A Paleocene Cold Seep System in the Panoche Hills, California

Peninsula Geological Society & UCSC Hellatite Field Trip
April 3, 2004

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DIRECTIONS TO THE FIELD SITE

From Palo Alto:

Take Hwy. 101 south (past San Jose and Gilroy) ~ 50 miles to Hwy. 152 intersection. Turn left (east).

Take Hwy. 152 East ~40 miles (towards Los Banos, past San Luis Reservoir) to the Interstate 5 intersection. Turn right (south).

Take I-5 South ~34 miles. Exit at Panoche Rd./Firebaugh offramp*. Meet on the south side of McDonald's (near outside restrooms).

> *This will be the SECOND (southernmost) Firebaugh offramp that you encounter on this stretch of Interstate 5.

From Santa Cruz:

Take Hwy 1 south to Watsonville. Exit at Hwy. 129 offramp. Turn left (east).

Take Hwy. 129 east ~ 14 miles to Hwy. 101 intersection.

Take Hwy. 101 north ~5.6 miles to Hwy. 25 offramp. Exit.

Take Hwy. 25 East ~ _ mile. Turn left on G7 (Bloomfield Road).

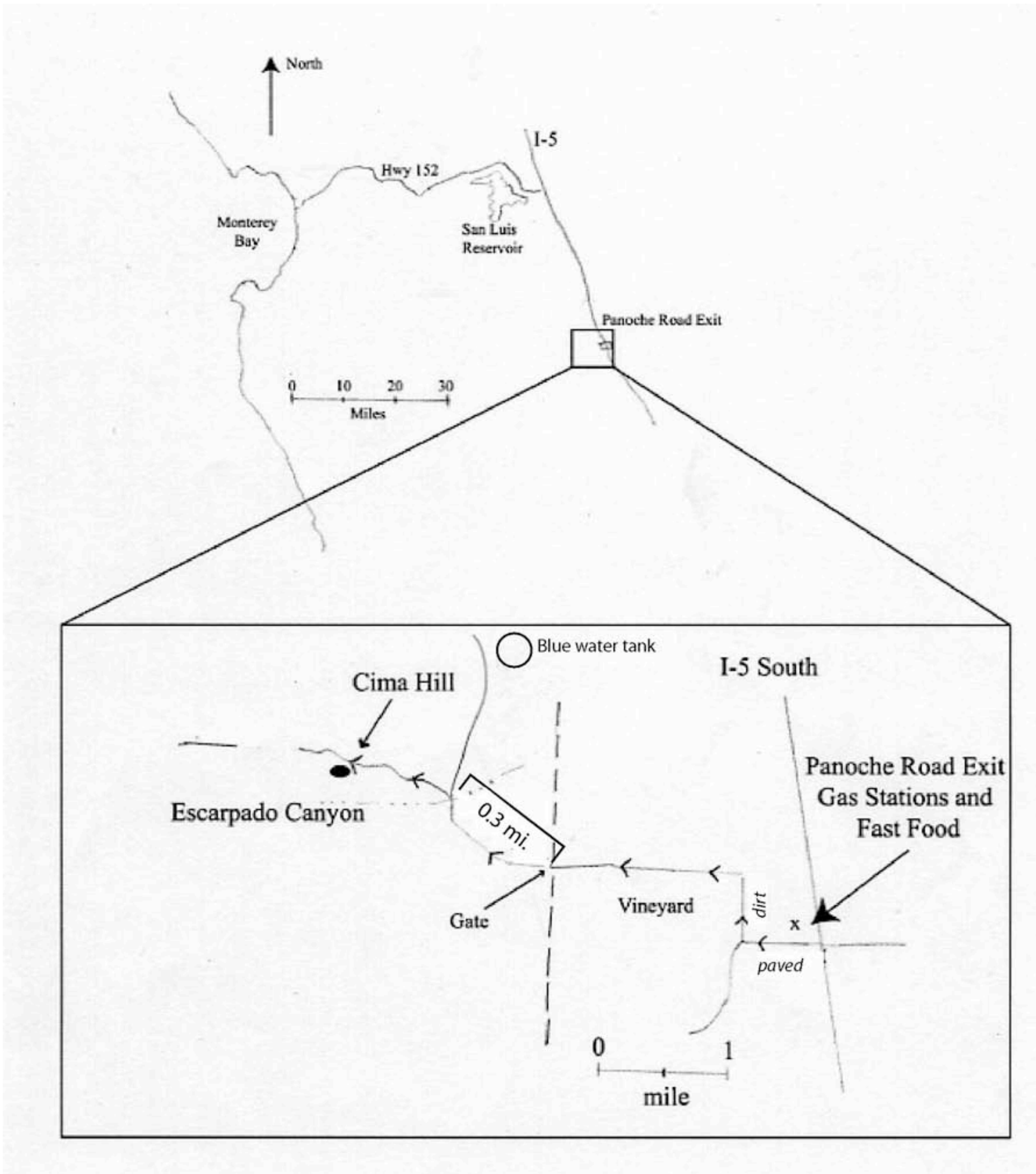
Take G7 ~4 miles. It dead-ends at Hwy. 152. Turn right (east) onto Hwy. 152.

Take Hwy. 152 East ~35 miles (towards Los Banos, past San Luis Reservoir) to the Interstate 5 intersection. Turn right (south).

Take I-5 South ~34 miles. Exit at Panoche Rd./Firebaugh offramp*. Meet on the south side of McDonald's (near outside restrooms).

> *This will be the SECOND (southernmost) Firebaugh offramp you encounter on this stretch of Interstate 5.

MEETING TIME: 9:45 a.m.


North
I-5
Hwy 152
Monterey
Bay
San Luis
Reservoir
Panoche Road Exit
0
10
20
30
Miles
Blue water tank
I-5 South
Cima Hill
Panoche Road Exit
Gas Stations and
Fast Food
Escarpado Canyon
0.3 mi.
Gate
Vineyard
dirt
x
paved
0
1
mile

INTRODUCTION & GEOLOGIC SETTING

Abstract

The Moreno Fm. in the Panoche Hills-Tumey Hills region preserves an extensive fluid migration system that developed along the western margin of the former Great Valley forearc basin. The 'system' includes a network of interconnected sandstone intrusions linked to overlying fossiliferous carbonates whose geochemistry, fauna, and petrology are characteristic of modern cold seeps. The entire system is at least 20 km long and approximately 800m thick, and represents episodic migration and seafloor expulsion of fluids over at least 2 million years. This locality has the most extensive exposure yet discovered of a complete seep system, from underlying fluid pathways to seep carbonates and associated chemosynthetic faunas. We believe this is also the first documented cold seep site in which sandstone intrusions, rather than faults, were the primary fluid conduits.

Panoche and Tumey Hills

The Panoche Hills and Tumey Hills (PTH) are located in the easternmost Diablo Range, along the western margin of the San Joaquin Basin (**Figure 1**). They consist of uplifted Cretaceous and Tertiary strata that were originally deposited along the western edge of the Great Valley forearc basin (**Figure 2**). The formerly flat-lying forearc sedimentary rocks in the Panoche Hills area now dip homoclinally eastwards 35° - 45° because of regional deformation and uplift associated with the San Andreas transform margin (Wentworth and Zoback, 1989; Bartow, 1991).

The oldest rocks exposed in the PTH are the Cenomanian-Maastrichtian aged Panoche Formation and the Maastrichtian-Danian aged Moreno Formation. These conformable units make up the Great Valley Sequence locally and are the focus of our study. The Panoche Fm. consists of approximately 6.5 km of predominantly coarse-grained submarine fan deposits. The overlying Moreno Fm. is predominantly fine-grained and only about 800 m thick; it is subdivided into four members (Payne, 1951): the Dosados Sandstone and Shale Member, the Tierra Loma Shale Member, the Marca Shale Member, and the Dos Palos Shale Member (which includes the Cima Sandstone Lentil) (**Figure 3**). The Panoche-Moreno sequence is thought to record shoaling from slope to shelf depths, from middle Maastrichtian to late Danian times, on the western margin of the Great Valley forearc (McGuire, 1988; Bartow and Nilson, 1990; Fonseca-Rivera, 1997). The proposed shoaling was accompanied in the late Danian by injection of basinal fluids and/or sediments into Panoche and Moreno strata (Schwartz et al., 2003).

Ancient Cold Seep System

Sandstone Intrusions

The abundant Moreno Fm. sandstone intrusions in the PTH are well known (e.g. Anderson and Pack, 1915; Payne, 1951; Smyers and Peterson, 1971; Weberling 2002). They propogate upwards from the sandy base of the Moreno Fm. as an interconnected system of sills and dikes, and most terminate 30 to 40 m below the base of the Cima Sandstone Lentil (**Figure 3**). Based on sandstone grain compositions, Payne (1951), Smyers and Peterson (1971) and Friedmann et al. (2002) concluded that the source materials for the intrusions were the Dosados Sandstone and Shale Member of the Moreno Fm. and/or the upper Panoche Fm. sands. We believe that these intrusions represent the 'plumbing' of the seep fluids that upsection produced carbonates and supported lush chemosynthetic ecosystems at the Paleocene seafloor.

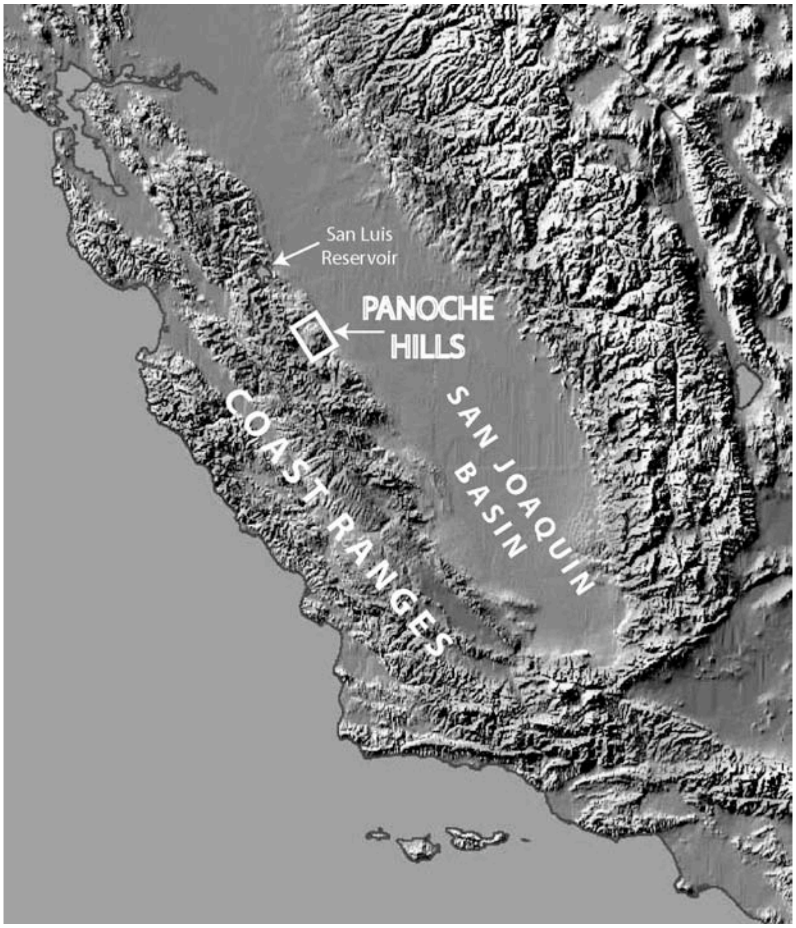


Figure 1.
Location of the Panoche Hills field area, central California.

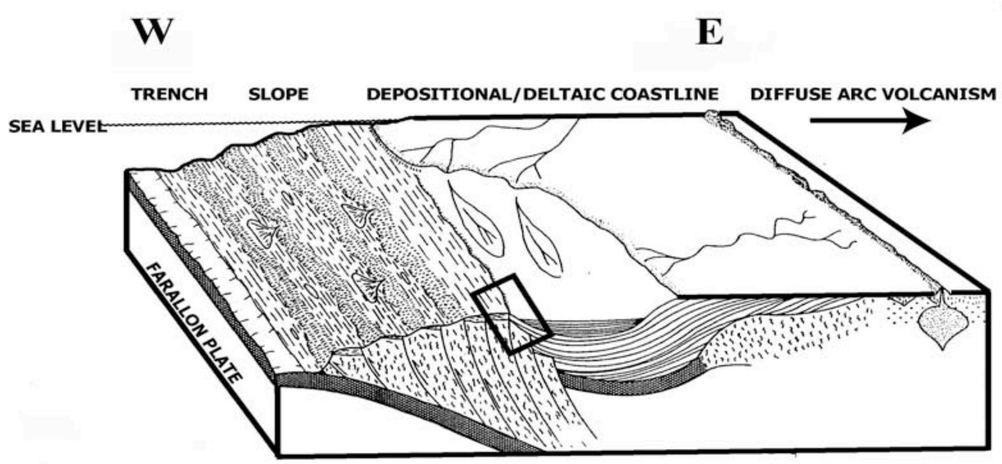


Figure 2.
Reconstruction of the early Paleocene (Danian) western Great Valley forearc at the latitude of the Panoche Hills, showing components of the convergent plate boundary. Box shows the location and paleotectonic setting of the Panoche Hills paleoseep. (Modified after McGuire, 1988)

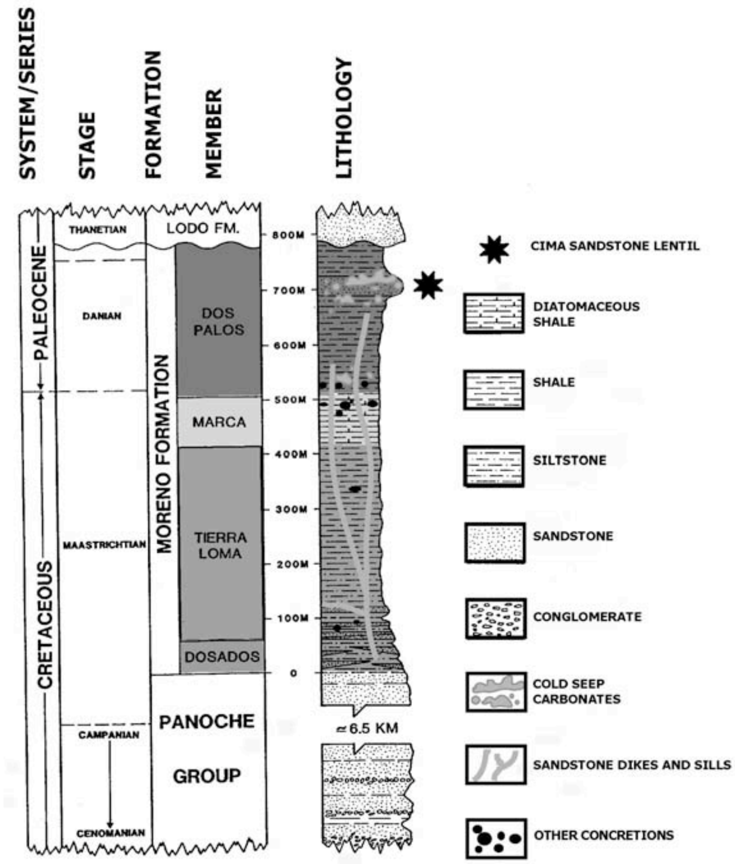


Figure 3.
Generalized stratigraphy of the Panoche and Moreno formations in the Escarpado Canyon region of the Panoche Hills (after McGuire, 1988).

Carbonates

Large, resistant carbonate bodies (frontispiece) are the most visible indicators of paleoseep activity in the PTH. The geochemistry and paleontology of these carbonates are key indicators that they formed in a reduced, methane-enriched cold seep environment. Isotopic analysis shows that they are moderately to strongly depleted in ^{13}C, indicating that their carbon component was derived from biogenic or thermogenic methane. Moreover, the range in carbon and oxygen isotope values in the carbonates (_$^{13}C_{PDB}$ = -42.6^{o}/oo to 0.6^{o}/oo and _$^{18}O_{PDB}$ = -5.7 ^{o}/oo to 7.3^{o}/oo) (**Figure 4**) is well within the range described from other modern and ancient cold seeps.

Regionally, the PTH carbonates are exposed for nearly 20 km along strike. However, they are densest in the Escarpado Canyon-Right Angle Canyon area (**Figure 5**). Stratigraphically, carbonates are most abundant in the Cima Sandstone Lentil of the Moreno Fm., but they occur at low density throughout the Dos Palos Shale Member of the Moreno Fm. (**Figure 3**). The 200 m stratigraphic range of paleoseep carbonates suggests a two million year history of seepage in this part of the forearc basin, but the

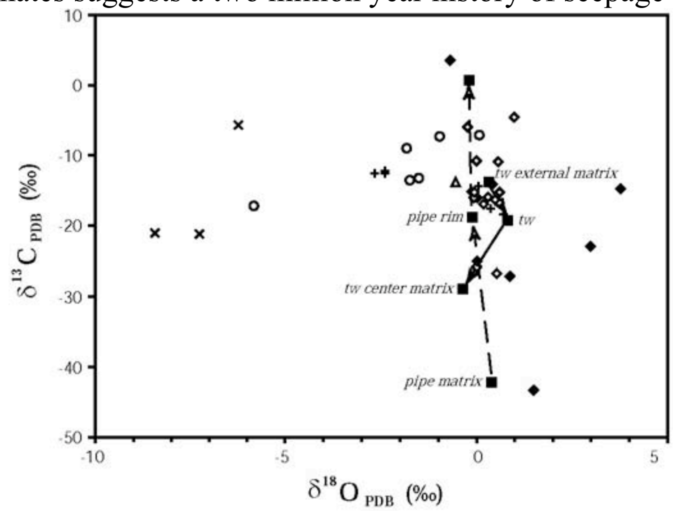
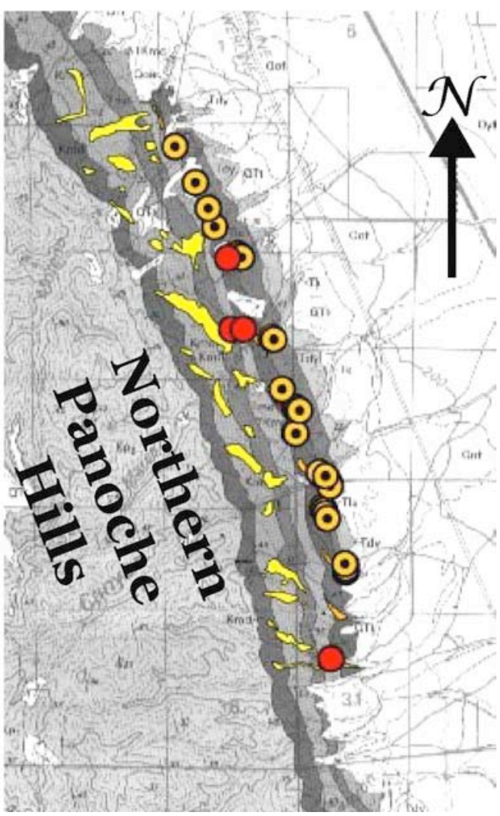


Figure 4.
Carbon and oxygen isotope data from the Panoche Hills paleoseep



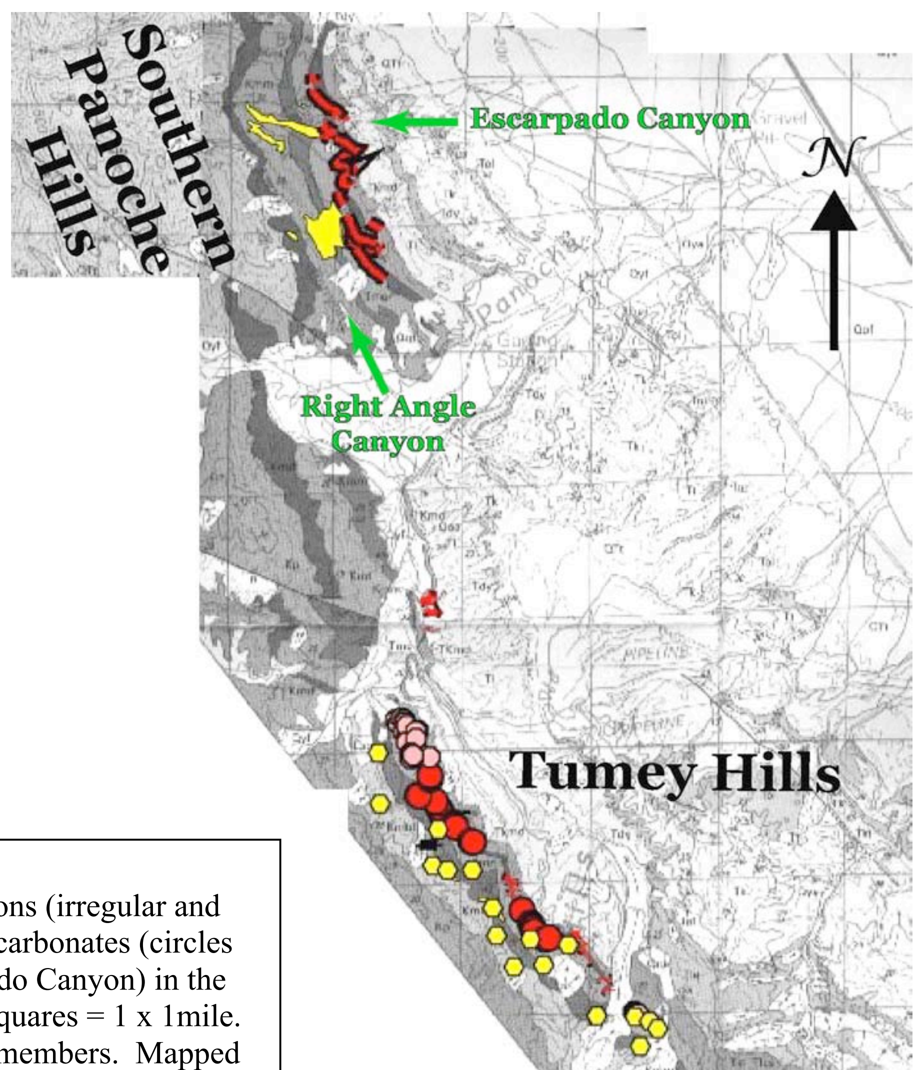


Figure 5.
Pattern of sandstone intrusions (irregular and hexagonal shapes) and seep carbonates (circles and barred zones in Escarpado Canyon) in the Panoche and Tumey Hills. Squares = 1 x 1mile. Dark bands are Moreno Fm. members. Mapped on Bartow (1996).

abundance of carbonate in the Cima Sandstone Lentil implies that it represents the 'main event' horizon.

The Moreno Fm. carbonates occur as cements, veins and replacement material in fine-grained sandstone and siltstone. Three main morphologies have been identified: 1) irregularly shaped mounds, 2) spherical to ellipsoidal concretions and 3) laterally discontinuous slabs and pavements (**Figure 6**). All three morphologies are associated with macrofossils and all occur throughout the main paleoseep horizon (the Cima Sandstone Lentil). Mounds and concretions also occur in portions of the Dos Palos Shale Member above and below the Cima Sandstone Lentil. Concretions formed below the ancient seafloor and mounds and pavements formed at and just below the seafloor. Most carbonate structures in the field area are in place, as indicated by incorporation of matrix sandstone and siltstone into many of the carbonate structures, lateral continuity of mound-pavement-concretion horizons and the presence of well-preserved fossils. Mounds and pavements have numerous features reminiscent of modern cold seep carbonates, including cement-filled pipe-like conduits, mottled coloration, wavy laminae, complex cements, brecciation, and traces of sulfide minerals and heavy hydrocarbons. The carbonate samples with the lightest carbon (most negative _^{13}C) show petrographic evidence of microbial activity, including micrite veneers and wavy laminae. Detailed geochemical analysis of several masses indicates that early carbonate cements formed from fluids rich in biogenic methane during periods of rapid seepage, while later cements were derived from seawater bicarbonate during periods of slow or negative seepage.

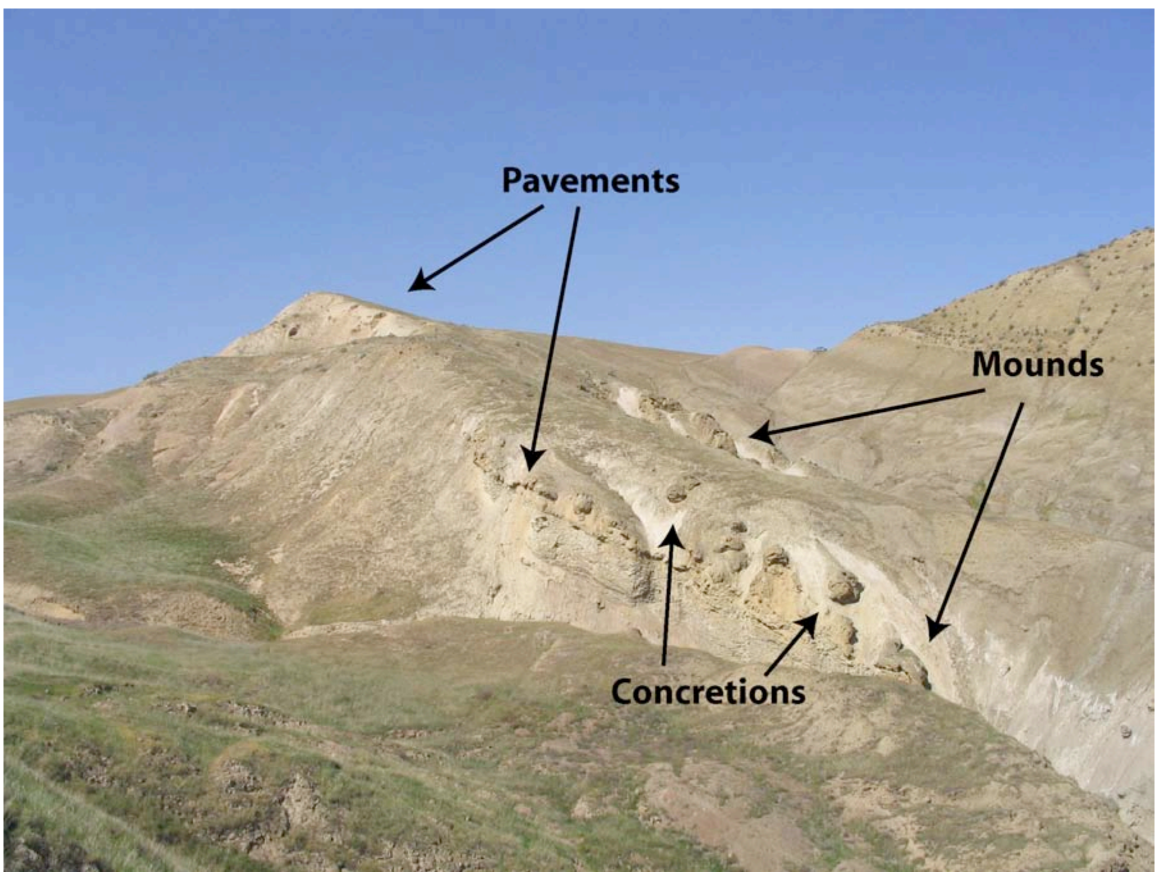


Figure 6.
Paleoseep carbonate morphologies, Cima Hill.

Fossils
Virtually all of the macrofossils in the Moreno Fm. are associated with carbonate mounds, concretions or pavements. The commonest are vestimentiferan tubeworm and lucinid bivalve remains. These represent 'chemosynthetic' organisms whose modern representatives harbor internal, sulfide-metabolizing symbiotic bacteria. Living lucinids and vestimentiferans live at cold seeps and in other sulfide-rich environments. Vestimentiferans live above the sediment surface and are attached by distal tube 'roots'; lucinid bivalves are shallow burrowers.

Vestimentiferan tubes are ubiquitous in the Moreno Fm. carbonates, occurring as isolated individuals and in clusters of tens of individuals (**Figure 7**). Lucinid bivalves (**Figure 8**) are not as common and are generally found as single individuals. Both tubeworms and bivalves are generally found in life position. Accessory fauna, associated mainly with the uppermost seep pavements, includes small, chemotrophic solemyid bivalves, and heterotrophic seep-type gastropods, corals and pholad bivalves. Wood fragments are also abundant in the seep horizon (as well as elsewhere in the Moreno Fm.). Except for the latter, the PTH paleoseep macrofossils appear to be in place: bivalves are articulated and delicate shells and elongate tubes are generally unabraded and unbroken.

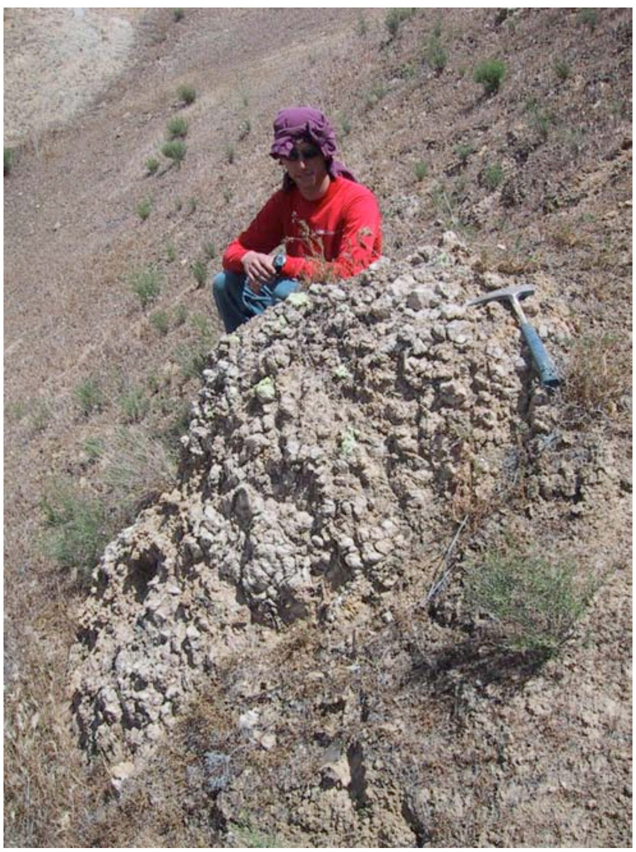
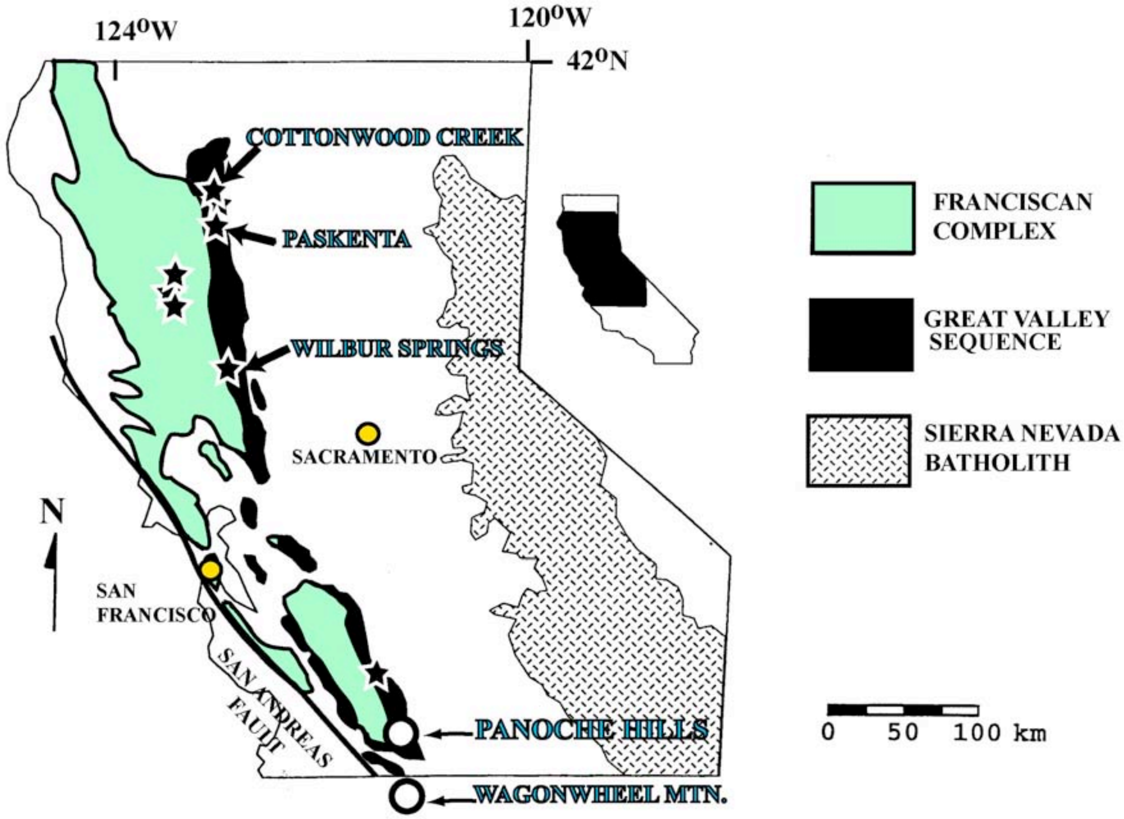


Figure 8.
Lucinid bivalve in life position.

Figure 7.
Paleoseep mound made of densely packed vestimentiferan tubeworms

Regional Significance

The early Paleocene PTH paleoseep system is one of several Mesozoic and Cenozoic paleoseeps known in the Great Valley forearc (e.g. Campbell et al., 1993; Squires and Gring, 1996; Campbell et al., 2002) and is an interesting spatial-temporal link between the Jurassic-Cretaceous seeps in the Sacramento Valley and an Eocene seep in the southern San Joaquin Valley (**Figure 9**).



Distribution of Mesozoic (★) & Cenozoic (○) paleoseeps in the Great Valley region

Figure 9.

FIELD TRIP STOPS

Stop 1
HEAD OF ESCARPADO CANYON: Seep System Overview

From this location we can stand at the base of the Moreno Fm. and look upsection and along strike to get a great view of the entire PTH paleoseep system (**Figure 10**). Looking directly eastwards to the San Joaquin Basin it is easy to imagine the forearc basin setting in which these marine strata were deposited and the cold seep system developed. Escarpado Canyon is directly in front of us. Right Angle Canyon and Panoche Creek are to the south and Dosados Canyon is the next canyon to the north. To the west, the uppermost Panoche Fm. sandstone holds up the very steep ridge. To the east, the dark and light brown shales are the Tierra Loma Shale, Marca Shale, and Dos Palos Shale Members of the Moreno Formation. Note that they are crosscut everywhere by lighter colored sandstone sills and dikes. Sandstone intrusions appear directly above the uppermost depositional sandstone bed in the Dosados Sandstone and Shale Member of the Moreno Fm. (visible in Dosados Canyon) and continue into the Dos Palos Shale. The Cretaceous-Tertiary boundary lies about 1 m above the upper contact of the whitish Marca Shale Member.

Cima Hill, to the east and directly south of the jeep trail, is underlain by the carbonate-rich Cima Sandstone Lentil paleoseep horizon. Here, an extensive carbonate pavement caps the main seep zone and supports the dip slope on the northeast side of the hill. Similar pavements and dip slopes top Cima Sandstone ridges south of Dosados Canyon and east of Right Angle Canyon.

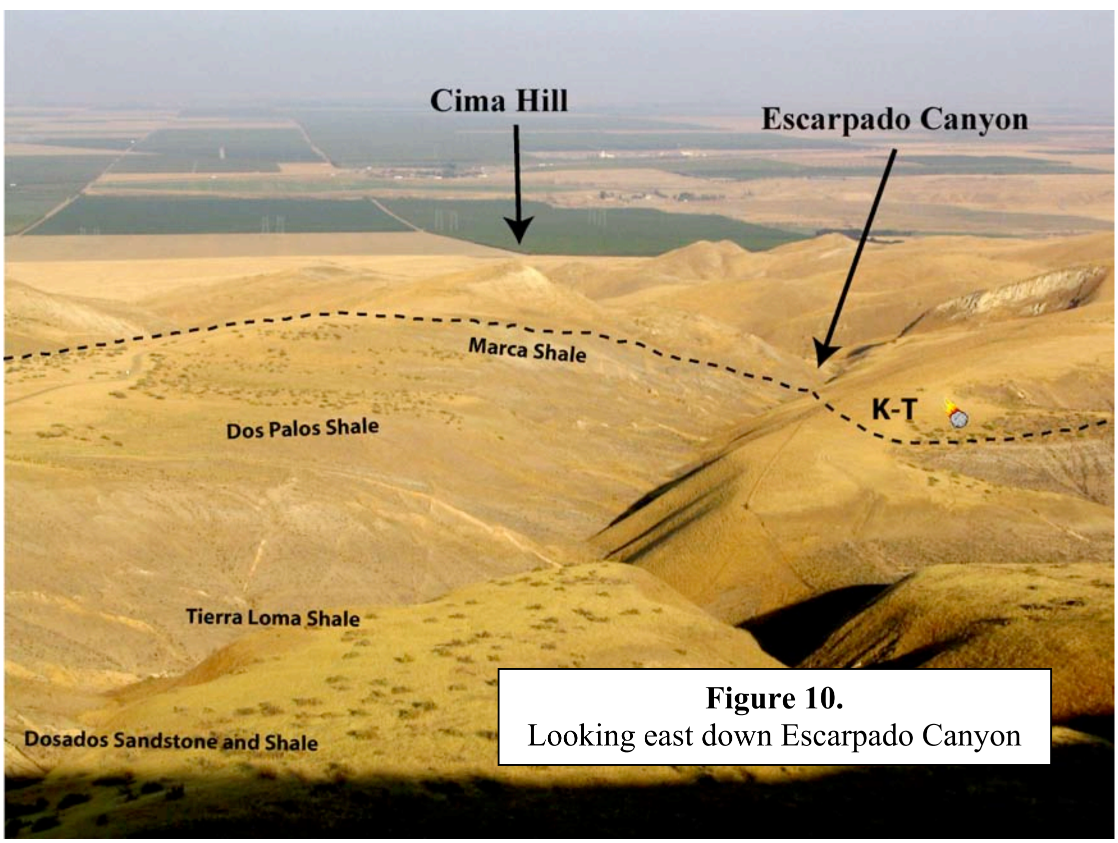


Figure 10.
Looking east down Escarpado Canyon

Stop 2
TIERRA LOMA SHALE MEMBER: Lower sandstone intrusions:

This stop provides an opportunity to observe the lowest sandstone intrusions in the Moreno Fm. One large sill, connected/crosscut by numerous smaller dikes, trends down Escarpado Canyon. Its very irregular margins and shale inclusions indicate that it is an injected, not depositional, feature. Watch for petrified wood!

Kevin Weberling (2002) measured the orientations of 100 separate dikes and sills in the field area. Intrusions propagate through the shales in widely varying attitudes (**Figure 11**). Contouring of the poles to intrusion planes indicates an apparent preferential occurrence of intrusions at 337^{o}, 44 NE (sills) approximately parallel with bedding, and another preference at 85^{o}, 90 (dikes). The wide variance in attitudes suggests that the intrusions were injected under a relatively isotropic state of stress. The two localized maxima suggest preferential extension along bedding planes (sills) as well as in the north-south direction (dikes).

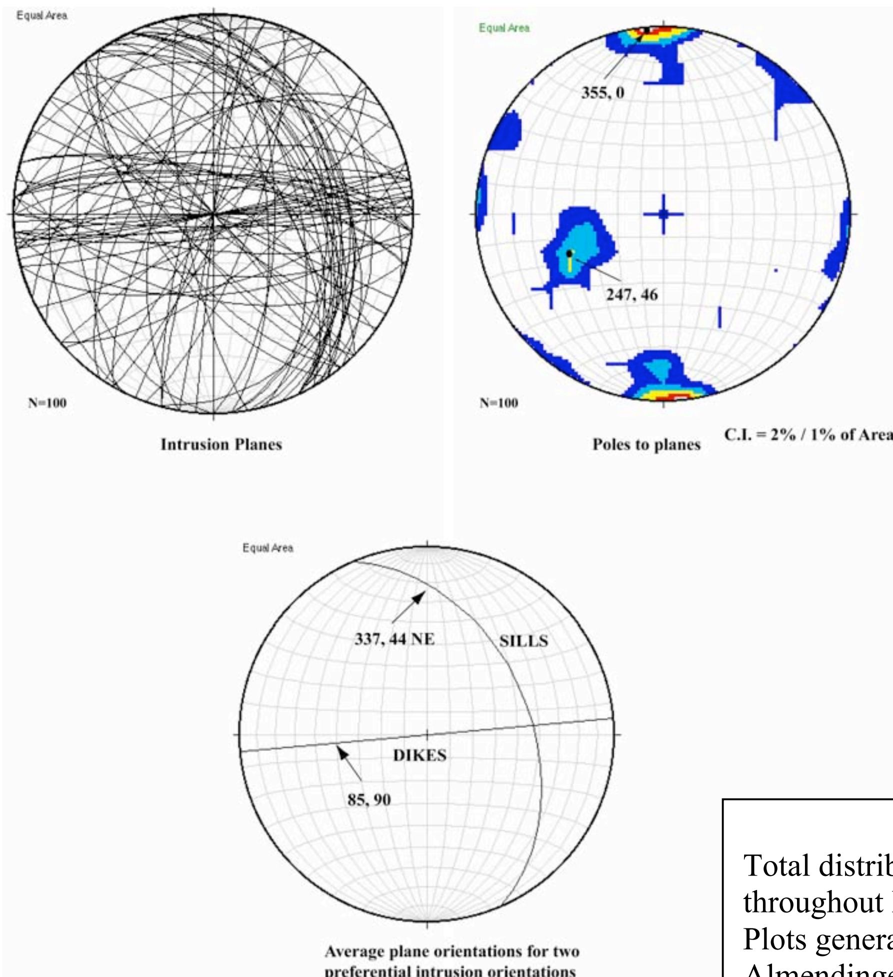


Figure 11.
Total distribution of intrusive orientations throughout Escarpado and Right Angle Canyons. Plots generated with Stereonet courtesy of R. Almendinger.

Well logs show that the Moreno Fm. thickens to the east (towards the axis of the forearc basin) to at least 1,100 m (McGuire, 1988). A combination of the lateral thickness imbalance and a triggering mechanism could have caused fluid to be driven to the thinner eastern basin margin, where over-pressure and hydrofracture of the overlying shales occurred (cf. Jolly and Lonergan, 2002) **(Figure 12)**. Possible triggering mechanisms include seismicity, tectonic changes to the stress field and/or hydrocarbon generation (Schwartz et al., 2003)

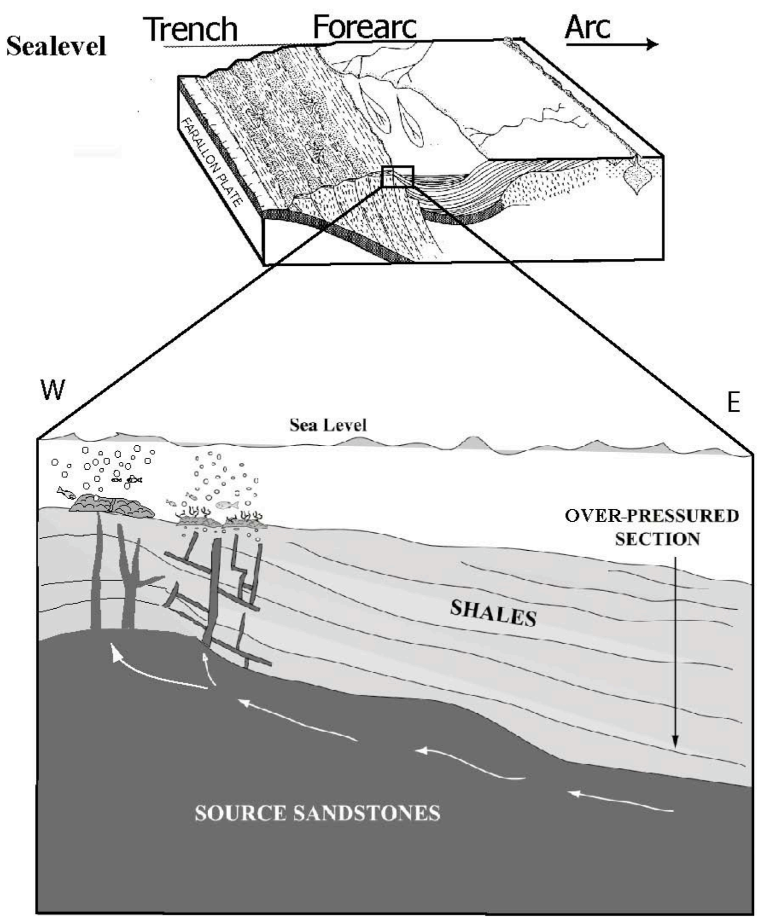


Figure 12.
Generalized reconstruction of the early Paleocene western Great Valley forearc showing components of the subduction-driven seep system, including the over-pressured central basin, lateral fluid migration, mobilization of sand intrusions and marginal seepage (after Weberling, 2002).

Stop 3: THE K-T BOUNDARY

Walking from Escarpado towards Cannonball Ridge we will cross the whitish Marca Shale Member. Ammonites, plesiosaurs, mosasaurs and other Mesozoic relicts have been found in this unit (Payne, 1951)! Note that a horizon marked by discontinuous calcareous concretions occurs just below the contact between the Marca Shale and Dos Palos Shale. The conformable K-T boundary lies about 5m above the uppermost layer of concretions. Here, the tragic boundary layer is a 1 cm thick condensed section containing glauconitic phosphatic debris (including fish bones and small shark teeth). In Dosados Canyon to the north, the K-T boundary layer contains altered glass (goyazite) spherules (Fonseca-Rivera, 1997).

Stop 4: CANNONBALL RIDGE (EAST):
Upper sandstone intrusions and Cima Sandstone paleoseep carbonates

At this stop we will examine the uppermost Cima Sandstone Lentil, paleoseep carbonates and the uppermost sandstone dikes in the field area. Three types of carbonate structures are visible: spherical concretions, irregular mounds and thin pavements (**Figure 13**). We believe that these different morphologies reflect variable flow velocity and directedness of paleoseep fluids. Mounds typically contain evidence of fluid conduits, and thus directed flow. Pavements and concretions do not contain conduits, and are presumed to be the result of diffusive flow. We suspect that concretions were formed during slower diffusive flow and pavements during more vigorous diffusive flow. The variety of carbonate morphotypes in this relatively small area is typical for this region of the paleoseep. Fossils are unusually rare on this ridge. Late-stage gypsum cement is pervasive throughout the Moreno Fm., including the Cima Sandstone. Some of the carbonates on this ridge are distinctly and uniquely brownish-orange. Why??

Thin sandstone intrusions (1 cm to 2 cm thick) crosscut the Cima Sandstone all the way to the ridge top here. Elsewhere, intrusions in the PTH appear to terminate about 20-30 m below the Cima Sandstone. We previously speculated that seep fluids feeding the main seep horizon traveled by diffusive flow above the dike termination level, but now it appears that at least some intrusions broke through to the ancient seafloor. Since the dikes thin dramatically upsection and are difficult to identify on weathered surfaces, it may be that most of the dikes reach the Cima Sandstone horizon.

Figure 13.
The main seep horizon as exposed at Stop 4. View to the northeast.

Stop 4: CIMA HILL AND ESCARPADO CANYON:
Concretions, pavements, mounds and fossils

Cima Hill contains one of the densest and most diverse concentrations of paleoseep carbonates in the PTH and is an excellent place to examine paleoseep carbonates, textures and fossils. We will begin by walking to the top of the hill. Note the lithologies of the Cima Sandstone and the carbonates: the former ranges from glauconitic siltstone to sandstone, and the carbonates range from silty/sandy micrite to micrite. The pavements that support Cima Hill contain tubeworms, corals and many wood fragments. The presence of corals suggests that the pavements were exposed and acted as hardgrounds for faunal encrusters. Much of the wood in the local pavements and mounds contains pholad bivalve borings. The Cima Hill carbonate mounds are generally one to several meters long and, in contrast to pavements, are located at a variety of stratigraphic levels. Mottled coloration, numerous vugs and several generations of fracturing give these mounds a messy appearance (**Figure 14**) and make them difficult to interpret. Towards the east end of Cima Hill, some mounds have a distinctly 'knobbly' texture derived from carbonate overgrowths on numerous tubeworm tubes. We interpret these as relict tubeworm 'bushes' analogous to the modern *Lamellibrachia* 'bushes' (30 cm to > 9.3 m in diameter) identified at modern cold seeps in the Gulf of Mexico (MacDonald et al., 1990) and elsewhere.

As we walk down Cima Hill towards Escarpado Canyon we will briefly be above the Cima Sandstone, and in a silty, barite-rich horizon. The very irregular unconformity between the Moreno Fm. and overlying Lodo Fm. is visible directly to the east. From further down the ridge, we can look west and see the apparent termination of clastic dikes in the lower Dos Palos Shale.

From the south side of Escarpado Canyon the diversity and complexity of the main paleoseep horizon is striking. Note that mounds, concretions and pavements are intermixed and that discrete carbonate-rich zones have very irregular lower boundaries. In Escarpado Canyon itself, cemented feeder conduits? are visible below one seep horizon.

Figure 14.
Fractured, vuggy paleoseep mound, east Cima Hill. Mound is approx. 0.6 m tall.

END OF THE TOUR

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