THE SAN ANDREAS FAULT ZONE NEAR POINT REYES: LATE QUATERNARY DEPOSITION, DEFORMATION, AND PALEOSEISMOLOGY

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INTRODUCTION

This field trip will examine late Quaternary sedimentary deposits along a section of the San Andreas Fault (SAF) that lies in a valley between the Point Reyes Peninsula and Bolinas Ridge (Figure 1). The Point Reyes Peninsula (west of the fault valley) is part of the Salinian terrane, a displaced fragment of continental crust that consists of Cretaceous plutonic and older metamorphic rock overlain by lower Eocene to Pliocene marine sedimentary rocks (Clark and Brabb, 1997). Bolinas Ridge (east of the fault valley) consists of highly deformed Mesozoic Franciscan subduction-complex rock. Because of persistent right-lateral displacement, the SAF juxtaposes bedrock units that have been offset by at least 300 km.

The SAF at this location was last active during the 1906 San Francisco earthquake, when maximum horizontal displacement of about 5 m was measured by G.K. Gilbert near Olema (Lawson, 1908). Niemi and Hall's (1992) paleoseismology study on the 1906 trace south of Olema revealed a time-averaged minimum dextral slip rate of 24±3 mm/yr during the past 2,000 years and an average recurrence interval for large earthquakes of 221±40 yr. The 1906 SAF trace lies in the center of the valley whose edges are defined by additional faults that Galloway (1977) named the eastern and western boundary faults (Figure 1C). These faults probably extend the length of the valley, although in places they are obscured by alluvial fan, stream or landslide deposits, or by vegetative cover.

The narrowest part of the SAF valley, at Five Brooks (Figure 1C), is the north end of a topographic and structural high where Franciscan basement is exposed at the land surface and overlain to the south by the Plio(?)-Pleistocene Merced Formation, a shallow-marine deposit (Figure 2). North of Five Brooks, basement is mostly covered by a suite of late Quaternary sediments deposited in the SAF zone during a time of climate change and fault-related deformation.

This trip will focus on two late Pleistocene formations—the Millerton Formation (MF) and Olema Creek Formation (OCF)—and late Holocene deposits. The MF and OCF were deposited at seaward and landward ends of a paleoestuary; the transition between them is covered by younger sediments (Figure 2). The deposits have been incised and are now exposed in creek beds and Tomales Bay headlands. The MF and OCF provide a record of post-130 ka deposition and deformation in the fault zone. Late Holocene nonmarine deposits have been trenched to evaluate fault offset and deforma-tional style. They provide a record of recent deposition and deformation in the fault zone.

FIELD STOP DESCRIPTIONS AND ROAD LOG

Road log begins at the intersection of State Highway 1 and Dillon Beach Road, in the village of Tomales.

Miles	Cum Miles	Location
0.0	0.0	In Tomales, head west from Highway 1 onto Dillon Beach Road.
2.0	2.0	Turn left from Dillon Beach Road and go through the gate onto a dirt road. NOTE: Permission must be obtained from Audobon Canyon Ranch (ACR)

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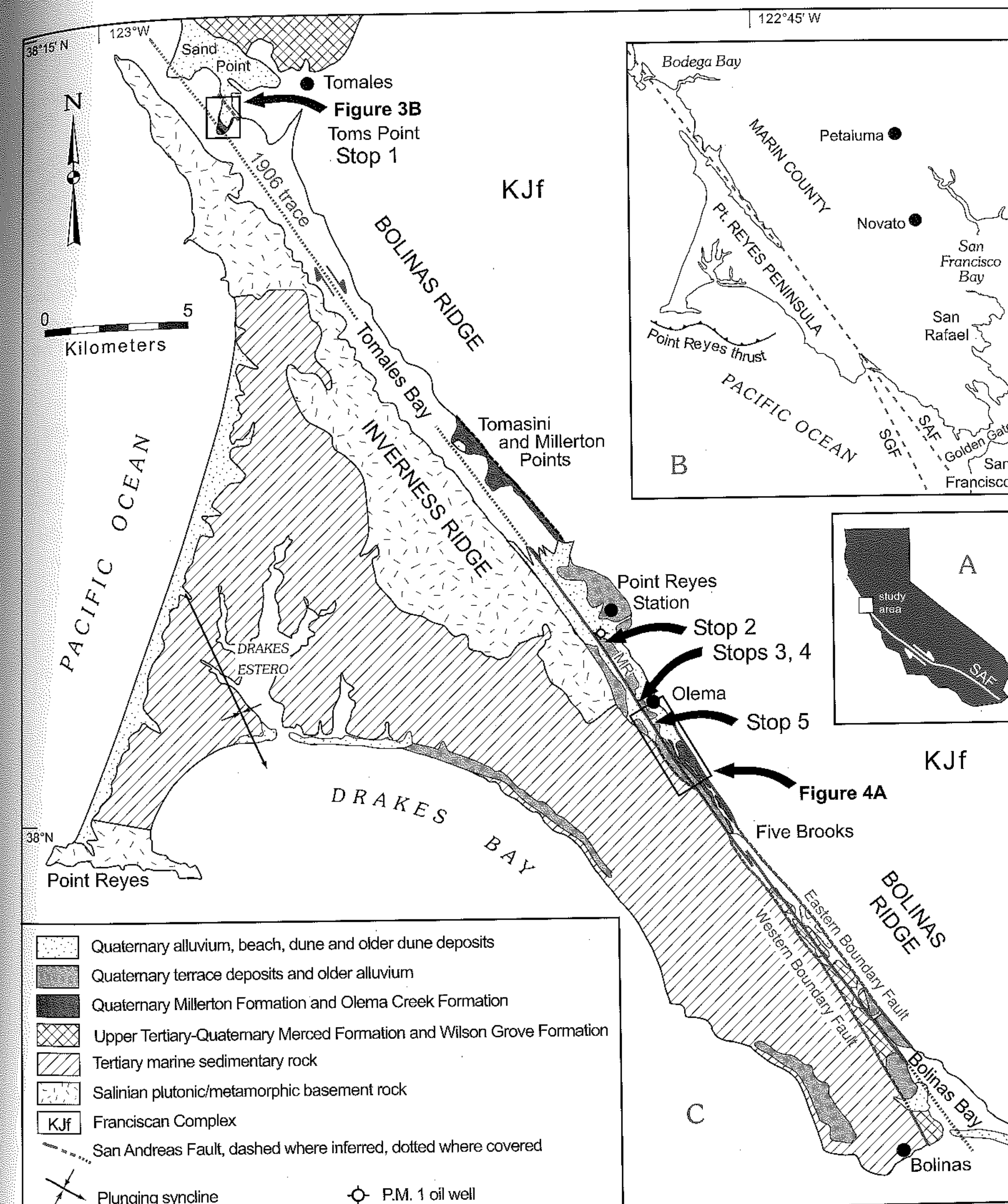

Figure 1. (A) Location of study area in California. SAF=San Andreas Fault. (B) The Point Reyes Peninsula, separated from Marin County mainland by SAF. The San Gregorio Fault (SGF) joins SAF south of study area. Offshore faults from McCulloch (1989). (C) Generalized geology map modified from Galloway (1977), Clark and Brabb (1997). MR, medial ridge.

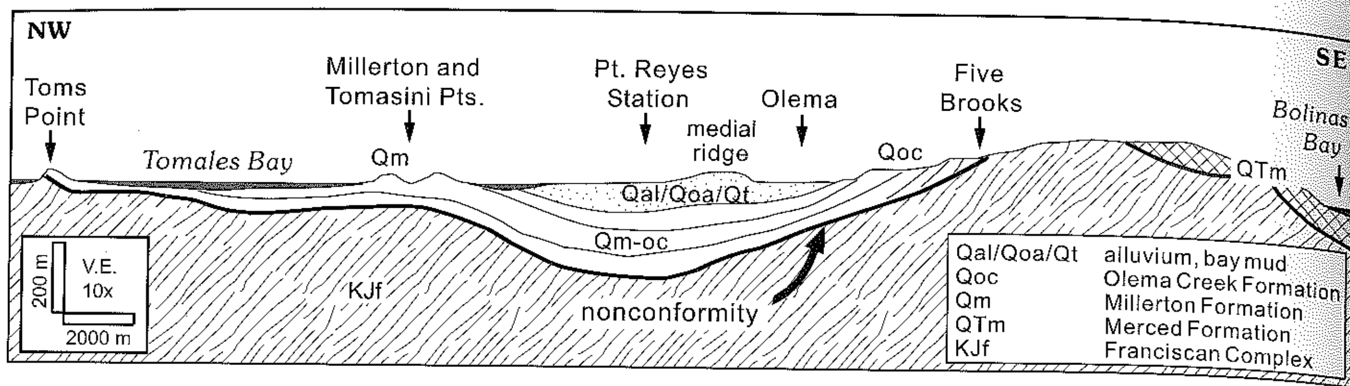

Figure 2. Interpretation of subsurface geology along length of SAF valley. Constraints are surface geology, an oil well log at the latitude of Point Reyes Station, water well logs in the valley between Point Reyes Station and Five Brooks, and gravity data between Point Reyes and Olema.

to enter the property and to obtain combinations for locked gates.

Miles	Cum Miles	Location
1.1	3.1	Intersection with second dirt road and first locked gate. Turn right and continue through gate, taking left fork when the choice arises.
1.1	4.2	Second locked gate and entrance to the ACR Preserve.

STOP 1—Toms Point

The coastal Miwoks were inhabiting the area around Tomales Bay when Europeans arrived in the region. Unfortunately (as throughout California), the natives and their culture were effectively exterminated soon after the Spanish missions were established in the early 1800s (Mason, 1980). Toms Point was named for Tom Wood, a deserter from a ship who settled with an Indian woman and her people, and built a home (constructed from wreckage salvaged from the sea) along the north end of Tomales Bay (Quinn, 1981). Tom's prowess with horses led to his acting as business manager for the tribes of Marin, Sonoma and Solano counties (Quinn, 1981). In the mid-1850s, American, English and French sailing ships would land near Toms Point to barter with the Indians: "summertime would see a thousand Indians along the shore, waiting to trade their hides, skins, and tallow for bright calicos, trinkets, blankets and whiskey" (Mason, 1980). Since the late 1850s, dairy farms established by European immigrants have dominated the landscape.

The MF is exposed at three headlands along the northeast edge of Tomales Bay—Millerton Point (type locality), Tomasini Point, and Toms Point (Figure 1C). These headlands are erosional remnants of deposits that formerly extended across the bay. The MF consists of estuarine and alluvial gravel, sand and mud, with extensive faunal and floral assemblages. Estuarine mud near the base of the formation at Toms Point has yielded ages around 130 ka from thermoluminescence dating (Grove and others, 1995; TL locality on Figure 3B) and aminostratigraphic dating (Kennedy and others, 1992).

The MF consists of fining-upward sequences that record interplay between tectonic activity and climatic change (Figure 3). The fining-upward sequences probably correspond to transgressions associated with the three stage 5 substages (Figure 3A). When sea level began to rise, streams that had become established during the lowstand (e.g., stage 6) deposited sand and gravel in the valley. As sea level rose (to substage 5e), marine water entered the valley and created a progressively deepening bay and a fining-upward sedimentary sequence (A in Figure 3D). When the sea withdrew (to substage 5d), marine water left the valley and some incision occurred until streams became established, and sand and gravel were again deposited. During

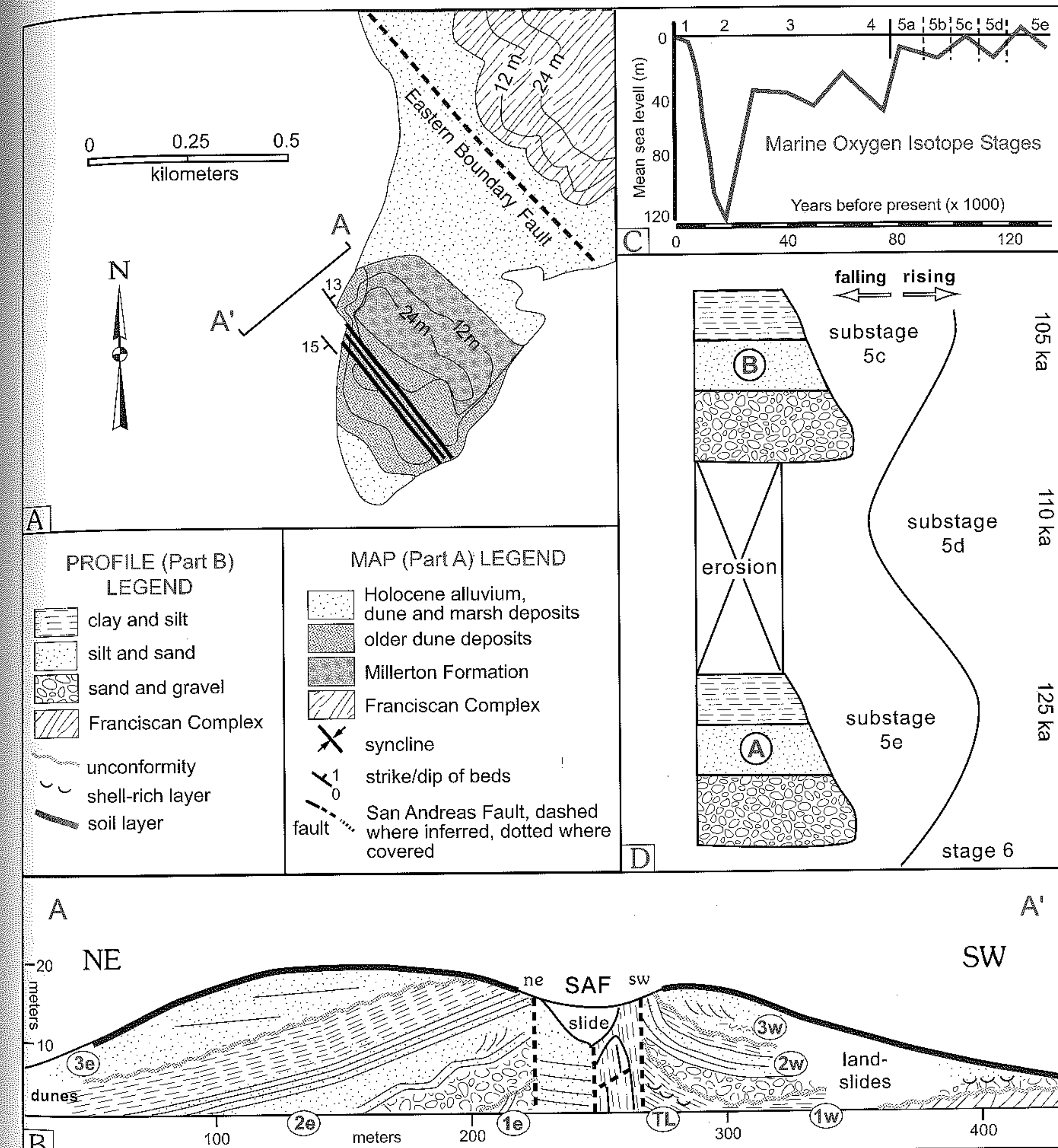

Figure 3. (A) Geology map of Millerton Formation (MF) at Toms Point. (B) Sketch from photomosaic of MF along northwest side of the headland (profile location A-A' in 3A). Note that direction of profile is rotated from map direction to match the view seen from beach level at Toms Point. Circled numbers refer to unconformity-bounded sequences on the northeast (e) and southwest (w) sides of fault zone. Matching numbers do not imply corre-lations across the fault. SAF=San Andreas Fault. TL=thermoluminescence sampling site. Vertical exaggeration, 3X. (C) marine oxygen isotope stages. *Adapted from Toscano, 1992.* (D) Model for Millerton Formation sequences. Lithologic patterns same as profile legend. Fining-upward cycles are deposited during times of rising sea level. During times of falling sea level there is nondeposition and erosion. Earthquakes deform the strata during that time, and an angular unconformity is produced when deposition resumes.

the depositional hiatus (erosion in Figure 3D), numerous earthquakes occurred and previously deposited sediments were deformed by faulting and folding. When streams became reestablished, they eroded the underlying tilted sediments and produced a surface of erosion. As sea level rose (to substage 5c), another fining-upward sequence was deposited with angular discordance, creating an angular unconformity (B in Figure 3D).

Following retreat of the sea at the end of stage 5, only nonmarine sediments were deposited in streams, marshes, ponds, and dunes that filled the low areas between uplifting fold limbs (cycles 3e and 3w in Figure 3B). During stage 2, when sea level fell at least 120 km below its present level, the valley was deeply incised and most of the MF, which extended across the valley, was removed. This erosional phase continues today as the bay headlands are subjected to weathering processes. Estuarine deposition resumed during the Holocene transgression in modern Tomales Bay.

Walk along the northwest side of the headland to obtain an "up-close view" of sedimentary facies of the MF and deformation associated with the SAF (a low tide is helpful). Note that slumping and erosion along the cliff cause exposures to change yearly; consequently your view may differ somewhat from that shown in Figure 3B. At Toms Point the MF is bisected by three active strands of the SAF, which truncate beds and juxtapose contrasting stratigraphic sequences. After the 1906 earthquake, G.K. Gilbert (*in* Lawson, 1908) described the deformation at Toms Point, but it is not clear from his descriptions which strands were active during the 1906 event.

Exposed on the northeast side of the fault zone is the uppermost part of one fining-upward sequence (1e on Figure 3B) and a complete sequence that fines upward from fluvial gravel to estuarine sand and mud (2e). A third sequence (3e) consists of nonmarine sand dune deposits. The beds dip northeast, and are increasingly steep in the older sequences (Figure 3B). A depositional model is presented above and in Figure 3D. Strata are highly sheared adjacent to the northeast SAF strand (Figure 3B).

A spring that causes perennial wetness corresponds to the middle SAF strand, which separates two deformed fault blocks (Figure 3B). Vertical beds between the central and southwestern strands include a distinctive peat bed offset by a small thrust fault. The stratigraphic sequence southwest of the fault zone is more difficult to see because of extensive landsliding and vegetative cover, but at least two fining-upward sequences and a nonmarine sequence is visible (Figure 3B). Franciscan basement rock is exposed at the base of this section.

Walk to the top of the headland to obtain a view of the valley and to see the morphology of the fault zone at the land surface. A linear depression parallel to the fault strands visible on the northwest cliff face probably resulted from the weak nature of the deformed strata. The sequences observed on the northwest cliff face are also visible on the southwest cliff face, but exposures are poorer because of extensive landsliding and vegetative cover. To the north, the SAF also cuts through Sand Point, but the trace is obscured by sand dunes.

Retrace the 4.2 miles to Tomales via dirt roads and Dillon Beach Road, being certain to close all locked and unlocked gates securely behind you. Log resumes in Tomales, at the intersection of Dillon Beach Road and State Highway 1.

Miles	Cum Miles	Location
0.0	0.0	Turn south (right) onto Highway 1. The road continues along the south side of Walker Creek and then along the east shore of Tomales Bay.
6.7	6.7	Cypress Point, ACR
4.3	11.0	Tomasini Point, MF exposures in the cliff faces.
0.7	11.7	Millerton State Park. Type locality for the MF.
5.0	16.7	Point Reyes Station. Continue south on Highway 1.
0.2	16.9	Intersection with Sir Francis Drake Road. Turn west (right).
0.8	17.5	Intersection with Bear Valley Road. Turn south (left).
0.5	18.0	Turn left onto dirt road leading to Olema Marsh.

STOP 2—Olema Marsh

Park in the dirt parking lot and walk up the ridge to the east. This is a medial ridge that bisects the valley (Figure 1C); the part to the east is drained by Olema Creek, and the part to the west is drained by Bear Valley Creek. At this stop we will get an overview of the valley and discuss the subsurface geometry of the fault zone. The marsh is over the 1906 trace of the SAF.

An oil well was drilled in the 1950s at the north end of the medial ridge close to this stop (location shown in Figure 1C). No oil was found, but the lithologic and electric logs provide information about the subsurface geology. Franciscan basement rock was encountered at a depth of about 280 m and a coarsening-upward sequence of interbedded coarse- and fine-grained sediments is probably the subsurface transition between the OCF and MF (Figure 2). The lithologic logs of water wells drilled in the valley contain descriptions of sediments similar to the OCF and MF. Facies beneath the surface at the Olema Marsh are probably transitional between more marine facies of the MF and more nonmarine facies of the OCF.

A high-resolution gravity survey parallel to the valley showed decreasing gravity values between Olema and Point Reyes Station (Quinn and Grove, 1994), consistent with increasing depth to basement rock between where it outcrops at the surface near Five Brooks (Figure 1) and where it is nearly 300 m deep here at Stop 2. The gravity data, combined with lithologic and electric-log data from wells, provide evidence for the subsurface configuration of units shown in Figure 2.

Stop 2 is at a subsiding part of the valley where sediments are collecting. Structural and stratigraphic data suggest that this basinal area was south of Olema during OCF deposition and that the basin was subsequently contracted, causing the subsiding area to migrate northward (Grove and others, 1995). This migration may be the result of interacting fault strands that include not only the 1906 strand but also the eastern and western boundary faults. Three fluvial terrace levels that overlie OCF deposits between Olema and Five Brooks attest to progressive uplift of the valley since OCF deposition. Truncation of the OCF by valley-bounding faults attests to their recent activity and progressive narrowing of the valley.

Return to Bear Valley Road, where mileage resumes.

Miles	Cum Miles	Location
0	0.0	Turn left onto Bear Valley Road and continue southward.
1.2	1.2	Turn right into the entrance for the Point Reyes National Seashore Headquarters and continue to parking lot at the end of the road.

STOP 3—Point Reyes National Seashore Headquarters

The Bear Valley Visitor Center of Point Reyes National Seashore is on the site of Skinner Ranch at the time of the 1906 earthquake. After the 1906 earthquake, G.K. Gilbert mapped 4.4 to 4.9 m of right-lateral slip from a displaced fence, a row of raspberry bushes, path, and the southeast corner of the cow barn on Skinner Ranch (Lawson, 1908).

Although none of these features have survived, the sidehill bench of the 1906 fault trace and a reconstruction of both the barn and the offset fence can be seen along the Earthquake Trail.

At this stop we will look at an exposure of the uppermost part of the OCF in the banks of Bear Valley Creek. The OCF is discontinuously exposed for 3.5 km along the length of the SAF valley between the 1906 trace and the eastern boundary fault, where it is primarily visible in the incised banks of Olema Creek and its tributaries (Figures 1C and 4A). Silty-clay deposits near the base of the OCF yielded a thermoluminescence date of 132±28 ka (Grove and others, 1995). The OCF is deformed into upright, open folds with axes trending northwest at low angles to the SAF trend (Grove and others, 1995).

Detailed stratigraphic measurements of the OCF revealed a minimum thickness of 160 m (Grove and others, 1995; Figure 4B). There is a general upward trend from marine mud to nonmarine alluvium. Fine-grained silt and clay are more prevalent in the southern (older) part of the outcrop belt, and coarser-grained sand and gravel dominate the northern (younger) part. The OCF probably grades upward into the older alluvium unit (Qoa) that makes up the medial ridge, including the location at Stop 3 (Figures 1C and 4A). Figure 4B illustrates the four depositional facies that comprise the OCF. Gravel clasts in the formation are predominately granitic, and sand clasts are primarily quartz and feldspar grains also derived from a granitic source. Since deposition of the OCF, the granitic bedrock source has been offset several km to the northwest from the OCF outcrop belt (Figure 1C).

The lower part of the OCF is interpreted as deposits from the fluvially-dominated part of an estuary interbedded with sand and gravel brought to the estuary by streams and alluvial fans (Grove and others, 1995). This setting was similar to the area around the head of Tomales Bay today. Because sea level during substage 5e was higher than today, marine water could flood farther south into the valley.

The upper part of the OCF is interpreted as deposits in a broad alluvial valley, where stream channels meandered over a floodplain with marshes and shallow lakes formed in depressions between faults. Alluvial fans fed sediment into the valley from the west. This setting was similar, although the valley was wider, to the modern Olema Creek floodplain located northeast of the medial ridge (Figure 1C). Marine water did not reach Five Brooks after the 5e substage. Alternations between fine- and coarse-grained deposits reflect the combined influences of subsidence along the SAF zone and climatic variations that affected the position of base level and the amount of sediment delivered to the basin.

Upward decreasing dips in the OCF imply that deposits in the south end of the outcrop belt began to be shortened and uplifted as deposition continued farther north. Sediments shingle northward from Five Brooks (Figure 2), as a result of the migrating depocenter. Angular unconformities, such as those observed in the MF, are not seen in the OCF, probably because at this position in the valley, deposition was more continuous during sea-level regressions, and deformation was more disseminated throughout the formation. The OCF is beveled by three levels of terrace deposits (Figure 4A).

To get to Stop 3, walk from the parking lot along the south (right) path of the Earthquake Trail several minutes until the path turns north (left). Instead of following the path, continue straight through the grass meadow and into Bear Valley Creek. NOTE: You must obtain permission from the Park Rangers to walk off the trail and into the creek. Also be aware of high creek flows during winter months. Exposed along the east bank of the creek are sediments of the OCF. The sediments are channel sand and gravel with interbedded finer-grained overbank deposits. This is the upper, alluvial part of the OCF (Figure 4), which north of Olema is mostly buried beneath younger alluvium, including terrace deposits (Figure 2). Note the granitic clasts, which were derived from granitic basement in the Salinian terrane. The south end of the granite basement is west

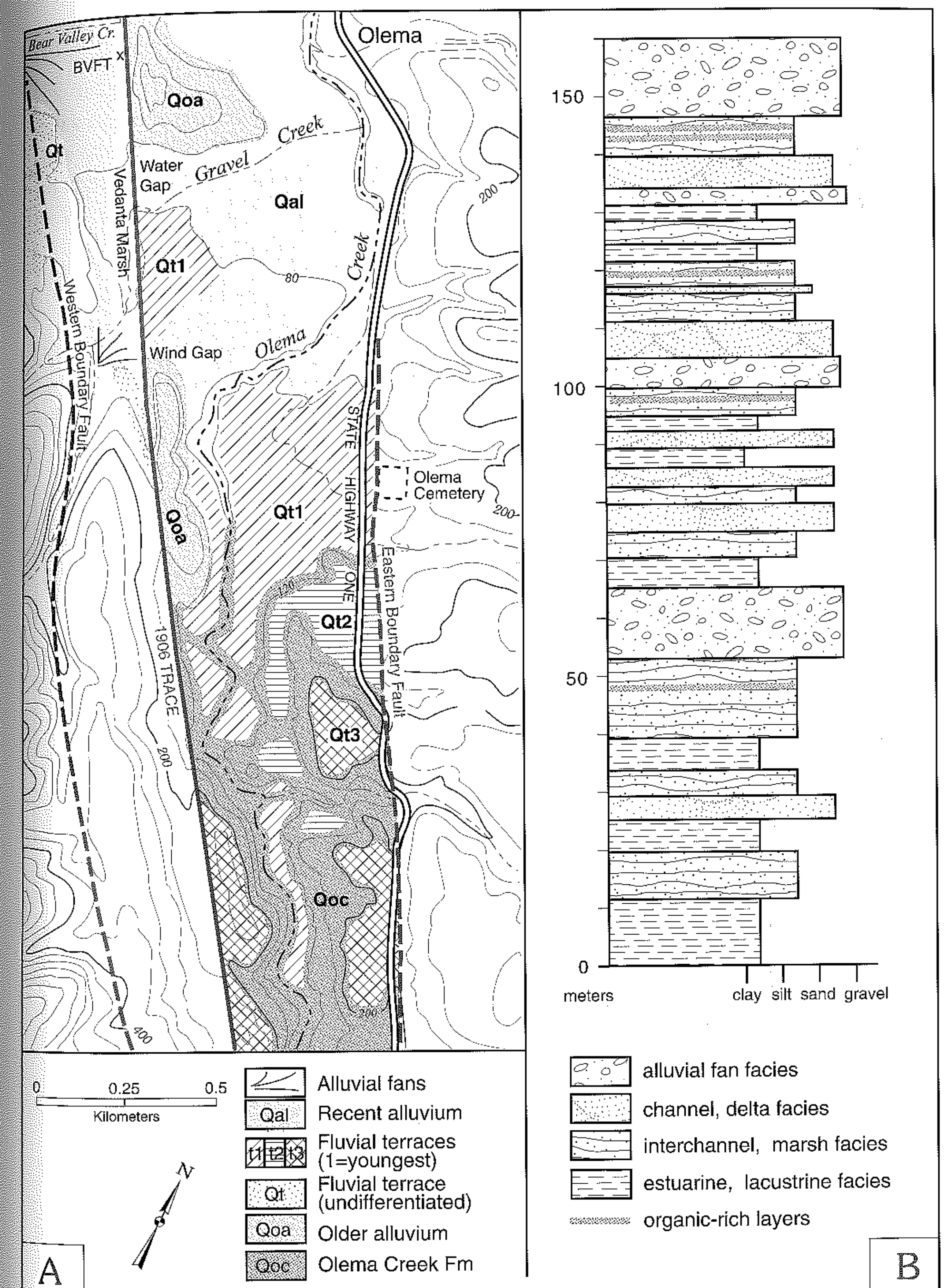

Figure 4. (A) Topographic map of the northern end of the OCF outcrop belt showing the exposure pattern of OCF (Qoc) and overlying cut-and-fill terrace deposits. Contour interval: 40 feet. Qt1: topographically lowest (youngest) terrace; Qt2 and Qt3: topographically higher and older. Qoa (older alluvium) overlies Qoc and is probably continuous with it. Both Qoc and Qoa have been incised and the incised valley is currently being filled with Qal (younger alluvium). *Adapted from Grove and others (1995).* (B) Generalized stratigraphic column of Olema Creek Formation (Qoc) facies. *Detailed measured section in Grove and others (1995).*

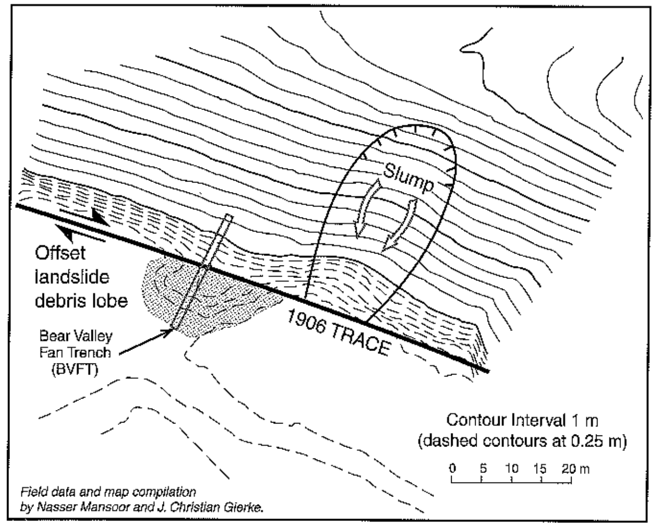

Figure 5. Detailed topographic map of a landslide debris lobe offset along the 1906 trace of the San Andreas Fault. See Figure 4 for location.

of Stop 3 but is offset northward from most of the OCF outcrop belt (Figure 1C).

STOP 4— Point Reyes National Seashore Headquarters / Vedanta Retreat

The outcrop of the OCF at Stop 3 is exposed in the banks of Bear Valley Creek. We will follow the creek southeast until it makes a sharp bend. Climb up the south bank of the creek across a fence onto private property of the Vedanta Retreat. Walk southeast along the 1906 trace of the SAF at the base of the medial ridge for about 100 yards. Here we will view a subsurface exposure of the SAF in a paleoseismic trench.

The SAF zone in this area contains stream deflections, shutter ridges, ponded drainages, and sag ponds that attest to the intricate relationship between fault slip and the evolution of drainage patterns. The topography of this region has been created by recurrent tectonic movement and by climatically-controlled cycles of incision and aggradation of fluvial systems. A medial ridge in the center of the fault valley is the remnant of late Pleistocene fluvial deposits (Qoa) and terraces (Qt) that stratigraphically overlie MF and OCF (Figure 2) (Hall and Hughes, 1980). The straight southwestern margin of medial ridge is largely coincident with the 1906 trace of the SAF while the northeastern margin has been eroded by the meanders of Olema Creek during the Holocene. The medial ridge is breached in three places—by a broad wind gap near the entrance to the park, a water gap and a wind gap (Figure 4A) on the Vedanta property to the south (Stop 5).

Bear Valley Creek is a perennial stream with a drainage area of approximately 12 km^2 predominantly within the Monterey Formation. It flows northeastward until it reaches the medial ridge where it is deflected to the northwest, parallel to the SAF. The Bear Valley drainage probably cut the 150-m-wide water gap in the medial ridge at the Vedanta Retreat approximately 460 ±75 m to the southeast (Figure 4A). Repeated slip on the SAF has offset the drainage from the gap. Assuming the erosion of the medial ridge occurred during the Wisconsinan deglaciation (after 18 ka), the measured offset yields a slip rate for the SAF of 21-30 mm/yr (Niemi, 1992).

At the Bear Valley fan trench site, several geomorphic units are exposed at the surface. The slopes of the medial ridge, here composed of granitic detritus, are pervasively disrupted by land-sliding. This is seen in the hillside landslide scars and hollows, colluvial aprons, and landslide debris at the base of the ridge. West of the medial ridge in the meadow are the gentle slopes of the Bear Valley alluvial fan. Along the fault between the fan and the ridge is a linear depression formed by localized coseismic subsidence.

The trench site was chosen at a location where a small landslide debris lobe has been offset from the hillside scar by repeated faulting of the SAF. Detailed topographic mapping of the site (Figure 5) shows the debris lobe has been offset about 20 m from the hillside hollow. The active trace of the SAF is clearly exposed in the trench as an west-dipping fault. The fault juxtaposes light-colored, ridge-derived debris to the west against dark-colored, organic rich soils to the east. Repeated earthquakes on the fault at this location caused the zone of subsidence between the debris lobe and the ridge.

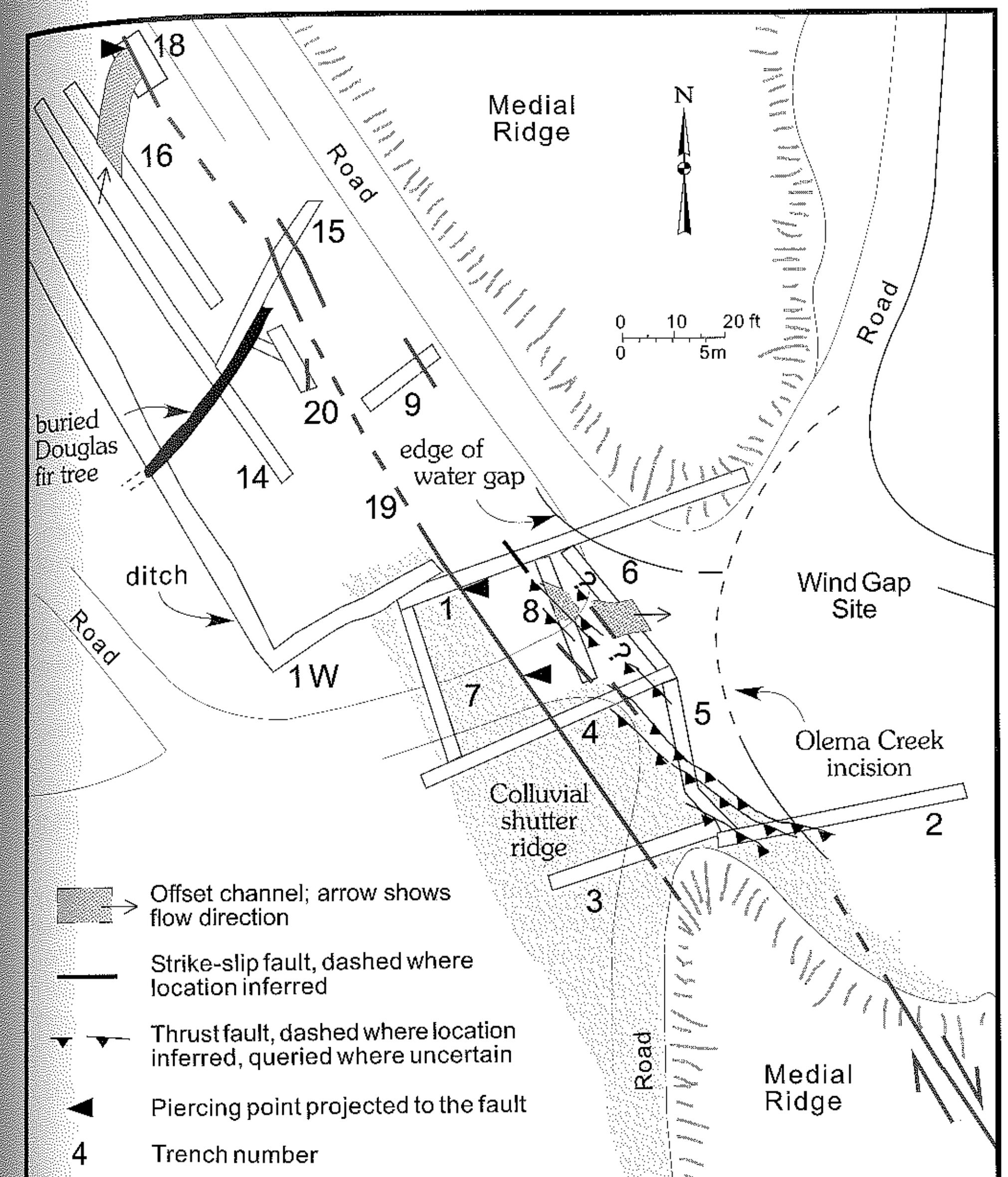

Figure 6. Sketch map of the wind gap showing locations of trenches and faults. Buried paleogeographic features shown include offset channel, limit of colluvial shutter ridge, edge of water gap, and incised Olema Creek cutbank. Projections of piercing points to the San Andreas Fault are marked by arrows.

Walk back to the Point Reyes Seashore Headquarters parking lot entrance, and proceed to the Headquarters entrance (at Bear Valley Road) where mileage resumes.

Miles	Cum Miles	Location
0	0.0	Turn right onto Bear Valley Road and continue east toward Olema.
0.5	0.5	Intersection of Bear Valley Road and Sir Francis Drake Road/Highway 1. Turn right and continue south to the stop sign in Olema.
0.1	0.6	Olema stop sign. Continue south on Highway 1.
0.2	0.8	Entrance to the Vedanta Society Retreat. Turn right and continue to the Retreat buildings.

NOTE: Permission must be obtained from the Vedanta Society to continue beyond the buildings.

STOP 5—Vedanta Retreat

This stop at the Vedanta Retreat is the site of a paleoseismological study of the SAF. The objective of this study was to document the late Holocene slip rate on the 1906 trace of the SAF from offset streams and to characterize pre-1906 seismic events based on the sedimentary record exposed in backhoe trenches (Niemi, 1992; Niemi and Hall, 1992).

Along the Vedanta driveway, we cross Olema Creek, which flows northwestward into Tomales Bay. The entrenchment of Olema Creek several meters into its floodplain deposits is apparently historical (Niemi and Hall, 1996). South of the driveway is the late Holocene floodplain of the once-meandering and aggrading Olema Creek. On the right, within a water gap in the medial ridge, is the large colonial white house built in 1869 as the residence of judge and cattleman Payne Shafter, who once owned nearly all of Point Reyes Peninsula. G.K. Gilbert made these observations of the 1906 rupture on the Shafter Ranch: 1) the SAF is a single strand within a secondary zone of cracking 3-4.5 m wide, 2) local subsidence ponded a lake of water 70 cm deep along the fault trace, and 3) the 1906 trace shifted from the base of the medial ridge to a sidehill bench southeast of a gap in the ridge (Lawson, 1908).

The wind gap study site is an abandoned water gap that was cut across the medial ridge, which at this location is composed entirely of Monterey Formation detritus probably derived from Bear Valley Creek (Figure 4A). South of the gap, the 1906 trace lies high on the ridge and is marked by a linear sidehill bench and sag. At the gap, the 1906 trace steps 20 m to the left, creating a restraining geometry marked by thrust faults (Figure 6).

Subsurface information about fault characteristics and channel morphologies within the wind gap and in the marsh to the west was obtained by trenching. Before 1,700 years ago, streams originating west of the fault, principally Gravel Creek, flowed eastward through the gap. Slip on the SAF has deflected this stream and diverted its drainage to the northwest by two processes: 1) lateral translation of a shutter ridge into the gap, and 2) development of a graben-like trough along the fault trace. Gravel Creek has subsequently built an alluvial fan into the south end of the marsh and now reaches Olema Creek by flowing through the water gap at the Vedanta Retreat barn.

East of the SAF at the north end of the wind gap, a distinct channel deposit, 2.5-3.0 m wide, of pebble- to cobble-sized Monterey clasts and wood debris represents the last narrow Gravel Creek channel to flow through the gap. West of the SAF in trenches parallel to and northwest of the wind gap, a channel of the same dimensions, lithology, and age has been identified (Figure 6). Detrital sticks within both channel deposits have radiocarbon ages that cluster about 1,800 years B.P. These matching channel segments show 42.5 ± 3.5 m of right separation, suggesting a minimum slip rate of 24 ± 3 mm/yr.

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GEOLOGY AND NATURAL HISTORY OF THE CENTRAL COAST RANGES: BERKELEY TO BODEGA HEAD, CALIFORNIA

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Carole Hickman,[1,2] Brent Mishler,[1,3] Zhigan Wang [2,5]

INTRODUCTION

Central California is one of the most biologically and geologically diverse regions in California—indeed, the United States. This field trip introduces the geological complexity of coastal California and the biological diversity in both the terrestrial and marine environments from Berkeley to the coast at Bodega Head. These are closely linked, as the geological history influenced biological development. The field trip shows the interrelations of these factors, as well as examples of each.

California is made of 11 different geologic provinces with quite different histories. The Coast Ranges of central California represent one of the most complex provinces. They are made of various geologic terranes, crustal pieces that have been assembled into the continent by plate tectonic activity. Some of the terranes formed far from where they are found today, juxtaposed to others that had completely different origins. In some cases, rocks originally near the equator are now next to rocks that formed off the coast of California. During Late Mesozoic and Early Cenozoic times, the oceanic plate was thrust beneath North America carrying other kinds of rocks or terranes formed farther out in the paleo-Pacific Ocean, including oceanic plateaus, oceanic islands, ridge or rise crests, and sea floor covered in pelagic sediments, as well as sediments deposited adjacent to the continent, to collide with and become incorporated into the continent. In addition, terranes were translated laterally along huge faults, like the San Andreas, to become part of present-day California (Figure 1).

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The marine environment of California is part of the larger Pacific Ocean oceanographic pattern. As the North Pacific drift moves from Japan and approaches North America from the west, it divides into the Alaska Gyre, moving north along the coast of Alaska, and the California Current, moving south from Washington to south of Baja California. The California Current is a subarctic current flowing slowly and warming as it moves and mixes with other water masses. It maintains a similar temperature regime off central California throughout the year, ranging from about 12-16°C. Upwelling during the spring and summer brings cool, nutrient-rich, deeper water to the surface near the coast. This produces cool, humid air that interacts with the warmer air of the interior, producing the famous fogs of San Francisco and the rest of the coast.

The major breaks in the marine biotas occur where the California Current is farther offshore. The biota of the shallow coast of western North America is divided into four provinces: the Aleutian, Oregonian, Californian and Panamanian, which are delineated by major oceanographic discontinuities and are increasingly warmer to the south. In general, species diversity increases in more southerly provinces, and has for the last 100 million years. In waters deeper than 200 m, the biota is ubiquitous from Alaska to Panama (Buzas and Culver, 1990), and species diversity and composition vary with depth. The central California fauna belongs to the Oregonian Province, defined on the basis of mollusks, fishes, arthropods and foraminifera. This Province extends from Puget Sound south to Point Conception where the coast of California swings eastward and the California Current remains offshore. Its biota is of moderate diversity and is usually dominated by a few species. Most Oregonian species also range into either the Aleutian Province to the north or the Californian Province to the south.

The coastal climate of western North America has been generally pleasant without extremes for at least the last 100 million years because the currents offshore tend to keep them rather similar from season to season. This influence extended far to the east (Nevada, Utah) during the Tertiary before the rise of the Coast Ranges and Sierra Nevada Mountains blocked the marine influence. Now this influence is restricted to the coastal regions.

The climate of California now is termed "Mediterranean," referring to the pattern of hot, dry summers and cool, wet winters. The biogeography of California is further influenced by its island or better yet, peninsular, aspect—the relatively humid strip west of the Sierran axis is isolated from the Rockies and the eastern US by very dry deserts. This results in a rich and unusual biota for the state, with many species that occur only here (endemics). For example, about 3,425 native species of vascular plants occur in the state, fully 24% of which are endemic, far more endemic species than in any other state, including Hawaii. Endemic species can be put in two categories. Paleoendemics are "old" species, whose ranges were once much wider and are now restricted to some particular area. An example in California is Giant Sequoia. Neoendemics, on the other hand, are "new" species that have recently evolved in an area. Many neoendemic species grow in places with unique soil types such as on serpentine outcrops. Both categories are common in California, making it a natural laboratory for the study of evolution.

Localized moisture, soil, and microclimatic conditions give rise to a diverse number of communities, ranging from marshes of various types, to alpine meadows and deserts. The composition and delimitation of these communities is dependent on environmental variables and the evolutionary and biogeographic history of the organisms. The benign climate has also been conducive to the establishment of many non-native species. More than 1,000 introduced vascular plant species have now established populations in the state and many habitats such as our grasslands are largely dominated by European species.

Field Trip Route

This field trip will explore the geology and major terrestrial and aquatic habitats from Berkeley to the coast north of San Francisco. Within this relatively short distance of fewer than 80 km, all the environments and geology characteristic of this area can be found. Beginning in Berkeley, the trip proceeds across the northern San Francisco Bay, across the Marin Peninsula to Tomales Bay, then moves to the University of California Bodega Marine Laboratory. The trip also will view geologic and tectonic features characteristic of central California including the right-lateral Hayward and San Andreas faults, the terranes of the Franciscan Complex between the two faults, the granitic complex west of the San Andreas Fault, and the Pleistocene deposits of Tomales Bay.

Berkeley to San Rafael: The trip begins near the Hayward Fault, which lies on the eastern margin of the University of California at Berkeley (UC Berkeley) where it passes through and displaces the University's Memorial Stadium. This fault, like the San Andreas to the west and the Calavaras to the east, is part of the NW trending system of transform faults connecting the crest of the East Pacific Rise in the Gulf of California to the crest of the Juan de Fuca Rise off northern California, Oregon and Washington. These are active faults and capable of catastrophic earthquakes at any time. Indeed, the Hayward Fault is considered the most dangerous because it has not had a major earthquake since 21 October 1868 when it slipped 1 m. Smaller quakes occur almost continuously. The faults separate different rock types that formed by processes of subduction and lateral accretion (Figure 1).

The Hayward Fault continues northwest on the east side of Berkeley. The Clark Kerr Campus of the University lies directly in this fault zone with the active trace along its eastern edge. The fault splits the UC Berkeley Memorial Stadium almost exactly in half. The stadium is built on a shutter ridge of the fault at the mouth of Strawberry Creek, which is offset some 400 m by the lateral slip of the fault. The fault is lost north of the campus under numerous landslides and slips on the highly populated, western slope of the Berkeley Hills. The zone between the Hayward and Calavaras faults contains Mesozoic and Cenozoic marine and nonmarine sediments.

The field trip leaves the campus and heads down University Avenue to Interstate 80 (I-80) where it turns north.

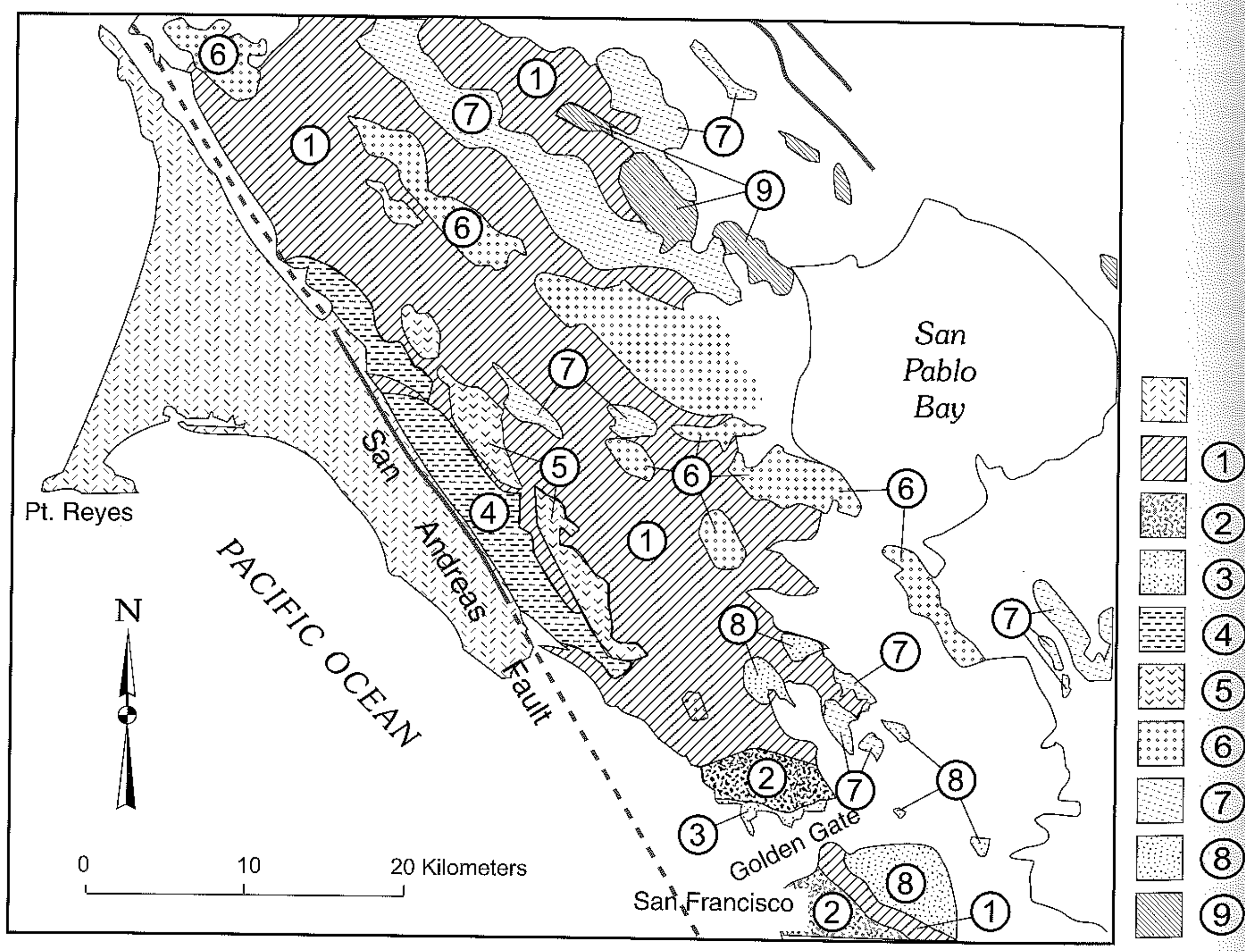

Figure 1. Geologic terranes north of San Francisco. Most of these terranes were accreted to the continent 200-20 million years ago. 1. Sandstone and shale originally deposited as turbidites off the continent and now complexly mixed (mostly 100-65 mya). 2. Mid-ocean ridge basalt and siliceous rock (chert) deposited as radiolarian skeletons beyond the influence of continental sedimentation (95-200 million years old). 3. Oceanic chert and basalt. 4. Turbiditic sandstones and shales. 5. Pillow basalt formed on the sea floor, chert and pelagic sediments (~135 mya). 6. Turbidites with Cretaceous fossils (75-84 mya). 7. Metamorphosed sedimentary rocks. 8. Tubidites. 9. Coherent and continuous sedimentary rocks of the Great Valley Sequence; mostly sandstones and mudstones (125-65 mya). Blank areas are young covering sedimentary rocks. Area west of the San Andreas Fault has been moved hundreds of miles from the SE along the fault. The rocks are intrusive granodiorites (100 mya) and later Tertiary sediments. *From Clark, Wahrhaftig and Brabb (1991).*

VIEW 1. Once on I-80 heading north, Albany Hill (a resistant part of the Franciscan melange) is passed on the right. The Berkeley Hills, with the Hayward Fault along the base of the slope, are on the far right and show the densely inhabited slopes and numerous landslides. Along the left side of I-80 and I-580 is relatively undisturbed marshland along San Francisco Bay. Less than 10% of the Bay's shoreline remains undisturbed today.

VIEW 2. As we start across the Richmond-San Rafael Bridge, a fine view (left, forward) of San Francisco and the Golden Gate Bridge can be seen. The bridge crosses the northern arm of San Francisco Bay, known as San Pablo Bay.

VIEW 3. At the end of the bridge, more marshlands are present along the shore; San Quentin Prison (State of California) is visible to the left.

Across the Marin Peninsula: The trip continues north on US 101 to Lucas Valley Road. Near that exit, the hills are covered with remnants of the characteristic Californian oak woodland or savanna, which represents the original community along the Bay. It is characterized by scattered oaks in a grassland matrix. The oaks are native and include both deciduous species (mainly *Quercus lobata*) and evergreen species (*Q. agrifolia*). The grasses are mostly European annual species that over the last 100 years or more replaced the native perennial bunch grasses (throughout a period of intense livestock grazing). Head west on Lucas Valley Road across the various terranes of the Franciscan Complex (Figure 1). The rocks exposed in outcrops and roadcuts are mostly part of the Central terrane. The following mileages are given from the signal just off the US 101 freeway at Lucas Valley Road.

Mile

4 The chaparral (dense spiny bushes) community, restricted to the hotter, drier places, often with thin soil, occurs high on the right. On the left is a forest of California Bay (*Umbelluaria californica*) with scattered live oak (*Quercus agrifolia*) on the moist north-facing slopes and on the deeper, moister soil of the valley bottom.

5.2 In this vicinity, serpentinite rock and serpentine soil (serpentinite is the California state rock) are exposed in roadcuts and hillsides. The unusual chemistry of soils derived from this rock (poor in some major plant nutrients, high in metals), coupled with the isolated outcrops, led to the evolution of many neoendemic plant species. Serpentine grasslands tend to have excellent wildflower displays because introduced grasses, which otherwise dominate California grasslands, do poorly on these infertile soils while native wildflowers can still grow and reproduce.

In this area also note large resistant rock outcrops protruding from fields and on hillsides—locally called "knockers." These resistant rocks have endured the subduction process more or less intact as the melange terrane was accreted to the continent. They consist of blocks of sandstone, basalt, chert, limestone, blueschist, eclogite and amphibolite. The melange is chiefly of Jurassic and Cretaceous ages, but in some places may be as young as Tertiary.

Mile

6.1 The deep valleys along the road contain fragments of the once common coastal redwood forests. All these are recovering redwood forests, completely logged over 100 years ago. This species regenerates from cut or burned trunks (unusual for conifers) forming rings of new trunks surrounding a single old dead trunk. Such rings of clones are also evident in burned redwood forests. This community in its intact state would have been magnificent. The trees here include Coastal Redwood (*Sequoia sempervirens*), California Bay, Douglas Fir (*Pseudotsuga menziesii*), and California Buckeye (*Aesculus californica*) with long, white flowering spikes.

9.3 STOP. The tall redwoods actually modify the microclimate, precipitating fog moving inland from the coast up the valleys. The water droplets falling from the branches add several inches of extra precipitation each year that are used in part by the other organisms in the forest. A short tree with serrate leaves, the Tan Oak (*Lithocarpus densiflora*), a biogeographic disjunct species, joins the others noted above. With no close relatives in North America, it is characteristic of the redwood forest, but the genus is otherwise restricted to Southeast Asia, where there are around 100 species! Also many ferns and mosses live here—in many ways this community is primitive in aspect, with relictual and paleoendemic species.

10.3 Turn right towards the town of Nicasio. In the fields to the left along here are vernal pools, another distinctive California habitat. Full of water in the winter, drying slowly in the spring and completely dry by the summer, they form in shallow depressions where drainage is impeded by a clay or iron hard pan that lies close to the soil surface. In the spring vernal pools are surrounded by rings or large patches of white, purple or yellow flowers. Many annual plants and animals are restricted to these habitats and many are endemic to California. This community is heavily impacted by human activity, including both urban and agricultural development.

10.7 The picturesque town of Nicasio.

11.6 Freshwater marshes occur here, as do breeding red-winged blackbirds. The males have territories where one to several females nest. The best habitats for nesting are those closest to open water; competition for territories can be intense. Males also advertise to attract females and often actively try to keep females within their territories. The hills nearby consist of the Central terrane melange and knockers abound.

13.2 The artificial Nicasio Reservoir illustrates tight ecological gradients around water (note the zonation in the vegetation). Plants are distributed differentially on the hills corresponding to moisture and air drainage. Especially in a semi-arid climate such as this, water relationships are the predominant factor determining the distribution of plants.

14.1 Turn left towards Pt. Reyes Station. On the north shore of the reservoir and in roadcuts on the right are thin-bedded radiolarian cherts, pelagic mudstones, and greywacke of the Nicasio Reservoir terrane. These were deposited far from land as the radiolarians and clay blown off land settled to the sea floor.

16.6 The tree canopies have been sculpted by the influence of persistent winds. Also, note the pendant lichen *Ramalina* (Old Professor's Beard), like all lichens, a symbiotic combination of a fungus with an alga, which thrives on the moisture carried in those same winds.

16. 9 STOP. Across the road are pillow basalts of the Nicasio Reservoir terrane, formed near a former spreading center, or oceanic rise, under perhaps 10,000 feet of water. The rounded shapes of the basalt (called pillows because they have a generally rounded and commonly elongate shape resembling a bed pillow), formed as lava erupted on the sea floor and cooled immediately forming a solid crust over still fluid, hot lava. This lava then broke through the crust and squirted out, much like toothpaste from its tube. The lava cooled in the pillow shapes. The dark green basalt is a spilite, probably resulting from reactions with sea water when it erupted. Larger crystals of albitized plagioclase are present in the basalt. The basalt is about 1,370 m thick, although it is broken by many faults. Fossil radiolaria associated with the basalts indicate a Valanginian to Barremian (Early Cretaceous) age. This terrane has been displaced about 16° N and 86° clockwise since accretion. The pampas grass growing on the cliff is an aggressive intruder from South America that is now common in many coastal habitats and can invade where there is very little soil.

17.2 Turn right towards Pt. Reyes Station. More pillow basalt and pelagic sediments are exposed in road cuts along this road.

20.3 Turn right (north) on California Route 1 towards Tomales Bay.

Pt. Reyes Peninsula: On the left, the high ridge in the distance is across the San Andreas Fault (SAF). The fault zone, eroded by fluctuating sea levels and streams, is filled to the south by terrestrial sediments and to the north by Tomales Bay. The fault zone passes through the muddy and marshy parts of Tomales Bay (left), as does the trace of the great 1906 San Francisco earthquake of April 18th. Movement along the fault here was 26 feet in that one quake alone!

The Pt. Reyes Peninsula, which dominates the view on the other side of Tomales Bay, is a displaced part of southern California, called Salinia, with a very different geology from the mainland. The hills across the Bay are made of granitic (mostly granodiorite) bedrock on the Pacific Plate (Figure 1) that has moved several hundred miles from its original location to the SE along the San Andreas Fault. These granitic rocks are about 100 million years old. Younger rocks of Paleocene, Miocene and Pliocene age occur on the Pt. Reyes Peninsula on the other side of the high ridge seen from Tomales Bay. The hills on the east side of the Bay where we are now driving are Jurassic and Cretaceous melange sandstones and shales on the North American Plate. These rocks belong to the San Bruno and Central terranes of the Franciscan Complex.

Striking differences in vegetation are supported on the two sides of Tomales Bay. The east side of the Bay has a typical coastal sage scrub vegetation, similar to chaparral but with softer, less drought-loving species. The dominant species is coyote bush (*Baccharis pilularis*), but some California sagebrush (*Artemisia californica*), which has soft aromatic leaves, is intermingled with many non-native plants in disturbed places. The vegetation on the west side of the Bay is a rich forest community dominated lower down by Red Alder (*Alnus rubra*), a species limited to streamside habitat or moist canyons near the coast, willow and other riparian tree species. Higher up is a mosaic of Douglas Fir (*Pseudotsuga menziezii*) forest and closed-cone pine forest (here dominated by the Bishop Pine, *Pinus muricata*) and coyote bush scrub. The plants in the Bishop pine forest are all fire-adapted, since fire is frequent in the dry summer or early fall before winter rains.

Table 1. Characteristics of Tomales Bay (McCormick and others, 1994).

Surface area	28.5 km^2	Volume	1.1 X 108 m^3
Water temperature	7-12°C	Precipitation	90% of all rain falls from October to April
Air temperature mean	11.2°C	Air temperature range	8.7-13.8°C
Winds, spring and summer	West to northwest	Winds, winter	South
Salinity, summer	32.22 -37.5%	Salinity, winter	20.32-33.48%
Tidal prism	4.5 X 107 m^3	Mean tidal range	1.1 m
Diurnal tidal range	1.6 m	Spring tides	up to 2.4 m

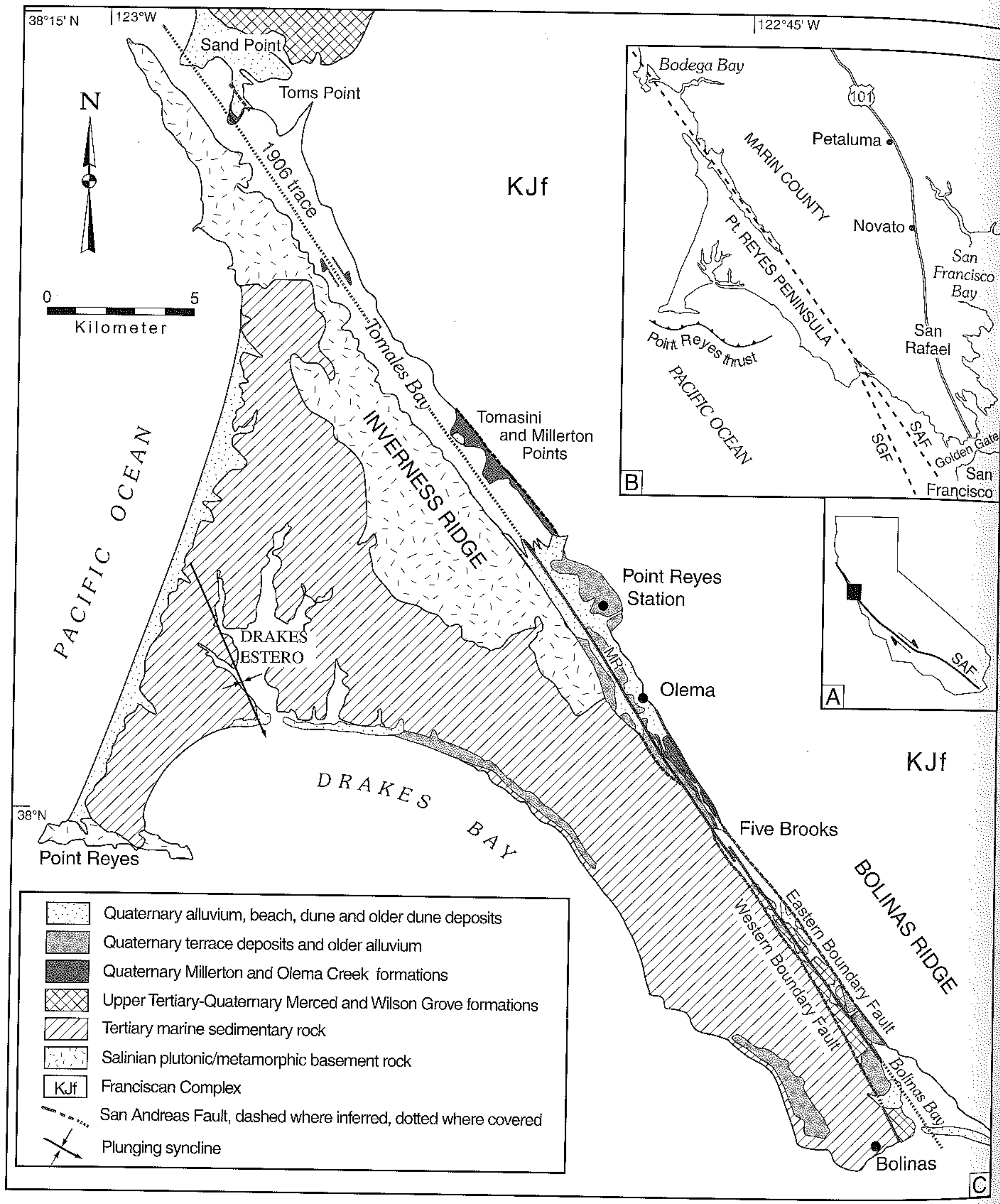

Figure 2. A) Tomales Bay region in California. B) The route of the field trip from Berkeley (off map to the east), across San Francisco Bay, past San Rafael, to Tomales Bay and Bodega Bay. C) Geologic map of the San Andreas Fault zone from Bolinas through Tomales Bay. *From Grove, in preparation.*

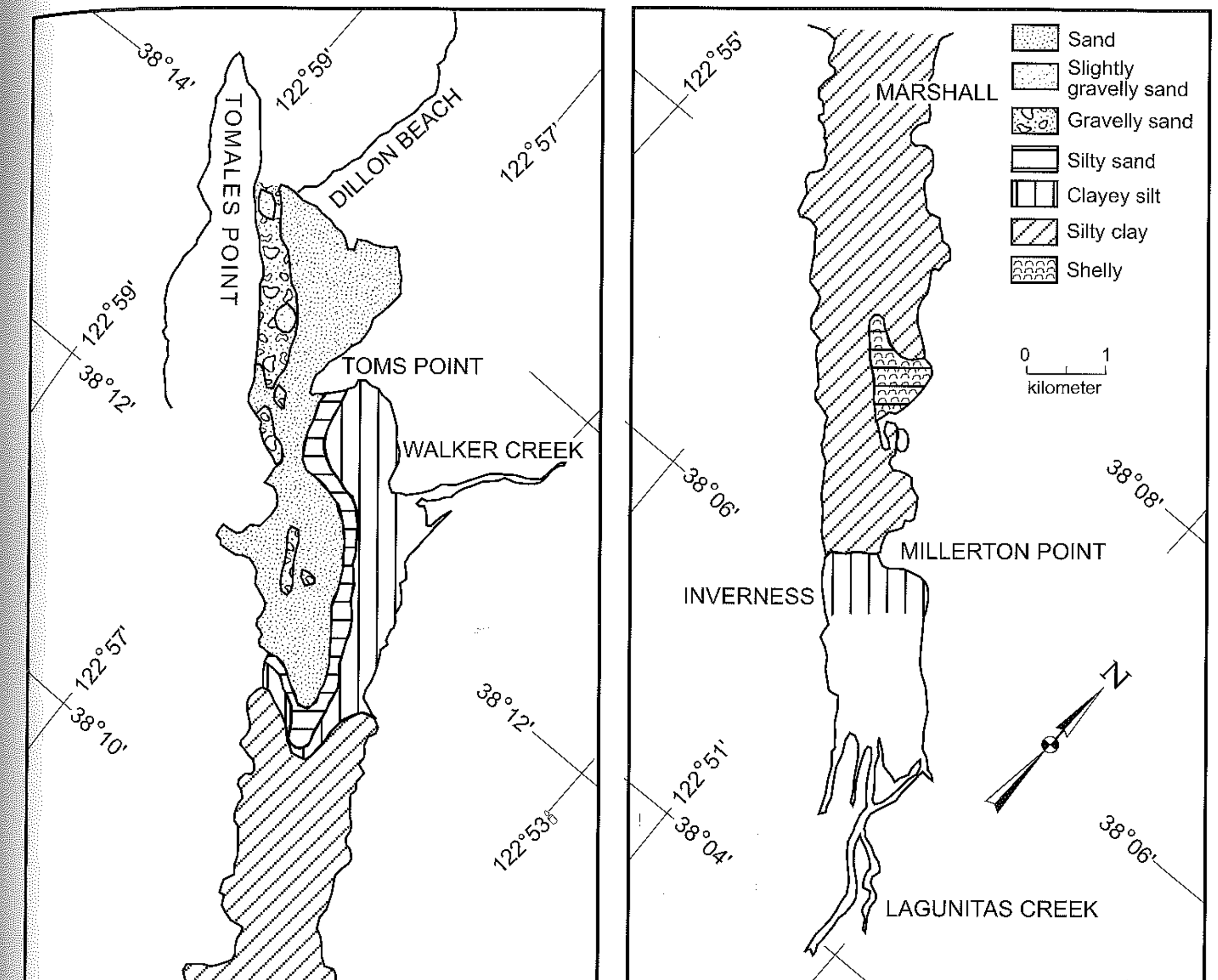

Figure 3. Tomales Bay sedimentary facies. *From Daetwyler (1966).*

Much of the Pt. Reyes Peninsula did burn during Fall 1995.

Tomales Bay: Tomales Bay (Figures 2 and 3) lies in a long, narrow trough eroded in the SAF zone. The trough has had a complex geologic history because of tectonic activity associated with the fault and sea level changes resulting from continental ice accumulation and melting during the Pleistocene. The Bay is 20.4 km long and ranges from 0.7 to 2.7 km wide. It averages about 4 m deep at mean lower low water, with a maximum depth of 18.5 m. The mouth of the bay shoals to about 3 m near Sand Point, sometimes creating dangerous wave conditions that can swamp fishing boats. Tidal channels in this area reach depths of about 12 m.

STOP at pullout at the southern end of Tomales Bay.

The modern biota of Tomales Bay includes marsh, estuarine, and truly marine species. Among the better documented organisms in the Bay are foraminifera (McCormick and others, 1994). Like most organisms there, foraminifera are diverse and different species assemblages characteristically live in different areas depending on salinity, temperature, substrate and food variations. Species composition varies from the mouth of the Bay towards its southerly end. The nearshore turbulent area with strong oceanic influence at the opening of the Bay contains species that are also found subtidally outside the Bay. In the middle of the Bay are foraminifera, mollusks and others that have southern, warm-water affinities and that prefer fine-grained substrata. The rest of the Bay is occupied by species of the Oregonian province that range from Point Conception to the Juan de Fuca Strait.

STOP at Millerton State Park.

We will follow the trail from the parking area down to the beach, walk along the beaches and around Millerton Point. Here we will see marshes, tidal channels, bay beaches of sand and cobbles, and cliffs consisting of the Pleistocene Millerton Formation on points jutting from the eastern shore of the Bay. Various animals are occasionally seen in the water or washed onto the beaches, including several species of oysters farmed nearby, bat rays, clams, snails, and the Moon Jellyfish *Aurelia*.

One of the best salt marshes of the many in Tomales Bay is adjacent to the beach. The marsh formed in the lee of Millerton Point where refracting waves created a beach and tidal channels kept sea water flowing into the area between the two. This marsh is zoned with the Pickleweed (*Salicornia*) near the water and where the tide covers them nearly every day, the grass *Distichilus* in the higher parts of the marsh, bare salt pans stranded in the highest parts where water from high tide evaporates depositing the salt, and the rush *Juncus* in the zone above that where inundation is uncommon. The sediment in the middle of the marsh is blue-black and smells of hydrogen sulfide. This is the anoxic zone (no oxygen) that forms as the organic debris from the marsh consumes oxygen as it decomposes. Animals and foraminifera that live there are subjected to stresses that include large salinity and temperature changes, low oxygen in the mud, and acidic conditions. In the marsh environment subtle changes in topography can result in dramatic changes in these conditions and result in faunal and floral changes as well. In only a few feet higher the normal grassland/coyote bush vegetation returns.

The geologic history of the SAF zone is complex; nevertheless, most of the modern environments can also be detected in Pleistocene rocks preserved south of and along the east side of Tomales Bay (Figure 2). These rocks were deposited as fluvial, freshwater and marine marsh, lagoon and bay sediments during the high stand of sea level about 130,000 years ago (Grove and others, 1995). From then until the present, sea level fluctuated in response to ice build up on the continents. At 18 ka at the maximum glaciation, sea level fell over 120 m, making Tomales Bay, the fault trough, and other modern streams, valleys that fed a much wider continental shelf (Figure 4).

The Millerton Formation (MF) and Olema Creek Formation (OCF) were deposited in the ancient SAF trough and represent marine bay and terrestrial sediments (Figure 2). The MF at its type locality, Millerton Point, is composed of several fining-upwards sequences from coarse-grained sand and gravel units separated by angular unconformities, exposed on both limbs of a syncline with its axis running NW-SE through the mid-part of Millerton Point (Figure 5). Fossils of mollusks, foraminifera (Table 2), diatoms, and plants are well known from the MF and OCF.

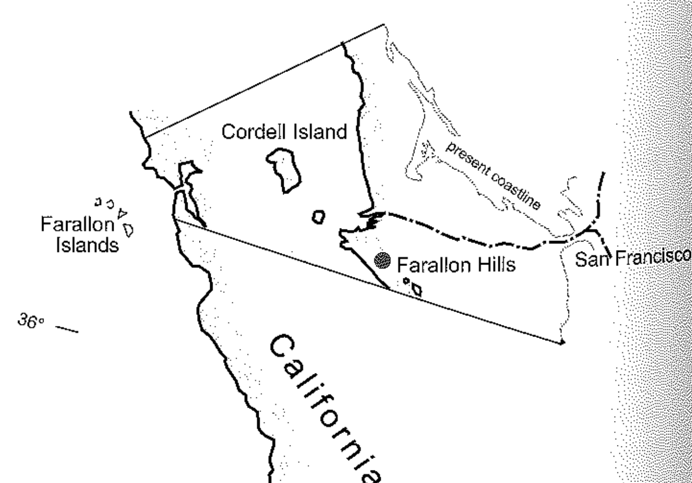

Figure 4. Central California, showing the present coastline (left) and the more extensive coastline at the 120m low stand of sea level (right). *From Lindberg and Lipps (1996).*

Table 2. Fossil foraminifera from the Millerton Formation.

FORAMINIFERAL SPECIES	TOMASINI POINT	MILLERTON POINT		
	T15 (Oyster bed)	M1	M2 (Oyster bed)	M11
Bolivina sp	2	9	2	
Brizalina striatula	5	74	26	2
Buccella tenerrima	131	72	44	
Bulimina denudata		48	55	3
Buliminella elegantissima		39	15	143
B. sp.		10	2	
Cassidulina sp.			6	
Cibicides fletcheri		6	5	
C. lobatulus		2		
C. sp.		1		
Discorbis vesicularis	121	3	2	
Elphidiella hannai		38	26	
Elphidium excavatum		50	170	17
E. sp.		130		
Fissurina lucida		13	10	3
Fursenkoina sp.		21	7	53
Glabratella ornatissima				2(?)
Globobulimina sp.		4	1	
Globigerina sp.			1	5
Lagena hispidula				1
L. striata		2		
L. sp. 1			1	
L. sp. 2			2	
Neoconorbina parkerae			9	2(?)
Nodosaria cf. N. perversa		1	2	
Nonionella basispinata			7	
N. mexicanus		4	2	1
N. stella				2
Quinqueloculina sp. 1	1			
Q. sp. 2			1	
Trochammina inflata	31			

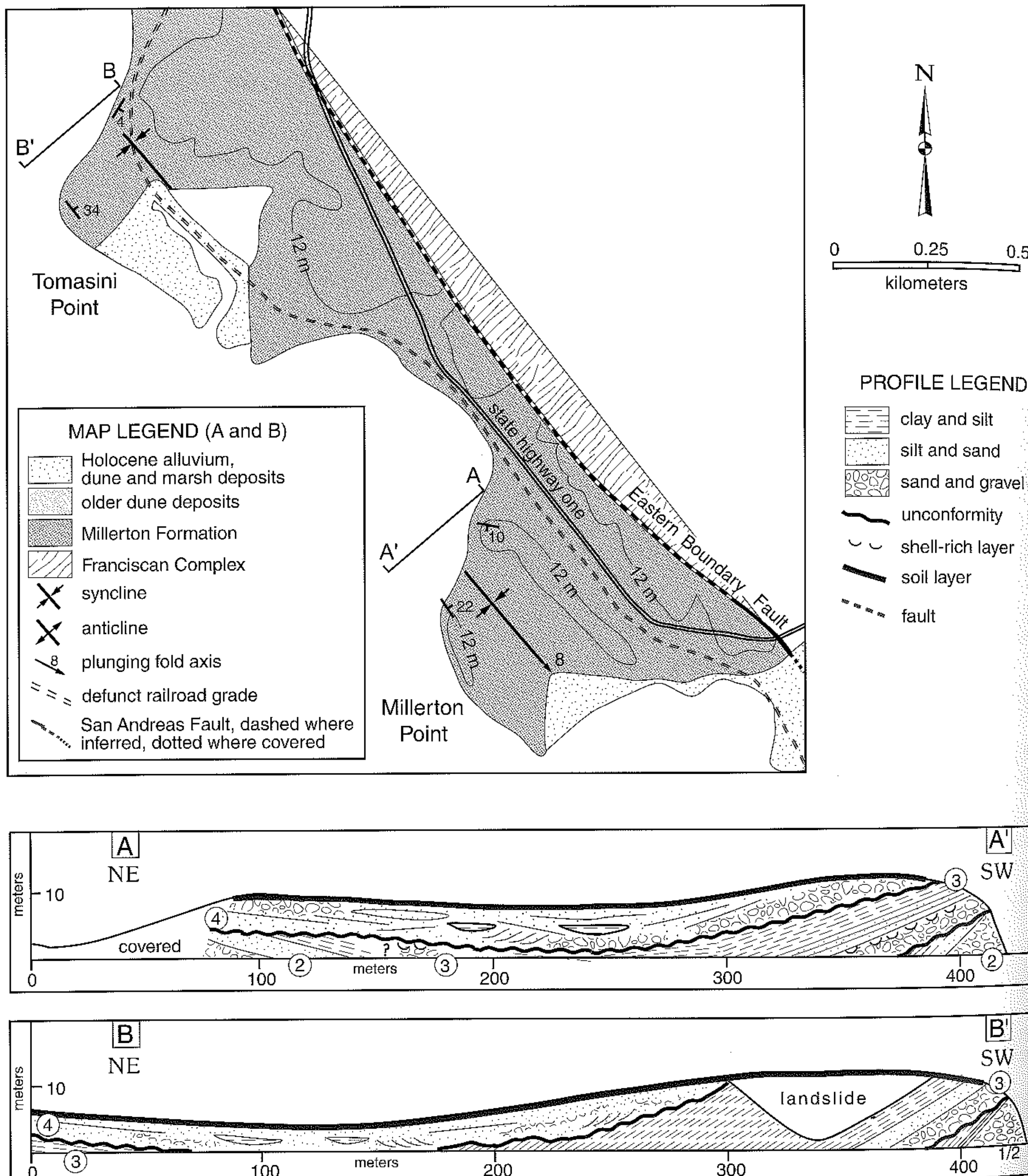

Figure 5. Geology and cross sections of exposures of the Millerton Formation along the east side of Tomales Bay. See Figure 2C for locations of Millerton and Tomasini points. *From Grove, in preparation.*

The foraminifera vary from sample to sample. Of more than 20 samples collected from the MF at Millerton and Tomasini points, only four had foraminifera. The oyster bed at Tomasini Pt. is less diverse than samples at Millerton Pt. It may have been deposited in more marginal parts of the ancient bay, whereas the others are similar to modern mid-Bay assemblages with an indication of good circulation to the open sea. These and the sedimentary record during this time indicate vastly different, yet fundamentally the same, environments in a constantly changing physical and climatic situation.

Tomales Bay to Bodega Head: The trip continues along the eastern shore of Tomales Bay, passes one of the largest marshes in the region at Walker Creek, leaves the SAF zone, goes through the small town of Tomales and continues past the headwaters of two estuaries—Estero San Antonio and Estero Americano. Each of these has very high freshwater outflow down their feeder creeks in the winter and no flow in the summer. In the summer, the estuaries become hypersaline with salinities near 50%. Continue past Valley Ford to the town of Bodega Bay. As the town is approached, Bodega Harbor comes into view. Bodega Harbor is also in the SAF zone (Figure 6). As elsewhere, the east side has rocks of the Franciscan Complex; across the Harbor at Bodega Head are granodiorites. Quaternary marine terrace deposits can be seen on Bodega Head, and some contain the fossil casts and molds of bivalves.

The harbor is shallow and fills with sand blown from the dunes on the west side. This sand is constantly supplied from Salmon Creek Beach, and thus a boat channel in the harbor is dredged every 10-20 years. In the harbor below is a marsh with salt pans well developed in the very high part of the tidal reach. Ostracodes and other arthropods may live in the pans, but little else does. Doran Beach is at the south end of the harbor. It is a fine-grained sand beach protected from severe wave action by Bodega Head. The rocky coast across the harbor is occupied by organisms that prefer protected coasts.

Continue through the town to East Shore Road and turn left, passing into the SAF zone again. At the bottom of the hill, turn right on Bay Flat Road and follow it around to the entrance to the Bodega Marine Laboratory (BML) of the University of California. Proceed to the lab.

Follow the path down to Horseshoe Cove. The rocks here are diorites translated 350 miles from the SE. On Bodega Head, they are the northernmost exposure of the Salinian Block. The rock is fractured and faulted in response to shear on the SAF, several hundred meters to the NE. The diorite is cut by later pegmatitic dikes and contains large phenocrysts in weathering relief. Here and there, inclusions of schist and gneiss occur. The beach at Horseshoe Cove marks a fault that cuts the diorite and passes through the eastern part of the BML. Above the beach and along the top of the diorite cliffs are sandstones deposited on an uplifted marine terrace dated at greater than 40,000 years.

Rocky intertidal habitats of the central California Coast, exemplified at Horseshoe Cove, show a striking pattern of zonation in which different organisms replace one another along an elevational gradient and gradients of physical parameters. Salt, desiccation, solar radiation, and the physical force of wave action are among the environmental factors organisms must deal with. Similar zonations of the distribution of organisms are characteristic of rocky intertidal habitats throughout the world. Assemblages of algae and invertebrates occur in four narrow bands, with more or less distinct breaks between assemblages. The causes of zonation are intensely debated and unresolved, with some favoring evidence for physical control of the observed pattern and others favoring biological control in the form of either competition or predation. The large body of theoretical explanation of the pattern is largely unsubstantiated by empirical testing. At Horseshoe Cove, the zonation from the subtidal to the supratidal is related to degree of wetting by the sea. On the point opposite the BML, the zonation of the upper three intertidal zones expands up the rocks in response to spray from impacting waves.

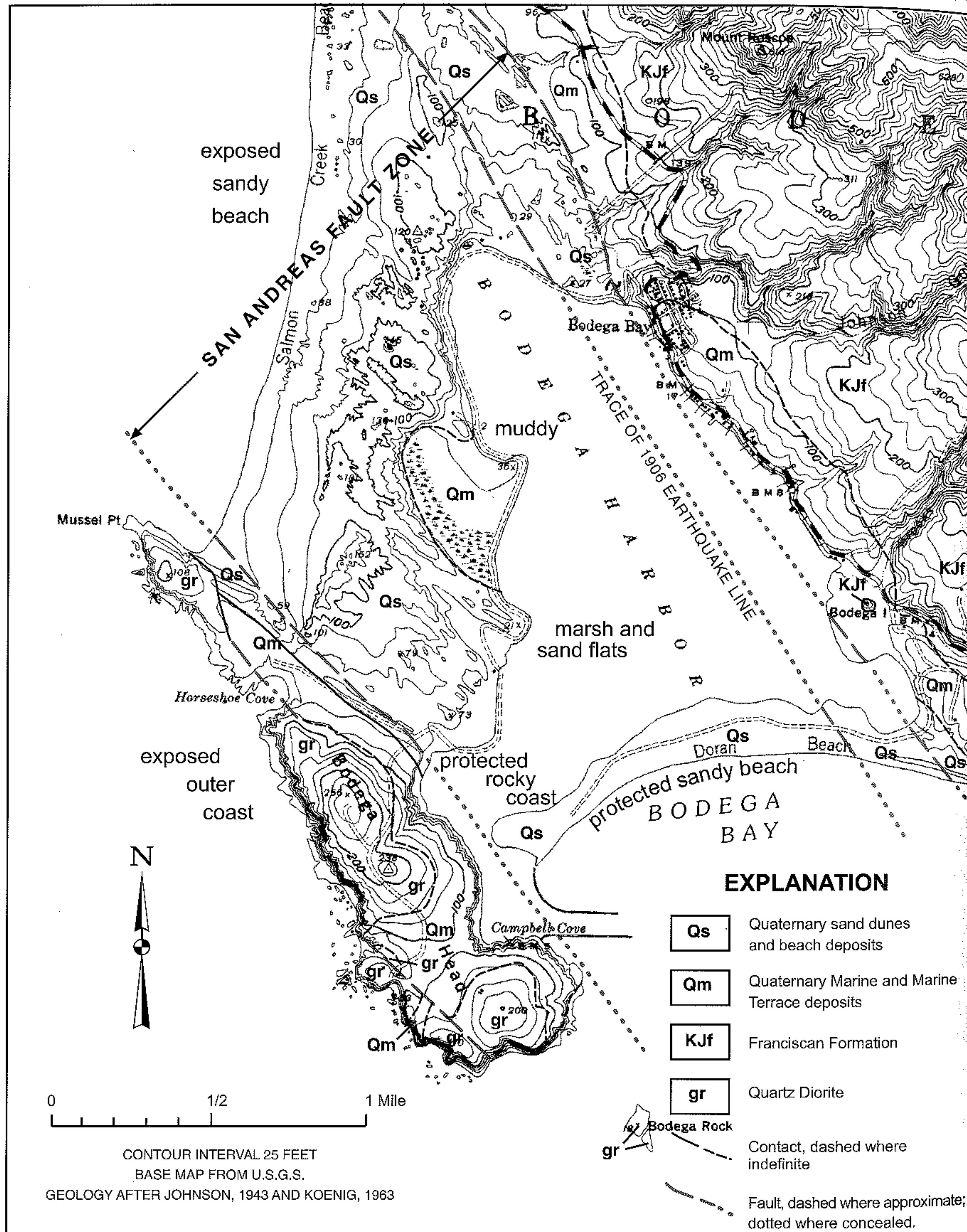

Figure 6. Geology and shallow-marine habitats at Bodega Head and vicinity. *From Koenig (1963) with marine environments by Lipps.*

Terrestrial vegetation, called the coastal prairie, is strongly influenced by the sea and its spray. This is restricted to fog-prone areas along the coast northwards from San Francisco Bay, and was originally characterized by bunch grasses with a diversity of flowering herbs.

On exposed bluffs, some plants here include: *Erigeron glaucus* (seaside daisy), *Armeria maritima* (thrift or sea-pink), *Echscholzia californica* (California poppy, the state flower), *Lupinus variicolor*, *Cirsium quercetorum* (brownie thistle), *Bromus carinatus*, *Abronia latifolia* (sand verbena with yellow flowers), and *Abronia maritima* (sand verbena with red flowers). Plants on more protected sites include the first six of these are native grasses: *Bromus carinatus, Hordeum brachyantherum*, *Danthonia californica*, *Leymus pacificus*, *Agrostis blasdalei*, *Poa unilateralis*, *Eriophyllum staechadifolium* (seaside woolly sunflower), *Lupinus arboreus* (bush lupine —large, with yellow flowers).

Across the road is a dune community dominated by *Ammophila arenaria* (European beach grass). This introduced species was planted throughout California for dune stabilization. It greatly alters the topography and stability of the sand and outcompetes native dune species. It is no longer being planted and in small areas is slowly being removed and replaced with native species. Here you can see how it forms dense, basically monospecific stands.

Miwok Indian living sites and middens occur commonly on Bodega Head. Middens can be seen in the soil profiles along the sea cliffs to the NW of the BML. A rather large camp was recently excavated in the sand dunes near the main road at the marsh.

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