 1	104 ka	124 ka	105 ka
Cement	120 ka	320 ka	125 ka
Western	230 ka	430 ka	213 ka
Wilder (proj.)	370 ka	800 ka	320 ka
Blackrock	450 ka	1000 ka	430 ka
Quarry	650 ka?	1300 ka	545 ka?

Recently, a completely different approach to dating the Ben Lomond Mountain marine terraces has been taken by Perg and others (in press), leading them to postulate dramatically higher uplift rates in the range of 1.1 m/k.y. Utilizing the relatively new technique of "surface-exposure dating," they sampled the five successive terraces northwest of Santa Cruz and measured the concentrations of two cosmogenic radionuclides, beryllium-10 and aluminum-26, in the soil profiles developed on the terrace deposits. Cosmogenic radionuclides (CRNs) are produced at constant rates in the upper atmosphere and accumulate steadily on any exposed surface that remains undisturbed (such as a marine terrace). Knowing the atmospheric production rate and the half-life of a CRN makes it possible to date the surface in question, provided that several additional parameters are taken into account. Foremost among these complicating factors are the initial concentration of the CRN in the parent material and subsequent mixing in the upper soil horizons.

The preliminary CRN dates suggest that the Ben Lomond Mountain terraces are significantly younger than previously thought. Perg and her colleagues, for instance, correlate the Santa Cruz terrace with oxygen isotope stage 3 (about 60 ka) rather than stages 5a, 5c, or 5e (80 to 125 ka), and they shift the entire sequence of terraces accordingly. The resulting uplift rates are two to three times higher than those proposed by researchers using conventional methods for estimating the terrace ages. Methodology aside, the CRN data cited above may be subject to alternative interpretations requiring a less drastic revision of the older models. Conceptually, the ultimate goal is to correlate a given shoreline angle with an independently documented high stand in sea level, but the CRN technique provides only a minimum age for this purpose since the surface being dated is not the wave-cut platform itself but the top of the terrace deposits. Moreover, CRN dating simply indicates when a terrace surface became *stabilized*, raising questions regarding the extent to which the terrace deposits might have been reworked as sea level dropped. Until these issues are resolved—and until the initial CRN terrace dates are either corroborated or refuted by additional data covering a wider area—we will continue advocating a more traditional view of the terrace ages and have written this guide accordingly.

Correlating Marine Terraces between the Santa Cruz Mountains and Pigeon Point Structural Blocks

Six marine terraces are clearly recognizable on the Pigeon Point structural block, which lies west of the SGFZ. The names of these terraces, their probable ages, and estimated uplift rates are shown in table 1.3. Prior to re-mapping of the terraces by Weber and others (1995), none of the terraces older than the Western terrace had been successfully correlated across the fault zone. Based on this re-interpretation, however, it now appears that the Pigeon Point terrace sequence can be correlated with the Ben Lomond Mountain terrace sequence as shown in table 1.4. Note that, except for the Cement terrace, there is one-to-one correlation between the terraces east and west of the SGFZ (see also fig. 1.7). The absence of the Cement terrace west of the fault zone is not surprising, since it occurs along only 3 km of coastline east of the fault zone, near Davenport, where it is both discontinuous and narrow. This correlation of marine terraces across the SGFZ allows estimation of late Quaternary crustal uplift rates, as well as both horizontal and vertical slip rates along the SGFZ. However, we emphasize the highly interpretative nature of both the terrace ages and uplift rates.

Table 1.3. Marine terraces in the Pigeon Point structural block—elevations, estimated ages and estimated uplift rates.

Marine terrace	Elevation (m)	Estimated age (ka)	Paleosea level (m)	Tectonic uplift (m)	Uplift rate (m/k.y.)
Año Nuevo	7 to 9	80	- 19	28	0.35
Pigeon Pt.	24	105	- 9	33	0.31
Bolsa	61	213	- 5	66	0.31
Gazos	90	320	0	90	0.28
YJ	122	430	0	122	0.28
Mesa	153	510 ?	0	153	0.30

Table 1.4. Correlation of marine terraces and/or wave-cut platforms (wcp) across the San Gregorio Fault Zone

Santa Cruz Mountains Structural Block	Pigeon Point Structural Block
Santa Cruz Terrace	
Davenport wcp	Año Nuevo Terrace
Highway 1 wcp	Pigeon Point Terrace
Cement Terrace	(absent)
Western Terrace	Bolsa Terrace
Wilder Terrace	Gazos Terrace
Blackrock Terrace	YJ Terrace
Quarry Terrace	Mesa Terrace

Uplift Rates

Quaternary uplift rate of the Santa Cruz Mountains structural block, as deduced from terrace elevations on the flank of Ben Lomond Mountain, is not uniform. Anderson and Menking (1994) discuss possible explanations for nonuniform rates, including the hypothesis that the coastline is being transported horizontally past a localized area of uplift. In our analysis we calculated uplift rates in the vicinity of Davenport, where the uplift has been uniform parallel to the coast and has averaged between 0.42 and 0.44 m/k.y. The uplift rate is slightly higher to the northwest, near Greyhound Rock, and somewhat lower to the southeast of Davenport. Another reasonable interpretation of the uplift rate in the Davenport area is 0.21 m/k.y., as suggested by Lajoie and others (1991) and Anderson and Menking (1994). The uplift rate for the Pigeon Point structural block (across the SGFZ) is most likely about 0.3 m/k.y. near Pigeon Point, decreasing slightly to the north and increasing slightly to the south. Another reasonable interpretation of uplift rate in this area is 0.15 m/k.y., which also explains the vertical spacing of the terraces. Figure 1.8 shows our preferred interpretation of these geographic variations on a “tilted shoreline” plot (after Lajoie and others, 1991).

Mileage/Notes

5.8 **Majors Creek.** The black-colored cliffs to the right (up Majors Creek) are composed of bitumen-saturated sandstone that was injected into the overlying Santa Cruz Mudstone in a liquid state. Numerous sandstone dikes and sills, most of which contain some bituminous material, are exposed in the modern seacliff between Wilder Creek and Greyhound Rock. The Santa Margarita Sandstone, the source of these intrusions, contains varying amounts of bitumen throughout its outcrop area, from Santa Cruz to the vicinity of Big Basin State Park. The hydrocarbons are believed to have migrated into the Santa Margarita Sandstone from the underlying Monterey Formation.

The bituminous sandstones in this area have been mined since the late 1880’s for paving material. The asphaltic content of the sand ranges from about 4 percent to as much as 18 percent by weight. These oil-impregnated layers vary from 1 to 40 feet in thickness and range in character from dry and brittle to soft and gummy. In some outcrops, tar will drip or flow out of the bituminous sands when sufficiently warmed by the sun. San Francisco streets were reportedly paved in the 1890’s with bituminous sandstone mined near Majors Creek and transported to San Francisco by boat. An estimated 614,000 tons of asphaltic paving material, worth approximately $2,360,000, was produced from this area between 1888 and 1914 (Page and Holmes, 1945). Production was intermittent after the 1920’s, with the last of the quarries (Calrock Quarry) ceasing operations in the 1940’s. Page and Holmes (1945) estimated reserves of approximately 9.8 million cubic yards of asphaltic sand in the area west of Santa Cruz. This sand contains approximately 10 million barrels of asphalt. In oilfield terms, this is about 24 gallons of bitumen per ton, or equivalent to a tar sand with 38 percent porosity, 53 percent oil saturation, and a recovery factor of 1,562 barrels of oil per acre-foot.

Oil and Gas Production at Majors Creek

In 1955, Husky Oil Company, in partnership with the Swedish Shale Oil Company, began an experimental project to adapt the Swedish company's Ljungstrom method to the recovery of hydrocarbons. It was a thermal recovery experiment, utilizing down-hole, gas-fired burners to perform in-situ retorting. In the fall of 1957, Union Oil Company of California joined in the project. During the next 3 years, a total of 228 burner-producer wells, 78 temperature observation wells, 31 gas wells, and 32 miscellaneous wells were drilled (most of them on the Blackrock and Quarry terraces, where the oil-saturated sandstone was encountered immediately below the terrace deposits). The bituminous sandstone in these locations generally lay 8 to 10 feet below the surface and was about 40 feet thick in its saturated section, averaging about 8 percent by weight of 4-degree gravity tar throughout.

Wells were typically drilled in a triangular pattern on a ten-foot spacing to an average depth of 53 feet. They were completed with 14 feet of 4-inch surface pipe and 50 feet of 2-7/8 inch casing. Underground heaters fueled by propane were used in the heating phase of the test, with down-hole temperatures reaching 600 degrees F. The test area was heated from a depth of 15 to 45 feet, with much of the crude oil vaporizing. Products produced in a vapor form were condensed using a water-cooled condenser. The heating phase was completed in January of 1959, with a total production of 2,665 barrels of oil, 4,520 thousand cubic feet (Mcf) of gas, and 9,232 barrels of water. Average gravity of the recovered oil was 27 degrees. The operator reported that in zones 30 feet thick, a recovery of about 18,000 barrels per acre could be achieved—a recovery of 38 percent of the oil in place. Although this is a respectable recovery factor (similar to some steam stimulation projects), it is doubtful that such an operation could be economical because of high heat losses and high fuel costs.

Mileage/Notes

6.1 **Back Ranch Road.** Private road to the right (under the suspended pipe). Note the bituminous sandstone dikes exposed in the road cut; one of the larger, abandoned asphalt quarries in Santa Cruz County is located along Back Ranch Road. Until recently, Santa Cruz Biotechnology operated a large goat ranch up this road for medical research, but the California Coastal Commission shut down the operation amid concerns about runoff contaminated by manure.

To the left, an isolated hill near the edge of the modern seacliff is a stabilized Holocene sand dune (Sand Hill Bluff). It is capped by a 1-meter-thick midden deposit containing remains of an extinct flightless scoter (*Chendytese*, a type of sea duck). The dune is dated at 3,500 to 5,000 years old by ^{14}C analysis of marine shells from the midden deposit. It is possible that the bird became extinct as a result of hunting by the coastal Native Americans.

The development near the hill is Pacific Mariculture's Abalone Farm. The project will ultimately consist of 400 abalone grow-out tanks under 2.5 acres of shade cloth structure. Raising abalone to commercial size (4 inches) takes about 3 to 4 years. Production is projected to reach 500,000 red abalone per year, yielding about 170,000 pounds of meat. The abalone will be fed a mixture of kelp and commercial feed, with the kelp harvested by hand from kelp beds off the coast.

As we drive past the intersection of Old Coast Highway and Highway 1, note the vertical contact zone in the road cut on the north side of Highway 1 (and also in the cut along Old Coast Highway). Hard siliceous bedrock of the Santa Cruz Mudstone is juxtaposed against moderately dipping colluvial deposits along a nearly vertical contact. This is the old 103 to 105 ka seacliff associated with the Highway 1 platform of the Santa Cruz marine terrace. The basal portion of the old seacliff is preserved by the accumulation of talus and colluvium at the base of the cliff. The upper half of the ancient seacliff has been eroded back. It is along this section of coast where Hanks and others (1984) used the profiles of the ancient seacliffs between terraces to develop their paper on scarp degradation.

North of this point the Wilder terrace is no longer preserved, having been destroyed by subsequent erosion during the formation of the Western terrace. Refer to figure 1.3.

7.7 **Yellow Bank Creek.** Large, complex sedimentary intrusions of Santa Margarita Sandstone, injected into the Santa Cruz Mudstone, are exposed in the seacliff near the mouth of the creek. Two higher terraces are visible out the window to the right (northeast).

8.5 Intersection of Highway 1 with Bonny Doon Road. We continue north on Highway 1. Bonny Doon Beach, to the left, is clothing optional, as are most north county beaches.

9.6 **Town of Davenport.** One of several historic, land-based whaling stations that existed along the central California coast during the late 1800's. Grey whales migrating from the Bering Sea to Baja California (and back again) each year pass close to shore at this location. During the whaling days, a lookout stationed at the top of the cliff watched for passing whales. When whales were spotted, an alarm was sounded and the whalers launched their skiffs from the shore. Slain whales were hauled to the beach where they were cut up and the blubber rendered locally in try pots. This method of hunting allowed the whalers to live on shore rather than spending the better part of each year at sea.

Just south of the town of Davenport, the Davenport and Highway 1 wave-cut platforms of the Santa Cruz terrace are exposed in the modern seacliff (see figure 8 of Bradley and Griggs, 1976). Recently, a careful examination of the Davenport wave-cut platform in its type locality suggests that it is actually a stream terrace of San Vicente Creek (Weber and others, 1995). Elsewhere, however, the original concept of the Davenport platform remains the most plausible explanation.

9.8 **RMC Pacific Materials Cement Plant.** Now operated by RMC Pacific Materials (formerly RMC Lonestar), this plant was built between 1905 and 1907, and has been a major producer of cement in the San Francisco Bay area. Limestone and siliceous mudstone are both quarried locally. The relatively pure limestone (actually marble) is quarried about 2 miles northeast of the plant and transported to the plant on a 2-mile-long enclosed conveyor belt. Energy for producing Portland cement is derived from low-sulfur bituminous coal mined in eastern Utah and shipped to the plant by rail. The plant was extensively remodeled in the 1970's, resulting in a great reduction in stack emissions, and is now one of the most advanced cement manufacturing operations in the world.

The railroad tracks are part of a rail system originally intended to connect Santa Cruz and San Francisco (Ocean Shore Railroad). In the early 1900's, the stretch between Davenport and Tunitas Creek (about 30 miles to the north) was graded, but the tracks were laid no farther north than Swanton siding (3 miles north).

10.4 **Molino Road.** We are now paralleling Cement Plant Road, to the right. The private side road off Cement Plant Road leads to the Molino Creek Farm and the old, now abandoned, limestone (marble) quarry operated by the predecessor of RMC Pacific Materials. Portland cement for the Golden Gate Bridge was allegedly produced from this quarry.

10.7 **Davenport Landing Road.** The road to Davenport Landing intersects Highway 1 on the left. It leads to a small group of residences at Davenport Landing and Silverking Oceanic Farms.

Water wells in the Davenport Landing area produce sizable amounts of methane gas with the water. Analysis of gas samples collected from a well at Davenport Landing indicated the gas contained 74 to 91 percent methane, <1 percent ethane, 7 to 23 percent nitrogen, and 2 percent carbon dioxide (Mullins and Nagel, 1982). The sampled well was drilled to a depth of 655 feet, with a standing water table near 330 feet. The gas is produced along with hot water (90° F, 32°C). The Silverking Oceanic Farms well may produce as much as 200 Mcf per day. At present, the gas is simply discharged to the atmosphere and is not used. The gas apparently originates in the Santa Cruz Mudstone, a siliceous organic mudstone, and is thought to be of thermogenic origin.

Cement Terrace. Note the narrow bench between the Santa Cruz and Western terraces. This marine terrace, called the Cement terrace, is present only between San Vicente Creek and Molino Creek (about 2 miles), near Davenport. As discussed earlier, it probably corresponds to the 125 ka high stand of sea level.

11.1 Swanton Road to the right; north end of the Davenport Landing Road loop to the left.

11.3 **El Jarro Point.** The terrace on both sides of the road was the proposed site of a Pacific Gas & Electric nuclear power plant in the late 1960's. The site was abandoned largely because of the close proximity of the active San Gregorio Fault Zone.

12.2 **Scott Creek.** Here we can observe a large drowned valley with a lagoon confined by sand dunes and a well-developed berm. The dune area near the mouth of the creek was once the site of a mushroom farm that was abandoned in the 1960's and torn down in the 1970's. At that time, the dunes were stabilized by extensive growths of thick beach-dune vegetation. However, off-road vehicles, such as 4-wheelers and dirt bikes, started using this beach, destroying the vegetative cover in about 2 years. This allowed the dunes to remobilize, and sand soon started to drift once again across Highway 1 (much to the "delight" of Caltrans). The beach was then closed to off-road vehicles. It is ironic that the vehicles barred from the beach are what returned the back berm to its original condition—drifting sand.

As we drive north out of the valley of Scott Creek, the road again climbs up onto the Santa Cruz terrace, following almost exactly the back edge (shoreline angle) of the Greyhound Rock platform of the Santa Cruz terrace. The terrace platforms in this area are covered with a thick wedge of colluvial and alluvial cover. From here north to Waddell Creek, there is only one higher terrace present—the Western terrace. Note that the gently sloping Santa Cruz terrace surface lies to the left (southwest) and that the roadcuts expose Santa Cruz Mudstone to the right (northeast).

North of Scott Creek, the Santa Cruz terrace is postulated to contain two wave-cut platforms, the Greyhound Rock platform (upper) and the Highway 1 platform (lower) of Bradley and Griggs (1976). We believe that this interpretation is incorrect. The Greyhound Rock platform is a shore platform or storm-wave platform, formed at the back edge of the Highway 1 wave-cut platform.

The seacliff is 140 to 160 feet high and nearly vertical along this portion of coast. The views are spectacular, but the cliff is dangerous. The local Davenport Voluntary Fire Department and Rescue Team rescues numerous unfortunate individuals each year who get "stuck" on the cliff face or are injured trying to climb the cliffs.

13.6 **Colluvium Filled Gullies.** At about 6 locations between Scott Creek and Greyhound Rock, small "V" shaped gullies filled with colluvium are present in road cuts. Fluvial deposits are absent and the colluvial deposits are crudely stratified subparallel to the sides of the "V" shaped channel. These gullies apparently formed following the culmination of the sea-level rise that formed the Highway 1 platform (103 to 105 ka). As erosion modified the original seacliff, some of the initial gullies expanded their drainage networks, developing into the small present-day streams. As the drainage system evolved, the smaller gullies—those that had lost the battle for drainage area—were abandoned and eventually filled with colluvium. Note there is no surface evidence (geomorphic or vegetative) of their presence, as the ground surface passes unbroken over these gully fills.

14.1 **Texas Oil Co. Poleti No. 1 (Optional Stop).** Immediately west of this point near the edge of the seacliff is the site of the deepest exploratory oil well drilled in Santa Cruz County: the Texas Oil Co., Poleti No. 1. Drilled between June and December of 1956 to a depth of 9,201 feet, the well penetrated 9,135 feet of sedimentary rocks (mostly Santa Cruz Mudstone) before entering granitic basement. The target of the drilling was the Santa Margarita Sandstone, about 300 feet thick near the bottom of the hole, which proved to be dry. Apparently, the Texas Oil Co. was looking for the up-dip edge of a stratigraphic pinchout of the Santa Margarita Sandstone on the west limb of the Davenport syncline—or for a bowing of beds against a branch of the SGFZ.

The Santa Cruz Mudstone presents one of the most striking stratigraphic contrasts across the SGFZ: the mudstone is 8,850 feet thick (more than 2,700 meters) in Poleti No. 1, east of the fault zone, but is totally absent less than a mile offshore, west of the fault zone. Farther north, near Bolinas in Marin County, a lithologically similar section of Santa Cruz Mudstone is exposed in the seacliffs west of the juncture of the SGFZ and the San Andreas Fault. There, a composite section is estimated to be as thick as 2,000 meters (6,560 ft.) and has yielded benthic foraminifers including *Bolivina obliqua*, diagnostic of the late Miocene (Clark and others, 1984). Restoration of about 44 to 50 miles (70 to 80 km) of right slip on the SGFZ would juxtapose these thick Santa Cruz Mudstone sections.

Additional stratigraphic contrasts across the SGFZ are depicted in figure 1.9. Along the south shore of Point Año Nuevo, the missing late Miocene formations (Santa Margarita Sandstone and Santa Cruz Mudstone) are represented by an angular unconformity separating the siliceous Monterey Formation of middle Miocene age from Purisima Formation mudstone of early Pliocene age (Clark and Brabb, 1978). As much as 76 meters of Purisima Formation mudstone is exposed between this unconformity and the Green Oaks fault trace; farther east, between the Green Oaks and Coastways traces, sandstone beds of the Purisima Formation are discontinuously exposed in the seacliffs. These sandstone beds are folded and extensively faulted and are separated into two faunally distinct sections by the Frijoles Fault trace. The molluscan fauna from the section west of the Frijoles was believed by Branner and others (1909) to be similar to the type Purisima; in contrast, the section between the Frijoles and Coastways traces has yielded mollusks and echinoids diagnostic of the late Pliocene (Clark, 1981). The distinctiveness of this younger molluscan assemblage led Arnold (*in* Branner and others, 1909) to assign these sandstone beds to the Merced Formation instead, which in seacliff exposures south of San Francisco ranges in age from Pliocene (3.2 Ma) to Pleistocene (200 ka; A. M. Sarna-Wojcicki, written commun., 1996).

15.2 **Greyhound Rock (Optional Stop).** Time permitting, the bus will stop in the large, dirt parking area south of the actual turnoff for Greyhound Rock, and we will walk to the edge of the seacliff for a nice view to the northwest of Greyhound Rock, in the foreground, and Año Nuevo, in the distance. Greyhound Rock is a *tombolo*, an offshore rock connected to the beach by a sand spit. As exposed in the seacliff below the paved parking lot, the Highway 1 wave-cut platform is offset by the Greyhound Rock strand of the SGFZ. The Greyhound Rock strand actually consists of two discrete zones of faulting that offset the 103 to 105 ka wave-cut platform and the overlying terrace deposits. The “eastern fault zone” lies almost directly below the parking lot and consists of three closely spaced, steeply dipping fault planes that offset the Highway 1 platform about 10 meters, with apparent normal motion. These faults are also exposed along the beach access road north of and below the parking lot, where they cut the marine terrace deposits.

A second, “western fault” is exposed below the access road to the beach, about 60 meters west of the eastern fault zone, and offsets the wave-cut platform and overlying marine terrace deposits about 1.5 meters vertically. However, the western fault is truncated by fluvial sediments overlying the marine terrace deposits. This fault was well exposed in the cut for the access road until it was buried by a small landslide in the early 1990’s. Both the western fault and the eastern fault zone have been traced more than 300 meters to the northwest. Unfortunately, poor exposures away from the seacliff preclude conclusive demonstration that these are eastern branches of the main SGFZ. Nevertheless, it appears that the SGFZ consists of at least seven faults that offset the wave-cut platforms of the Santa Cruz terrace in a zone about 4.7 km (3 miles) wide.

Looking north toward Año Nuevo in the distance, the entire SGFZ is visible from this vantage point (fig. 1.10). The area of low cliffs delineates the small graben filled with the deposits of Año Nuevo Creek. The Frijoles Fault lies along the western side of this low area, forming the east-facing fault scarp. The Año Nuevo Creek Fault lies along the eastern side of the low area, in the valley of Año Nuevo Creek. The Coastways Fault lies in the next seacliff reentrant to the east. To the west of the Frijoles Fault, the Green Oaks Fault lies at the west end of the tall sandstone cliffs, and the Año Nuevo Thrust Fault lies west of the white cliffs. The westernmost faults, with demonstrable late Quaternary ground rupture, lie in the channel between Point Año Nuevo and the island. Their presence is confirmed by the Año Nuevo terrace, which lies some 3 to 4 meters (10 to 13 ft) higher in elevation on the island than on the point.

16.0 **Swanton Road/Laguna de Las Trancas.** Near the top of this ridge, east of Highway 1, a small pond (Laguna de Las Trancas) on a rotational landslide was cored and studied by Adam and others (1979). A piece of pine wood from a depth of 3.12 meters at the base of the core yielded a ^{14}C age of 29,500±560 years before present (B.P.). The core represents the period between roughly 5,000 and 30,000 years B.P. Pollen studies indicate that the flora and climate were significantly different during the Wisconsin glaciation that ended about 15,000 to 17,000 years ago. The presence of grand fir pollen suggests a southward displacement of floral zones by about 150 km. This was probably equivalent to a mean monthly temperature depression of 2 to 3°C and precipitation about 20 percent higher than at present. These changes apparently are valid only for the coastal area, reflecting the ameliorating effect of the ocean (but not the orographic effect of the Santa Cruz Mountains).

More recent pollen studies of two cores from Clear Lake, north of San Francisco Bay, indicate that Wisconsin climatic changes were far greater at inland locations. At Clear Lake temperatures were 7 to 8°C cooler during the Pleistocene, and precipitation was probably 300 to 350 percent of present (Adam and West, 1983). Wisconsin precipitation levels and temperatures in the Santa Cruz Mountains were probably somewhere between the values of Clear Lake and Laguna de Las Trancas.

16.4 **Big Creek Lumber Company.** The lumber mill on the right processes timber that has been selectively cut in the Santa Cruz Mountains. The lumber mill is built on the crest of a large, recently stabilized, late Holocene aeolian dune. This is part of a large stabilized dune ramp that extends from the beach at the mouth of Waddell Creek up onto the Santa Cruz terrace. Photographs from about 1900 indicate that the dune was active at that time.

17.0 **Waddell Creek.** This is another drowned valley. Just north of the creek, the high cliffs of Santa Cruz Mudstone (Waddell Bluffs) were originally undercut by waves. The highway, built in the 1940’s, is entirely on artificial fill. These bluffs formed a natural barrier to coastal travel in the 1800’s, when stagecoaches could pass the bluffs only during low tide on the wet beach. The southern tip of present-day San Mateo County was originally part of Santa Cruz County, but because access to the county seat in Santa Cruz was often impeded by this barrier, this land north of Waddell Bluffs was annexed by San Mateo County in 1868.

Debris that ravels down the cliff collects behind the cable netting on the eastern side of the road. This debris is periodically removed by Caltrans, stockpiled on the western side of Highway 1 and eventually dumped into the ocean to become part of the longshore drift of sediment to the south. Large rock falls are uncommon, probably because of the manner in which the Santa Cruz Mudstone weathers—by the raveling of small blocks and chips less than several inches in dimension. Occasionally, blocks the size of a small car fall and bounce onto Highway 1. About two decades ago, a passenger in a truck traveling north was killed by a rock that bounced through the front window, and litigation against Caltrans ensued for improperly maintaining the debris trap on the eastern side of Highway 1 (then a simple trench and berm). To reduce potential liability, Caltrans recently installed the Geobrugg steel wire rope net barrier, which seems to be working satisfactorily.

A resistant bed of siliceous mudstone is exposed in the surf zone and forms a natural groin at this location. The result is a protective beach up coast and active erosion down coast. Riprap was placed here in 1946 to protect Highway 1, then under construction. Because of its placement on a bedrock platform, this riprap has successfully protected the road for more than 50 years.

Poorly exposed at the top of the bluffs is the narrow remnant of a marine terrace, intermediate in elevation between the Santa Cruz and Western terraces, which is probably the Cement terrace. Exposed in the bluff is a broad anticlinal fold in the Santa Cruz Mudstone. The fold extends for several miles to the northwest, parallel to the trend of the San Gregorio Fault Zone. An unsuccessful exploratory oil well was drilled on this structure several miles north of here in 1956 (Seaboard Atkins No. 1, T.D. 3535).

18.7 Stop 2—Quaternary Faulting at Point Año Nuevo

Information on Stop 2

We will leave the bus and hike down the dirt road to the beach. From there we will hike north about 1.5 miles along the beach, examining the evidence for late Pleistocene and Holocene faulting. Bring your packs, water, and cameras. We will meet the bus in the parking lot for the Año Nuevo State Reserve. Please note that the road is on private property. If you are taking this trip at any time other than September 15, 2001, you must obtain a permit from Coastways Ranch to enter the property. Once we enter the State Reserve, sample collecting is prohibited.

Coastways Fault of the San Gregorio Fault Zone. The Coastways Fault crosses the highway at the small dip in the road just before Coastways Ranch. This fault has long been considered the primary trace of the SGFZ because of the obvious bedrock offset across a small reentrant in the coastline.

STOP 2A. When we reach the beach, examine the rocks on either side of the reentrant in the seacliff. West of the reentrant, fine-grained silty sandstones and sandy siltstones of the Purisima Formation are exposed in near-vertical seacliffs. The sandstones and their fauna are described in more detail above (see milepost 14.1). Bedding strikes approximately east-west and dips 10° to 20° to the south.

East of the reentrant are poorly exposed outcrops of the Santa Cruz Mudstone (also described above, milepost 14.1). Bedding, although hard to find, strikes about N 50° E, dipping about 40° NW. This discordant juxtaposition of two units differing greatly in age, lithology, and structure can be explained only by the presence of a major, Neogene-active fault running along the brush- and colluvium-covered drainage (figs. 1.10 and 1.11).

The fault is obscured by thick wedges of colluvium and dense vegetation, so it is not exposed anywhere in this drainage. Neither the 103 to 105 ka wave-cut platform nor the younger terrace deposits are exposed near the fault; however, leveling across the reentrant indicates that the marine terrace is offset about 5 meters (16 feet), with the northeast side up (W.C. Bradley, personal commun., 1974). Recently, several exploratory trenches were excavated across this fault trace on the Finney Creek alluvial fan, about 300 to 400 meters to the north (see fig. 1.11). The fault clearly juxtaposes well-sorted shallow marine sands with fluvial deposits composed almost entirely of Santa Cruz Mudstone fragments. Apparent fault separation in the trench exposures is west side up, east side down, but this offset may reflect right-lateral transport of the axis of the fan toward the northwest, thereby forming an east-facing scarp.

Walk northward along the beach. From here to the mouth of Año Nuevo Creek, the seacliff is cut in the Purisima Formation. In this area, away from the Coastways Fault, bedding strikes roughly north-south and dips gently 4° to 7° to the east. Exposed in the seacliff are numerous, hard, calcite-cemented layers of fossiliferous sandstone that form resistant ledges and concretions. The fossil fauna is largely shallow marine mollusks.

Age of the Marine Terrace at Point Año Nuevo

At this stop we will examine late Quaternary faulting exposed along the south shore of Point Año Nuevo, within the Año Nuevo State Reserve. We are in the SGFZ (figs. 1.7, 1.9, 1.10 and 1.11). The broad, gently sloping surface of the first emergent marine terrace is visible to the northwest and at the top of the seacliff directly above us. Although this terrace has been mapped as the Año Nuevo terrace, which is correlative with the Davenport wave-cut platform of the Santa Cruz terrace east of the SGFZ (Weber and others, 1995), the terrace here is probably actually equivalent to the Highway 1 platform, with an age of 103 to 105 ka.

This circumstance is a consequence of our inability to distinguish and definitively map the terrace surfaces within the SGFZ. At Pigeon Point the separation between the Pigeon Point terrace (103 to 105 ka) and the Año Nuevo terrace (80 to

83 ka) is clear. South of Whitehouse Creek we can no longer map the two terraces separately. The outer edge of the terrace at Point Año Nuevo can be traced northward into what is clearly the Año Nuevo terrace at Pigeon Point. Based on faunal assemblages and amino-acid racemization data, it appears that the central portion of the broad terrace at Point Año Nuevo is actually the Pigeon Point terrace (103 to 105 ka).

At Point Año Nuevo the first emergent terrace is unquestionably a compound terrace, containing two wave-cut platforms (analogous to the situation in westside Santa Cruz, illustrated in figure 1.5). Although mapped as one terrace surface, the outer portion of the terrace is probably underlain by the 80 to 83 ka wave-cut platform, normally associated with the Año Nuevo terrace. The inner portion of the terrace is underlain by the 103 to 105 ka wave-cut platform, associated with the Pigeon Point terrace west of the fault zone and the Highway 1 wave-cut platform east of the fault zone. Unfortunately, the hypothesized vertical discontinuity in the wave-cut platform of this compound terrace cannot be identified unambiguously in the seacliffs along the south shore of Point Año Nuevo. However, a small, 2-meter-high step in the wave-cut platform, exposed in the seacliff about 100 to 120 meters east of the Año Nuevo thrust fault, may represent the break between the two wave-cut platforms.

The 103 to 105 ka wave-cut platform at the base of the marine terrace deposits is visible near the top of the seacliff. It appears to be unbroken between the Coastways Fault reentrant and the mouth of Año Nuevo Creek. Continue north, toward the mouth of Año Nuevo Creek, until you reach the near-vertical contact between pebble conglomerates and the Purisima Formation.

Note: The locations of the field trip stops discussed below are shown on figure 1.12.

STOP 2B. Exposed in the seacliff is the contact (buttress unconformity) between fluvial deposits of Año Nuevo Creek and the upper sandstone member of the Purisima Formation (fig. 1.13). Detrital charcoal fragments collected near the base of the Año Nuevo Creek deposits have yielded a ^{14}C age of 10,200 ± 300 years B.P. This date, combined with ^{14}C dates on charcoal collected from the top of these deposits near the Frijoles Fault, would suggest that these sediments were deposited between 10,500 and 8,000 years B.P. The presence of abundant charcoal in these fluvial deposits is probably related to the seasonal burning of grasslands and undergrowth by Native Americans to promote growth of grasses and to aid in the capture of small game. Naturally occurring forest fires as a result of lightning are exceedingly rare in the Santa Cruz Mountains because of the lack of convection in the atmosphere during the dry summer season. Air masses are stable during the summer and fall because of temperature inversions in the atmosphere related to the seasonal formation of advection fogs.

Southeast of the mouth of Año Nuevo Creek, the 100-foot-high, near-vertical seacliff in the Purisima Formation is capped by about 20 feet of Quaternary marine terrace deposits. This terrace correlates with the main terrace at Point Año Nuevo, which has been identified as the 103 to105 ka terrace on the basis of amino-acid racemization studies and the cold-water aspect of the fauna. The base of the terrace deposits (the wave-cut platform) is about 70 to 80 feet in elevation southeast of the mouth of Año Nuevo Creek.

Approximately 30 meters to the southeast, a small fault offsets bedding in the Purisima Formation. Poor exposure near the top of the cliff, as a result of overhanging vegetation, makes it difficult to determine if this fault offsets the overlying marine terrace.

Hike northwest, crossing the mouth of Año Nuevo Creek. Exposed in the seacliff are the interbedded pebble conglomerates, poorly sorted sandstones, siltstones, and clays deposited by Año Nuevo Creek. The discontinuous strata are typically channeled and cross-bedded, with thin layers of silt, silty sand, and clay separating thick packages of pebble conglomerate. Some of the fine-grained layers appear to have relict soil structure. Charcoal is quite common in both the conglomerates and the fine-grained deposits. These strata are clearly the channel and overbank deposits of a small stream. The channel deposits are typically imbricated conglomerates, which are clast supported and contain pebbles and cobbles of Santa Cruz Mudstone. The matrix is clay and silty clay. The presence of abundant (>99 percent) Santa Cruz Mudstone clasts indicates a fluvial origin, as mudstone bedrock is present only in the drainage basins of streams that originate northeast of the Coastways Fault. Santa Cruz Mudstone bedrock is not present southwest of the Coastways Fault in San Mateo County, so the mudstone clasts must have been transported into this area from the east. Transport along the coast by littoral drift is not a viable hypothesis because the relatively soft mudstone does not stand up to abrasion by harder clasts derived from the Pigeon Point Formation. Note, for instance, the relative paucity of mudstone pebbles on the beach compared with the Año Nuevo Creek deposits.

Año Nuevo Creek deposits are continuously exposed along 500 to 550 meters (~1,700 feet) of seacliff from the mouth of Año Nuevo Creek northwest to the Frijoles Fault. These beds dip gently 3° to 5° to the northwest along this section of coastline (fig. 1.13), grading from predominantly pebble conglomerates on the southeast (near the mouth of the creek) to predominantly silts, clays, and sandy clays at the northwest end of the beach. The topographically expressed depositional surface on these fluvial sediments also slopes 3° to 5° to the northwest, mimicking the underlying bedrock surface. This northwest dip is, therefore, interpreted to be the result of post-depositional tilting in the late Holocene.

The contact between the Año Nuevo Creek deposits and the Purisima Formation is exposed intermittently for about 300 meters west of the mouth of Año Nuevo Creek, after which the contact lies below the level of the beach. This unconformable contact is typically highly irregular, exhibiting deeply cut channels and irregular bedrock highs. Careful examination of the contact indicates that it is a buttress unconformity, except as noted below.

STOP 2C. Here, in a small cove along the seacliff (fig. 1.12), deposits of Año Nuevo Creek overlie Purisima Formation. Examine the contact between the fluvial sediments and the Purisima Formation (see figs. 1.13 and 1.14). Note the presence of numerous pholad (a variety of clam) borings in the Purisima Formation along this contact. The pholad borings conclusively demonstrate that the surface between the Año Nuevo Creek deposits and the Purisima Formation is a former wave-cut platform—an ancient ocean floor—and is therefore associated with a marine terrace. Careful examination of the outcrop reveals a small wedge of well-sorted sand of marine origin (not composed of Santa Cruz Mudstone detritus) on the old wave-cut platform (fig. 1.14). This thin wedge of sediment, which fills some of the pholad borings, is a remnant of the near-shore marine deposits that once covered the wave-cut platform.

Apparently, the near-shore marine sediments originally deposited on the wave-cut platform were eroded away by ancestral Año Nuevo Creek, thereby exhuming the old wave-cut platform. The creek then deposited fluvial sediments on this exhumed surface originally formed by wave erosion. Examination of the seacliff outcrops west of the mouth of Año Nuevo Creek reveals that the contact between the fluvial deposits and bedrock usually follows the old wave-cut platform, although the creek channeled into the bedrock in several areas, thus destroying the wave-cut platform. The intensely bored surface of the wave-cut platform, stripped of its deposits, is exposed in several areas northwest of this cove.

Along the northwest side of the cove, a small, branching fault offsets the Purisima Formation, the wave-cut platform, remnants of the near-shore marine sediments, and the basal layers of the fluvial deposits (figs. 1.11, 1.13 and 1.14). However, the fault is truncated by younger beds within the creek deposits and does not extend to the surface. The fault is active, as it apparently offsets the basal deposits of Año Nuevo Creek, which are about 10,000 years old, yet there is no surface evidence of this fault. The obvious offset is vertical, northeast side up and southwest side down, but it is probable that this fault also experienced right-lateral strike-slip movement. NOTE: Consider the problem of trying to identify this Holocene-active fault using standard engineering geologic techniques. Without the luxury of a seacliff exposure it would be impossible even to find this fault, much less determine its activity.

Finally, note that directly east of this small fault lies a mudstone unit of the Purisima Formation, in depositional contact with an overlying sandstone unit of the Purisima Formation (fig. 1.14). The contact appears to be conformable and gradational. Bedrock faults on the eastern side of the cove offset the Purisima Formation but not the 103 to 105 ka wave-cut platform.

Age of the Wave-Cut Platform West of Año Nuevo Creek

As indicated earlier, the inner portion of the broad, low terrace at Año Nuevo State Reserve is interpreted to be 103 to 105 ka, based on amino acid racemization data and the presence of a cold-water fauna (Ken Lajoie, personal communication), and is thus correlative with the Highway 1 platform of the Santa Cruz terrace. The 80 to 83 ka platform is present near the actual point, about 1,300 meters (4,000 feet) west of here.

The age of the wave-cut platform exposed at Stop 2C, however, is not known. Which of the wave-cut platforms does it correspond with? Fossils are not present on the platform, and it is overlain by 10,000-year-old deposits. This feature is obviously not a product of the modern sea-level high stand, but it could have formed during the 103 to 105 ka high stand or perhaps one of the younger Pleistocene sea-level high stands.

The position of this localized, low-lying wave-cut platform, apparently on a down-dropped fault block between extensive outcrops of the 103 to 105 ka terrace, suggests it also represents the 103 to 105 ka wave-cut platform (fig. 1.13). Although it could have conceivably formed during one of the younger Pleistocene sea-level high stands, these alternatives can seemingly be eliminated by removing 400 to 500 meters (~1,500 feet) of slip from the Frijoles Fault. Sliding the Pigeon Point block back to the southeast along the Frijoles Fault would isolate the wave-cut platform in question from wave attack by surrounding it with 103 to 105 ka terrace.

The Año Nuevo Creek Fault

The elevation of the wave-cut platform immediately northwest of Año Nuevo Creek, at Stop 2C, is about 3 to 6 meters (10 to 20 feet) above sea level. This is about 18 meters (60 feet) lower than the 103 to 105 ka wave-cut platform southeast of Año Nuevo Creek (see figs. 1.12 and 1.13). This discrepancy in elevation requires the presence of a fault near the mouth of Año Nuevo Creek, offsetting the 103 to 105 ka wave-cut platform. Apparent fault offset is down to the west, up to the east. Based on regional geomorphology and the trend of other faults in the seacliff, it is probable that the fault lies near the axis of Año Nuevo Creek, trending roughly north-south. It apparently connects the Frijoles and Coastways Fault strands (see fig. 1.11) and appears to act as the east side of a small graben filled with the fluvial deposits of Año Nuevo Creek.

Interpretative History of Año Nuevo Creek. The Holocene deposits of Año Nuevo Creek lie in a small graben, late Pleistocene to Holocene in age, bounded by the Frijoles Fault and the Año Nuevo Creek Fault. Prior to approximately 12,000 years ago, Año Nuevo Creek flowed northwestward along what is now the course of Green Oaks Creek, entering the ocean on the north side of the point (fig. 1.15). About 12,000 years ago, Año Nuevo Creek was captured, probably by headward erosion of a high-gradient stream flowing along the trace of the Año Nuevo Creek Fault. After this capture, the short, high-gradient stream must have experienced a dramatic increase in both discharge and sediment load. Sea level was still on the order of 30 meters (100 feet) or more lower than at present, and the newly energized and redirected Año Nuevo Creek proceeded to erode the existing marine terrace deposits within the graben, thus partially exhuming the 103 to 105 ka wave-cut platform.

As the creek cleansed the graben of marine terrace deposits, sea level continued to rise, the graben continued to sink, and the climate gradually became warmer and drier. These combined processes interacted to change the stream from an erosional regime toward a depositional regime. Between about 11,000 and 8,000 years ago, as sea level slowly rose, Año Nuevo Creek deposited a sequence of fluvial sediments in the graben, which it had stripped of marine sediments just a few thousand years earlier.

The slow rise in sea level during the mid-Holocene was accompanied by rapid surf-zone erosion and seacliff retreat in the unconsolidated fluvial sediments. Seacliff retreat apparently was rapid enough to essentially lower base level for Año Nuevo Creek. After about 8,000 years ago, Año Nuevo Creek reverted to an erosional regime and began to incise the sediments it had deposited between 11,000 and 8,000 years ago. The return to an erosional regime was accompanied by a decrease in precipitation and runoff, thereby reducing the erosional ability of Año Nuevo Creek. Following the stabilization of sea level about 5,500 years ago, Año Nuevo Creek has continued to slowly incise its channel into the fluvial deposits, largely in response to the slow lowering of base level brought about by coastal retreat due to wave erosion.

Onward. Continue to hike northwest along the beach. In at least two other areas, small faults in the seacliff offset the exhumed wave-cut platform and the basal 3 to 6 feet of fluvial deposits (figs. 1.11, 1.13 and 1.14). Again, these faults are truncated by younger depositional units and do not extend to the surface. The Año Nuevo Creek fluvial deposits become finer grained to the northwest. Several weakly to moderately developed paleosols (buried soils) can be found in the fine-grained overbank deposits exposed in the seacliff outcrop northwest of Stop 2C.

Waddell's Wharf, Coastal Erosion, and Littoral Drift

A large wet area in the seacliff represents seepage from a poorly sealed reservoir (pond) that lies several hundred feet north of the seacliff. This seepage approximately marks the location of Waddell's Wharf, built in 1864 by William Waddell. The wharf, about 700 feet long, was used for loading lumber cut in Waddell Creek and transported to the wharf on flatbed cars hauled by horses along a three-mile-long wooden railway. The wharf operated until about 1877, serving several small mills, but business declined after Waddell was killed by a grizzly bear in 1875. The wharf burned in the early 1880's. The shallow excavation for the roadway to the wharf, now filled with dark gray soil, can be identified by comparing the disturbed and undisturbed soil profiles near the top of the seacliff.

In 1974, a single piling from this wharf was found in place on the beach at the base of the modern seacliff. The piling was about 3 feet from the face of the cliff, indicating that through 1974 little if any erosion had occurred in the 110-plus years since the wharf was built. However, a period of extensive cliff erosion was initiated in the winter of 1977-78, when 10 feet of cliff retreat occurred in a single storm season. In the following 5 to 6 years, more than 50 feet of cliff retreat occurred along the coast between Año Nuevo Creek and the steep cliffs that form the south shore of the point. The piling was ripped out of the beach and destroyed during a large storm on December 21, 1979. Since then, the rate of seacliff retreat has slowed and become more intermittent, but active surf erosion still occurs along this seacliff almost every winter. The apparent absence of cliff erosion along the coast north of Año Nuevo Creek for 113 years, followed by almost yearly wave erosion and cliff retreat during the past 24 years, suggests a major change in the erosional equilibrium along this section of coast. Consider for a moment that the coast from west of the Frijoles Fault to Año Nuevo Creek has retreated between 60 and 80 feet during the past 24 years. This change may reflect a decrease in the littoral drift moving northwest to southeast down the coast, resulting from the gradual depletion of the wide beach that lay north of Point Año Nuevo before the channel between the mainland and the island opened up in the 1700's (Weber, 1981). In other words, it may have taken two centuries for the littoral cell to reequilibrate, and in the interim the cliffs along the south shore were protected somewhat from surf attack by the extra sand.

STOP 2D—Frijoles Fault. Exposed in the seacliff is one of the two primary fault strands of the SGFZ, the Frijoles Fault. It juxtaposes moderately to steeply dipping fluvial deposits of Año Nuevo Creek, to the southeast, with crushed Purisima Formation, to the northwest (fig. 1.13).

The Holocene fluvial deposits, which we first encountered in the seacliff near the mouth of Año Nuevo Creek, dip uniformly to the northwest about 3° to 5° for a distance of roughly 500 meters (1,600 feet). Approaching the Frijoles Fault, however, these Holocene beds are abruptly folded upward, forming a small syncline. This drag fold has formed in response to movement on the Frijoles Fault. The fold plunges to the north, suggesting right-lateral strike-slip movement with a vertical component (southeast side down, northwest side up). Projecting the 103 to 105 ka wave-cut platform into the fault from both sides suggests that the vertical offset of the platform is approximately 30 to 35 meters (100 to 110 feet). The amount of strike-slip displacement cannot be approximated at this outcrop.

Northwest of the main fault exposure lies a broad zone of crushed Purisima Formation, or fault gouge, about 75 meters (250 feet) wide (figs. 1.12 and 1.13). Upon closer examination, the active movement within this shear zone appears to be concentrated in three areas. The crushed rock is weak and susceptible to both erosion and slope failure. The landslides on this slope typically reactivate and enlarge their headscarps each rainy season, depositing debris on the beach that is usually removed each year by wave erosion. The height and angle of the cliff face also reflect the effect of the intense bedrock shearing on slope stability and resistance to erosion.

Landslides of the type present in this shear zone (slumps) are not typically found in seacliffs formed in the sandstone of the upper Purisima Formation. These sandstone cliffs generally fail as block falls and topples controlled by steeply dipping joint sets and triggered by the undercutting action of waves. Large slump landslides are found only in the shear zones at Point Año Nuevo and 15 miles to the north near San Gregorio Creek, where the SGFZ goes offshore. Walk northwest to the end of the beach. Note the difference in hardness, bedding, and internal structure of the intact Purisima Formation bedrock at this location compared to the shear zone along the Frijoles Fault.

Onward. Hike up the stairs to the top of the cliff and out onto the levee that dams the small pond. The levee is porous, permeable, and leaks badly. Compaction is inadequate, and the dam is not stable. During the heavy rains in 1982-83, a 150-foot-long slab of this dam failed and slid off of the face of the dam into the reservoir. Although the main scarp formed down the centerline of the levee, the dam was not breached, and water did not escape from the reservoir. The levee was repaired the following summer, but its stability remains questionable.

Note that the dam for the reservoir lies across the axis of a northwest-trending depression representing the locus of the Frijoles Fault. The steep slope to the west is the northeast-facing Frijoles Fault scarp, heavily modified by erosion. To the east and southeast is the depositional surface on the Año Nuevo Creek fluvial sequence that we observed earlier in the seacliff. A broad linear valley has formed along the trace of the Frijoles Fault. This linear valley and a well-developed set of northeast-facing scarps mark the trace of the Frijoles Fault to the northwest, where the fault crosses the surface of the marine terrace.

Hike west, following the trail up onto the marine terrace. Hike off the trail (fight your way through the Coyote brush) and across the field to the top of the seacliff near the first small headland west of the main beach.

STOP 2E. This is an excellent vantage point from which to view the geology described in this guide, and to put it in perspective (fig. 1.12). To the west and northwest, the Año Nuevo terrace is visible as a broad, nearly planar surface sloping gently to the west. The vegetated remnants of the Año Nuevo dune field (Holocene) overlie this terrace. To the north, the surface trace of the Frijoles Fault is marked by the linear topographic trough. The alluvial fan of Año Nuevo Creek and the depositional surface on the Año Nuevo Creek deposits form the surfaces east of the small reservoir, and further to the southeast lies the graben formed between the Frijoles and Año Nuevo Creek Faults. The Dickerman Barn, which houses the visitor center, lies on fluvial deposits of Año Nuevo Creek within the graben. Farther east, the base of the west-facing slope of the Santa Cruz Mountains marks the trace of the Coastways Fault. Higher, forested marine terraces are visible southeast of Año Nuevo Creek. The surface of the Santa Cruz terrace is visible southeast of Año Nuevo Creek, gradually thinning and finally disappearing just north of the Waddell Bluffs. Looking south, the Santa Cruz and Western terraces are visible in the distance as far south as Scott Creek. Highway 1 lies at the back edge of the Santa Cruz terrace and below the

Western terrace. The headland jutting out from the coastline just south of Scott Creek is El Jarro Point, the proposed site of the Davenport Nuclear Power Plant in the 1960's.

Resume hiking to the bus. Hike back to the northeast toward the parking lot that lies just north of the Dickerman Barn. Along the path you will walk down the scarp of the Frijoles Fault, and after crossing the fault you will walk up the tilted depositional surface of the Holocene graben-filling deposits of Año Nuevo Creek.

Late Quaternary Slip Rates on the San Gregorio Fault Zone

Measurements of late Quaternary fault slip rates are difficult even under the most ideal conditions. Discussion below describes measurement of offset in both the horizonal and vertical directions. Horizontal slip rates in the late Quaternary were determined using offset marine terrace shoreline angles, along with offsets of late Pleistocene streams on alluvial fans near Point Año Nuevo. Although both of these techniques are fraught with assumptions, it appears that the original estimates of late Quaternary slip by Weber (1980), Weber and Cotton (1981), and Weber (1990 a, b) are probably the most reasonable.

The horizontal slip rate determined from the offset of the Santa Cruz and Western terrace shoreline angles across the SGFZ is 6 to 11 mm/yr, with the best estimate being 8 mm/yr. Figure 1.7 is a plot of shoreline angles (or paleostrandlines) on opposite sides of the SGFZ; figure 1.16 is a more detailed map of offset shoreline angles at Point Año Nuevo. Although higher and older marine terraces can be correlated across the fault zone, their shoreline angle positions and fault offsets cannot be accurately determined. Nevertheless, the distribution of the terrace remnants (fig. 1.7) suggests continuous horizontal slip on the SGFZ of 6 to 11 mm/yr during the past 500 k.y.

The late Quaternary slip rate across the fault zone, determined from offset streams on alluvial fans at Point Año Nuevo, is 4 to 10 mm/yr (see fig. 1.15). This is comparable to the rate determined from offset marine terrace shoreline angles (above) and to the slip rate of 6 mm/yr postulated by Clark (1997) for the past 3.0 m.y.

Vertical slip rates are measured by geographic variations in the uplift rates of marine terraces. If the marine terraces record the long-term, late Quaternary uplift rates of both the Santa Cruz Mountains and Pigeon Point structural blocks, the difference between these uplift rates must represent the late Quaternary slip rate across the fault zone. The interpretation most strongly supported by field data is that, over the past 500,000 years, the Ben Lomond Mountain terrace sequence has been uplifting at 0.42 to 0.44 m/k.y., while the Pigeon Point terrace sequence has risen 0.3 m/k.y. (see discussion of Stop 1). The difference is 0.13 m/k.y., a very low rate of vertical displacement.

It is possible that these estimated uplift rates are incorrect; however, using alternative uplift rates generally results in even lower rates of vertical displacement across the SGFZ. If we arbitrarily assume that the highest uplift rate for Ben Lomond Mountain (0.44 m/k.y.) and the lowest rate for the Pigeon Point structural block (0.15 m/k.y.) are valid, then the long-term vertical displacement rate would be 0.29 m/k.y.

Both of these hypothetical displacement rates of vertical offset across the SGFZ are extremely low, lying within the range of long-term uplift rates for the central California coast as a whole. A vertical slip rate of 0.13 to 0.29 m/k.y. indicates that any vertical component of slip on the SGFZ is relatively small.

Road Log for Those Not Hiking

Mileage/Notes

19.2 **Año Nuevo Creek.** Strath terraces of Año Nuevo Creek are visible in the agricultural fields to the east, where the creek is deeply incised into its fan. Both north and south of Año Nuevo Creek, Highway 1 cuts through the alluvial fan formed by the creek. The basal portions of these Highway 1 road cuts expose clean quartzose beach sands, whereas the upper portions of the cuts expose fluvial pebble conglomerates (with clasts derived from the Santa Cruz Mudstone). If you plan to examine these deposits, you should be prepared to dig into the face of the road cut.

19.5 **Entrance to Año Nuevo State Reserve:** Turn left and enter reserve. For trips other than September 15, 2001, pay the ranger and proceed to the main parking lot. Restrooms are available. Exhibits and a natural history bookstore are usually open in the Dickerman Barn, one of the remaining buildings of the historic Steele Ranch.

End of Trip

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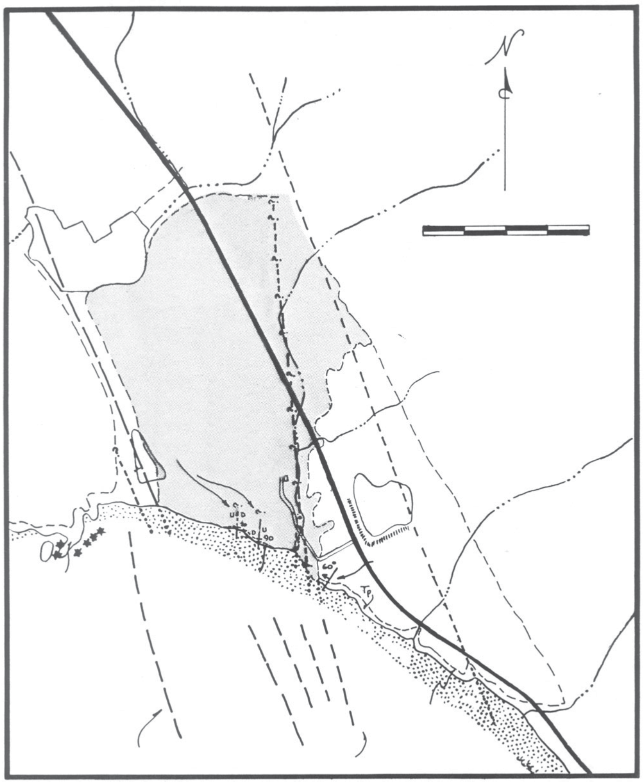

Figure 1.1. Regional map of central California showing major faults.

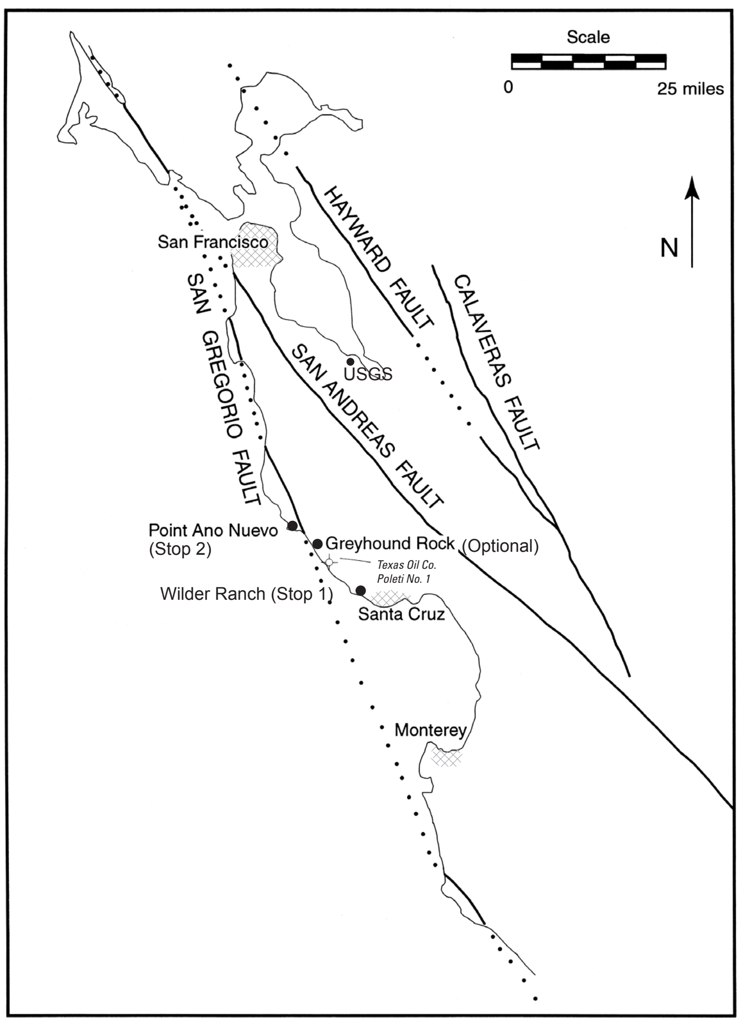

Figure 1.2. Stops of National Association of Geoscience Teachers field trip to the San Gregorio Fault and Pleistocene marine terraces, originating at the Geological Survey in Menlo Park. Faults dashed where approximate.

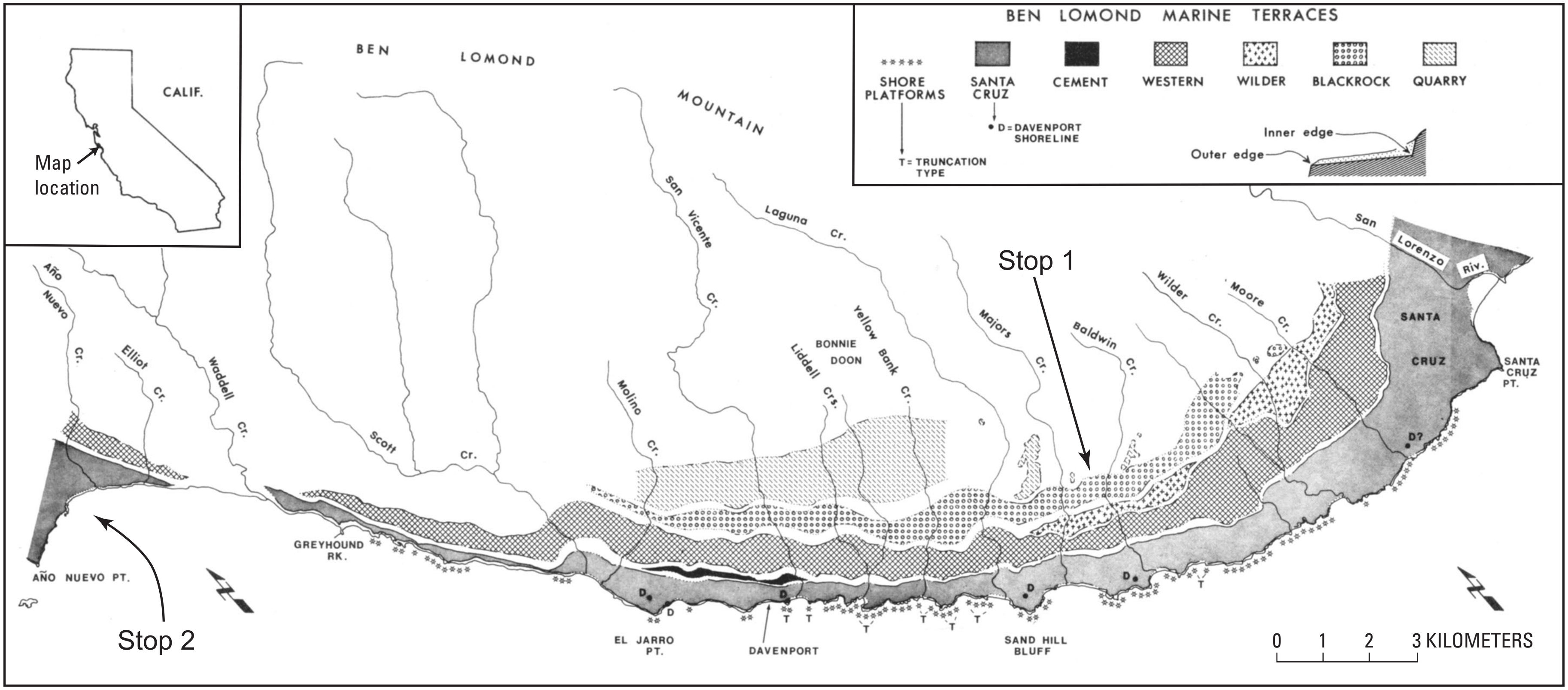

Figure 1.3. Map of marine terraces on the flank of Ben Lomond Mountain; modified from Bradley and Griggs (1976).

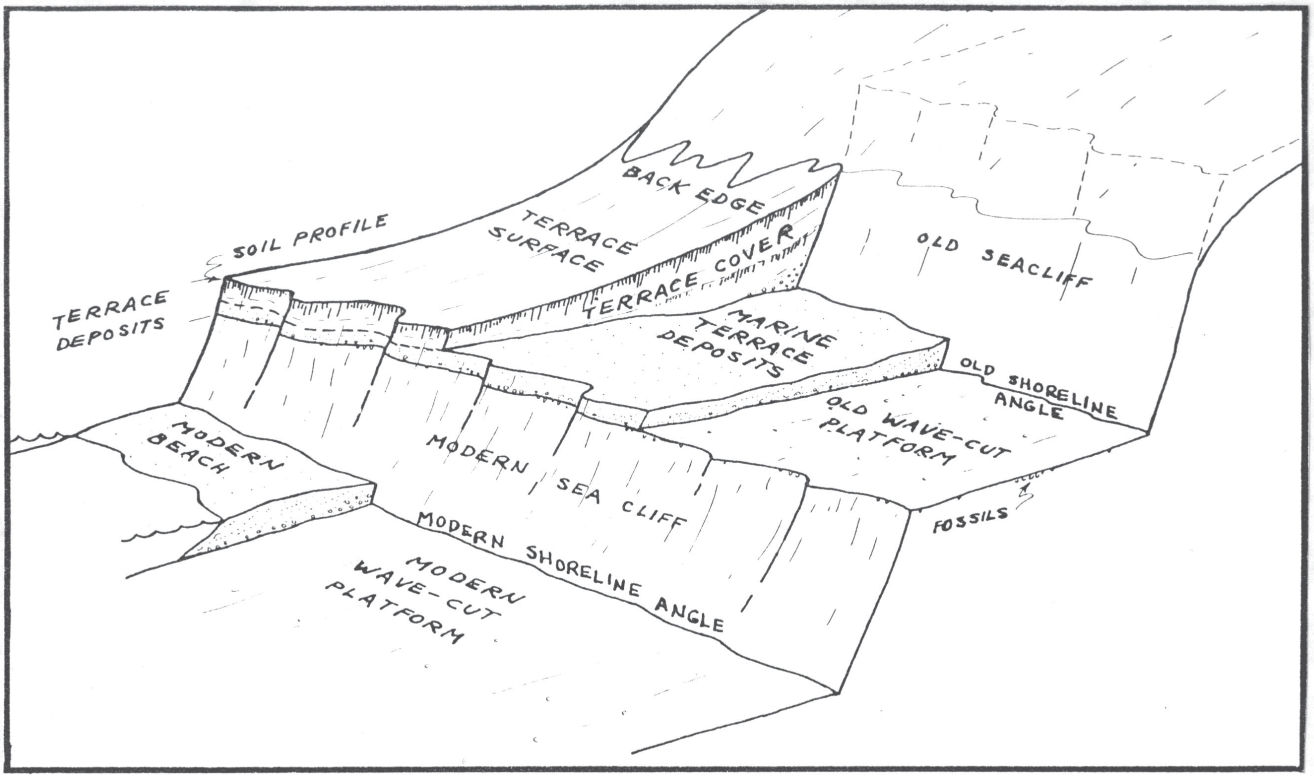

Figure 1.4. Schematic diagram of a marine terrace, indicating the relationship of the wave-cut platform to the shoreline angle and the overlying terrace deposits.

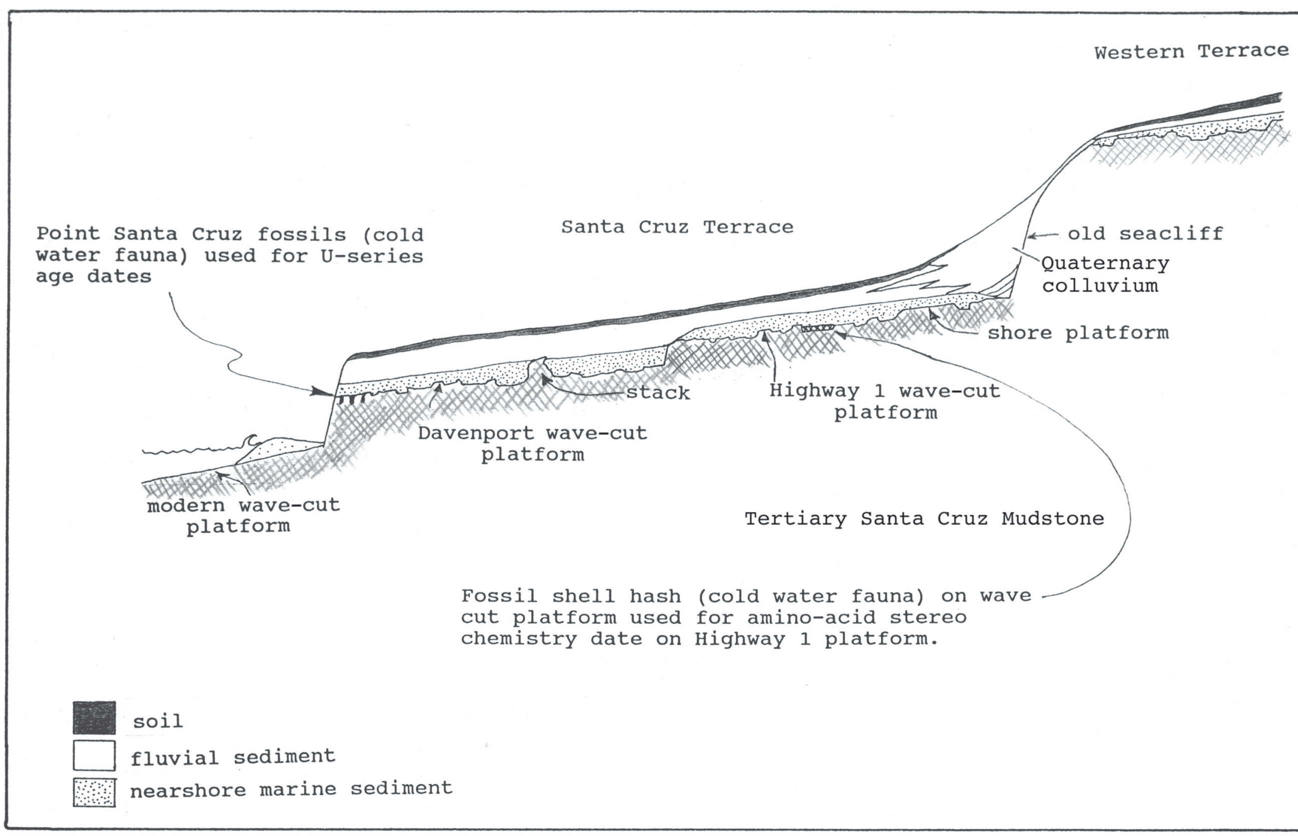

Figure 1.5. Diagrammatic cross section of the Santa Cruz terrace on the west side of Santa Cruz, showing the relative positions of the Davenport and Highway 1 wave-cut platforms.

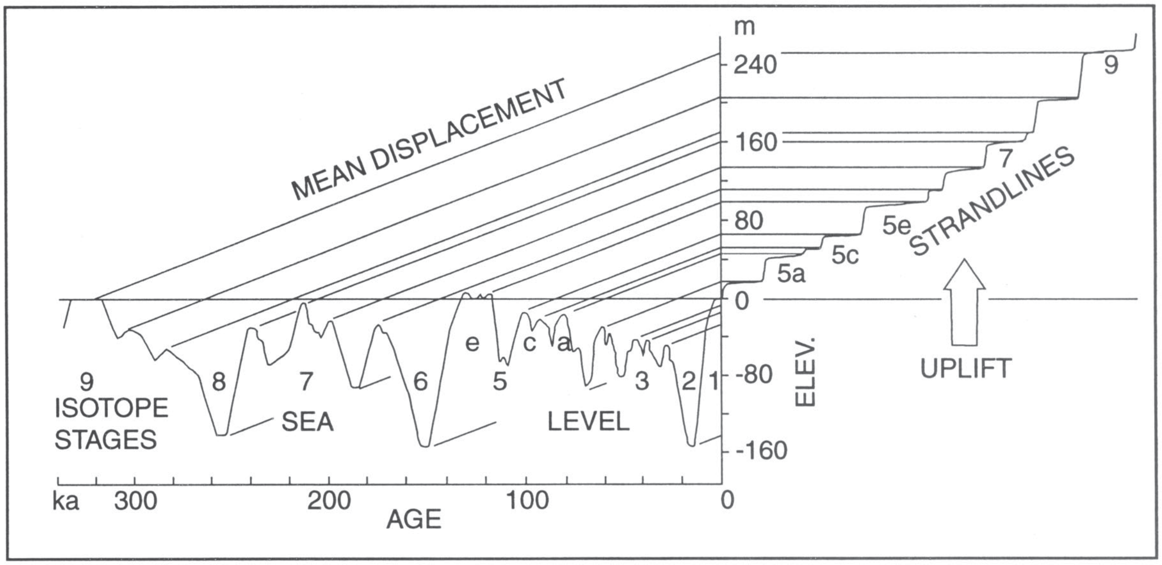

Figure 1.6. Graphic technique for determining the ages of marine terraces and uplift rates. On a rising coastline, the shoreline angle of each terrace (strandline) records a sea-level high stand. Consequently, the slope of the line connecting a shoreline angle elevation with the corresponding sea-level high stand is the average uplift rate. If the uplift rate has been constant, then (1) all of the lines connecting shoreline angle elevations with sea-level high stands will be parallel, (2) knowing the age of one terrace will allow the ages of the other terraces to be determined, and (3) trial and error can be used to approximate the ages for all of the terraces even if the age of one terrace is not known. Sea-level curve from U-series dated corals in the terraces on the Huon Peninsula, Papua New Guinea (Chappell, 1983); diagram from Lajoie (1986).

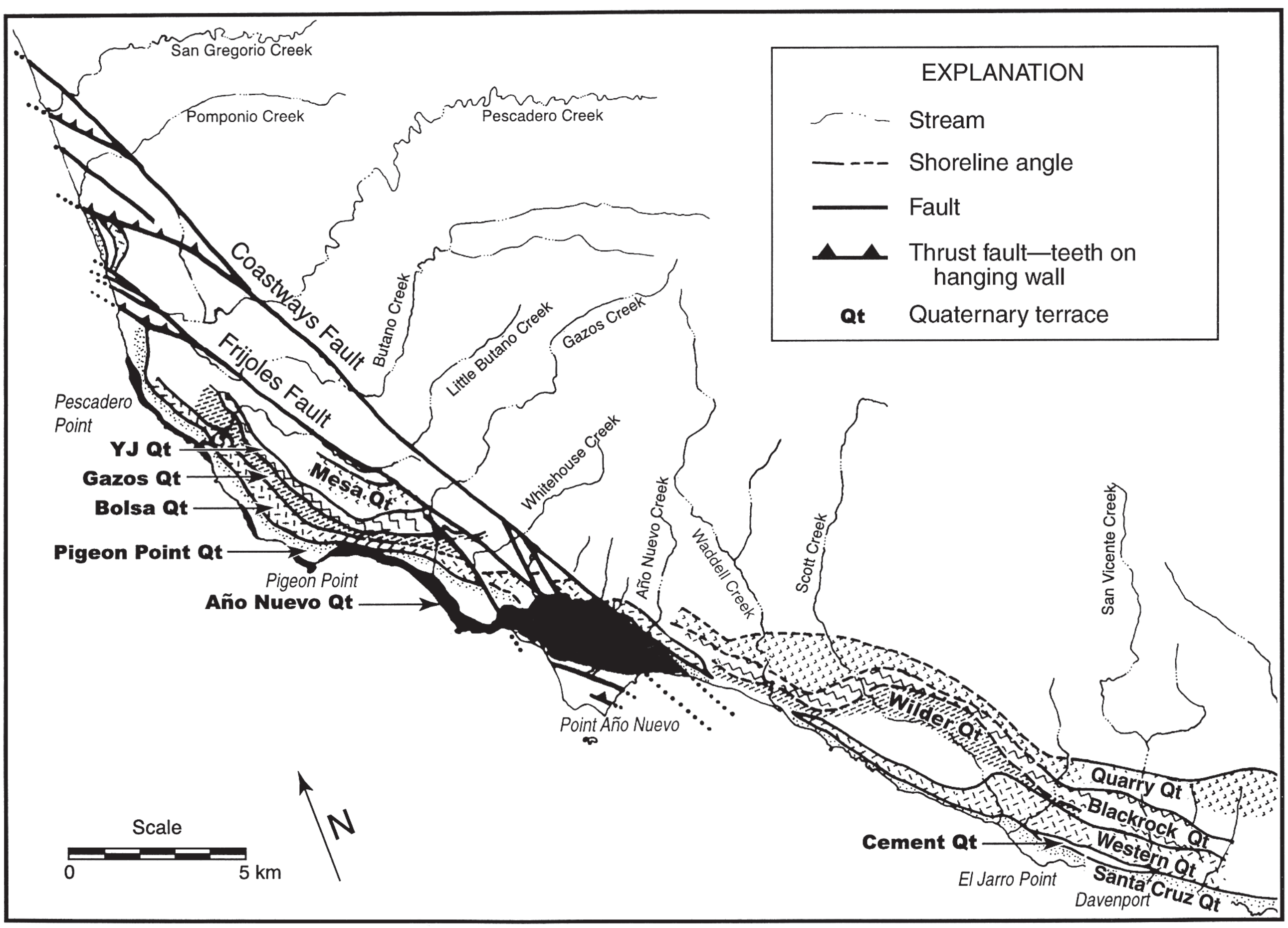

Figure 1.7. Offset Pleistocene strandlines across the San Gregorio Fault Zone; modified from Weber and others (1995). Refer to table 1.4 for the specific terrace correlations across the fault zone.

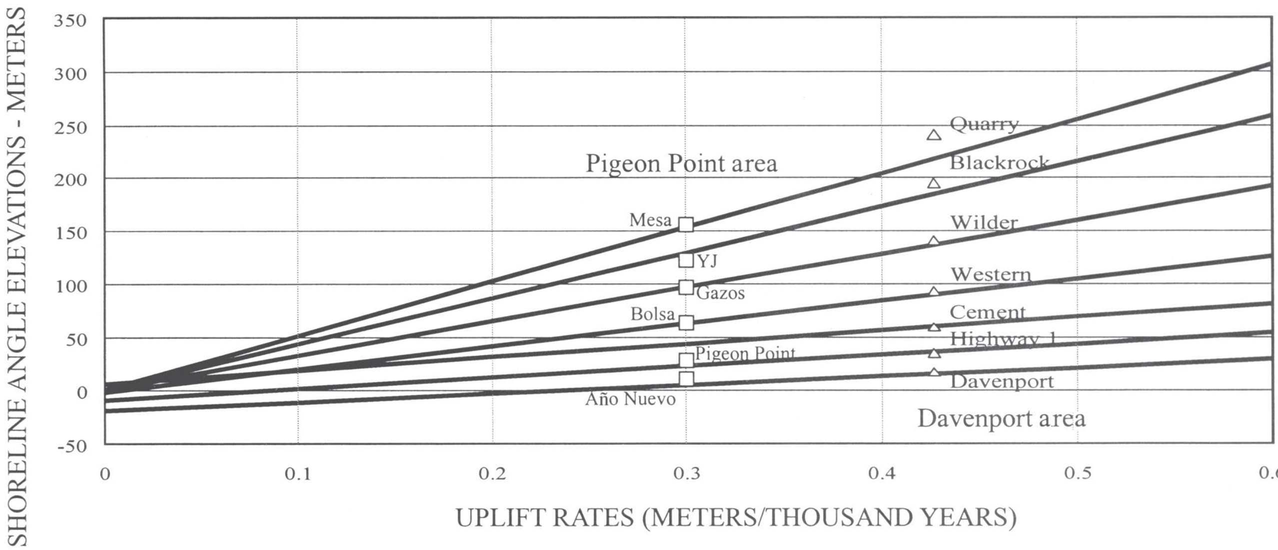

Figure 1.8. Diagram showing proposed correlations and tectonic uplift rates of the emergent marine terraces on opposite sides of the San Gregorio Fault Zone—the Pigeon Point structural block to the west and the Santa Cruz Mountains structural block (Davenport area) to the east. The solid black lines represent theoretical shoreline angle profiles produced by sea-level high stands on a tilted shoreline.

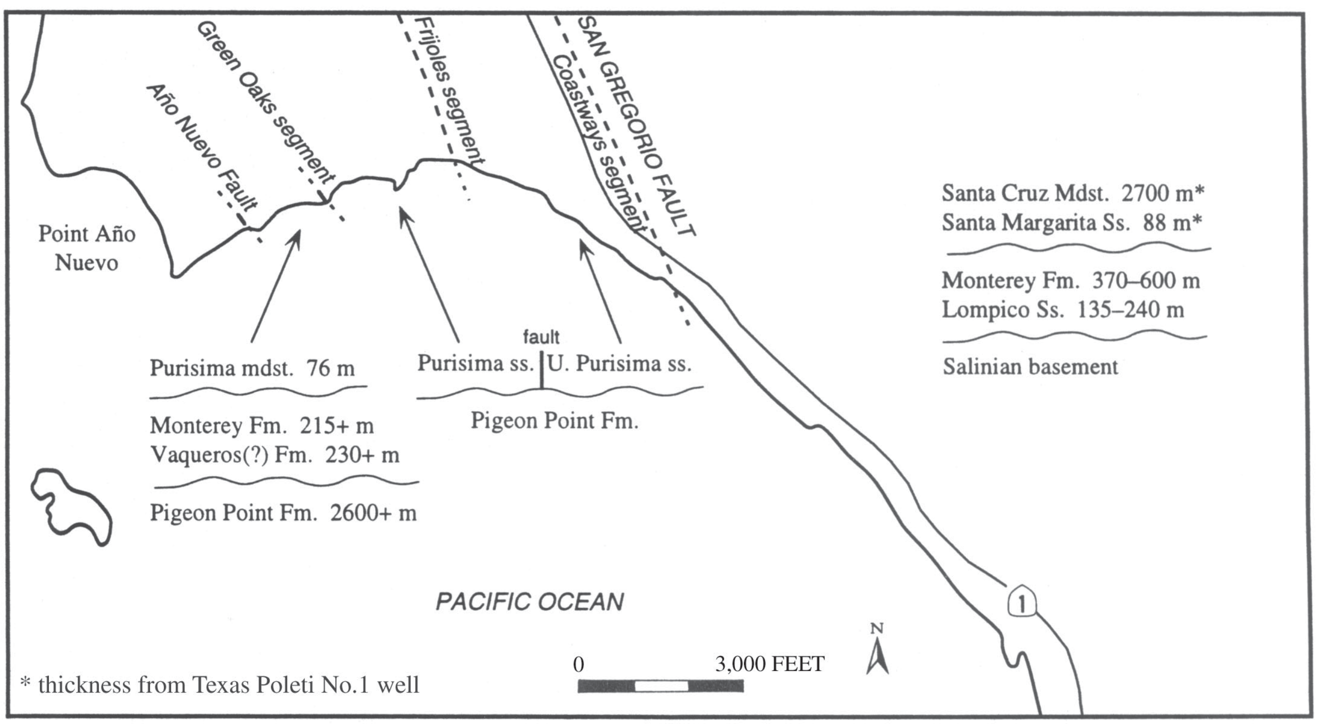

Figure 1.9. Pre-Quaternary stratigraphic contrasts across the San Gregorio Fault Zone at Point Año Nuevo.

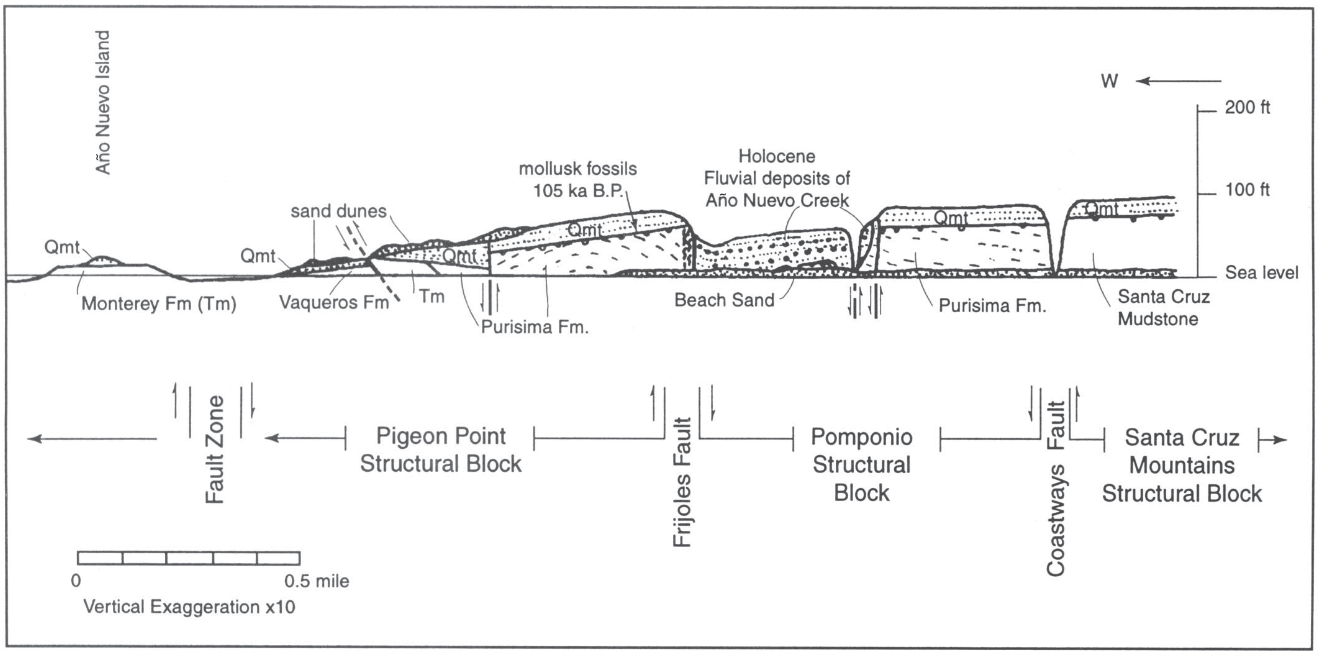

Figure 1.10. Schematic sketch of seacliff geology along the south shore of Point Año Nuevo; modified from Lajoie and others (1979).

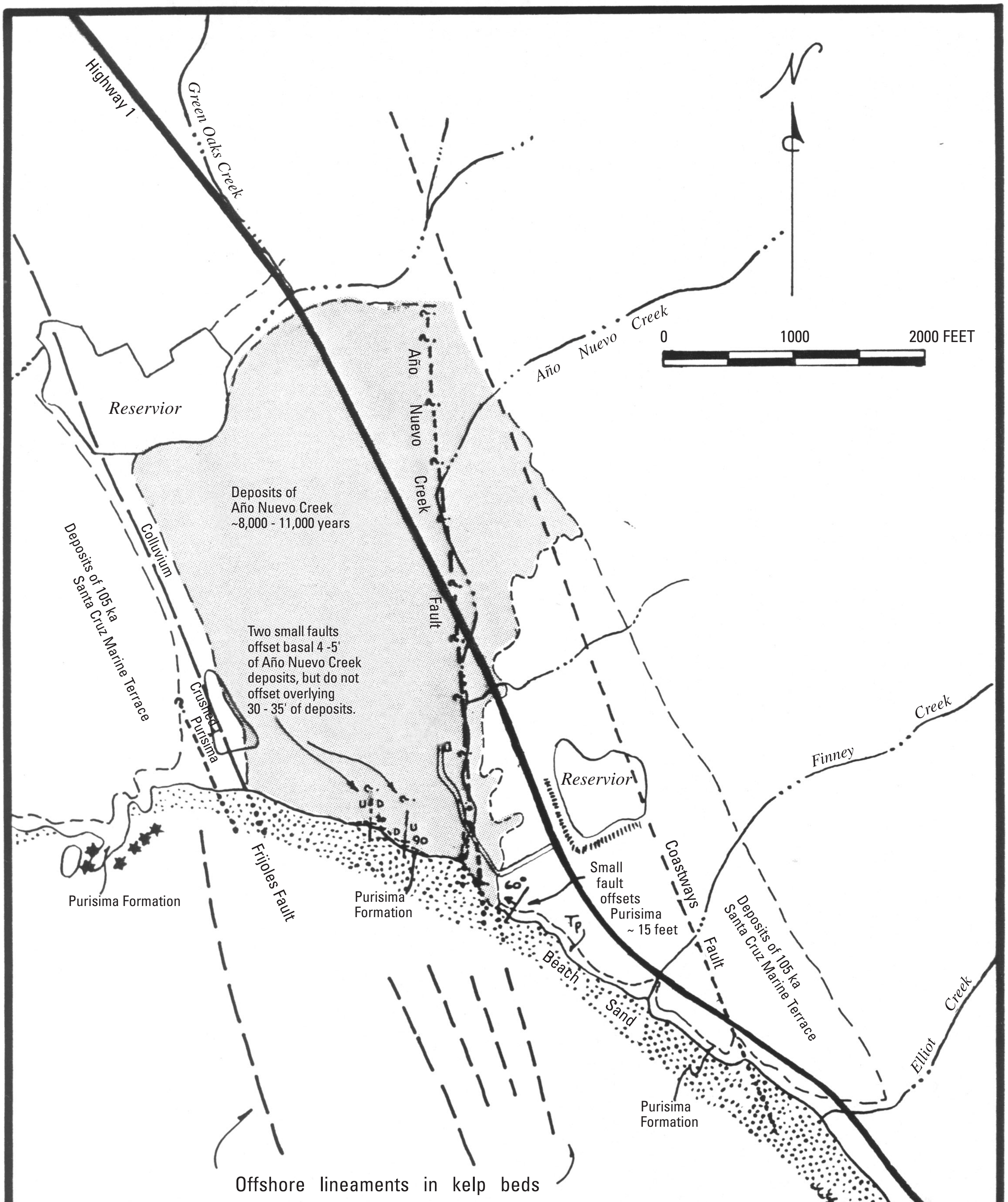

Figure 1.11. Generalized geologic map of the eastern portion of Point Año Nuevo; modified from Weber and Lajoie (1980). Note: The Santa Cruz terrace depicted here is equivalent to the Año Nuevo terrace of Weber and others (1995).

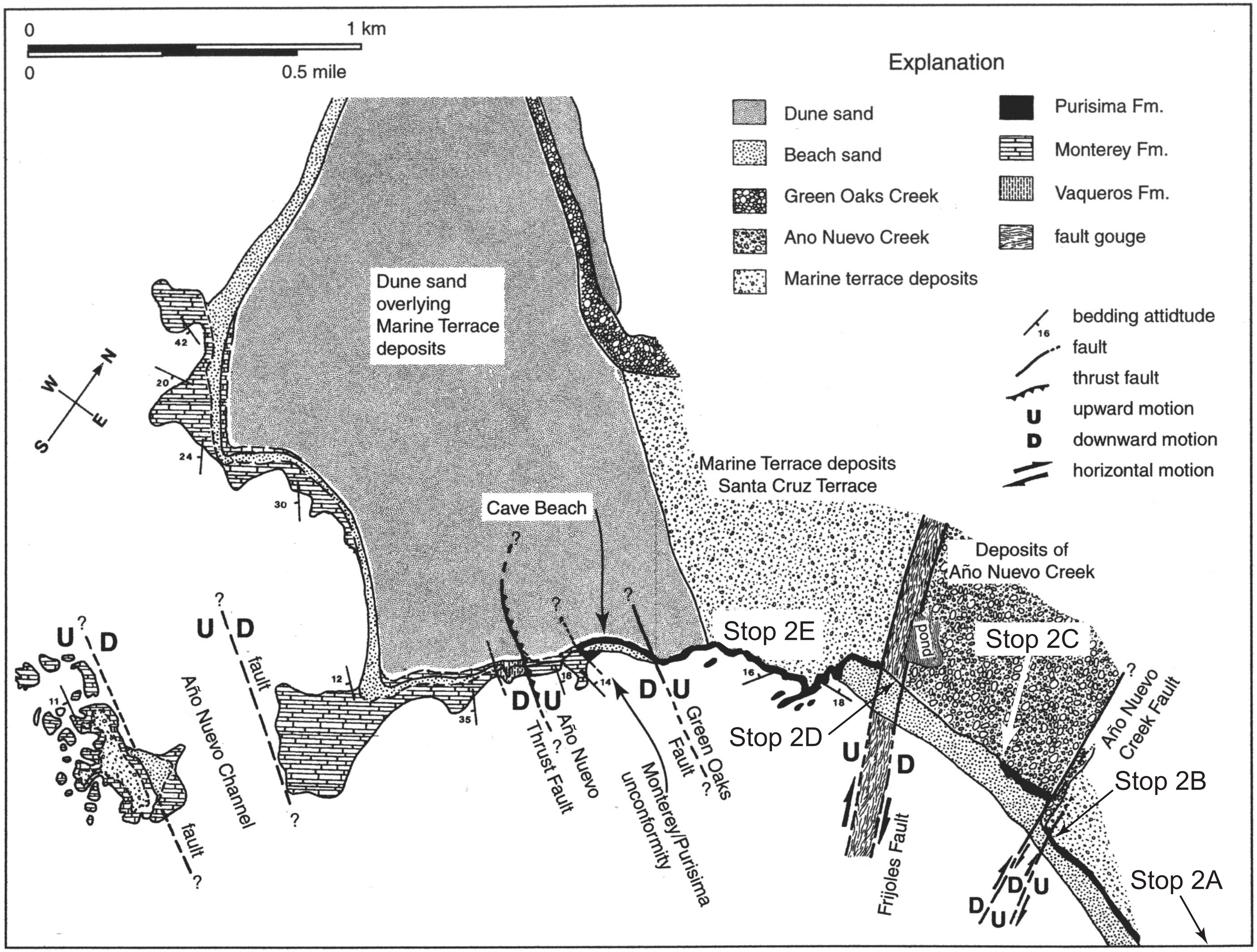

Figure 1.12. The San Gregorio Fault Zone at Point Año Nuevo, showing field trip stops 2B through 2E; see text for discussion. Note: The Santa Cruz terrace depicted here is equivalent to the Año Nuevo terrace of Weber and others (1995).

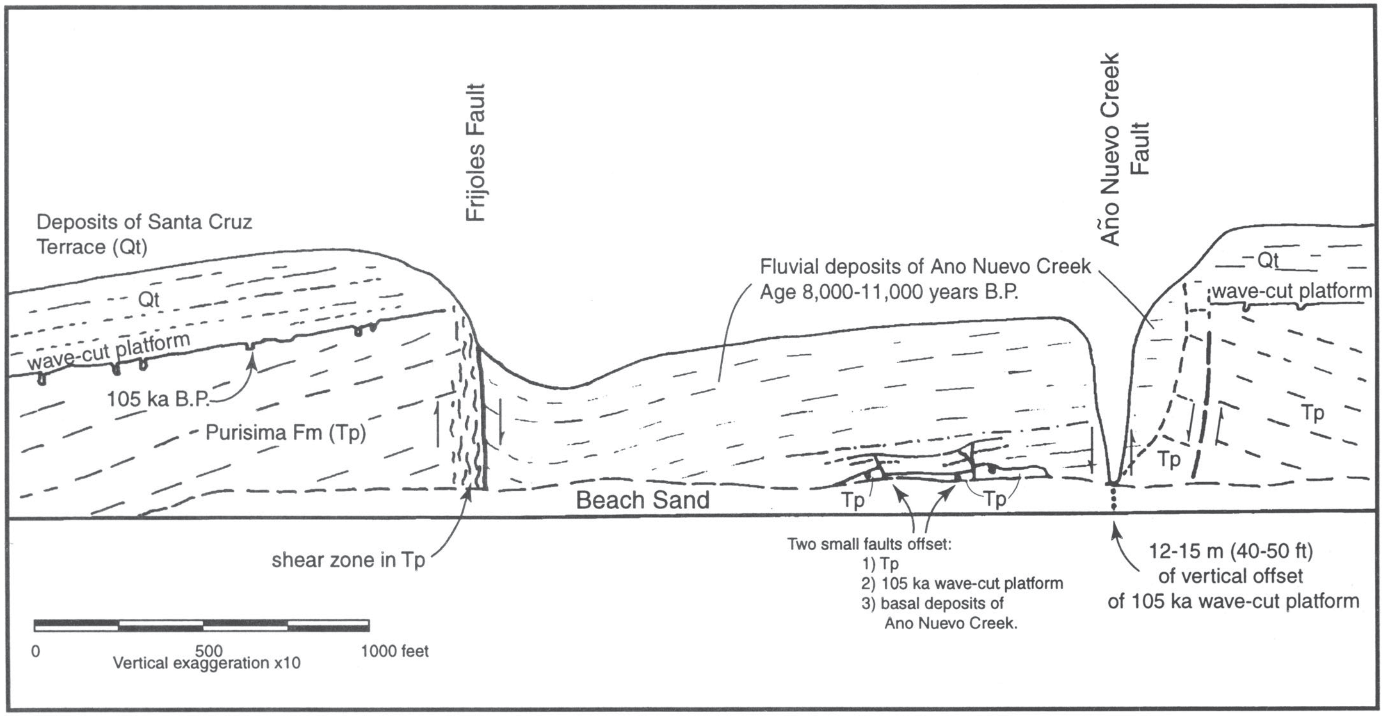

Figure 1.13. Highly schematic sketch of the seacliff geology west-northwest of Año Nuevo Creek, showing Holocene fluvial deposits of Año Nuevo Creek occupying a graben bounded by the Frijoles and Año Nuevo Creek Faults. Note the westward tilt of these fluvial deposits, except where a small drag fold has formed adjacent to the Frijoles Fault. Several minor Holocene faults offset the basal beds of the Año Nuevo Creek deposits (see also fig. 1.14). Note: The Santa Cruz terrace depicted here is equivalent to the Año Nuevo terrace of Weber and others (1995).

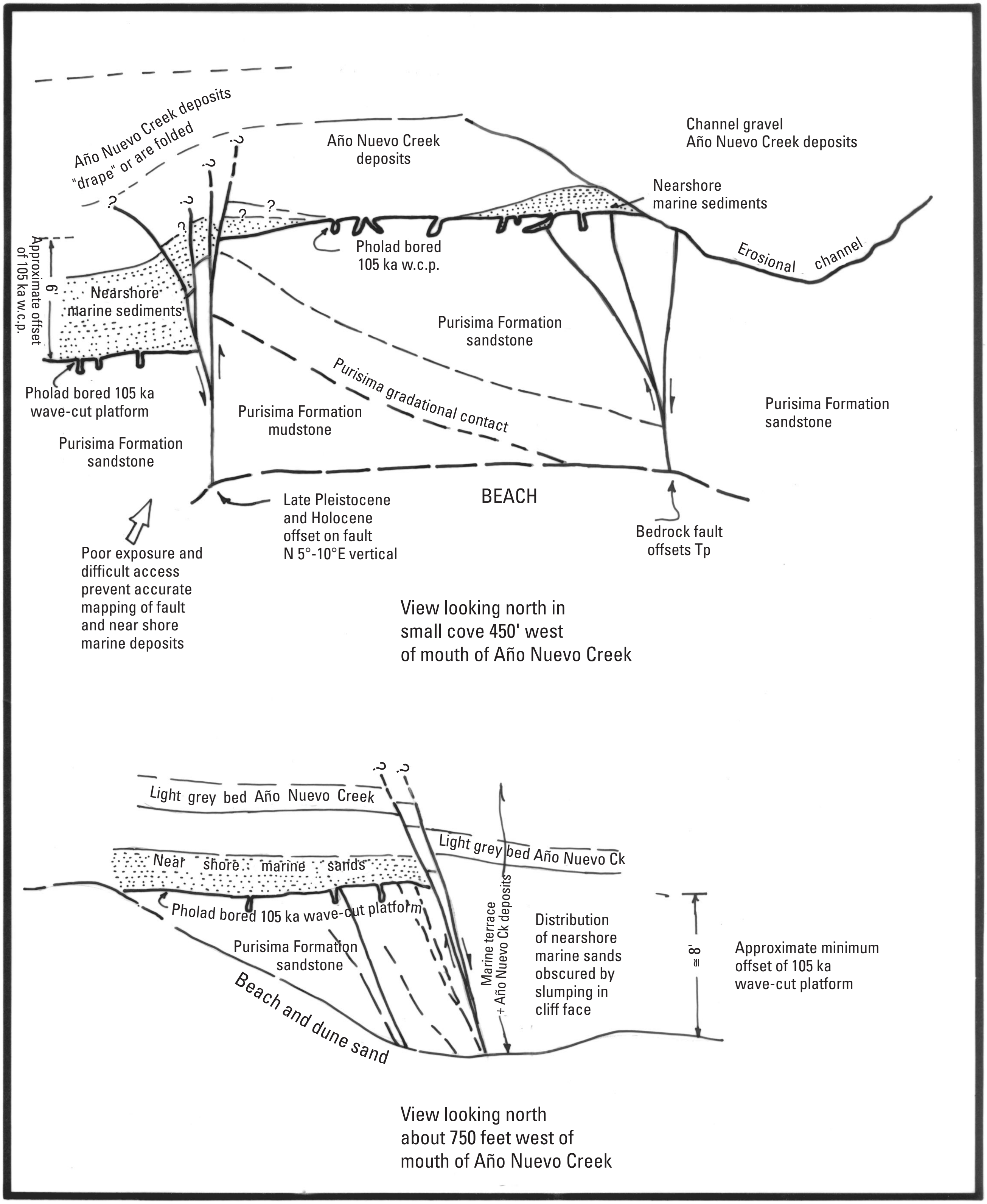

Figure 1.14. Field sketches of seacliff exposures west-northwest of the mouth of Año Nuevo Creek.

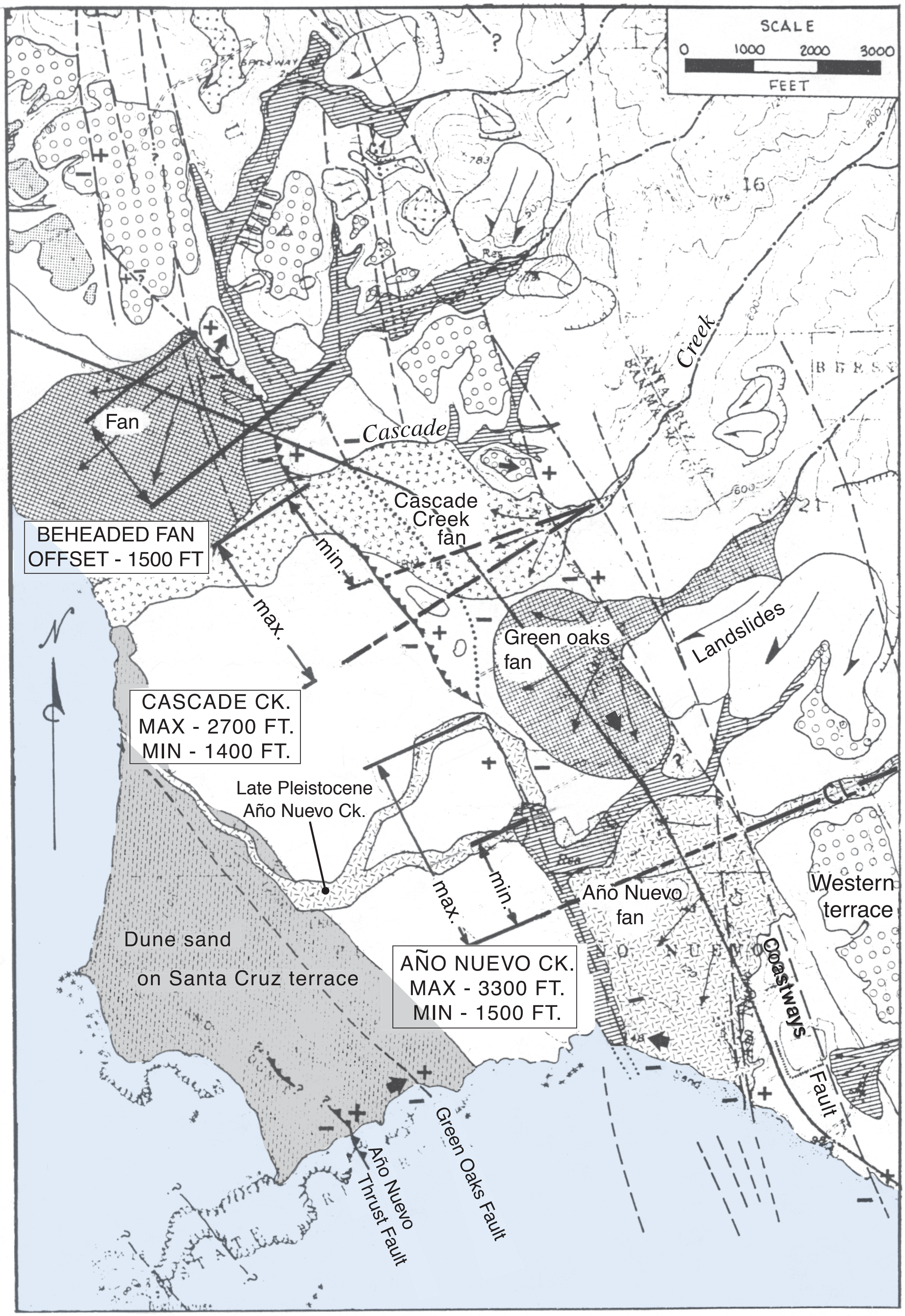

Figure 1.15. Interpretive map showing the probable offset of late Pleistocene drainages near Point Año Nuevo. Refer to text for a discussion of the assumptions employed in these reconstructions. Note: The Santa Cruz terrace depicted here is equivalent to the Año Nuevo terrace of Weber and others (1995).

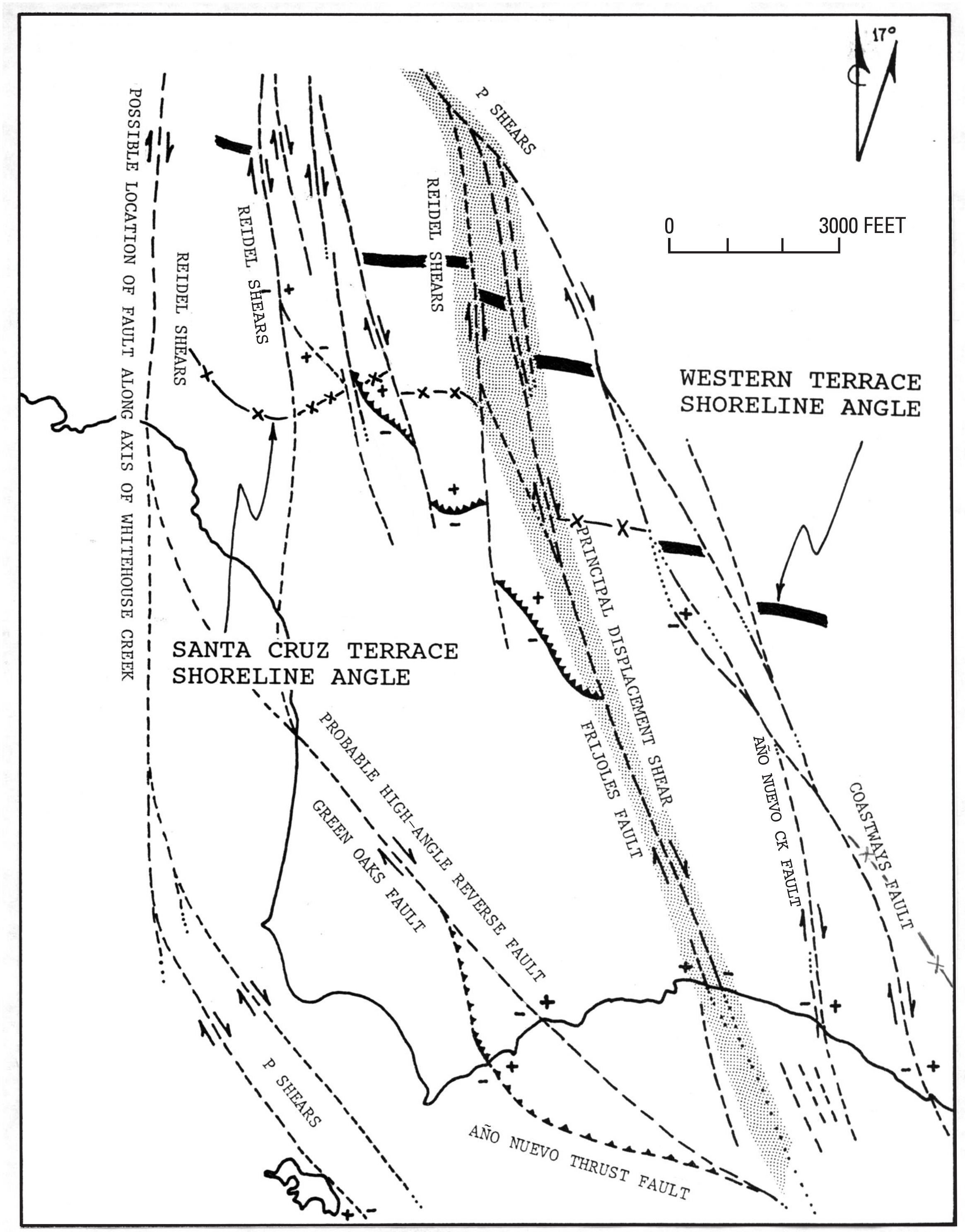

Figure 1.16. Preferred interpretation of displaced marine terrace shoreline angles in the San Gregorio Fault Zone at Point Año Nuevo. Note: The Santa Cruz terrace depicted here is equivalent to the Año Nuevo terrace of Weber and others (1995).