Petroleum Systems of the Santa Cruz-San Mateo County Coast

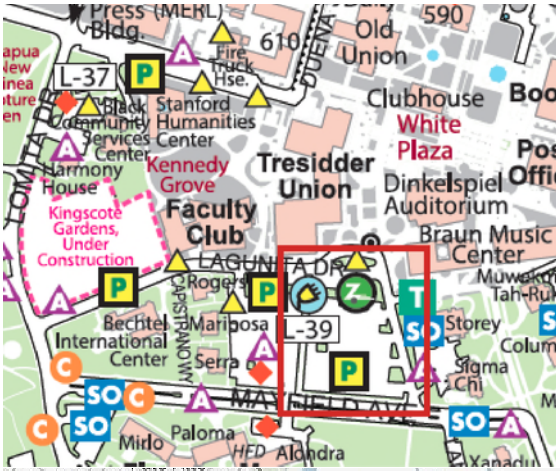
Road Log

Arrival	Departure	Cum. Miles	Stop #	Stop Description	Special Notes/Hazards
7:30 a.m.	7:45 a.m.		0	Stanford parking lot	Leave on time.
8:45 a.m.	9:00 a.m.	43.9	1	Safeway in Santa Cruz	Restroom stop, coffee (last restrooms before lunch).
9:05 a.m.	9:30 a.m.	45.5	2	Carbonate cold seeps (p. 96)	Minor rock scrambling if tides permit; waves.
9:45 a.m.	10:15 a.m.	51.7	3	Majors Creek (p. 99)	Look across highway (do not cross road).
10:20 a.m.	10:40 a.m.	52.7	4	Santa Cruz Mudstone outcrop (p. 101)	Stay off the road.
10:45 a.m.	11:45 a.m.	53.3	5	Yellowbank and Panther beaches (p. 102)	Moderate rock scrambling from parking lot to beach; waves.
Noon	1:30 p.m.	55.4	6	Bonny Doon Vineyard Tasting Room	Lunch and restroom stop, wine tasting (optional).
2:00 p.m.	4:00 p.m.	65.6	7	Año Nuevo State Park (p. 106)	Moderate walking; waves.
5:00 p.m.		114.5	1	Stanford parking lot	Time to relax.

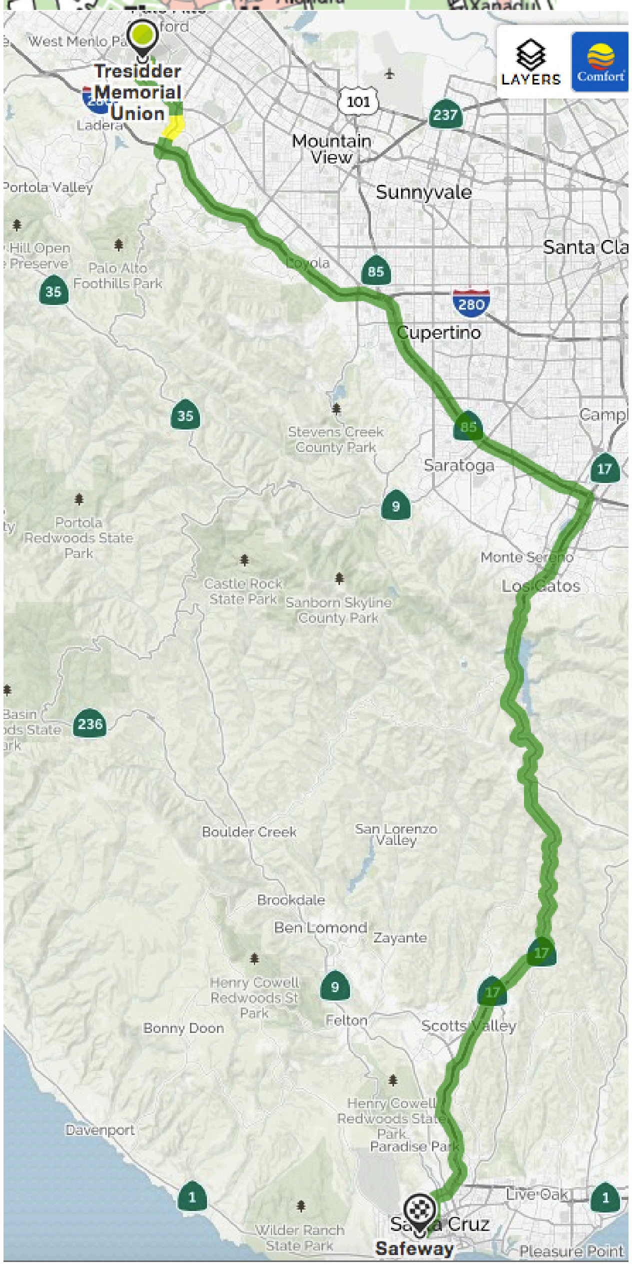
Sunrise: 7:36 a.m. Sunset: 6:09 p.m.
Low tide: 2.8 at 6:48 a.m. High tide: 4.7 at 12:31 p.m.

This field guide is organized as follows:

All photos are by Allegra Hosford Scheirer unless otherwise noted. This field guide is for internal use only and is not to be published.



Stop 0: Stanford University Parking lot between Mayfield Ave and Lagunita Dr on Stanford campus, Stanford, CA. Use reserved parking spaces in first row of lot L-39. -122.1705° 37.4231°



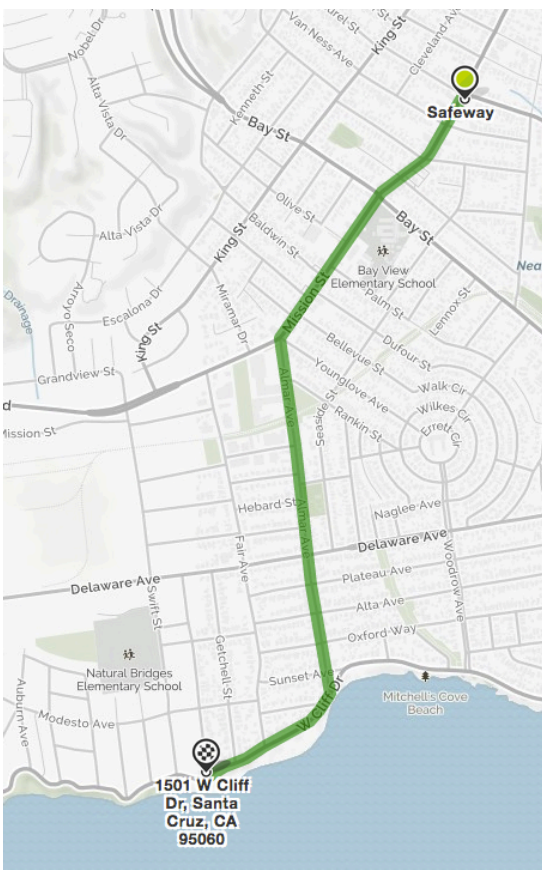
Mapquest map from Stanford to Safeway

Driving directions to Stop 1: Safeway, 1203 Mission St., Santa Cruz, CA

Route	Distance
Parking lot at Mayfield Ave & Lagunita Dr: drive SE (turn L) on Mayfield Ave to stop sign, then turn R to continue on Mayfield Ave to stop sign	0.0 mi
Turn R on Campus Dr East	0.5 mi
Turn L on Junipero Serra Blvd	1.5 mi
Turn R on Page Mill Rd	1.3 mi
Merge onto I-280S toward San Jose	7.7 mi
Merge onto CA-85S toward Gilroy	7.7 mi
Merge onto CA-17S toward Santa Cruz	22.5 mi
Exit R onto CA-1N	1.1 mi
Continue on CA-1N, which becomes Mission Blvd	1.6 mi
Safeway is on the L just past Laurel St	Restroom

Driving directions to Stop 2: Carbonate Cold Seeps

Route	Distance
Continue southwest on Mission St	0.6 mi
Turn L on Almar Ave	0.7 mi
Turn R on W Cliff Dr. Park on street between John & Swift St.	0.3 mi



Stop 2: Carbonate Cold Seeps (parking lot on W Cliff Dr between Swift St and John St, Santa Cruz, CA)
-122.0470° 36.9498°

Mapquest map from Safeway to seeps.

Geologic discussion on pp. 96-98.

Special Notes/Hazards: Minor rock scrambling if tides permit; waves.

Driving directions to Stop 3: Majors Creek overlook

Route	Distance
Exit parking lot and drive N on Swift St to Coast Rd/Hwy 1.	0.75 mi
Turn L on Coast Rd/Hwy 1 and drive to pull-off at northern intersection with Scaroni Rd (pass the first occurrence of Scaroni Rd).	5.4 mi
Turn L onto Scaroni Rd and park safely.	

Stop 3: Majors Creek overlook (north spur of Scaroni Rd at intersection with Coast Rd/Hwy 1) -122.1394° 36.9806°

Mapquest map.

Geologic discussion on pp. 99-100.

Special Notes/Hazard: Look across highway. Do not cross road.

Driving directions to Stop 4: Santa Cruz Mudstone Outcrop (if time)

Route	**Distance**
Carefully turn L to continue northwest on Coast Rd/Hwy 1.	
Drive to pull-off at northern intersection with Laguna Rd (pass the first occurrence of Laguna Rd). Pull off to the R into a parking lot.	1.0 mi

Stop 4: Santa Cruz Mudstone outcrop (north spur of Laguna Rd at intersection with Coast Rd/Hwy 1) -122.1555° 36.9873°

Geologic discussion on p. 101.

Special Notes/Hazard: Stay off the road.

Driving directions to Stop 5: Yellowbank Beach/Panther Beach

Route	Distance
Continue northwest on Coast Rd/Hwy 1.	
Turn L into a narrow dirt parking area. Drive to the far end of the parking area. Across the railroad tracks will be a sign marked "Coast Dairies." If you reach Bonny Doon Rd, you've gone too far.	0.6 mi

Stop 5:
Yellowbank and Panther Beach (Coast Rd/Hwy 1)
-122.1681°
36.9929°

Geologic discussion on p. 106.

Special Notes/Hazard: Moderate rock scrambling from parking lot to beach; waves.

Driving directions to Stop 6: Bonny Doon Vineyard Tasting Room

Route	Distance
Carefully turn L to continue northwest on Coast Hwy/Hwy 1.	
Bonny Doon Vineyard Tasting Room is on the R. Tour bus may choose to park in public lot across the street.	2.1 mi

Stop 6: Bonny Doon Vineyard Tasting Room
-122.1956°
37.0112°

Lunch and restroom stop. Wine will be provided on the tables and you may also choose to taste flights (on your own).

Driving directions to Stop 7: Año Nuevo State Park

Route	Distance
Continue northwest on Coast Hwy/Hwy 1.	
The entrance to the park is on the L.	10.2 mi

Stop 7: Año Nuevo State Park
-122.3082°
37.1247°

Geologic discussion on page 106-108.

Special Notes/Hazard: Moderate walking; waves.

Driving directions to return to Stop 0: Stanford University

Route	Distance
Continue northwest on Coast Hwy/Hwy 1.	27.5 mi
Turn R onto CA-92 E and drive east.	7.9 mi
Merge onto I-280 S toward San Jose and drive south.	9.4 mi
Exit I-280 S at Sand Hill Rd E and drive east.	2.25 mi
Turn R onto Santa Cruz Ave and then an immediate L onto Junipero Serra Blvd.	1.1 mi
Turn L onto Campus Drive E.	0.5 mi
Turn L onto Mayfield Ave. Turn L to continue on Mayfield Ave.	0.15 mi
Turn R into the parking lot at Mayfield Ave & Lagunita Dr.	0.1 mi

Petroleum Systems of the Santa Cruz-San Mateo County Coast

Introduction

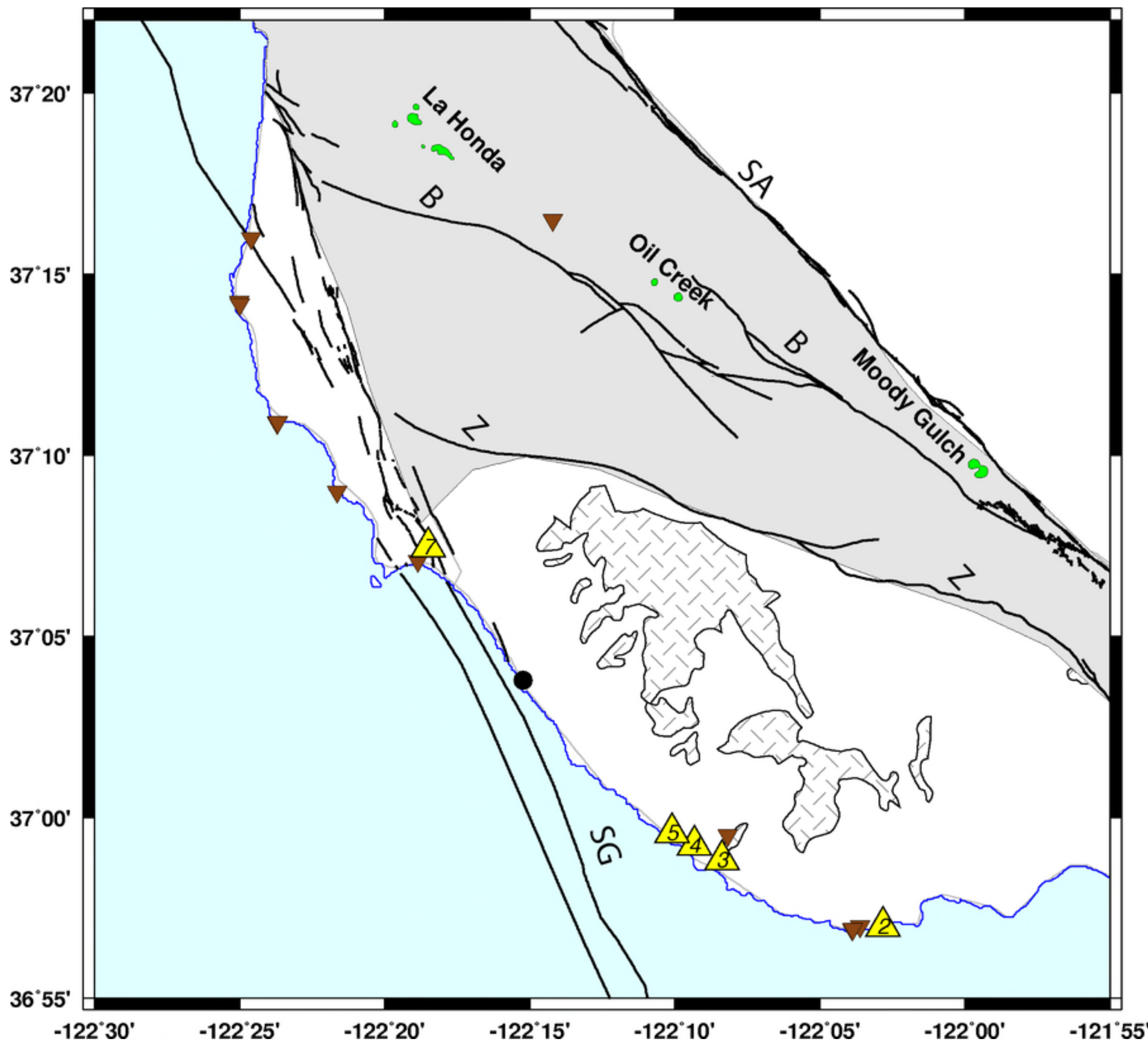


Figure 1. Santa Cruz-San Mateo County Coast (blue line), La Honda Basin (gray shading) and its oil fields (green-filled polygons; some fields plot out of the map area), Ben Lomond Mountain (dark gray stippling.) Yellow-filled, numbered triangles are field trip stops (non-geologic faults not shown). Filled circle, Texaco Poletti NCT-1 well. Brown-filled inverted triangles, seeps, tarball, and oil samples from Peters et al (2008). Stop 2, Carbonate cold seeps; Stop 3, Majors Creek Anticline; Stop 4, Santa Cruz Mudstone outcrop; Stop 5, Panther Beach & Yellowbank Beach; Stop 7, entrance to Año Nuevo State Park. Major faults are from the USGS Quaternary Fault and Fold Database: SG, San Gregorio; B, Butano; Z, Zayante; SA, San Andreas. (http://earthquake.usgs.gov/hazards/qfaults/). Map by Allegra Hosford Scheirer.

Figure 1 sets the stage for the geologic and petroliferous features of the Santa Cruz-San Mateo County Coast visited on this field trip. The outcrops of interest lie south-southwest of the La Honda Basin (gray shading, **Figure 1**), a petroliferous region of small areal extent containing five oil fields that have produced nearly 2 million barrels of oil and 300 million cubic feet of gas (Stanley, 1990). Despite this (relative) commercial success, petroleum was commercially produced along the coast mainly as asphalt for road paving material because of the abundance of asphalt-saturated sandstones on the flanks of the Santa Cruz Mountains (**Figure 2**). The only commercial development of oil that we are aware of occurred in the 1950's, when about 2600 barrels of oil were produced by retorting the asphaltic sandstone at Majors Creek. (Clark et al., 1999).

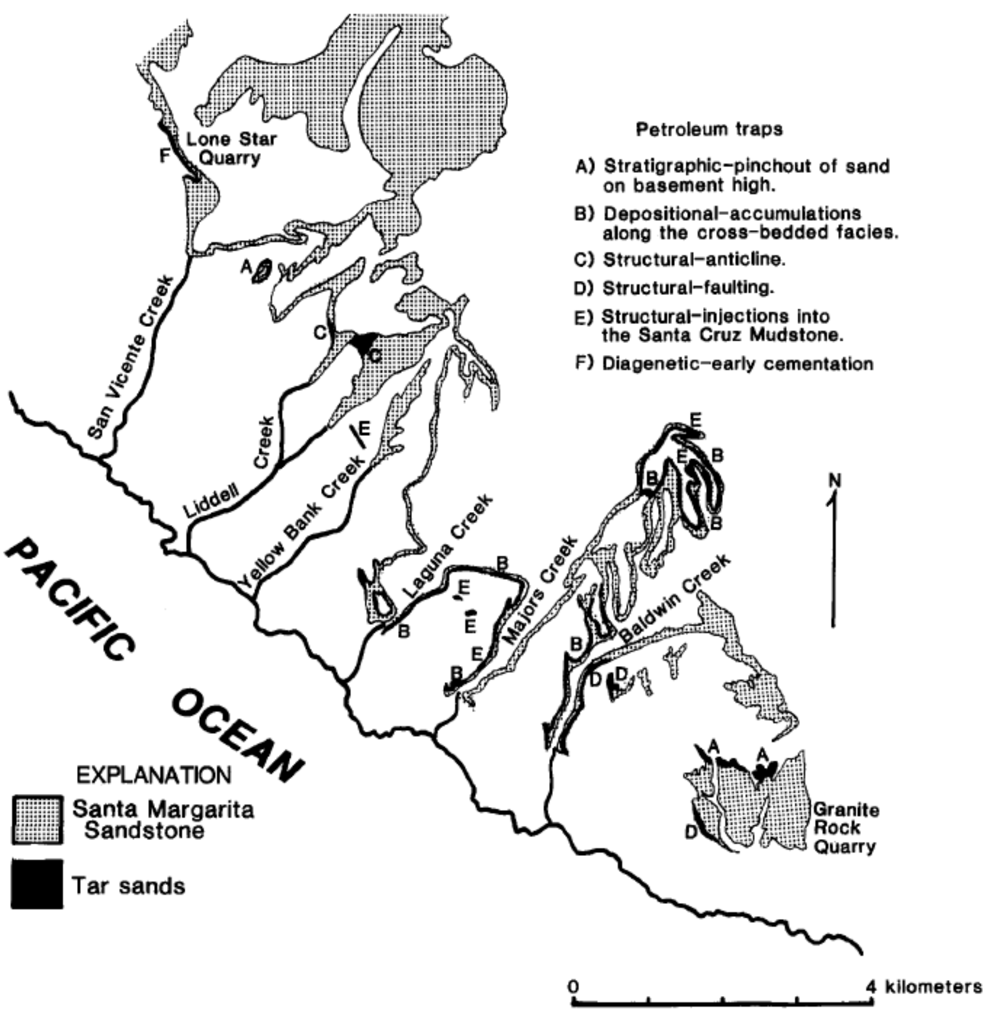


Figure 2. Asphalt-sand outcrops and trapping mechanisms of Santa Cruz County Coast. Map and interpretation from Phillips (1990).

Figure 2 provides the motivation for our field trip—asphalt-saturated sandstone and asphalt seeps along the Santa Cruz County coast. Natural seeps of asphalt and bitumen in this area are documented by numerous workers, including Hodgson (1987), Thompson (1999), and Peters (2008) (see .kmz files available at http://walrus.wr.usgs.gov/seeps/where.html).

Stratigraphy

At our first several field trip stops, we will be standing on marine terrace deposits that range in age from 65 ka to 220 ka (Perg et al., 2001), but our main study objective is the Santa Cruz Mudstone, and to a lesser extent, the Santa Margarita Sandstone (**Figure 3**). Although the Monterey Formation crops out extensively surrounding Ben Lomond Mountain, there are no *coastal* exposures of the formation on the east side of the San Gregorio Fault. The Monterey Formation in the La Honda Basin, like in other Neogene basins of California, consists of siliceous and calcareous organic-rich shale and mudstone, with locally abundant phosphate and interbeds of turbiditic sandstone (Stanley, 1990). Together these characteristics point to accumulation in low-oxygen bathyal water depths.

The Santa Margarita Sandstone is a shallow-marine unit that in most areas overlies the siliceous shales, porcelanites, and cherts of the Monterey Formation. This unit occurs throughout much of the western part of central and southern California (Hosford Scheirer and Magoon, 2008). In the Santa Cruz coastal area, the Santa Margarita Sandstone may have been deposited in a narrow (10 km) seaway that linked the marine San Joaquin Basin to the east with the Pacific Ocean to the west (Phillips, 1983). Depositionally, the sandstone represents a transgressive, coarse clastic unit influenced by tidal currents. The evolutionary stages and characteristics (cross-beds, bioturbation, lag deposits, etc.) of the Santa Margarita Sandstone are detailed by Phillips (1983).

A marine transgression terminated the deposition of the coarse clastic Santa Margarita Sandstone, allowing for the deposition of the fine-grained Santa Cruz Mudstone about 7 to 9 Ma (Stanley and Lillis, 2000). The mudstone conformably overlies the Santa Margarita Sandstone (Phillips, 1990). It is correlative with age-equivalent upper Monterey Formation in other Neogene basins of California. Like the Monterey Formation, the Santa Cruz Mudstone is highly biosiliceous (El-Sabbagh and Garrison, 1990). Silica rich sediments originate in marine basins as an "ooze" comprised of diatom tests. The silica crystal lattice in these tests is in its thermodynamically unstable opal-A phase. With burial—perhaps 500 to 1500 m or 40° to 50°C—opal-A transforms to the more stable opal-CT phase, which upon further burial transforms to quartz (~80°C; **Figure 4**) (Keller and Isaacs, 1985).

The basal age for the overlying Purisima Formation is 6.7 Ma (Mullins and Nagel, 1982). The Purisima records the final filling of the basin via a rapid marine transgression followed by a regression in the late Pliocene (Stanley, 1990).

A major geologic feature of the Santa Cruz County Coast is the presence of sand injectites. "Sand injectite" is a general term used to describe "all features attributable to sediment injection, including dikes and sills" (Hurst, 2012). Those scientists who study the San Joaquin Basin may know that the Panoche Giant Injectite Complex has a stratigraphic thickness of 1200 m and crops out over an area of 300 to 400 km^2 in the Panoche and Tumey Hills (Hurst, 2012). On this field trip we will see a large subaerially exposed injectite complex—thought to be the largest exposure in the world—at Yellowbank and Panther beaches. Here, fluidized sands from the Santa Margarita Sandstone were injected upward into fractured Santa Cruz Mudstone (Thompson et al., 1999). The physics of sand injection remain uncertain, but hypotheses concerning the emplacement of these intrusions center on an increase in confining pressure within the underlying clastic unit due to deposition and induration of the Santa Cruz Mudstone; the influx of water, oil, and gas; and liquefaction during seismic shaking (Thompson et al., 1999).

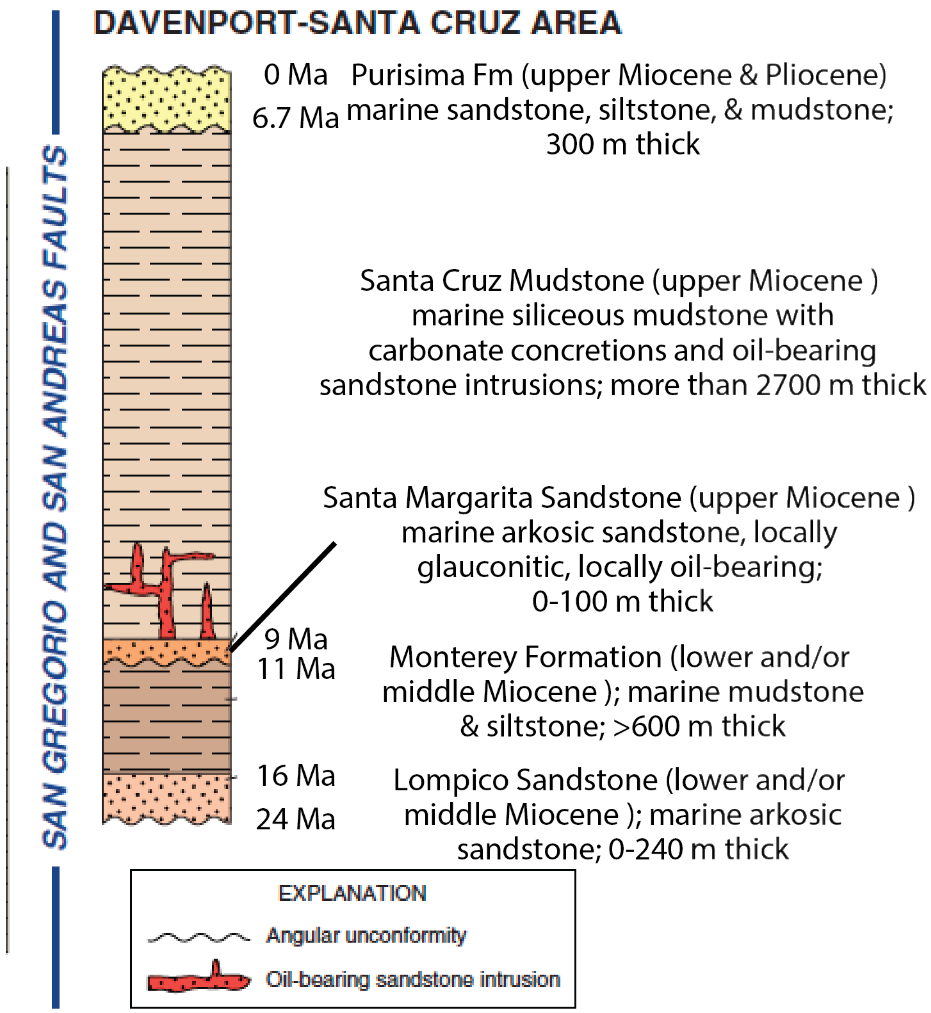


Figure 3. Stratigraphic column of Santa Cruz County Coast from Stanley and Lillis (2000).

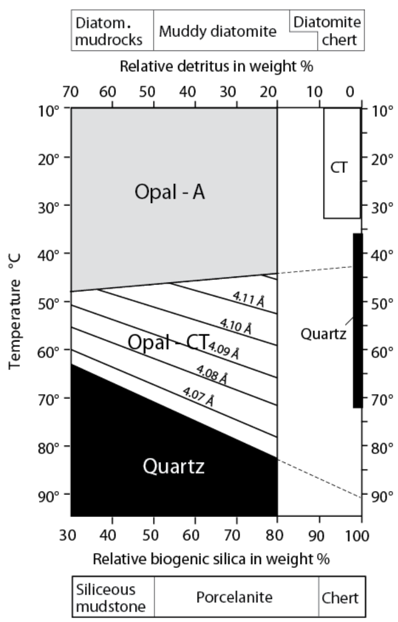


Figure 4. Relationship between temperature, silica content, and detrital content in silica-rich rocks. Figure from Keller and Isaacs (1985).

San Gregorio Fault

The major structural feature that has affected this coastal region is the San Gregorio Fault ("SG" in **Figure 1**). A right-lateral strike-slip fault of the North America-Pacific Plate boundary system, the fault trends obliquely to the San Andreas Fault from south of Point Sur but merges with the San Andreas Fault north of San Francisco in the Point Reyes area. Over much of this 200 km distance, the fault is located offshore. Using seven pairs of offset geologic features, Graham and Dickinson (1978) documented as much of 115 km of slip on the San Gregorio Fault, and its southern extension (the Hosgri Fault) since early Miocene time. Stanley and Lillis (2000) correlated carbon isotope and biomarker compositions from oil samples on the east side of the San Gregorio Fault in Davenport (our field trip area) with oil samples from Point Reyes on the west side of the fault (**Figure 5**). This correlation results in a displacement estimate of 115 ± 10 km along the San Gregorio Fault (**Figure 6**). Subsequently, Dickinson et al. (2005) reinterpreted onshore and offshore geologic mapping and revised cross-fault ties. In that study, the total fault offset estimate was 156 ± 4 km.

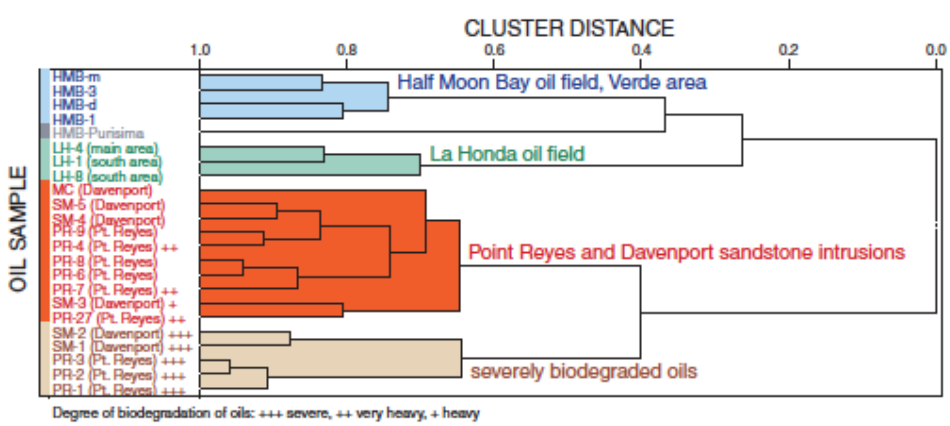


Figure 5. Dendrogram of genetic similarity between oil samples near Santa Cruz and Point Reyes. Figure from Stanley and Lillis (2000).

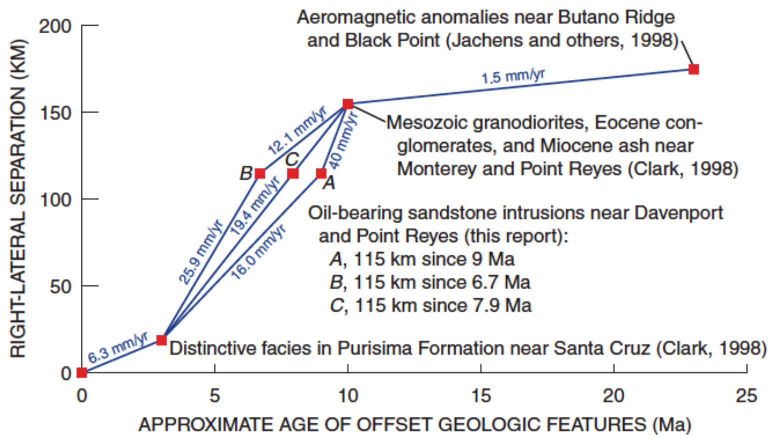


Figure 6. Determinations of offset along the San Gregorio Fault. Figure from Stanley and Lillis (2000).

Petroleum Geochemistry

Lillis and Stanley (1999) analyzed stable carbon isotope and biomarker signatures in samples from the five oil fields of the La Honda Basin as well as from nearby seeps, and outcrops of bituminous sandstone. Although oil-source rock correlation was lacking, they concluded that petroleum from all of the oil samples derived from Miocene age source rock (**Figure 7**), with at least some of it likely generated from the Monterey Formation. A sample from Majors Creek along the Santa Cruz Coast, in contrast, appeared genetically related to the Santa Cruz Mudstone (Lillis and Stanley, 1999). A subsequent study of five samples from sandstone intrusions in the Santa Cruz Mudstone along the coast confirmed Miocene age for the parent source rock, but a definitive source rock—either the Monterey Formation or the Santa Cruz Mudstone—was not identified. (Stanley and Lillis, 2000).

Finally, a comprehensive study of coastal California crude oil, seep, and tarball samples from Los Angeles to Point Reyes also found that all of the samples in our field trip area derive from Miocene age source rocks (Peters et al., 2008). Biomarkers indicative of source rock lithology indicate that these samples originated in source rock of clay, marl, and shale compositions (Figure 8; Peters et al., 2008).

The close proximity of the La Honda Basin to the Santa Cruz-San Mateo County Coast may cause the reader to suspect that the petroleum systems are related in the two areas. We reject the possibility of such a correspondence on the basis of geochemical evidence—the oil in Oil Creek Field appears to derive from an Eocene age source rock and the other fields each contain oil from distinct Miocene age source rocks—and physiographic evidence: the positive topography of Ben Lomond Mountain (**Figure 1**) likely provides a barrier to oil flow either from the La Honda Basin to the coast (northeast to southwest) or vice versa (from southwest to northeast).

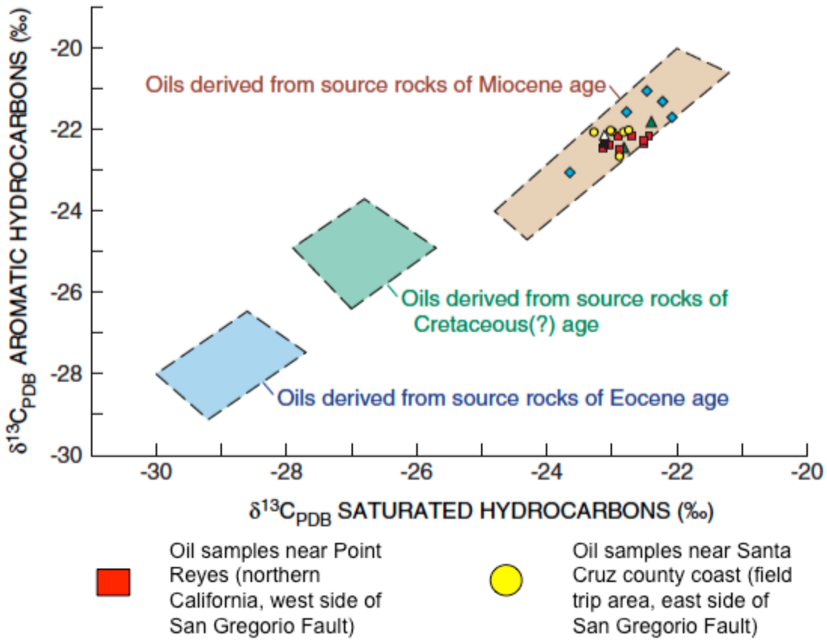


Figure 7. Geochemical arrays of aromatic vs. saturated hydrocarbons for the three main oil families in California: blue, Eocene age source rocks; green, Cretaceous age source rocks; tan, Miocene age source rocks. Figure from Stanley and Lillis (2000).

Figure 8. Location and biomarker-based source rock lithology for samples from Peters et al. (2008) in the field trip area. Yellow square, Tribe 1 from shale source rocks; red diamond, Tribe 2 from marl source rocks; green square, Tribe 3 from carbonate source rocks.

Basin and Petroleum System Modeling

We developed a simple basin and petroleum system model (BPSM) for the deepest well on the Santa Cruz County Coast, the Texaco Poletti NCT-1 (**Figure 9**). Drilled in 1956, the well has a total depth of 9201', reported to be in crystalline basement. The well reportedly contains almost 6000' of Santa Cruz Mudstone, a number that has been widely repeated in the literature, but definitive evidence of this information is lacking.

Based on the geochemical evidence presented above, the main source rock is undoubtedly of Miocene age (**Figure 7**), and likely is California's "super-star" source rock, the Monterey Formation. Lillis and Stanley (1999) and Hurst (2012), among others, suggest that the Santa Cruz Mudstone could serve as a local petroleum source rock. However, in the absence of definitive oil-source rock correlation, we believe that the combined overburden thickness (Santa Cruz Mudstone, Santa

Margarita Sandstone, and Purisima Formation) is insufficient for thermal maturation and petroleum generation from the Santa Cruz Mudstone itself.

The Monterey Formation was assumed to be the organic-rich source rock in this petroleum system. Moreover, we chose a siliceous, 95% Opal-CT lithology for this source rock in accordance with observations (**Figure 10**). We used a Total Organic Carbon of 3 wt %, a Hydrogen Index of 700 mg HC/g TOC, and kinetics of Behar et al. (1997) to model petroleum generation. Other modeling inputs included paleowater depth, seawater-interface temperature, and basal heat flow through time. We used a commercial petroleum systems modeling software package. Two calibration points guided input values for amount of eroded section and basal heat flow.

According to this simple 1D BPSM, the base of the Monterey Fm entered the oil window ~7.5 Ma (**Figure 11**). The petroleum system was only active for about 1 Ma, when tectonic activity likely ended thermal maturation of the source rock and "froze" in a vitrinite reflectance of 1.0%. The Monterey Formation only reached about 60% transformation before the petroleum system became inactive (**Figure 11**).

A unique feature of this study is that we know the critical moment ahead of time because of the timing of movement along the San Gregorio Fault, *if* we operate under the assumption that we know the slip history of the fault. Usually a BPSM model is used to determine the critical moment so one can evaluate whether a trap formed before petroleum generation-migration-accumulation. The critical moment is the time that best depicts the generation-migration-accumulation of petroleum in a petroleum system (Magoon and Dow, 1994). In this case, we assume the preferred slip history of Stanley and Lillis (2000): slip occurred between about 9 and 7 Ma (**Figure 6**). This then determines when traps were charged so that the basin model can be used to evaluate whether there is sufficient overburden on the Santa Cruz Mudstone to thermally mature it or if we can reject that hypothesis in favor of the Monterey Formation as the only source rock. A BPSM scenario with the Santa Cruz Mudstone failed to reach the petroleum generation window. Thus, with the Monterey Formation as the source rock, the critical moment occurs in a narrow time window, after 7 but before about 5 Ma (**Figure 12**).

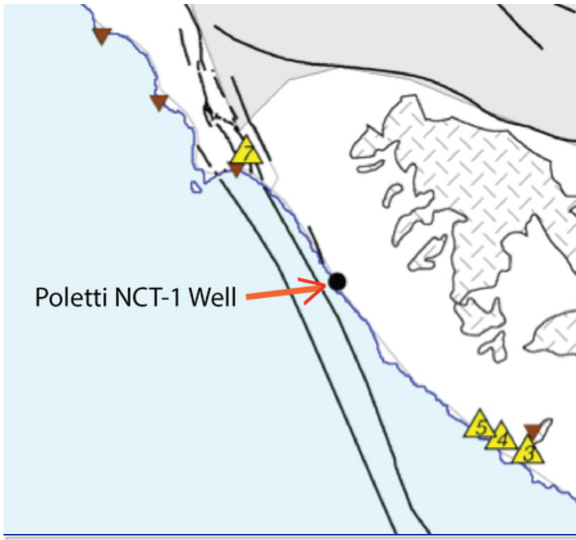


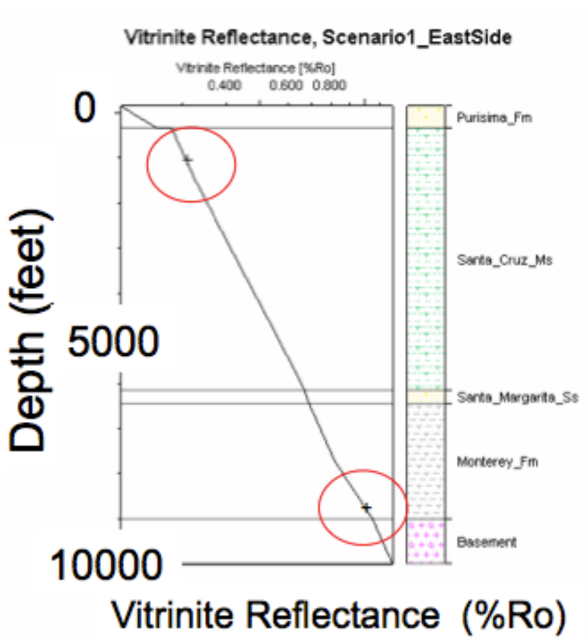
Figure 9. Detail map of Santa Cruz-San Mateo County Coast. Field trip stops are shown by yellow triangles. Brown inverted triangles denote the locations of seep, tarball, and oil samples analyzed by Peters et al. (2008). Map by Allegra Hosford Scheirer.

Main Input for Scenario1_EastSide

Depth Input: Top Base Thickness Assign from Well Pick

Layer	Top [ft.]	Base [ft.]	Thick. [ft.]	Eroded [ft.]	Depo. from [Ma]	Depo. to [Ma]	Eroded from [Ma]	Eroded to [Ma]	Lithology
Purisima_Fm	-145	347	492		5.00	0.00			Sandstone (clay rich)
Santa_Cruz_Ms	347	6147	5800	2000	9.00	6.70	6.70	5.00	Siltstone (organic lean)
Santa_Margarita_Ss	6147	6435	288		11.00	9.00			Sandstone (typical)
Monterey_Fm	6435	9000	2565		16.00	11.00			Shale (organic lean, siliceous, 95% Opal-CT)
Basement	9000	10000	1000		70.00	50.00			Granite (150 Ma old)
						70.00			

Figure 10. Input parameters for a petroleum system model of the Poletti well.



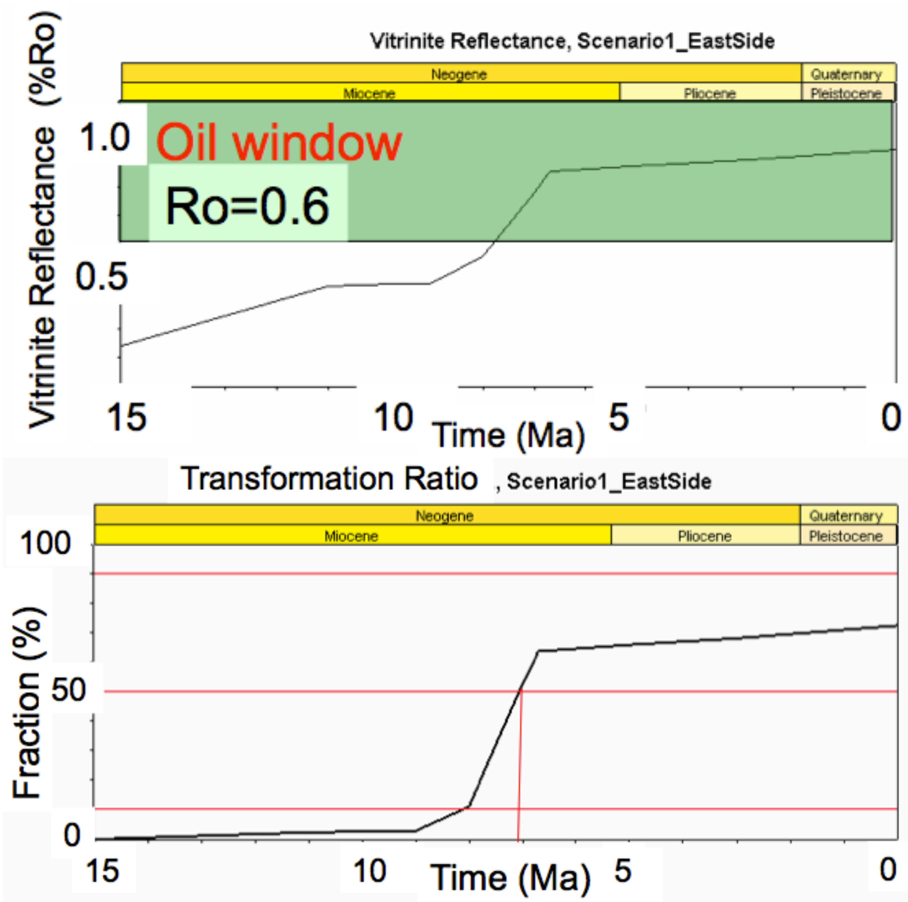


Figure 11. Output from the petroleum system model of the Poletti well.

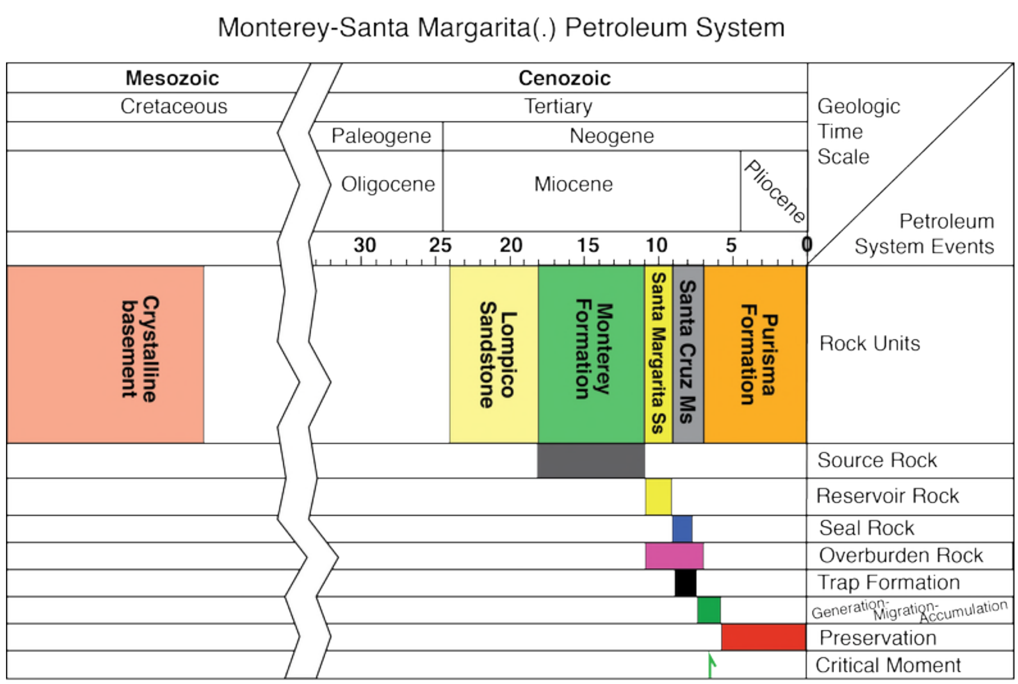


Figure 12. Events chart for the Monterey-Santa Margarita(.) petroleum system.

No investigation of a petroleum system is complete without some discussion on the plumbing system from source to trap. In this area, acceptable scenarios must explain oil occurrences on both sides of the San Gregorio Fault. A model for the configuration of the basin during its petroliferous period is shown in **Figure 13.** Stanley and Lillis (2000) propose three scenarios for oil generation and migration in the Santa Cruz County coast area: 1) Prior to movement on the San Gregorio Fault, oil was generated locally in a small depocenter they call the Davenport Syncline (scenario "1" in **Figure 13**) and charged traps both east and west of the fault. This is the authors' preferred model; 2) Prior to movement on the San Gregorio Fault, oil was generated in an unidentified region offshore and migrated eastward (scenario "2" in **Figure 13**); and 3) Oil occurrences on either side of the fault are unrelated. Whichever scenario is true, evidence of oil migration is seen at the Majors Creek field trip stop, where we will discuss the role of dikes, sills, and injectites in the petroleum system. A sketch of a cliff face updip from Majors Creek summarizes geologic relationships between essential elements of the petroleum system (**Figure 14**).

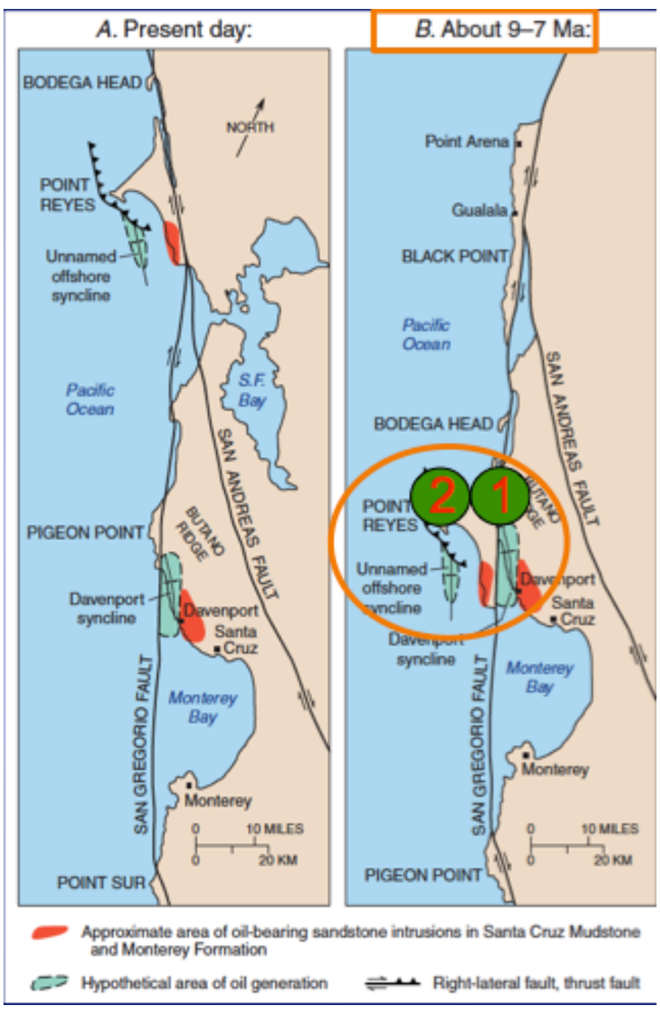


Figure 13. Present-day geography of the central-northern California coast (left) and paleogeographic reconstruction (right) accounting for 115+/-10 km of right-lateral slip on the San Gregorio Fault. Figure from Stanley and Lillis (2000).

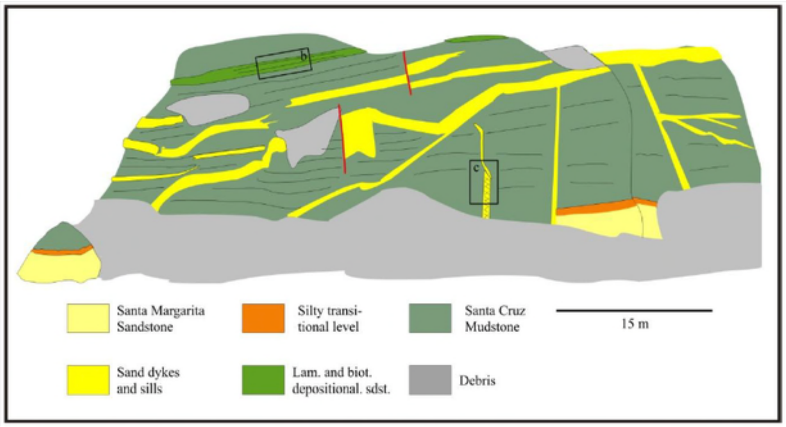


Figure 14. Geologic sketch of a quarry face updip from Majors Creek illustrating the reservoir rock (Santa Margarita Sandstone) and seal rock (Santa Cruz Mudstone) of the Monterey-Santa Margarita(.) petroleum system. Figure from Hurst (2012).

Summary of Petroleum System Elements

<u>Source Rock:</u> Probably the Miocene Monterey Formation; possibly the Santa Cruz Mudstone

<u>Reservoir Rock:</u> Sand injectites in the Santa Cruz Mudstone, Santa Margarita Sandstone, possibly the Lompico Sandstone

<u>Seal Rock:</u> Santa Cruz Mudstone

<u>Overburden Rock:</u> Santa Margarita Sandstone, Santa Cruz Mudstone, Purisima Formation

<u>Trap Timing:</u> beginning 8 Ma when Pacific-North American transform margin became slightly compressive (Atwater and Stock, 1998).

<u>Generation-Migration-Accumulation:</u> Generation began about 7.5 Ma, before late Miocene emplacement of sandstone intrusions ("injectites"); migration occurred via injectites and possibly by fracture-enhanced permeability in carbonate vents.

<u>Critical Moment:</u> 7-9 Ma, assumed when the two asphalt-bearing units were juxtaposed across the San Gregorio Fault.

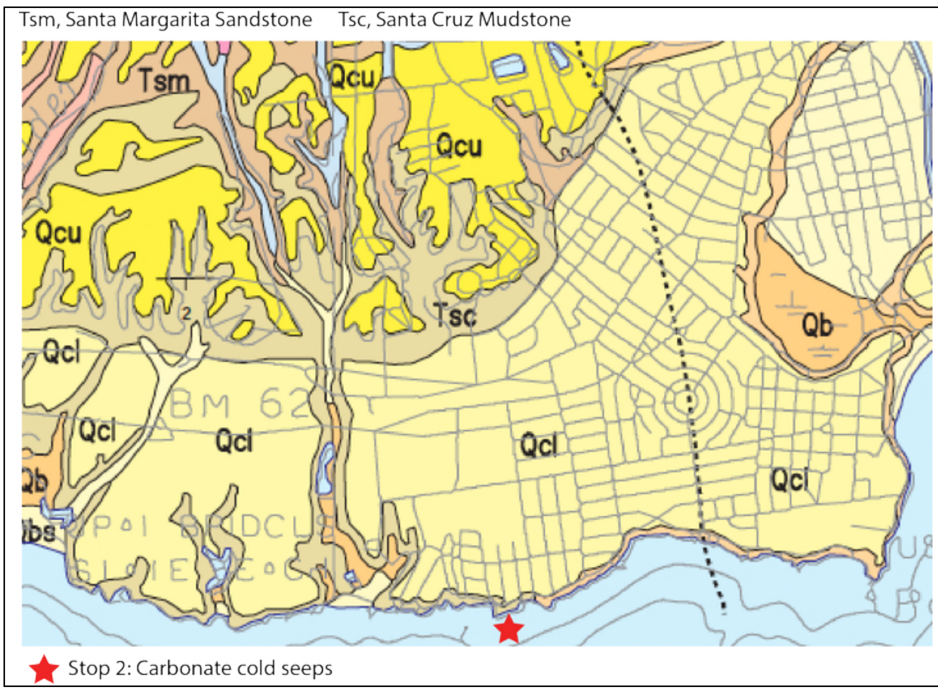
Commercial Production of Petroleum

The main petroleum product historically produced in the area was asphalt, which was mined from the Santa Margarita Sandstone in numerous locations. This asphalt was used for road materials from the late 1880's to the 1940's (Clark et al., 1999). From Clark (1999): "reserves of about 9.8 million cubic yards of asphaltic sand [exists] in the area west of Santa Cruz. This sand contains approximately 10 million barrels of asphalt. In oilfield terms, this is…equivalent to a tar sand with 38% porosity, 53% oil saturation, and a recovery factor of 1562 barrels of oil per acre-foot."

Majors Creek (field trip stop 3 in **Figure 1**) is the only location we know of where oil was commercially produced, and this was only by retorting the oil-saturated Santa Margarita Sandstone. Between 1957 and 1959, more than 350 wells were drilled on a ten foot spacing to an average depth of 53 feet (Clark et al., 1999). In this area, the Santa Margarita lies about 8 to 10 feet below the surface, is about 40 feet thick, and averages about 8% by weight of 4° API gravity oil (Clark et al., 1999). Underground heaters mobilized (and vaporized) the oil from the sandstone for a grand total of 2665 barrels of 27° API gravity oil, 4520 Mcf of gas, and 9232 barrels of water (Clark et al., 1999).

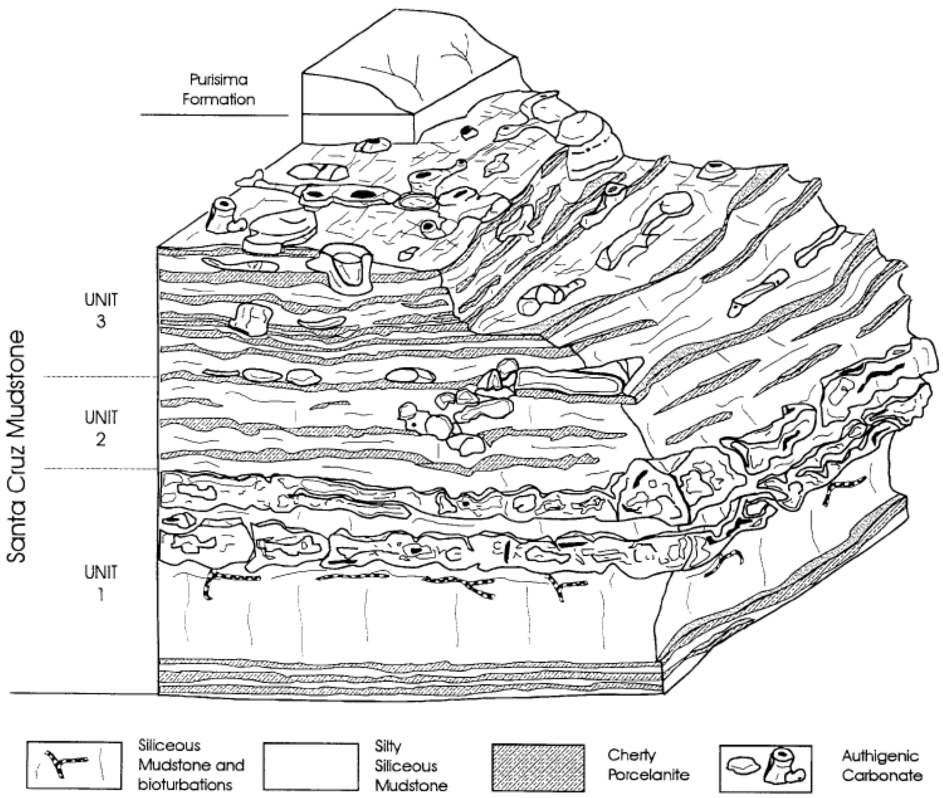
Stop 2: Carbonate Cold Seeps

Beautiful exposures of Santa Cruz Mudstone and the unconformably overlying Purisima Formation are visible just west of our stop (photo 1 and geologic map, below), but the focus of this stop are carbonate concretions (photo 2 and 3, below) located in the upper 5 m of the Santa Cruz Mudstone resulting from seepage of fluids and gases.

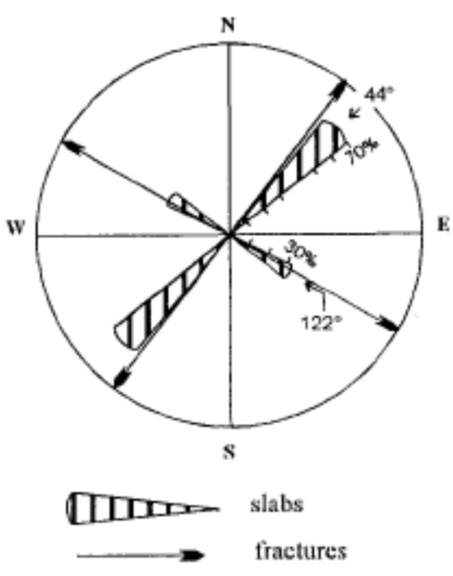


Geologic map of Brabb et al. (1989) with field trip stop 2 (red star) in the city of Santa Cruz.

Garrison et al. (1999) highlight the following characteristics of these structures: 1) brittle, highly fractured porcelanite beds composed of opal-CT, 2) different geometric shapes (pipes, slabs, etc.), 3) circular conduits, and 4) relationships between the fracture patterns and orientations of the vents.



This schematic block diagram from Garrison et al. (1999) illustrates the distribution of authigenic carbonate in vent structures in the upper 5 m of Santa Cruz Mudstone. At this stop, we are in unit 3; we are unable to see units 1 and 2 because of the high tide, but a prior fieldtrip guide (Garrison et al., 1999) suggests walking 50 m from the parking lot west along the sidewalk to view a cross section of all three units at low tide.

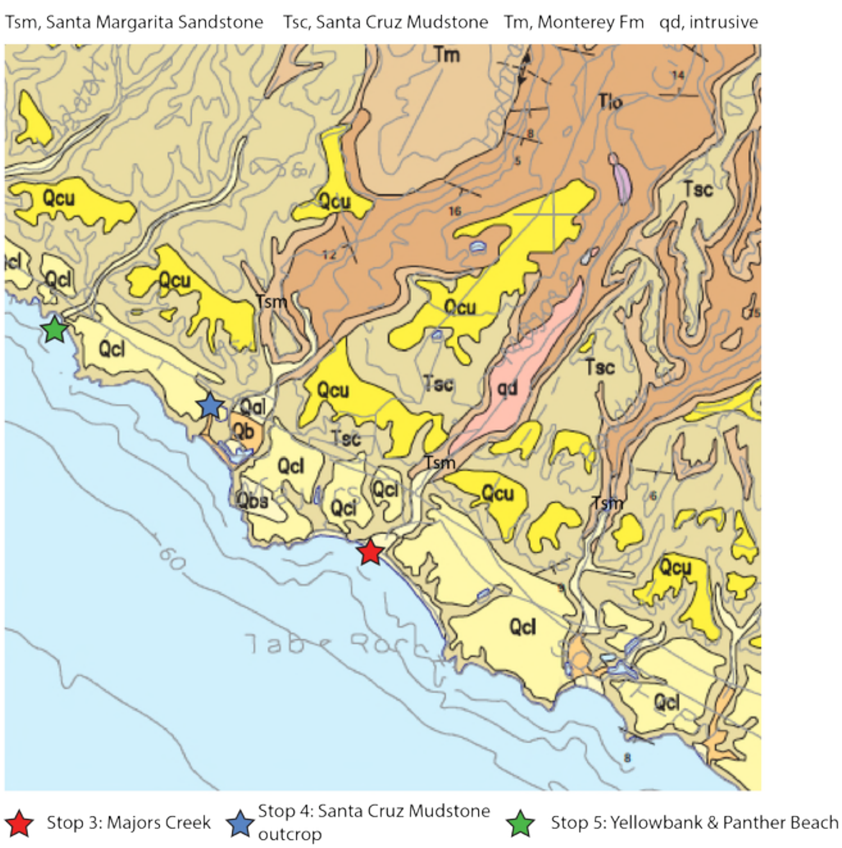


You may see two dominant fracture sets, one at N30°E and one at N60°W, that align with the carbonate vent structures (figure above). This suggests that fracture permeability plays a role in the precipitation of authigenic calcite and in the flow of fluids and gas from the subsurface. The cylindrical holes visible in many of the vent structures may be the actual conduits for that fluid flow.

These vent structures closely resemble modern-day examples found on the floor of Monterey Bay (Aiello et al., 1999). Both modern and fossil vent features appear to be closely associated with fault systems. Specifically, the Miocene vent field of Stop 2 lies near the intersection of the Monterey Bay Fault (offshore) and the Ben Lomond Fault of the La Honda Basin. Although it is unknown if these particular features are methanogenic, modern-day vents in Monterey Bay are associated with water-column methane anomalies (Mullins and Nagel, 1982) and the occurrence of carbonate slabs in areas of active hydrocarbon seepage is common in other seafloor settings (Naehr et al., 2007).

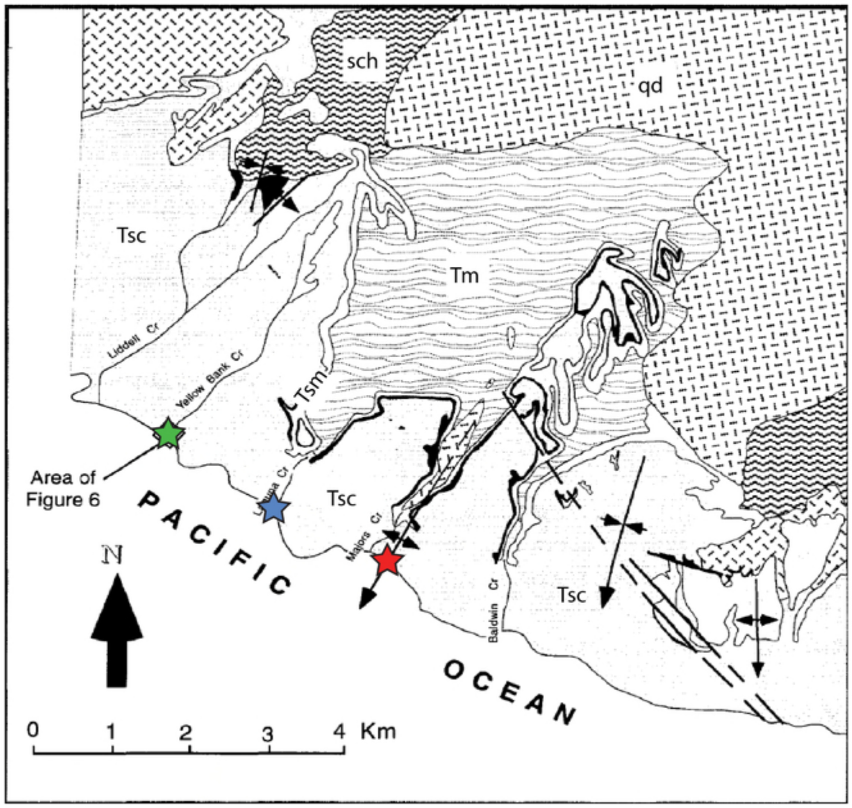
Maps for stops 3, 4, 5:

Geologic maps showing the relative locations of field trip stops 3, 4, and 5.



Geologic map of Brabb et al. (1989) with field trip stops 3 at Majors Creek (red star), 4 at Laguna Creek (blue star), and 5 at Yellowbank Creek (green star).

sch, metamorphic roof pendant



Stop 3: Majors Creek | Stop 4: Santa Cruz Mudstone outcrop | Stop 5: Yellowbank & Panther Beacl

Detail of petroleum-bearing sediments by Thompson et al. (1999). Formations and field trip stops as above.

Stop 3: Majors Creek overlook

As we stop at the intersection of Coast Rd/Highway 1 with the northern spur of Scaroni Rd, we look across the highway at an anticline featuring oil-saturated Santa Margarita Sandstone lying on basement and capped by Santa Cruz Mudstone. Although this has been described in the literature as an "exhumed oil field," it has never been produced so is more accurately described as an exhumed oil accumulation. Numerous low angle dikes and sills in the vicinity of Majors Creek (Thompson et al., 1999) may have leaked the bulk of the petroleum away.

Look to the north, across the road, at dark outcrops lining both sides of the gully, especially on the left side. A small quarry just above the road on the left exposes the contact of these dark rocks and the light-colored rocks. Light-colored cap rocks, the Santa Cruz Mudstone, overlie the dark, resistant rocks—hydrocarbon-saturated Santa Margarita Sandstone. In this creek, these Miocene age units they directly overlie Mesozoic granitoid igneous basement, hidden in the brushy gully bottom. The petroleum trapping style illustrated by this field trip stop is type B in **Figure 2**, "depositional-accumulations along the cross-bedded facies."

The role of this stop in our investigation of the coastal petroleum system is that it illustrates the "plumbing system," or migration of petroleum from the (offshore?) thermally mature source rock immediately updip of Majors Creek at an inland quarry. That spot, which we won't visit on this trip, is the site of an abandoned asphalt quarry called the City Street Improvement Company (http://quarriesandbeyond.org/states/ca/quarry_photo/ca-scruz_photos_2.html). At the quarry, evidence of petroleum migration abounds: thin, aligned joint sets are filled with asphalt; boulders of asphalt pepper the hillside; and an extensive asphalt outcrop/talus slope is seen. Asphaltic content of the sands in this quarry and locations like it range from 4 to 18% by weight (Clark et al., 1999).

This location represents the accumulation of a normal oil of ~ 30° API gravity that was trapped on a regional high 7-8 Ma based on the movement of the San Gregorio Fault. Oil migrated into the sand injectites of Santa Margarita Sandstone and fractures in the Santa Cruz Mudstone where it was later biodegraded at a temperature less than 80°C to a heavy oil (<10° API). When the heavy oil was exposed to the surface, further thickening of the lighter hydrocarbons caused full conversion to asphalt.

Majors Creek overlook

Quarry updip from Majors Creek (not visited on this trip)

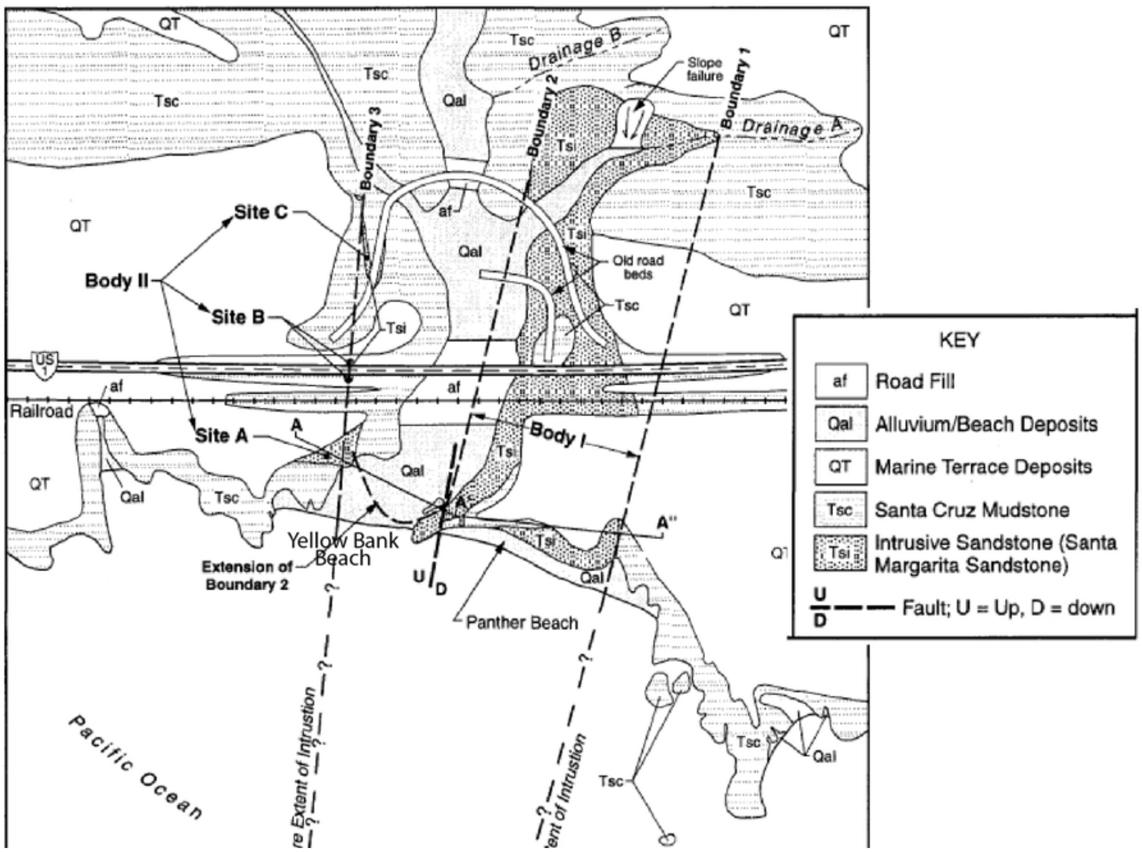
Stop 4: Outcrop of Santa Cruz Mudstone

This road cut at Laguna Creek lies about halfway in between Majors Creek and Yellowbank Beach and marks a dividing line between bituminous, small-size intrusions to the southeast and non-petroleum-bearing, large-size intrusions to the northwest (see map on preceding page; Thompson et al., 1999). In the photos below, bedding can be observed dipping to the northwest. A thin sheared dike is visible cutting through the entire outcrop (bottom left; camera lens cap for scale in bottom two photos) and a conchoidal fracture is seen on the margin of the dike (bottom right).

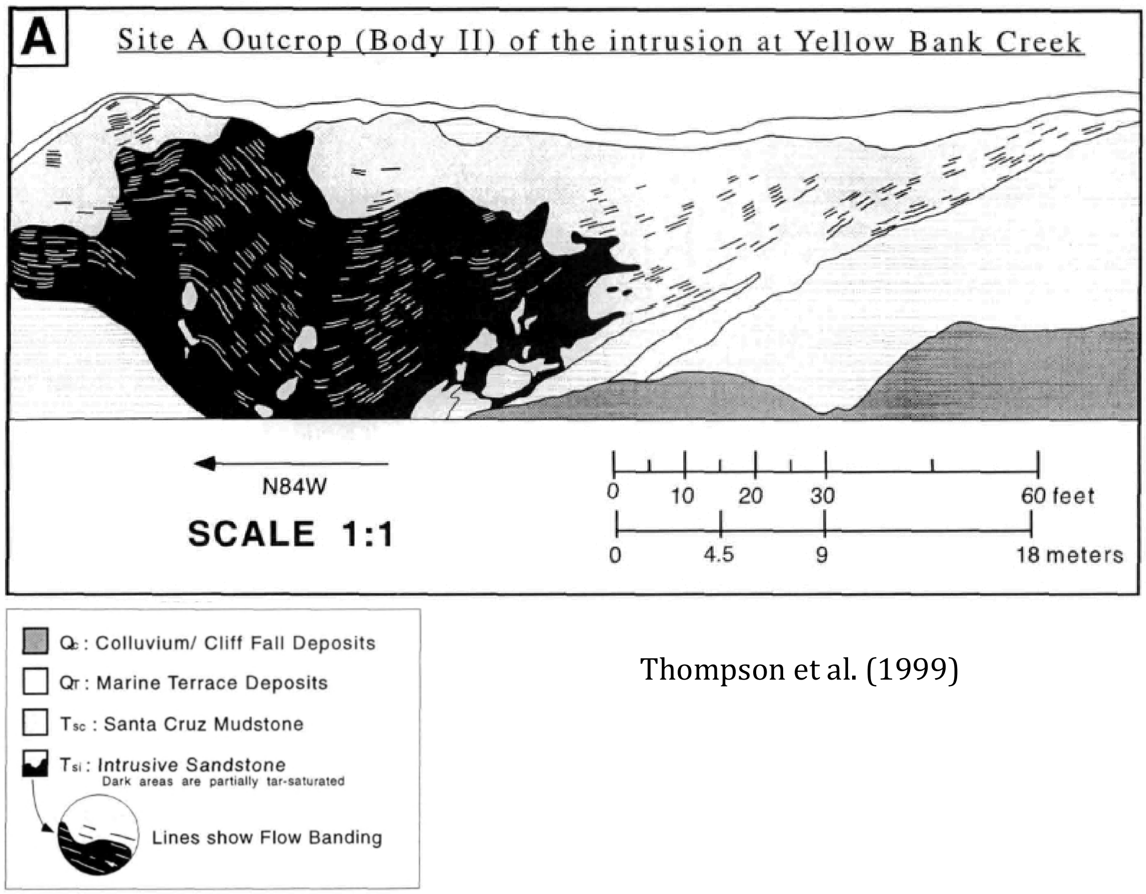
Stop 5: Yellowbank Beach and Panther Beach

The geology at this stop is complex and we will spend the bulk of our field time here investigating a massive injectite complex. As we descend the sea cliff from the parking area, Yellowbank Beach is to our right (northwest; photo 1, below). The intrusion seen in the distance is called Body II, Site A by Thompson et al. (1999) (photo 2, below).

The role of this stop in the investigation of the coastal petroleum system is to illustrate the reservoir rocks.



The red rectangle approximately outlines the injectite and part of its host rock. From the field guide of Hurst (2012): "The internal structures are steep and dolomite cemented. Here, the lower margins of the injectite are exposed (panel a). The exposure is fan-shaped in cross section and internal structures tend to steepen toward the center and lie approximately parallel to the margins (panel b). Superficially the margins appear sharp and erosive but in detail smaller dikes and sills intrude into the host strata (area of detail, panel b). The contact surface with the host-strata is marked by the presence of tensional structures. Above this contact surface, large blocks and rafts of the host-strata occur. The latter are locally fractured and diffusely intruded by sand."



Thompson et al. (1999)

Hurst (2012) concludes that "the space necessary to accommodate such a thick laterally extensive body is unlikely to have formed by sand injecting into simple fractures." Instead, he argues for forceful, erosive, and rapid emplacement of the sand.

Thompson et al. (1999) summarize the development of the Yellowbank injectite in the following diagram.

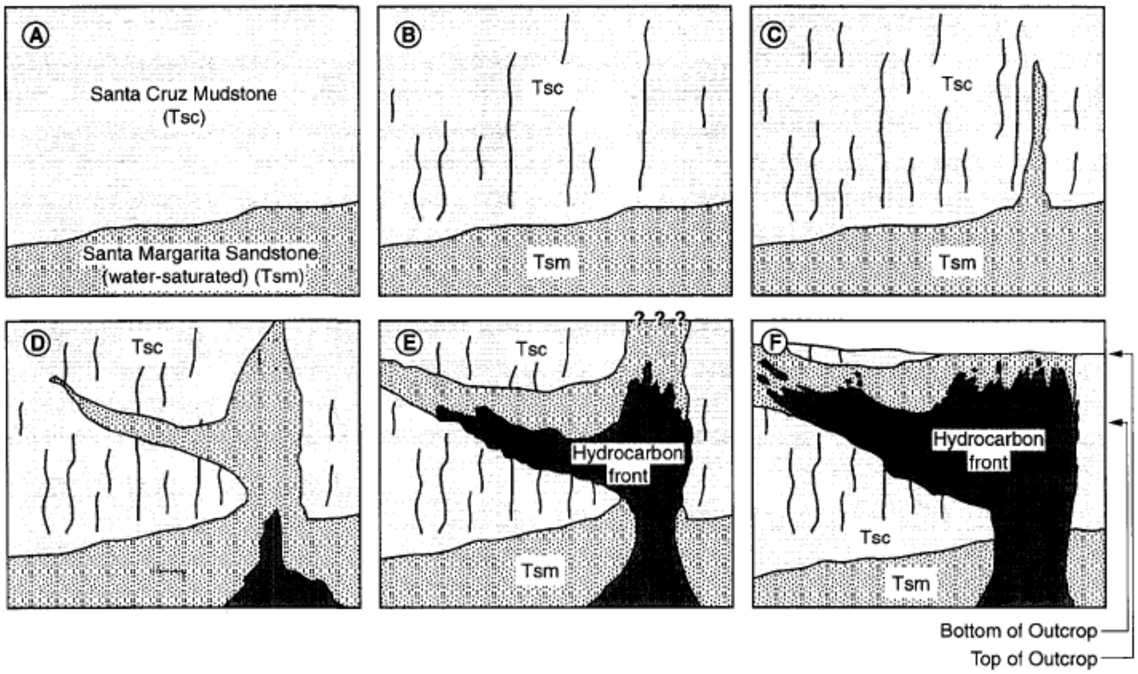
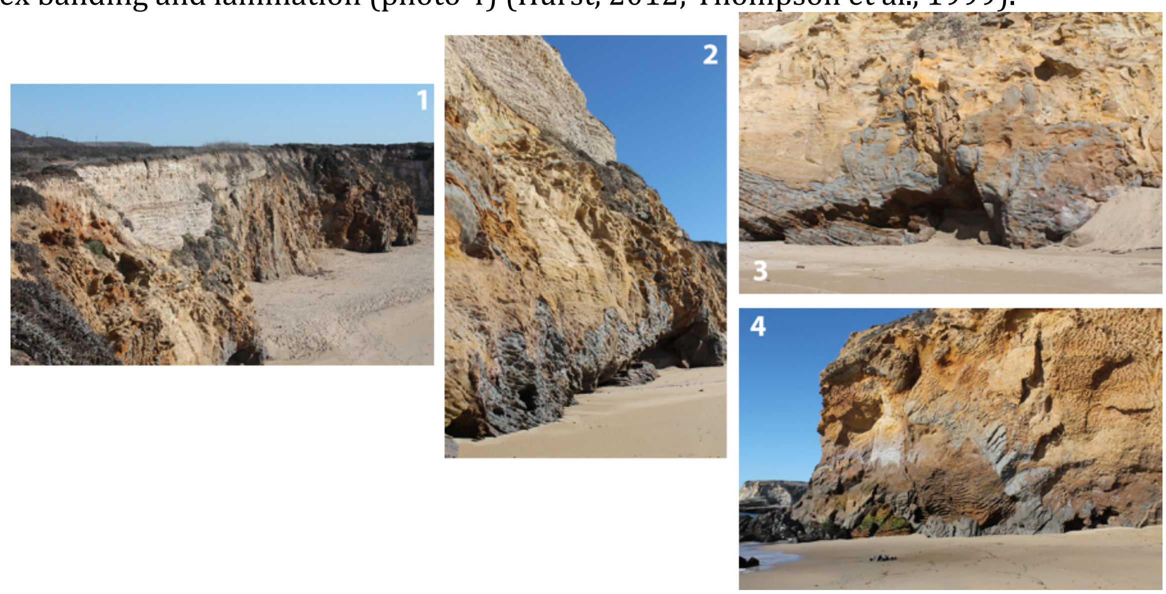


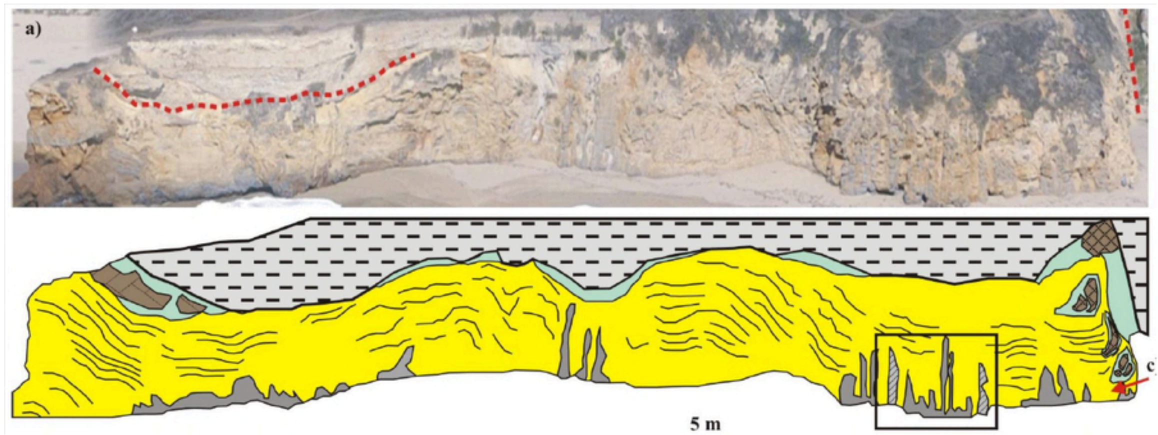
Figure 16. Schematic diagrams illustrating development of the sandstone intrusion at Yellow Bank Creek: A) Middle to late Miocene sedimentation of the Santa Margarita Sandstone and the overlying Santa Cruz Mudstone; B) Late Cenozoic fracturing or faulting is most intense in relatively brittle siliceous mudrocks of the Santa Cruz Mudstone and less pronounced in unlithified, water-saturated parts of the Santa Margarita Sandstone; C). Vertical injection of water-saturated sands from the bioturbated facies of the Santa Margarita Sandstone along a fracture or fault creates a dike; D) Horizontal breakout of the water-saturated sands along bedding planes in the Santa Cruz Mudstone creates a sill extending from the dike. Flow banding develops in the sill at this stage. A hydrocarbon front begins to migrate into the intrusion, being sourced from layers (cross-bedded facies ?) in deeper levels of the Santa Margarita Sandstone; E) Continued fluidized sediment flow from the Santa Margarita Sandstone and emergence of the hydrocarbon front which is injected into the water-saturated intrusion as immiscible bodies of petroleum and hydrocarbon-bearing sands. These form vertically elongated "pipes" in the area of the dike and spheroidal "bubbles" which cut across the flow banding in the area of the sill. Question marks indicate the possibility that fluidized sedimentes broke through to the seafloor and erupted as a sediment volcano. Dolomitic cementation occurs within the hydrocarbon front; and F) Uplift and erosion expose the intrusion to groundwater flow which produces complex patterns of limonite staining. Arrows show an outcrop geometry that is similar to the seacliff exposure of Body I of the intrusion at Yellow Bank Creek (Figure 10B).

Tide permitting, next we visit Panther Beach, located through the sea arch from Yellowbank Beach (photos below taken from Yellowbank Beach, left, and from Panther Beach, right).

The cliffs at Panther Beach expose a 305 m wide by 24 m high outcrop (photo 1, below) of an injectite containing extensive dolomite cement (photos 2, and 3), and complex banding and lamination (photo 4) (Hurst, 2012; Thompson et al., 1999).



From Hurst (2012): "Here the margin of the sand injectite is approximately vertical, probably along a fault. Near the margin large clasts of the host Santa Cruz Mudstone are incorporated into the injectite. Looking northward the upper margin of the intrusion is visible. The margin is irregular, probably scalloped, and bedding in the host strata is observed to be truncated by the sand. Dolomite cements form sub-vertical columns along the base of the outcrop that were interpreted to have formed along an upward-migrating front of petroleum, which post-dated sand injection; if so, the dolomite cements form evidence of a hydrocarbon migration front. If this hypothesis is correct it is unclear why petroleum did not fill the entire sand body and certainly why they did not rise to the top of the sand body." Hurst's (2012) interpretation of the entire cliff at Panther Beach is provided below.



In summary, the light-colored Santa Cruz Mudstone at these localities were both water- and oil-saturated, suggesting the source of the sands was near the oil-water contact of a Miocene oil field, possibly on the northwestern flank of the Majors Creek accumulation. Overall, this intrusive reflects a complicated history of multiple intrusions plus the immiscibility of oil- and water-saturated sands.

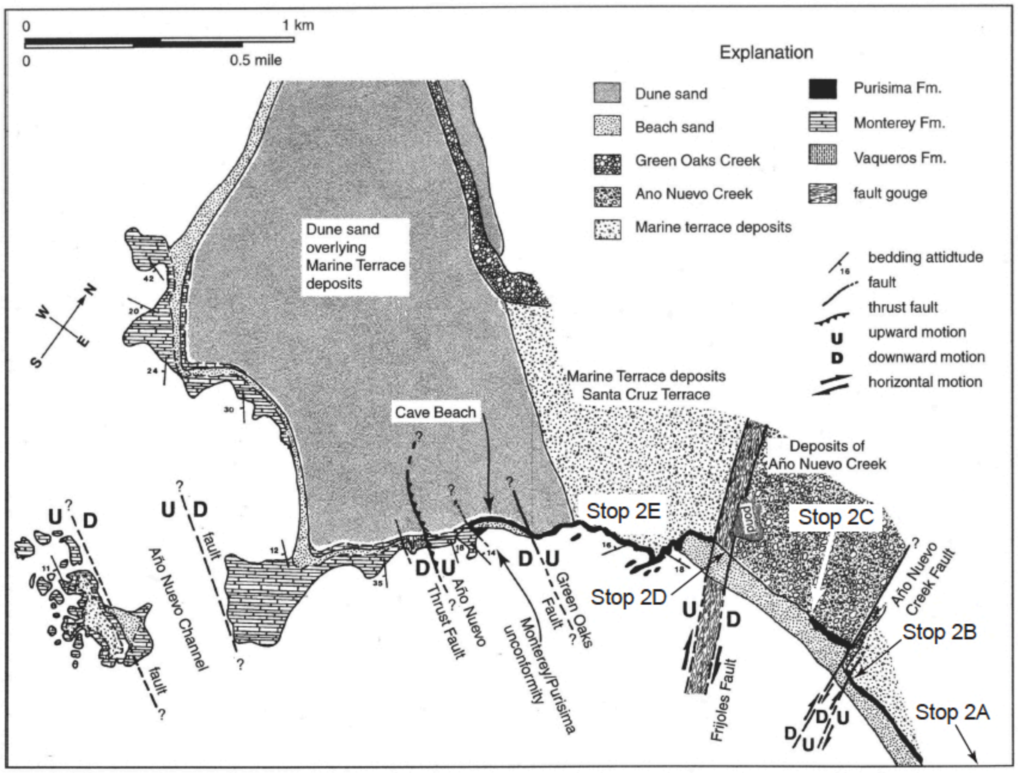
Stop 7: Año Nuevo State Park

Our northwestern most field trip stop in coastal San Mateo County takes advantage of an exposure of the Monterey Formation, not seen anywhere on the coast in Santa Cruz County. Point Año Nuevo itself is a small onshore fragment of the offshore Outer Santa Cruz Basin (White, 1990). Perhaps more importantly, this stretch of land lies on the west side of the San Gregorio Fault (**Figure 1**), meaning that although it is instructive to examine the Monterey Formation in this setting, it is not the organic-rich source rock that generated the oil that charged the Santa Margarita Sandstone of the Santa Cruz County coast. Similarly, the Santa Cruz Mudstone that is so ubiquitous east of the fault is missing entirely west of the fault; the correlative section west of the San Gregorio Fault lies some 150 km north near Point Reyes (**Figure 13**).

The San Gregorio Fault zone at Point Año Nuevo is about 2.5 to 3 km wide from the base of the Santa Cruz Mountains to Año Nuevo Island seen offshore. Within this zone, at least seven individual faults accommodate right-lateral slip (Weber and Allwardt, 2001).

The Monterey Formation at Año Nuevo records the deepest burial (hottest temperatures) yet seen on this trip, because silica is predominantly quartz in the cherty lithologies and opal-CT in the porcelanite (White, 1990). At this spot we are examining a dip section of Monterey several tens of meters thick that is folded into a NW trending anticline between the Año Nuevo Fault and the overlying Purisima Formation (Clark, 1981). Here the Monterey Formation is also thrust over the older, underlying Vaqueros Sandstone, which charged with oil (see photo below).

Figures below from Weber and Allwardt (2001).



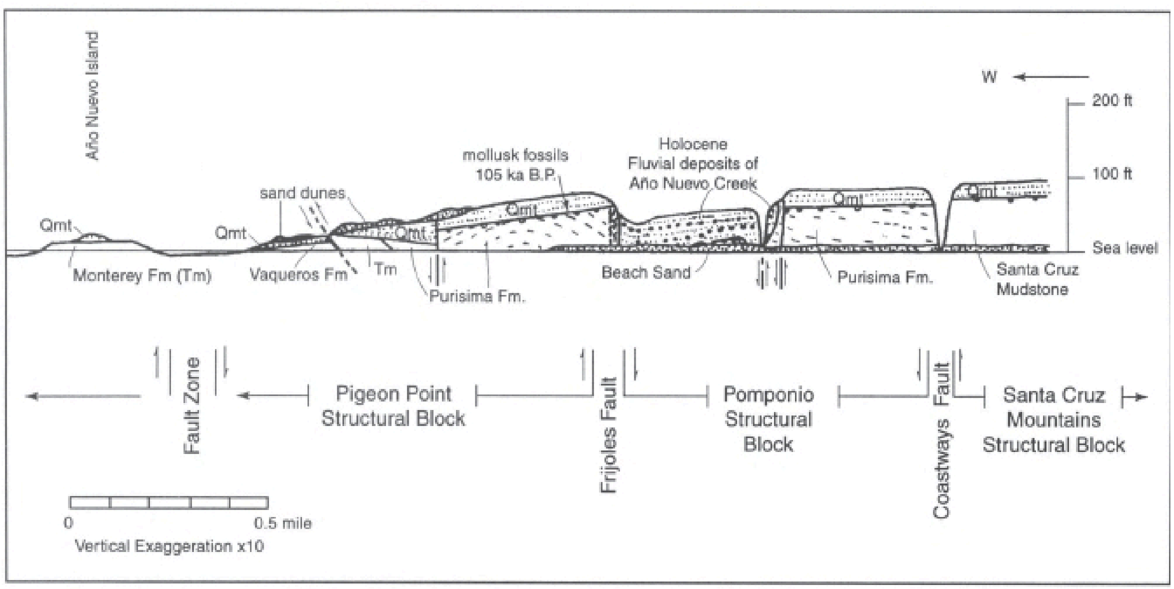
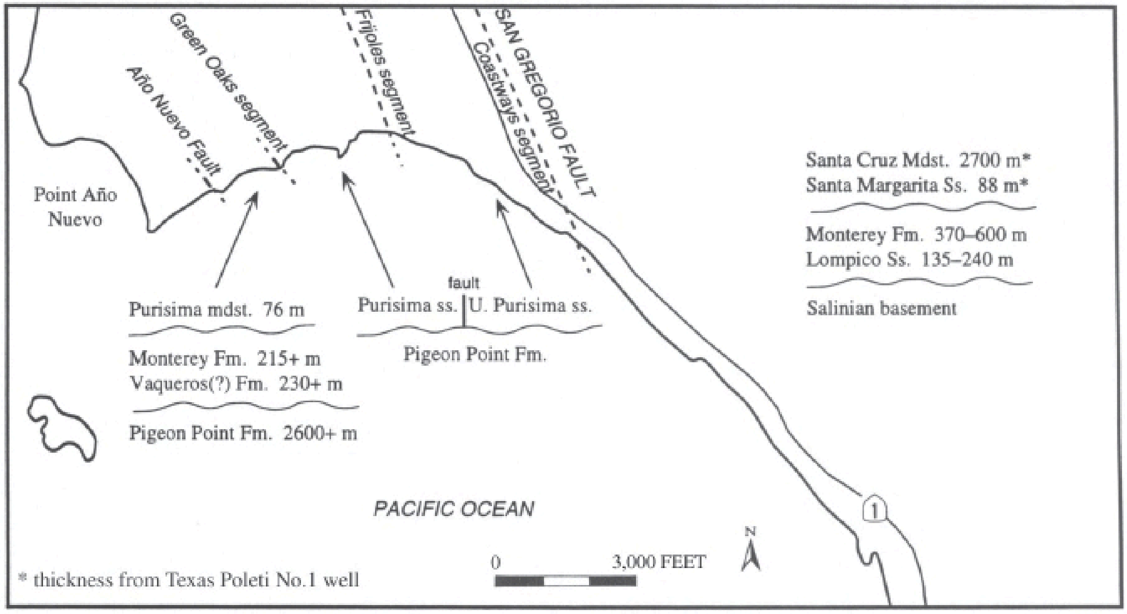
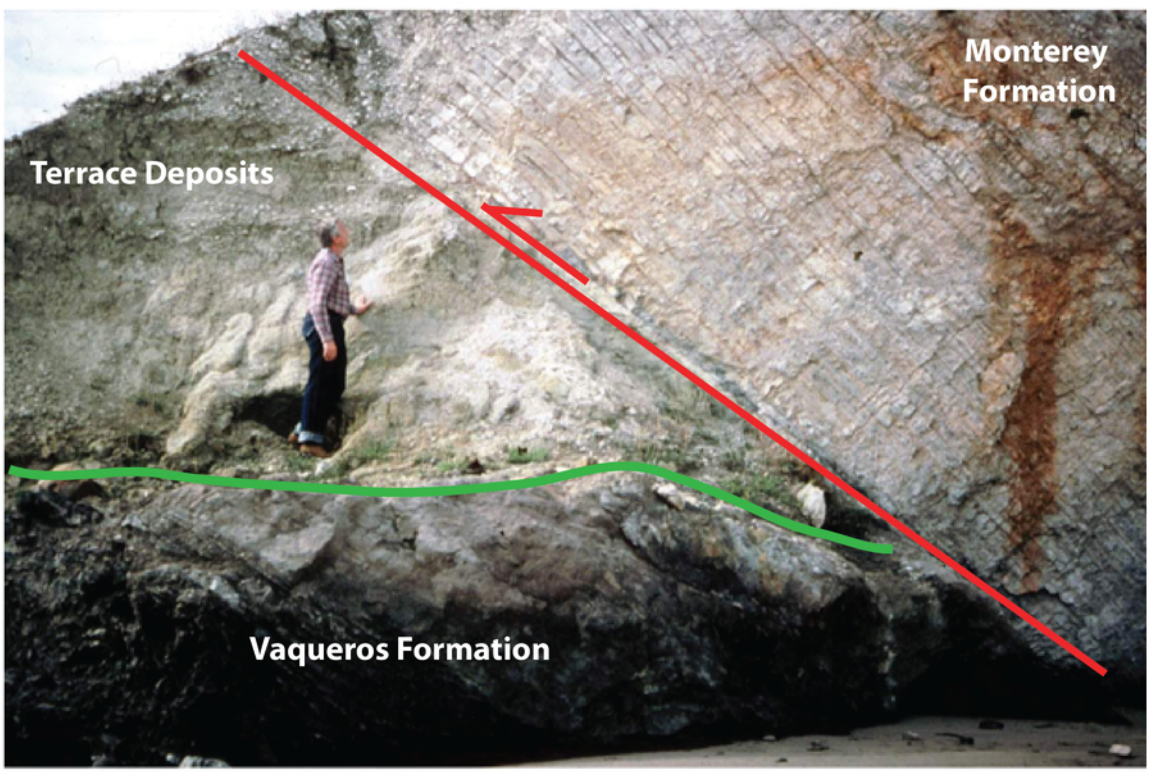


Figure from Weber and Allwardt (2001). Photo illustrating fault contact between overlying Monterey Formation and underlying Vaqueros Formation is what we are seeking at this stop. Photo by Steve Graham.





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Notes

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