2012 Field Trip Guide

Objectives: We will drive south of Stanford on I-280, 85, and Calif. Hwy. 17 to Santa Cruz. The day will be spent examining Tertiary sedimentary rocks of the Miocene/Pliocene Santa Cruz Mudstone and a swarm of hydrocarbon saturated sandstone dikes ("injectites"). There will be five (5) main stops. To end the day, we will drive north on highway 1 and back to the Peninsula via highway 84. A safety briefing will occur at each stop.

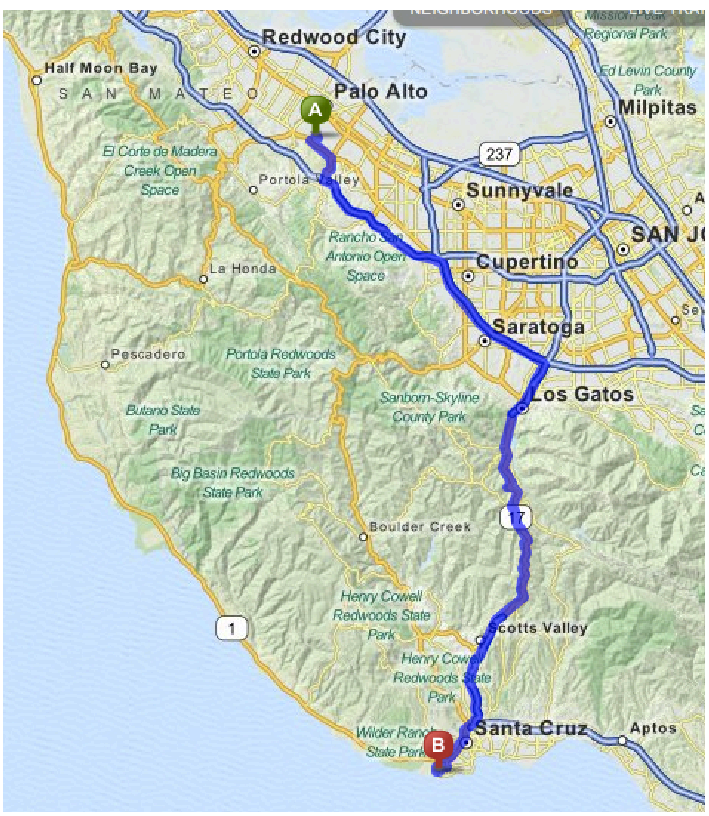
Arrival	Departure	Miles	Stop #	Stop Description	Special Notes/Hazards
7:45 a.m.	8:00 a.m.		0	(p. 27-28)	Leave on time.
8:00 a.m.	9:00 a.m.		1	Natural Bridges State Beach (p. 29)	Restroom break (last restrooms before lunch) (1 hour/45 miles).
9:30 a.m.	10:00 a.m.		2	Carbonate cold seeps (p. 30, p. 46)	Minor rock scrambling.
10:15 a.m.	10:45 a.m.		3	Majors Creek (p. 31, p. 48)	Look across highway (do not cross road).
11:00 a.m.	noon		4	Yellow Bank and Panther beaches (p. 32, p. 49)	Moderate rock scrambling. Take valuables with you.
12:15 p.m.	1:45 p.m.		5	Beauregard Vineyards (p. 33)	Lunch and restroom break, wine tasting.
2:15 p.m.	3:00 p.m.		6	Quarry (p. 34, p. 54)	Asphalt-filled fractures.
3:05 p.m.	3:30 p.m.		7	Quarry (p. 34, p. 55)	Asphalt outcrop.
3:35 p.m.	4:45 p.m.		8	Stanford University (p. 35)	Return to vineyard for restroom break, stop at San Gregorio State Beach for restroom, or return to campus.

Sunrise: 7:01 a.m. Sunset: 4:52 p.m.

High tide: 5.7 at 9:42 a.m. Low tide: -0.4 at 5:13 p.m.

Stop 0: Stanford University parking lot behind Tresidder Memorial Union (corner of Mayfield Ave and Lagunita Dr on Stanford campus, Stanford, CA) -122.1705°/37.4231°

Parking lot behind Tresidder



Mapquest map from Stanford to Natural Bridges

Driving directions to Stop 1: Natural Bridges State Beach

Route	**Distance**
Parking lot at Mayfield Ave & Lagunita Dr: drive SE (turn L) on Mayfield Ave to stop sign, then R turn 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	7.6 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
Turn L on Swift St	0.7 mi
Turn R on W Cliff Dr	0.5 mi
Take W Cliff Dr into Natural Bridges State Park (lead car will pay entrance fee for all vehicles)	0.2 mi

Stop 1: Natural Bridges State Beach (W Cliff Dr, Santa Cruz, CA) -122.0570°/36.9522°

This is a restroom stop only, however you may be interested to know that the boardwalk trail just beyond the gift shop and restrooms takes you to a grove of Eucalyptus trees that serve as the winter (October-February) home for thousands of Monarch butterflies. On a warm day, their wings are open and the trees appear to be dripping with orange leaves. On a cool day, what appear to be thousands of brown leaves are actually the closed wings of the Monarchs.

Driving directions to Stop 2: Carbonate Cold Seeps

Route	**Distance**
Exit Natural Bridges State Park.	0.0 mi
Take W Cliff Dr to just past intersection of Swift St.	0.5 mi
Enter parking lot on R (if full, find street parking nearby; if you get to John St on the L, you've missed the parking area).	0.1 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°
Geologic discussion on page 46

Driving directions to Stop 3: Majors Creek overlook

Route	**Distance**
Exit parking lot and drive N on Swift St to highway 1/Coast Rd.	0.7 mi
Turn left on Cabrillo Hwy/Hwy 1 and drive to pull-off at northern intersection with Scaroni Rd (pass the first occurrence of Scaroni Rd).	5.4 mi

Stop 3: Majors Creek overlook (north spur of Scaroni Rd at intersection with Cabrillo Hwy/Hwy 1)
-122.1394°/36.9806°
Geologic discussion on page 48

Driving directions to Stop 4: Yellow Bank Beach/Panther Beach

Route	Distance
Carefully turn L to continue north on Cabrillo Hwy/Hwy 1.	
You will pass two turn-offs for Laguna Rd. Continue driving north and turn L into a narrow dirt parking area on the left. 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.	1.8 mi

Stop 4: Yellow Bank Beach and Panther Beach (Cabrillo Hwy/Hwy 1)
-122.1681°/36.9929°
Geologic discussion on page 49
Do not leave any valuables in the car.

Driving directions to Stop 5: Beauregard Vineyards

Route	Distance
Carefully turn L to continue north on Cabrillo Hwy/Hwy 1.	.9 mi
Turn R on Bonny Doon Rd. The Vineyards entrance is just past the golden-colored grape leaves on your right.	3.7 mi

Stop 5: Beauregard Vineyards (10 Pine Flat Rd, Bonny Doon, 95060) -122.1504°/37.0420°

Here we will stop and eat lunch at Beauregard Vineyards. Following lunch, whomever is interested in tasting a flight of 5 Chardonnay and Pinot Wines may do so inside. This is also a restroom break.

Driving directions to Stop 6: Quarry (asphalt-filled fractures)

Route	**Distance**
Drive southeast on Bonny Doon Rd to edge of vineyards and turn L on Smith Grade Rd.	.4 mi
Drive slowly and with caution on Smith Grade Rd.	3.0 mi
Just following hairpin turn creek crossing, turn R onto Moore Ranch Rd. Continue past Lupine Lane, over two prominent speed humps. Stay L where road branches, past a red house with two turrets on the R, and into quarry.	1.5 mi
Continue on paved road, bearing to the right, and park at far end of wide area.	0.2 mi

Stop 6: Quarry asphalt-filled fractures (Dead-end of Moore Ranch Rd, past Lupine Lane)
-122.1073°/37.0051°
Geologic discussion on page 54

Driving directions to Stop 7: Quarry (asphalt outcrop)

Route	**Distance**
Exit parking area and turn L at intersection with gate back to wide pullout on R.	0.2 mi

Stop 7: Quarry asphalt outcrop (Dead-end of Moore Ranch Rd, past Lupine Lane)
-122.1098/37.0060°
Geologic discussion on page 55

Driving directions to return to Stanford University

Route	**Distance**
Exit quarry and re-trace route to Moore Ranch Rd.	0.2 mi
Turn R on Moore Ranch Rd and drive to hairpin turn at Smith Grade Rd.	1.5 mi
Turn L on Smith Grade Rd	3.0 mi
Turn L on Bonny Doon Rd	3.3 mi
Turn R on Cabrillo Hwy/Hwy 1.	28.0 mi
Turn R on La Honda Rd/Hwy 84.	15.2 mi
At intersection with Skyline Blvd (Alice's Restaurant), continue straight, then turn L to remain on La Honda Rd.	3.2 mi
Turn sharp L onto Portola Rd.	0.8 mi
Turn L on Sand Hill Rd.	3.8 mi
Turn R on Santa Cruz Ave.	0.1 mi
Turn L on Junipero Serra Blvd.	1.0 mi
Turn L on Campus Dr East.	0.5 mi
Turn L on Mayfield Ave.	0.1 mi
Turn L at 4-way stop and R into parking lot at Lagunita Dr	

Background Geology

Summary of Petroleum System Elements

Source Rock: Probably the Miocene Monterey Formation of the adjacent offshore Outer Santa Cruz Basin

Reservoir Rock: Sand injectites in the Santa Cruz Mudstone, Santa Margarita Sandstone, possibly the Lompico Sandstone

Seal Rock: Santa Cruz Mudstone

Overburden Rock: Santa Margarita Sandstone, Santa Cruz Mudstone, Purisima Formation

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

Generation-Migration-Accumulation: generation timing uncertain, but before late Miocene emplacement of sandstone intrusions ("injectites"); migration occurred via injectites and possibly by fracture-enhanced permeability in carbonate vents.

Tectonic Context

The major structural feature that has affected the Santa Cruz County Coast is the San Gregorio Fault (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) document 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) obtain an displacement estimate of 115 ± 10 km along the San Gregorio Fault by correlating 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 2). Subsequently, Dickinson et al. (2005) reinterpreted onshore and offshore geologic mapping to revise cross-fault ties. They refined the total fault offset estimate to 156 ± 4 km.

Geologic Context

At our first four stops along the Santa Cruz County coast, we will be standing on marine terrace deposits that range in age from 65 ka to 220 ka (Perg et al., 2001), but looking up-close primarily at Santa Cruz Mudstone, and to a lesser extent, Santa Margarita Sandstone (brown and yellow units, respectively, figure 3; figure 4). Although the Monterey Formation crops out extensively in between stops 5 and 6/7, there are no exposures of the formation along the coast in our field trip area. 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 interbeds of turbiditic sandstone (Stanley, 1990). The Santa Margarita Sandstone is a shallow-marine unit that dates 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). The Santa Cruz Mudstone was deposited about 7 to 9 Ma (Stanley and Lillis, 2000) and conformably overlies the Santa Margarita Sandstone (Phillips, 1990). The basal age for the overlying Purisima Formation is 6.7 Ma (Mullins and Nagel, 1982).

Stop 5, located 3 miles north of the coastal highway, lies near the southern edge of intrusive and metamorphic basement rocks comprising Ben Lomond Mountain (term of Stanley, 1990). The route to Stops 6 and 7, located several miles southeast of Stop 5, traverses Monterey Formation and Lompico Sandstone (a middle Miocene unit underlying the Monterey Formation), before ending within the Santa Cruz Mudstone at an abandoned quarry.

A major geologic characteristic 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 300-400 km^2 in the Panoche and Tumey Hills (Hurst, 2012). On this field trip we will see a large subaerially exposed injectite complex at Yellow Bank and Panther beaches. Here, fluidized sands from the Santa Margarita Sandstone were injected upward into fractured Santa Cruz Mudstone (Thompson et al., 1999). The emplacement of these intrusions was facilitated because deposition and induration of the Santa Cruz Mudstone increase confining pressure within underlying clastic unit; stresses triggered the injection of sands into the lower pressured fractures in the mudstone (Thompson et al., 1999).

Petroleum Context

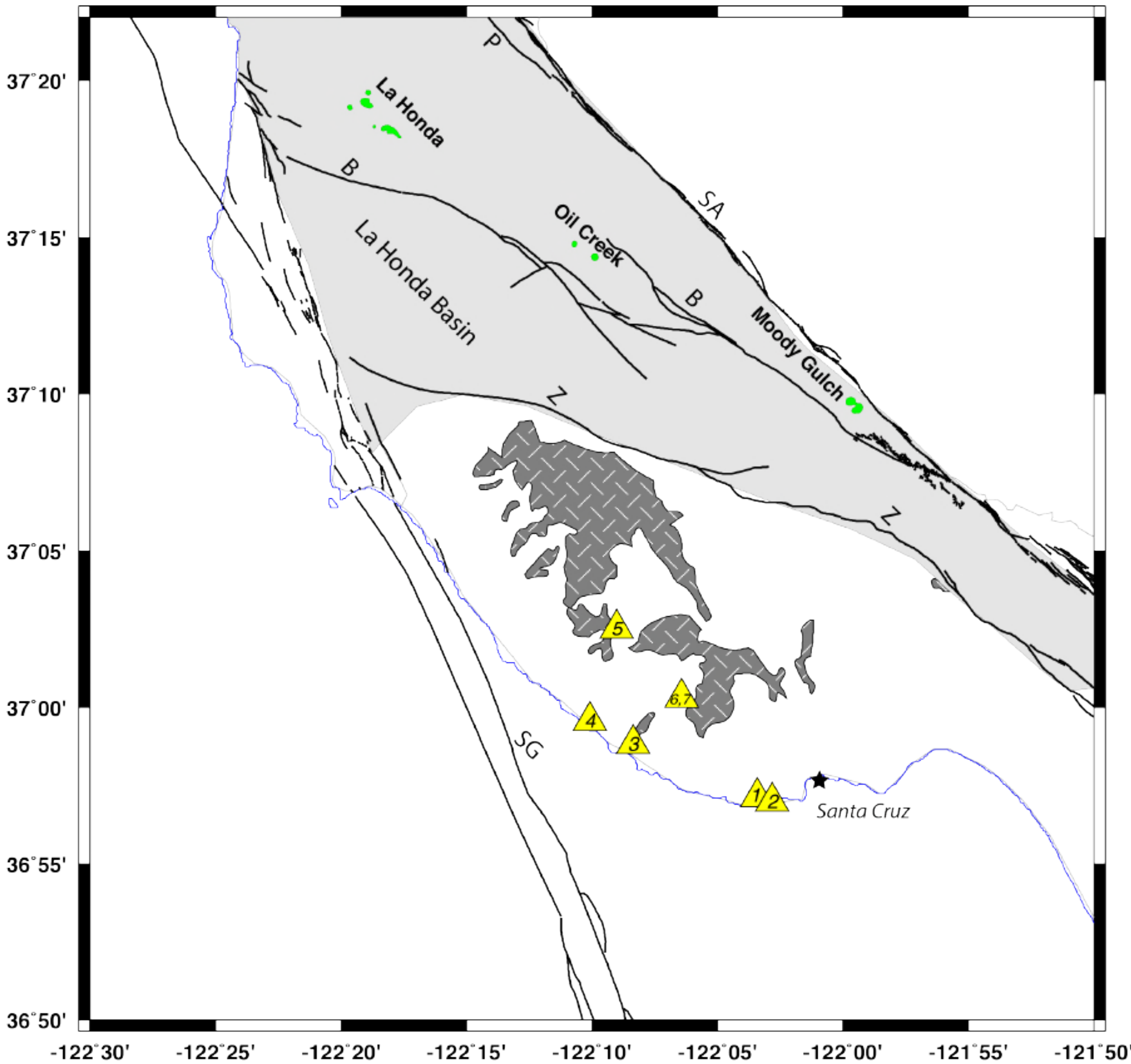
The outcrops of the Santa Cruz County Coast lie due south of the La Honda Basin, described in detail by Stanley (1990). The La Honda basin is a petroliferous basin containing 5 small oil fields that have produced nearly 2 million barrels of oil and 300 million cubic feet of gas. Lillis and Stanley (1999) performed a stable carbon isotope and biomarker analysis of the five oil fields of the La Honda Basin. Although oil-source rock correlation was lacking, they conclude that hydrocarbons from at least 3 of the 5 fields were generated from Monterey Formation. The close proximity of the Santa Cruz County coast to the proven petroleum system of the La Honda Basin indicate that similar petroleum system elements are at work along the coast.

Petroleum deposits south of the La Honda Basin consist of asphalt-saturated sandstone. Natural seeps of asphalt and bitumen are documented along the Santa Cruz County coast by Hodgson (1987) and Peters (2008) (see .kmz files available at http://walrus.wr.usgs.gov/seeps/where.html). The likely source rock is California's "superstar" oil producer, the Monterey Formation, in the Outer Santa Cruz Basin offshore. The Outer Santa Cruz Basin extends from Monterey Bay to a point offshore Half Moon Bay, a distance of about 65 km (Heck et al., 1990). It is about 20 km wide. Two exploratory test wells were drilled within the basin in 1967 by Shell Oil Company (Heck et al., 1990). The P-036 #1 well, drilled on an anticline, had a total depth of 9,490 feet (figure 5); nearly 3,000′ of the section was Monterey Formation (Heck et al., 1990). The P-035 #1 well, located 20 km southeast of the P-036 #1 well, was also drilled on an anticline and encountered 3,700′ of Monterey Formation (Heck et al., 1990); some of this is probably the result of structural thickening. The total depth of that well was 7,736′.

Lillis and Stanley (1999) and Hurst (2012), among others, suggest that the Santa Cruz Mudstone could also serve as a local hydrocarbon source. However, overburden thicknesses in the two offshore wells range between 1,800′ and 2,500′, making burial depths sufficient for thermal maturation and petroleum generation unlikely. Uplift and erosion associated with active strike-slip faulting in the area has likely breached any existing traps in the region.

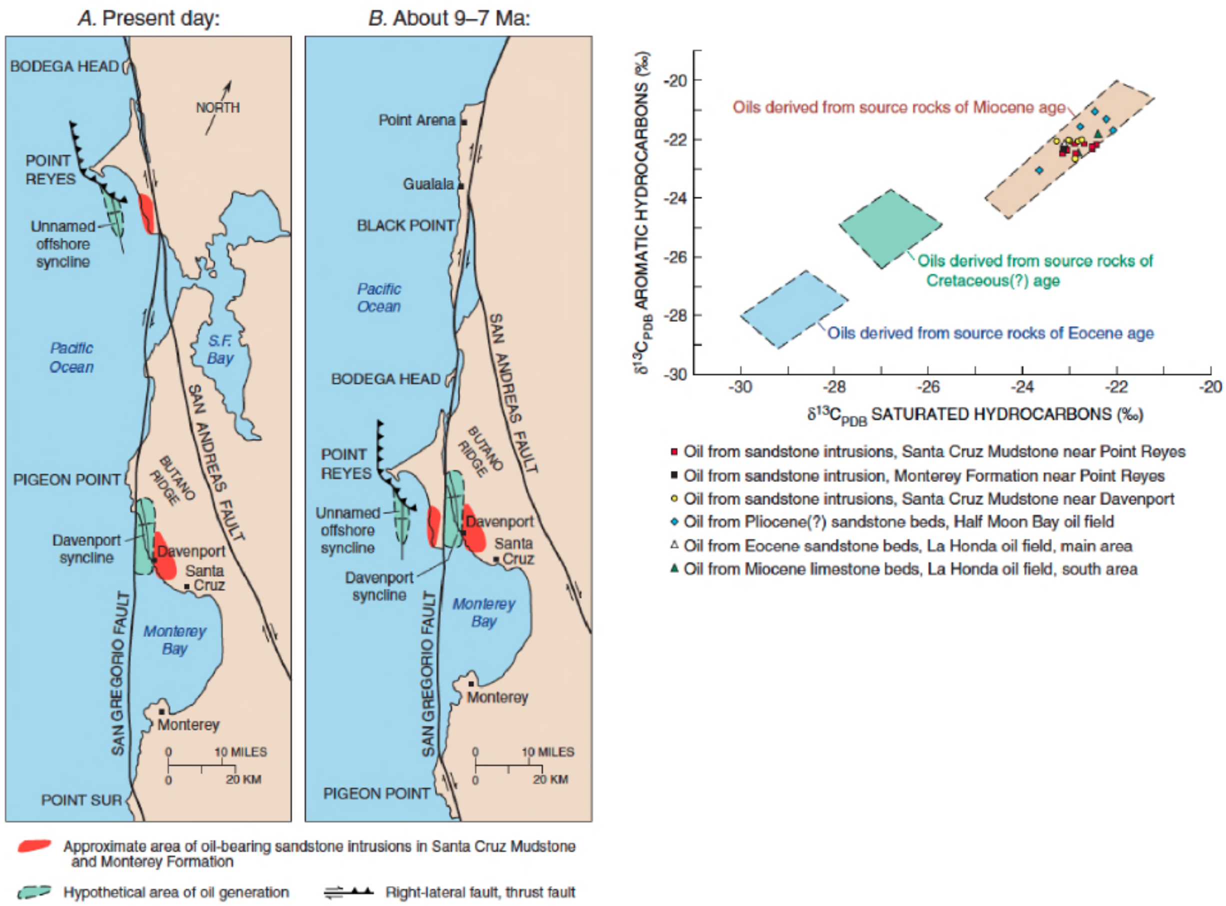
The next several figures provide an overview of the region. Detailed descriptions of each field trip stop follow. All photographs are by Allegra Hosford Scheirer, 2012.

Figure 1, Location Map, Santa Cruz County Coast



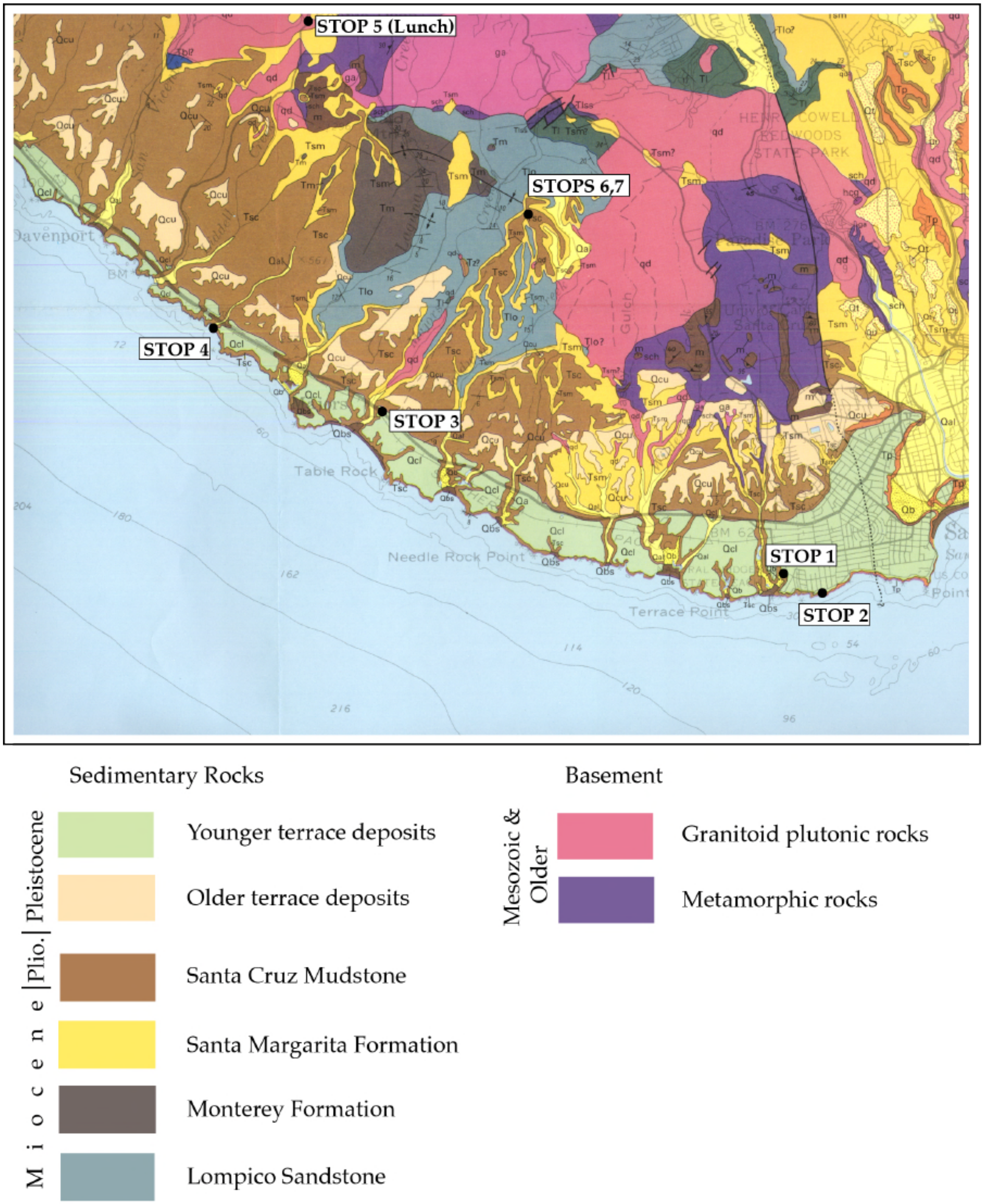
Gray shaded area indicates the La Honda Basin. Green-filled polygons are three of the 5 oil fields in the basin; the other two are located to the northwest outside of the map area. Dark gray stippling denotes basement rock of the Santa Cruz Mountains. Yellow-filled, numbered triangles are field trip stops. Major faults are from the USGS Quaternary Fault and Fold Database (http://earthquake.usgs.gov/hazards/qfaults/).

Figure 2, Regional context for San Gregorio Fault



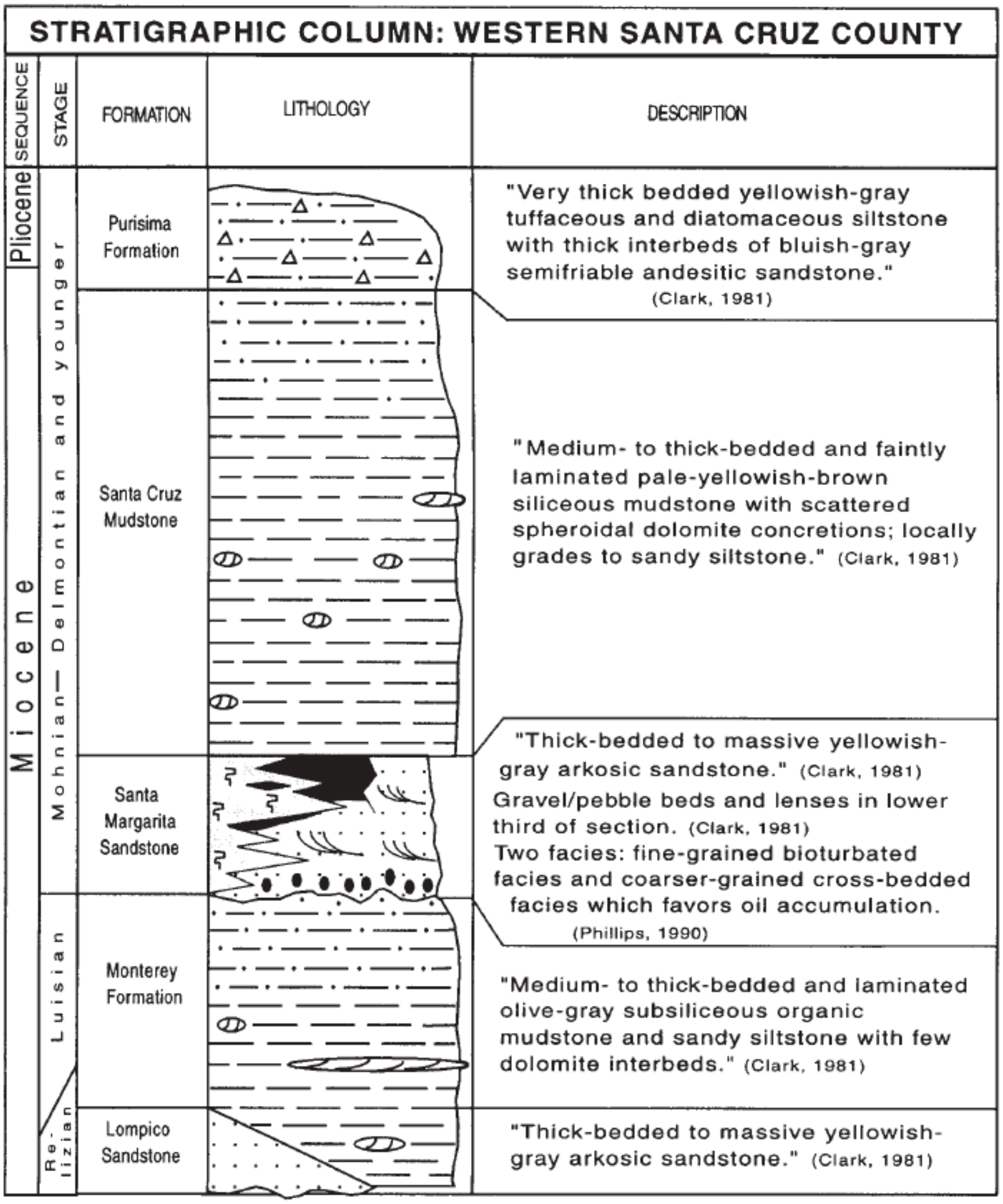
Stanley and Lillis (2000)

Figure 3, Geology Map, Santa Cruz County Coast

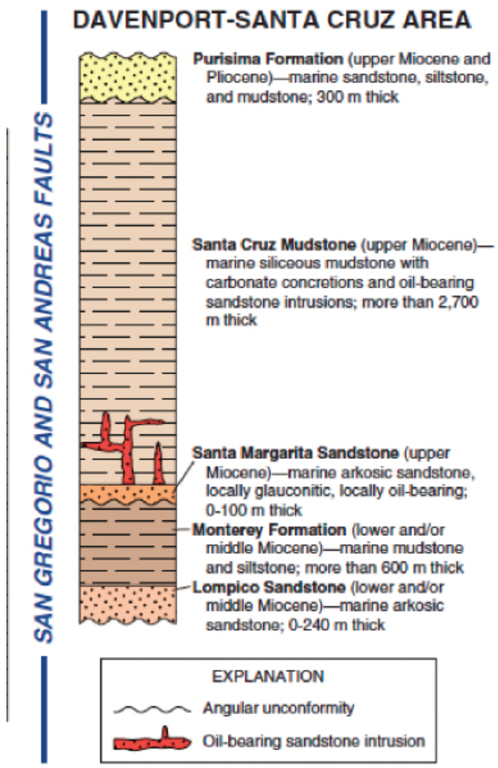


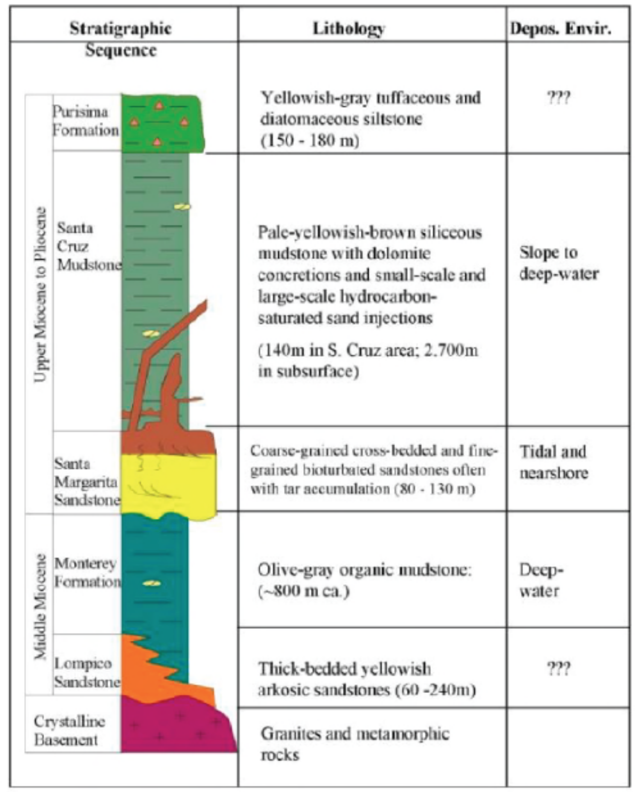
Modified from Brabb (1989)

Figure 4, Stratigraphic Columns of Santa Cruz County Coast



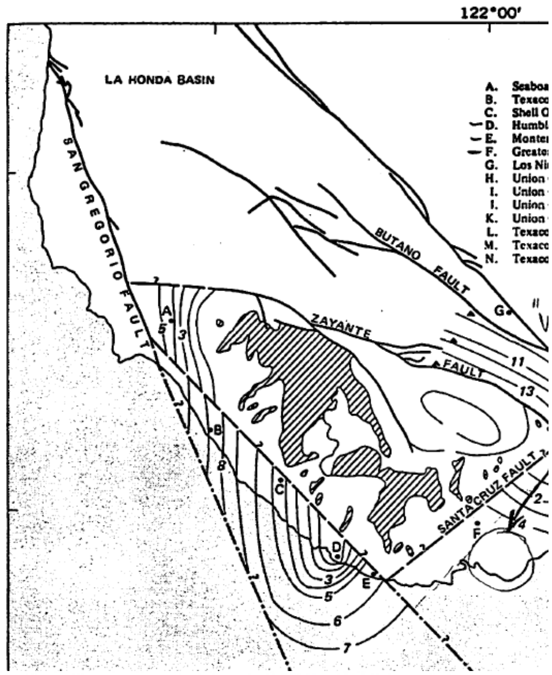
Brabb (1989)



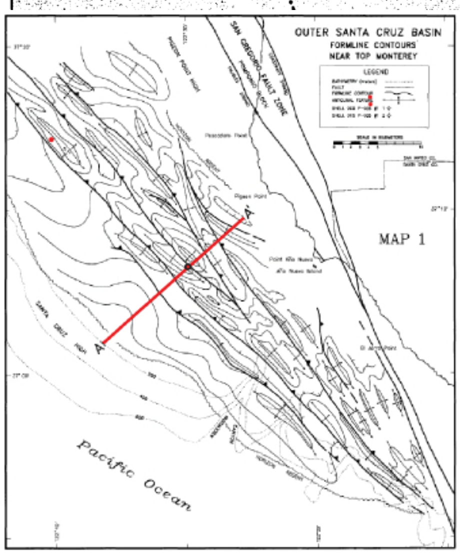


Stanley and Lillis (2000) Hurst (2012)

Figure 5, Subsurface structure in vicinity of Santa Cruz County coast



Basement depth in thousands of feet below sea level (Ross and Brabb, 1973). Santa Cruz Fault is unsupported by subsequent data (Stanley, personal communication).



Heck (1990)
Filled red circles indicate the locations of P-035 #1 and P-036 #1 wells. Seismic line A-A' shown below.

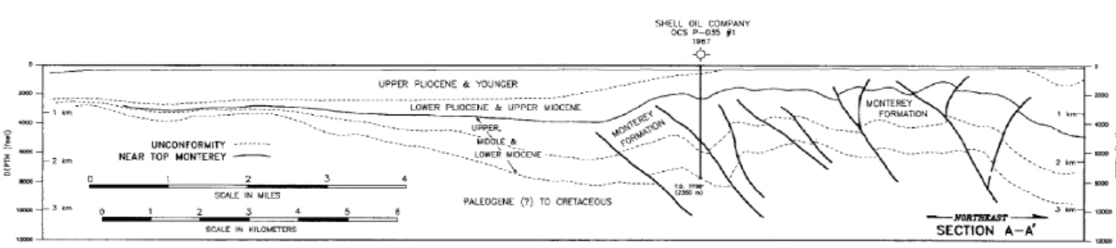
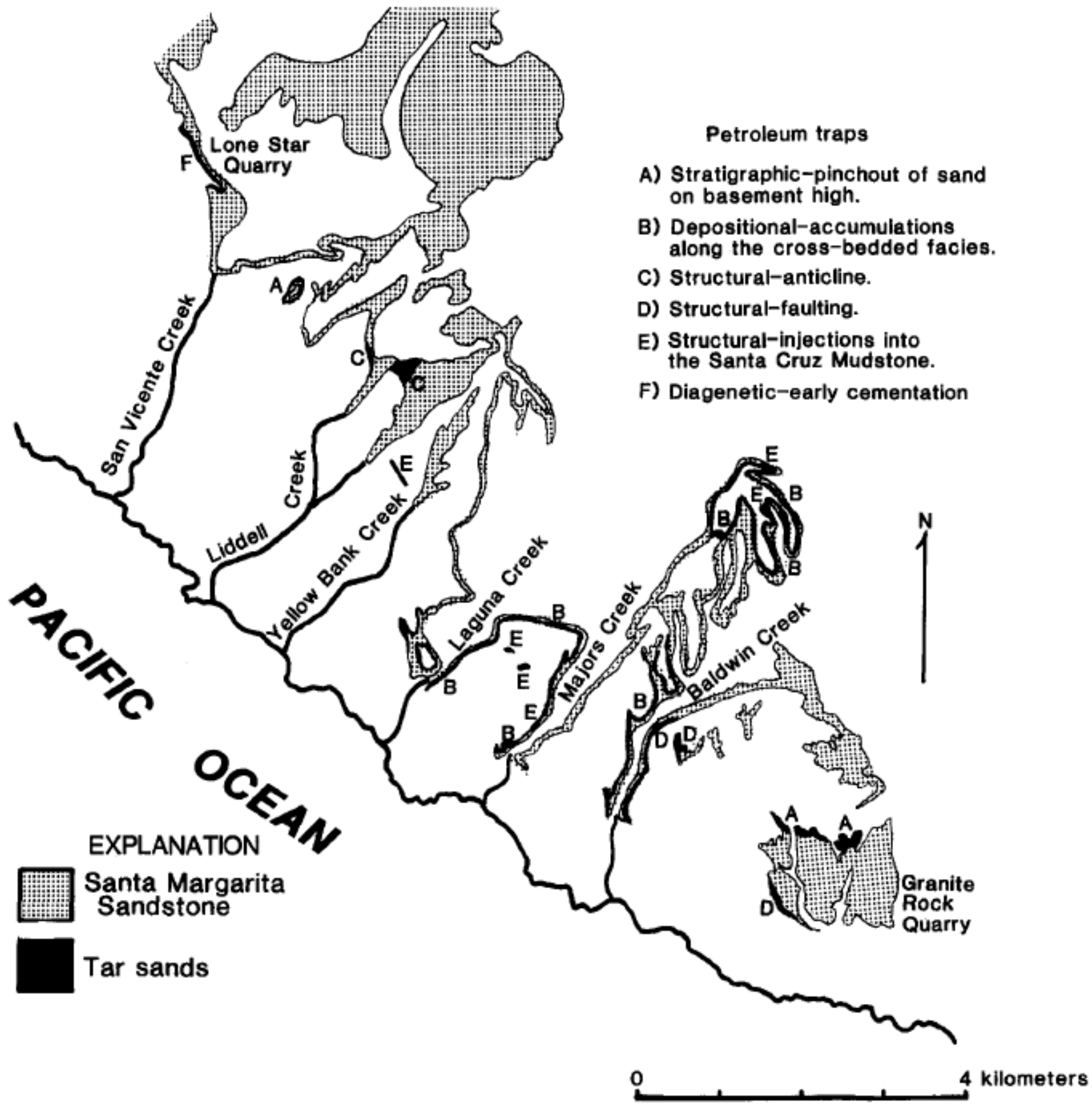


Figure 6, Asphalt-sand outcrops and trapping mechanisms of Santa Cruz County Coast

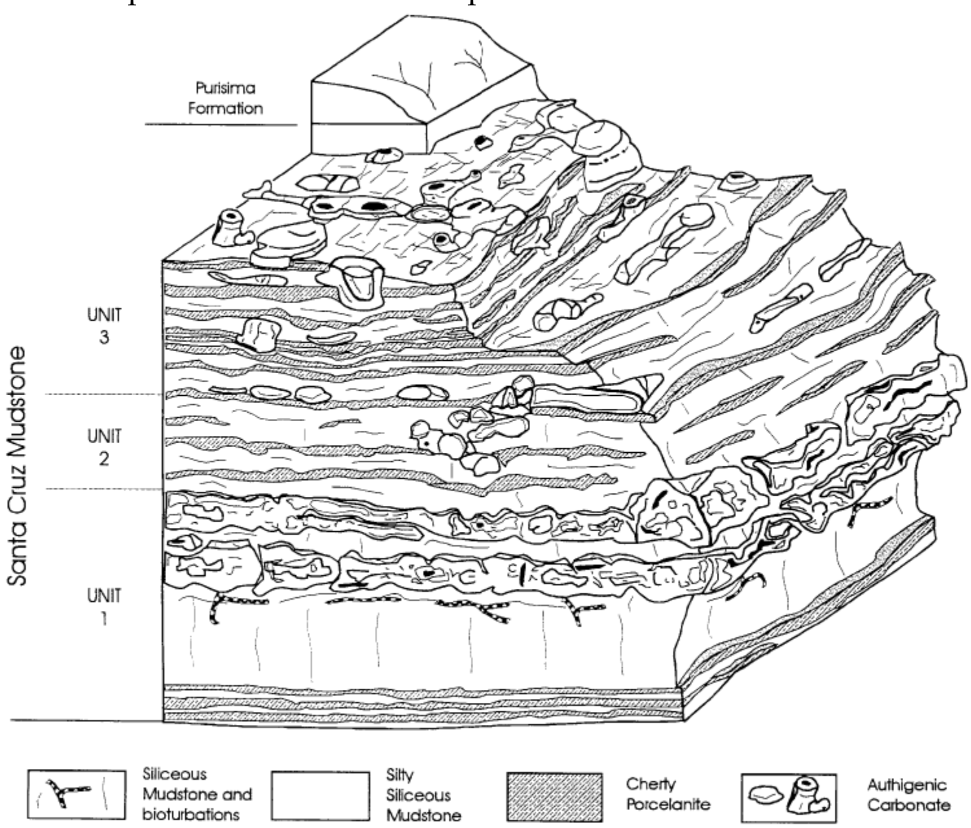


Phillips (1990)

Stop 2: Carbonate Cold Seeps

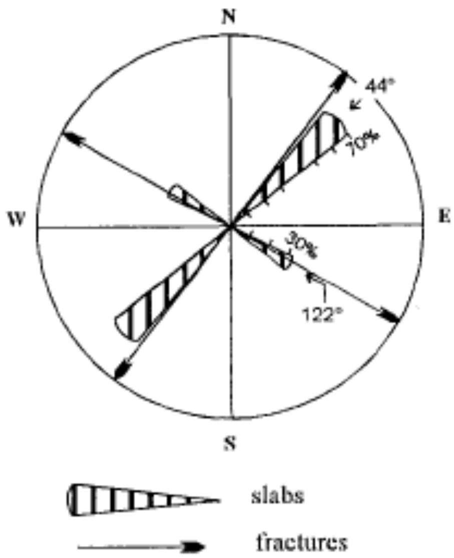
Beautiful exposures of Santa Cruz Mudstone are visible just west of our stop (photo 1, below), but the focus of this stop are carbonate concretions (photo 2 and 3, below) located in the upper 5 m of the Santa Cruz Mudstone resulting from seepage of fluids and gases.

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 will not be able 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.



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).

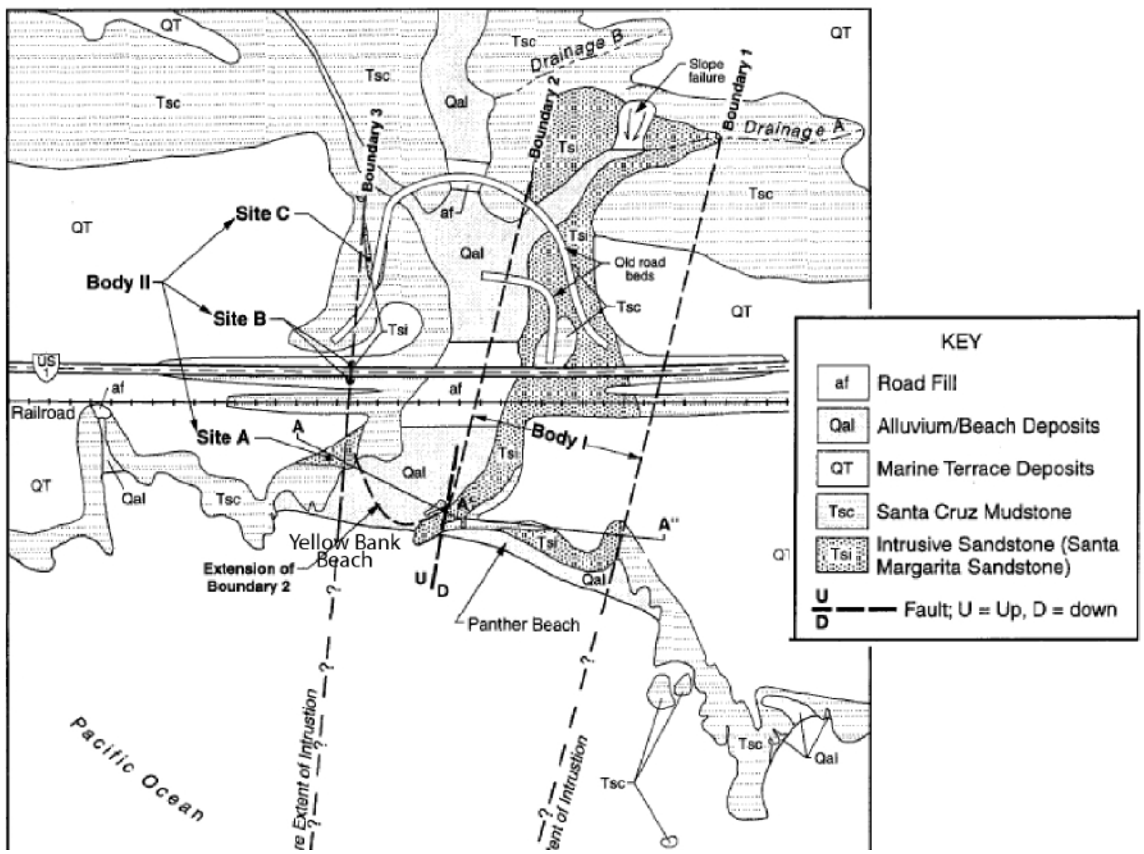
Stop 3: Majors Creek overlook

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 anticlinal 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 hydrocarbons away.

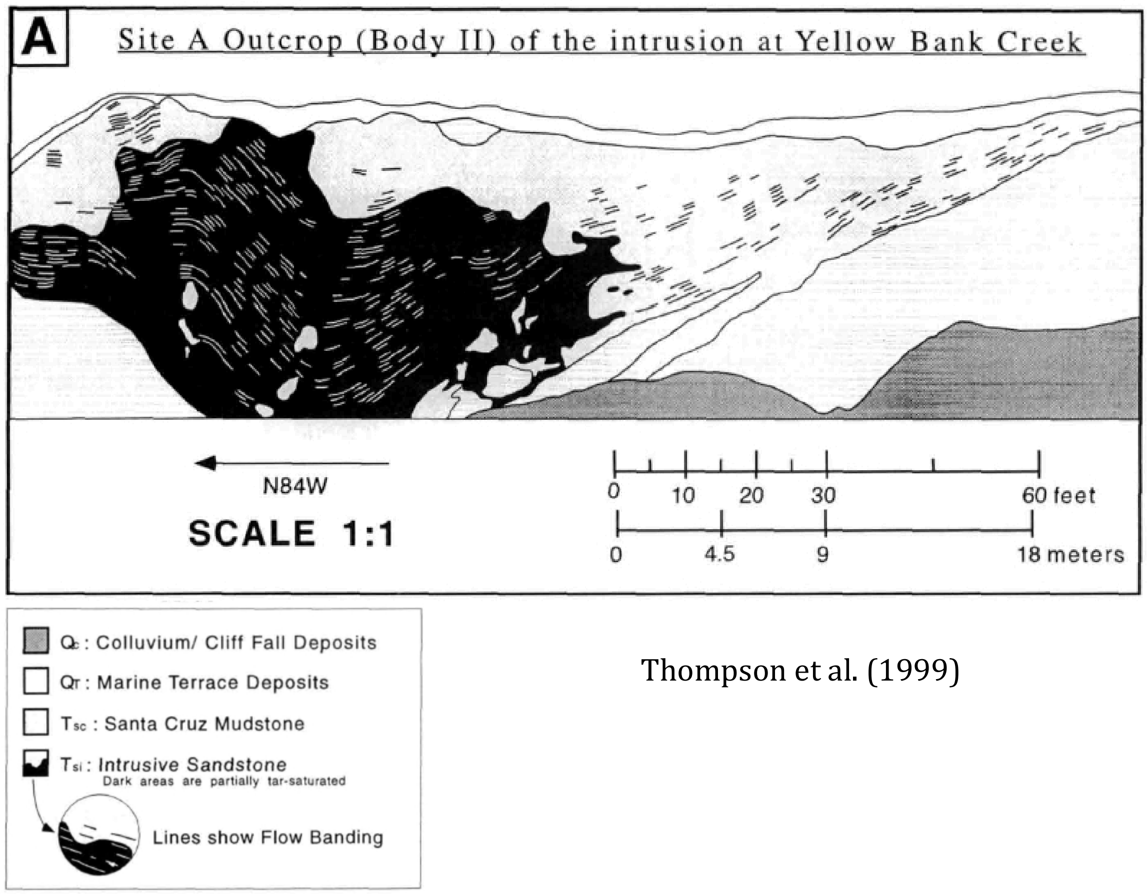
Look to the north, across the road, at dark outcrops lining both sides of the gully, especially on the left side. A small quarry just above the road on the left exposes the contact of these dark rocks and the light-colored rocks of the Santa Cruz Mudstone. The dark, resistant rocks are hydrocarbon-saturated sandstones of the Santa Margarita Formation. In this creek, 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 6, "depositional-accumulations along the cross-bedded facies."

Stop 4: Yellow Bank 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, Yellow Bank 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 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 hot-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 Yellow Bank injectite in the following diagram.

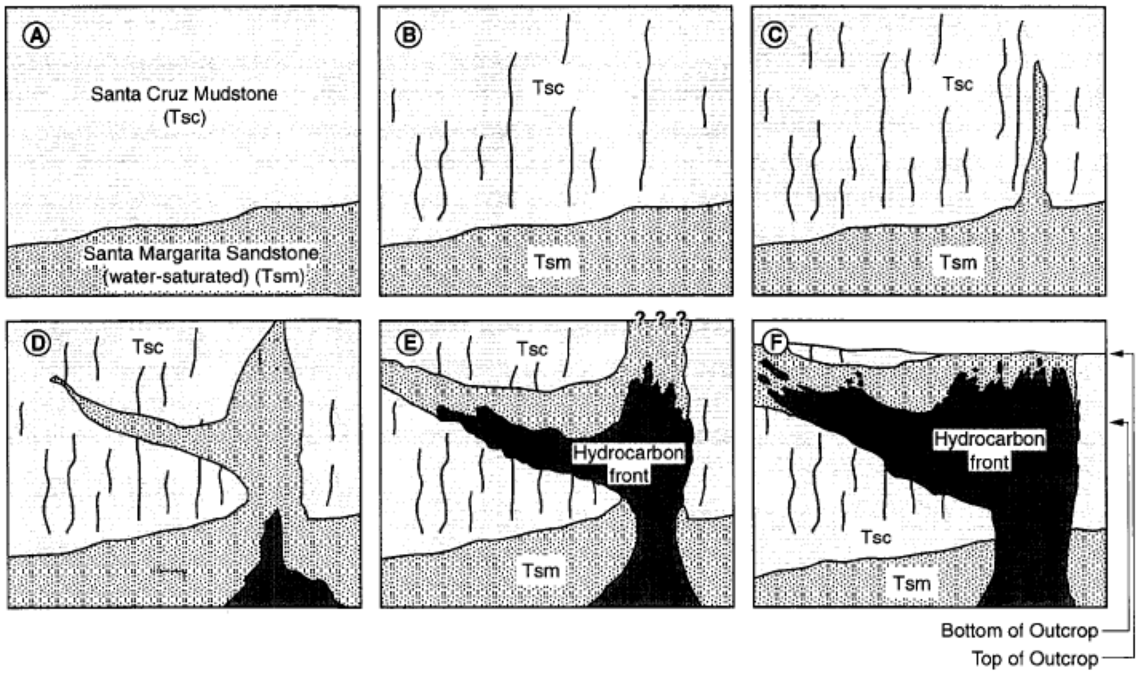
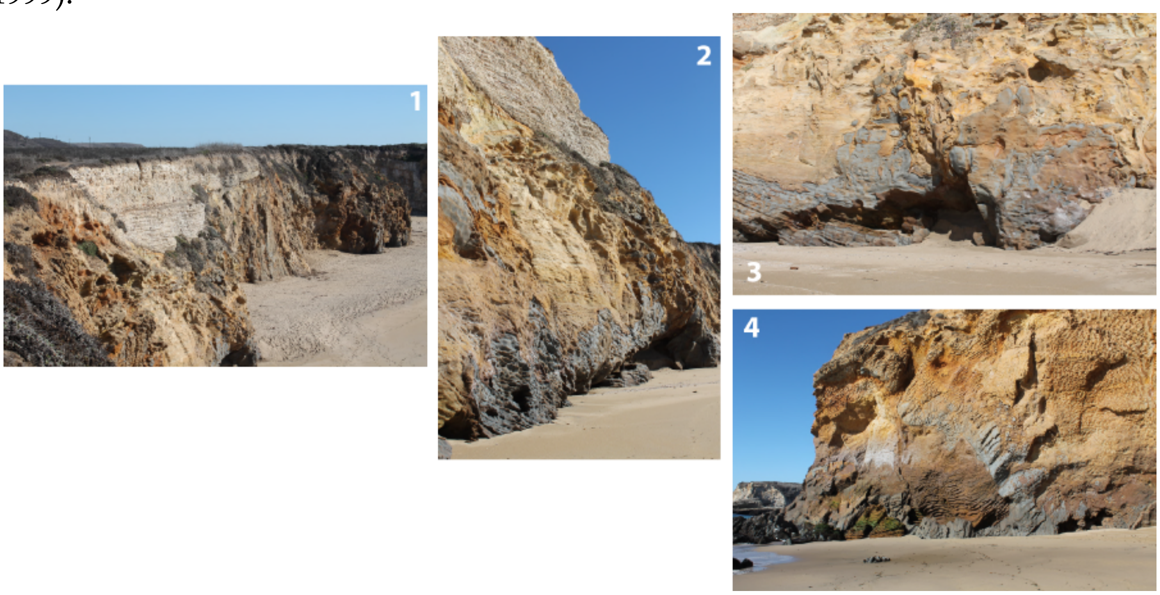


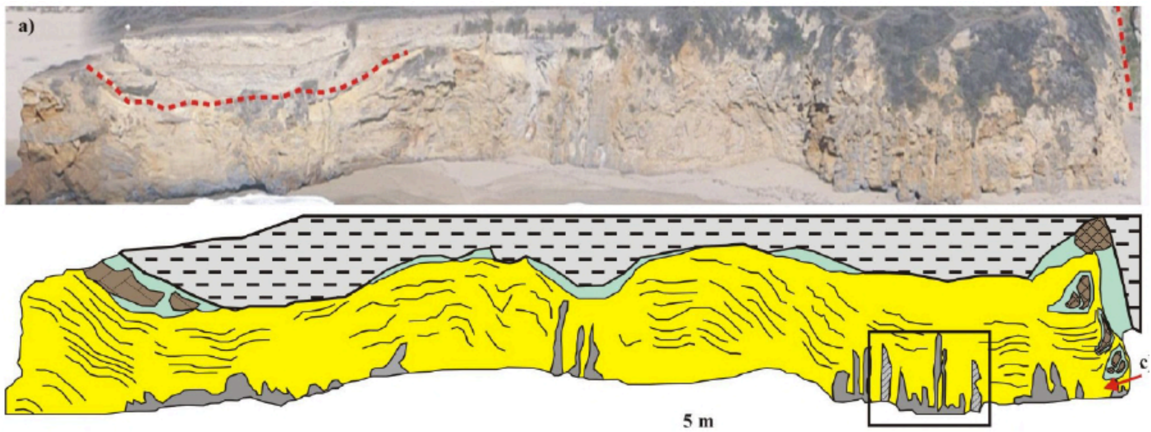
Figure 16. Schematic diagrams illustrating development of the sandstone intrusion at Yellow Bank Creek: A) Middle to late Miocene sedimentation of the Santa Margarita Sandstone and the overlying Santa Cruz Mudstone; B) Late Cenozoic fracturing or faulting is most intense in relatively brittle siliceous 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).

Next we visit Panther Beach, located through the sea arch from Yellow Bank Beach (photos below taken from Yellow Bank 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 hydrocarbons, 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 hydrocarbons 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.

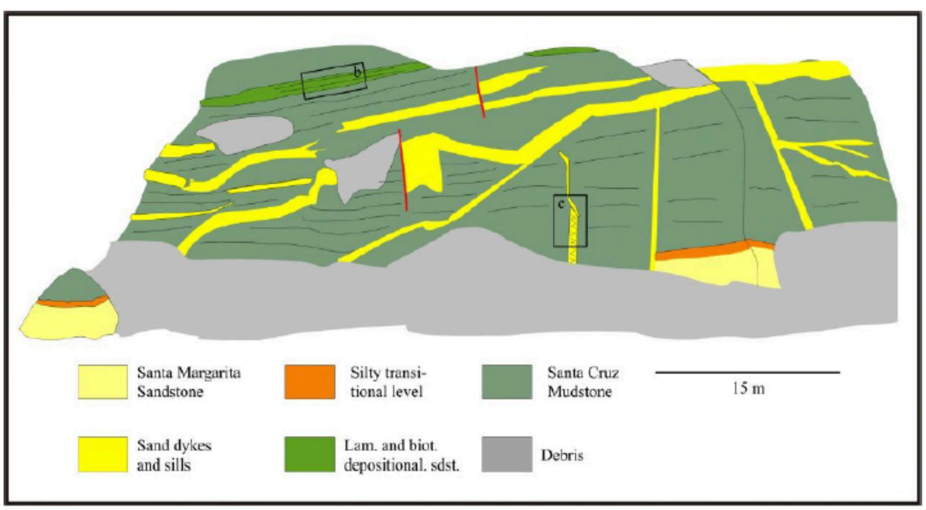
Stop 6: Quarry asphalt-filled fractures

This inland stop 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), also sometimes referred to as Garfinkel's Quarry. This quarry dates to the late 19th and early 20th centuries. A beautiful outcrop of tan-colored Santa Cruz Mudstone features black asphalt on bedding plane surfaces (photo 3, below). The highlight of the stop, however, is atop the outcrop, where thin, aligned joint sets are filled with asphalt (photos 1 and 2). If the weather is warm enough, you may even see asphalt oozing from fractures. This stop 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. The normal 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.

Stop 7: Quarry asphalt outcrop

As you exit the car you will immediately see small boulders of naturally occurring asphalt on the ground (photo 1, below) and an extensive asphalt outcrop/talus slope (photo 2) near the base of a cliff (photo 3). We will not examine the cliff face in detail because it is quite steep and covered with vegetation.

Just to the left of the quarry face is a large surface coated with asphalt that had flowed down over the Santa Cruz Mudstone. A number of large, dark, petroleum-saturated dikes and sills cut the Santa Cruz Mudstone in the lower part of the quarry face, but higher on the cliff is an extrusive bed composed of laminated and cross-stratified sandstone (geological sketch, below). The sandstone has infiltrated and fills burrows in the underlying Santa Cruz Mudstone to a depth of several 10's of centimeters and the upper part of the sandstone is itself burrowed. The presence of burrows in the top of the sandstone suggests that the sandstone was extruded as water-saturated sediment and later saturated with petroleum.



Hurst (2012)

References

Aiello, I.W., Stakes, D.S., Kastner, M., Garrison, R.E., 1999. Carbonate vent structures in the upper Miocene Santa Cruz Mudstone at Santa Cruz, California, in: Garrison, R.E., Aiello, I.W., Moore, J.C. (Eds.), Late Cenozoic fluid seeps and tectonics along the San Gregorio Fault zone in the Monterey Bay region, California. American Association of Petroleum Geologists, Pacific Section, Bakersfield, Calif., pp. 35-51.

Atwater, T., Stock, J., 1998. Pacific-North America plate tectonics of the Neogene southwestern United States—An update. International Geology Review 40, 375-402.

Brabb, E.E., 1989. Geologic map of Santa Cruz County, California. U.S. Geological Survey Miscellaneous Investigations Series I-1905, Reston, Va., p. 1 sheet.

Dickinson, W.R., Ducea, M.N., Rosenberg, L.I., Greene, H.G., Graham, S.A., Clark, J.C., Weber, G.E., Kidder, S., Ernst, W.G., Brabb, E.E., 2005. Net dextral slip, Neogene San Gregorio-Hosgri fault zone, coastal California—Geologic evidence and tectonic implications. Geological Society of America Special Paper 391, 1-43.

Garrison, R.E., Aiello, I.W., Moore, J.C., 1999. Late Cenozoic fluid seeps and tectonics along the San Gregorio fault zone in the Monterey Bay region, California, Volume and Guidebook, GB-76. American Association of Petroleum Geologists, Pacific Section, p. 156.

Graham, S.A., Dickinson, W.R., 1978. Evidence for 115 kilometers of right slip on the San Gregorio-Hosgri fault trend. Science 199, 179-181.

Heck, R.G., Edwards, E.B., Kronen, J.D., Jr., Willingham, C., 1990. Petroleum potential of the offshore outer Santa Cruz and Bodega basins, California, in: Garrison, R.E., Greene, H.G., Hicks, K.R., Weber, G.E., Wright, T.L. (Eds.), Geology and tectonics of the Central California Coast Region—San Francisco to Monterey. American Association of Petroleum Geologists, Pacific Section, Calif., pp. 143-163.

Hodgson, S.F., 1987. Onshore oil and gas seeps in California. California Division of Oil and Gas,, Sacramento, Calif., p. 97.

Hosford Scheirer, A., Magoon, L.B., 2008. Age, distribution, and stratigraphic relationship of rock units in the San Joaquin Basin Province, California, in: Hosford Scheirer, A. (Ed.), Petroleum systems and geologic assessment of oil and gas in the San Joaquin Basin Province, California. U.S. Geological Survey Professional Paper 1713, chapter 5, pp. 1-107 [available at http://pubs.usgs.gov/pp/pp1713/%5D.

Hurst, A., 2012. Sand injectites of Central California, unpublished field course, p. 63.

Lillis, P.G., Stanley, R.G., 1999. Petroleum systems of the La Honda Basin, California. AAPG Bulletin 83, 694-694.

Mullins, H.T., Nagel, D.K., 1982. Evidence for shallow hydrocarbons offshore northern Santa Cruz County, California. AAPG Bulletin 66, 1130-1140.

Naehr, T.H., Eichhubl, P., Orphan, V.J., Hovland, M., Paull, C.K., Ussler, W., III, Lorenson, T.D., Greene, H.G., 2007. Authigenic carbonate formation at hydrocarbon seeps in continental margin sediments—A comparative study. Deep-Sea Research II 54, 1268-1291.

Perg, L.A., Anderson, R.S., Finkel, R.C., 2001. Use of a new (super 10) Be and (super 26) Al inventory method to date marine terraces, Santa Cruz, California, USA. Geology 29, 879-882.

Peters, K.E., Hostettler, F.D., Lorenson, T.D., Rosenbauer, R.J., 2008. Families of Miocene Monterey crude oil, seep, and tarball samples, coastal California. American Association of Petroleum Geologists Bulletin 92, 1131-1152.

Phillips, R.L., 1990. Depositional and structural controls on the distribution of tar sands in the Santa Cruz mountains, California, in: Garrison, R.E., Greene, H.G., Hicks, K.R., Weber, G.E., Wright, T.L. (Eds.), Geology and tectonics of the Centrail California Coast Region—San Francisco to Monterey. American Association of Petroleum Geologists, Pacific Section, Calif., pp. 105-121.

Ross, D.C., Brabb, E.E., 1973. Petrography and structural relations of granitic basement rocks in the Monterey Bay area, California. Journal of Research of the U.S. Geological Survey 1, 273-282.

Stanley, R.G., 1990. Evolution of the Tertiary La Honda Basin, Central California, in: Garrison, R.E., Greene, H.G., Hicks, K.R., Weber, G.E., Wright, T.L. (Eds.), Geology and tectonics of the Central California Coast Region—San Francisco to Monterey. American Association of Petroleum Geologists, Pacific Section, Calif., pp. 1-29.

Stanley, R.G., Lillis, P.G., 2000. Oil-bearing rocks of the Davenport and Point Reyes areas and their implications for offset along the San Gregorio and northern San Andreas faults, in: Bokelmann, G., Kovach, R.L. (Eds.), Proceedings of the 3rd Conference on Tectonic Problems of the San Andreas Fault System. Stanford University, Stanford, Calif., pp. 371-384.

Thompson, B.J., Garrison, R.E., Moore, J.C., 1999. A late Cenozoic sandstone intrusion west of Santa Cruz, California—Fluidized flow of water- and hydrocarbon-saturated sediments, in: Garrison, R.E., Aiello, I.W., Moore, J.C. (Eds.), Late Cenozoic fluid seeps and tectonics along the San Gregorio Fault zone in the Monterey Bay region, California. American Association of Petroleum Geologists, Pacific Section, Bakersfield, Calif., pp. 53-74.