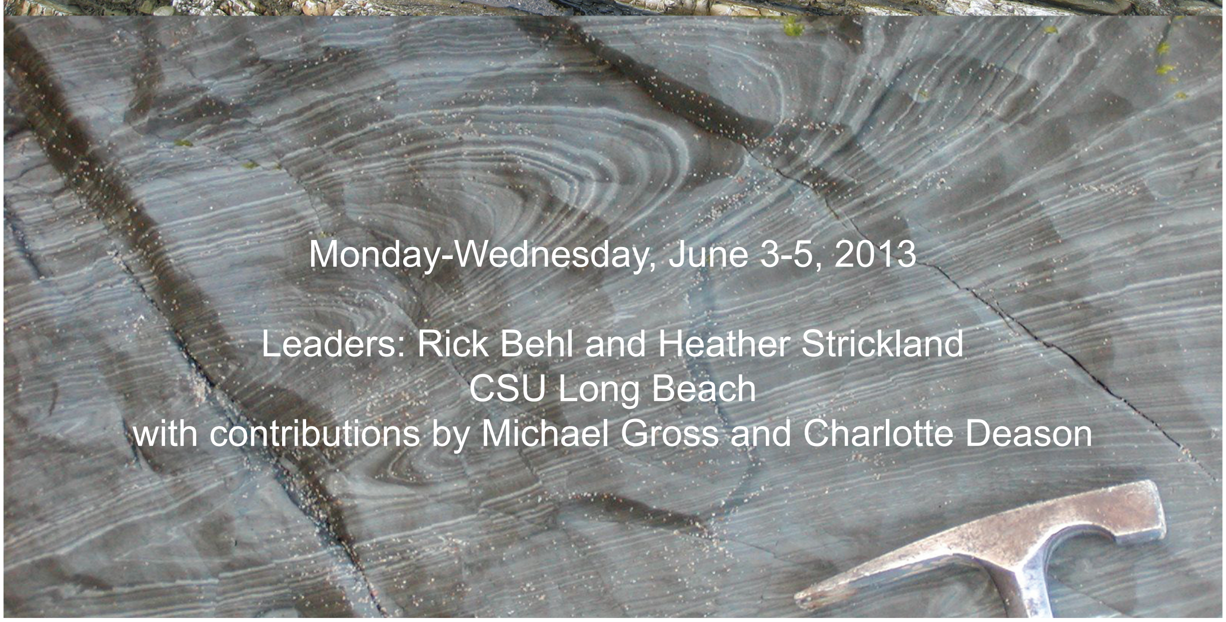
# MARS Project (Monterey and Related Sediments)
# 2013 Field Trip & Seminar

Monterey, Sisquoc, and Pismo formations,
Santa Luis Obispo and Santa Barbara Counties



Monday-Wednesday, June 3-5, 2013

Leaders: Rick Behl and Heather Strickland
CSU Long Beach
with contributions by Michael Gross and Charlotte Deason

## Seminar and Field Trip Itinerary

***Day 1: Monday, June 3.***
Drive to and assemble in Pismo Beach, CA.
Meet 2–5 PM for overview presentations, discussions, logistics, at:
Pismo Lighthouse Suites, Crow's Nest Meeting Room
2411 Price St., Pismo Beach, CA 93449    805-773-2411
Dinner at Spyglass Inn Restaurant

***Day 2: Tuesday, June 4.***
Breakfast at hotel.
Assemble in front of lobby at 8 AM.
Drive to Montana de Oro State Beach for day. (~40 minute drive)
We will combine into carpools to the extent that your company's policies permit.
Lunch and drinks will be provided.
Please wear stout shoes or light hiking boots. The wave-cut terraces are very uneven, presenting a hazard for twisted ankles. We will also scramble up and down steep sand bluffs, but walking distances will be fairly limited.
Return to Shore Cliff Inn ~5 PM.
Dinner in informal groups.

***Day 3: Wednesday, June 5.***
Breakfast at hotel.
Check-out of hotel for some participants.
Combine into carpools taking account who will return to Pismo Beach for the evening and who will drive back to their homes after the day in the field.
Depart for Guadalupe Dunes/Mussel Rock (~40 minute drive)
Lunch and drinks will be provided.
We will make a ~2 mile walk on the beach to the first outcrop, then another 0.5-07 miles to further outcops. Running shoes or light boots are appropriate. Here, we will also do some scrambling up and down steep sand bluffs.
Walk back to Guadalupe Dunes County Park parking.
Field day will end at approximately 4 PM and participants can either drive back to Pismo Beach or return to their homes.

## Field Trip Logistics

1. Arrival: We will meet at 2:00 PM at the Pismo Lighthouse Suites on Day 1.
   We will meet at 8 AM in front of lobby of the Shore Cliff Inn on Days 2 and 3.
   We will finish each day between 3-6 PM.

2. Safety: The most dangerous thing that we will be doing is driving. So we will caravan and have phones in each car. We will drive as close to the speed limit as is safely possible. Other safety items will be noted at each stop, but they include

dehydration, slips & trips (especially on the coast), waves (rogue waves are always possible at the beach), animals, etc.

3. Driving: We are a group of about 25 total. CSULB MARS Project will provide a 12-person van, but we will need to form carpools to transport the other half of the group. Many people will probably drive themselves on Wednesday if they plan to depart at the end of the field day instead of returning to Pismo Beach. We will not driving off-road. Please inform the leaders if you can take others in your vehicle..

4. Activity: We will be doing some short hikes at Montana de Oro with some steep scrambles (on all fours) up sand bluffs. We will walk approximately 5 miles total at Guadalupe Dunes/Mussel Rock on the second field day. This hike will also include a few steep scrambles up sand bluffs..

5. Weather / Dress: Expect the coast to be cool (60's) and if it's windy is can be pretty cold. The key thing is to dress in layers and have a jacket on-hand. A good shade-providing hat and sunscreen (we will provide some) is necessary, even if the air feels pleasantly cool. A good pair of sturdy hiking shoes/boots will be required for both field days.

6. Evening/Non-field activities: Monday evening, we have reservations at 6 PM for drinks and diner out on the terrace at the Spyglass Inn Restaurant. Tuesday and Wednesday evening will be in ad hoc groups.

7. Collecting (rocks): Sampling or damaging the outcrop is not permitted at Montana de Oro State Park, but is OK at Mussel Rock/Guadalupe Dunes. In no place are we allowed to collected any archeological artifacts (e.g., flaked chert).

8. Food & drink: We'll have plenty of snacks & drinks with us in the cars. Lunches will be provided each day. If you have any dietary restrictions, please let me know.

9. Health: Please let the leaders know if you have any medical / health conditions (allergies, injuries, critical medication, etc) that the field trips leaders and myself need to be aware of.

10. Hotels: Shore Cliff Inn, 2555 Price Street, Pismo Beach, CA 93449 800-441-8885

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## INTRODUCTION PART 1 - GENERAL OVERVIEW

This 2 ½ -day meeting will examine two of the classic locations of the Miocene Monterey Formation in the Pismo-Huasna and Santa Maria basins (Fig. I-01) in order to gain insight into the structural, stratigraphic, lithologic, and diagenetic nature of these rocks.

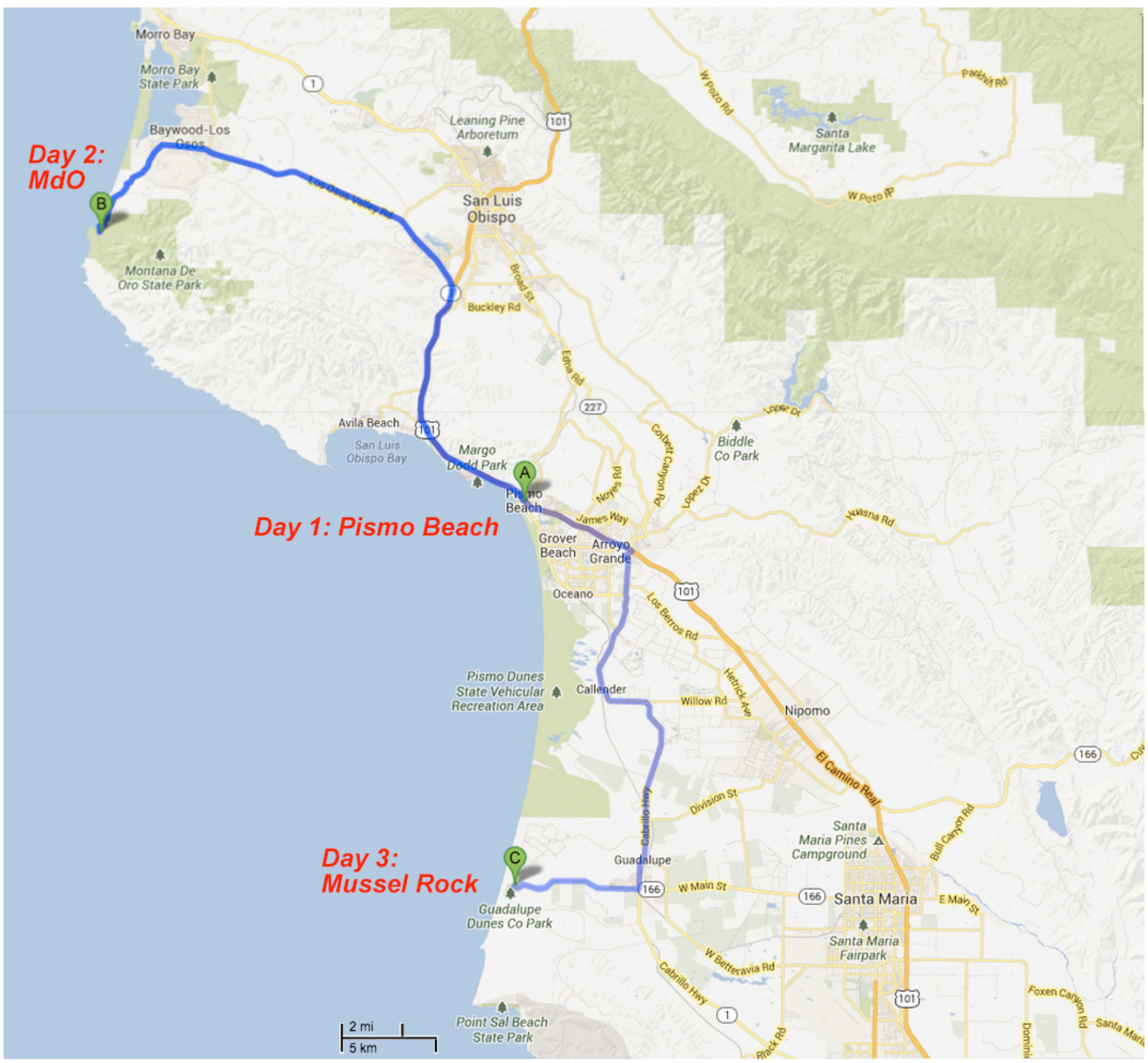


Figure I-01. Location map for field trip stops.

This guidebook is built upon the contributions of geologists from CSULB, both past and present, colleagues in industry, and previous publications. The first part – Introduction and geologic framework to the stratigraphy, sedimentology, and structural deformation of the Monterey Formation – is built from a field guide written by Michael Gross (now with Shell) and Rick Behl that has been partially published by the Pacific Section AAPG for the field trip "Fracture characterization of the Monterey Formation" co-lead with Heather Strickland, Stefano Mazzoni, and Kati Kovacs. The background material for Montana de Oro is also from this guidebook, but includes real data produced by Heather Strickland for her MS thesis research. The Mussel Rock part of the guidebook is based on work by Behl, former MS student Charlotte Deason, and previous workers.

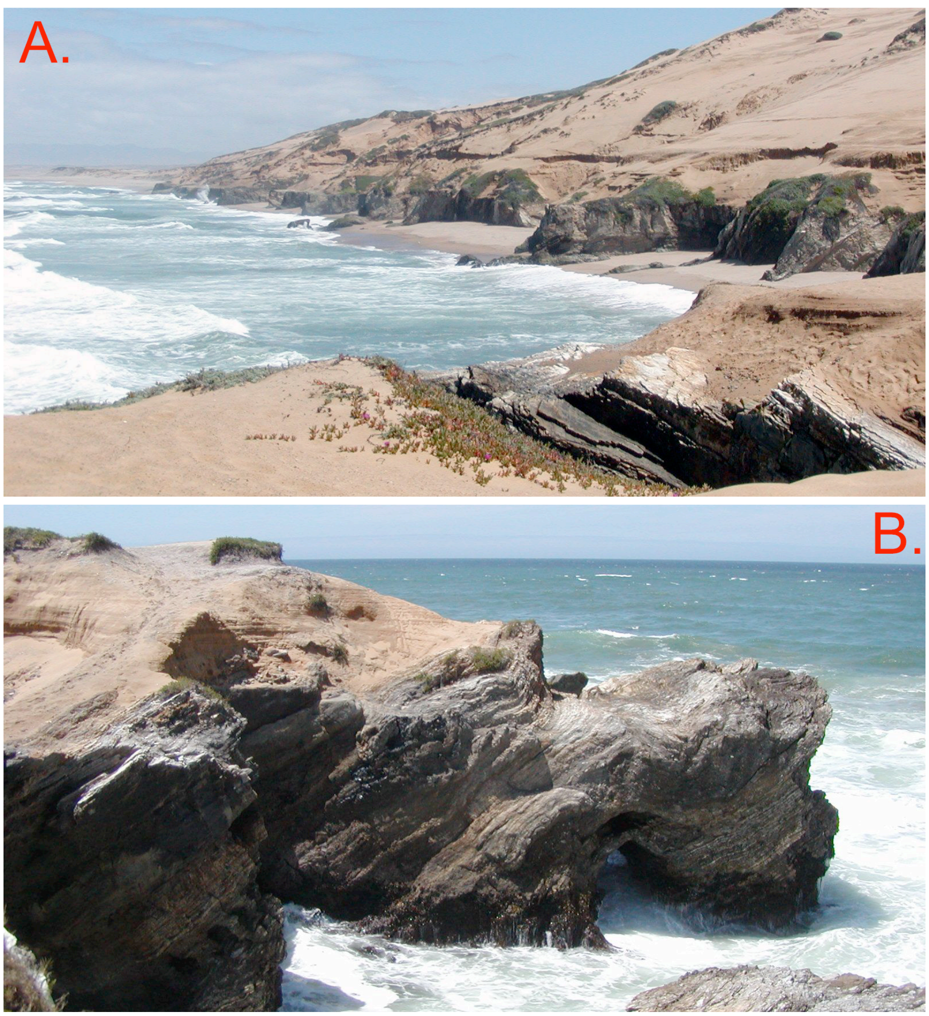
## THE MONTEREY FORMATION

The Miocene Monterey Formation is spread across much of onshore California and the offshore California margin (Bramlette, 1946; Behl, 1999), and equivalent extend around the Pacific Rim. It is a largely bio-siliceous, fine-grained deposit that accumulated in small basins that formed in the early to middle Miocene in response to the subduction of the Pacific-Farallon spreading center and development of the San Andreas transform margin (Blake *et al*., 1978; Pisciotto & Garrison, 1981; Isaacs, *et al*., 1983; Atwater, 1989; Nicholson *et al*., 1994). The Monterey is primarily known as a diatomaceous, organic-rich hemipelagic unit deposited mostly beneath a strong upwelling zone and well-developed oxygen minimum zone (Ingle, 1981; Pisciotto & Garrison, 1981). However, the conditions of its deposition led it to also be unusually enriched in phosphate, or dolomite or limestone in certain locations or stratigraphic levels – this serves as the basis for separating different members or units within the Monterey overall (Fig. I-03). Typical Monterey lithologies are: diatomite, diatomaceous and siliceous shale, porcelanite, chert, calcareous and phosphatic shale, dolostone and limestone. These rocks are differentiated by composition, texture, and their physical properties.

### *Silica diagenesis*

The Monterey Formation has been buried and uplifted to different depths, consequently it contains all silica phases (Fig. I-04)(Bramlette, 1946; Murata & Larson, 1975; Pisciotto, 1981; Isaacs, 1981a; Pisciotto & Garrison, 1981). These silica phases include: biogenic opal-A (hydrous silica with an X-ray amorphous structure) which makes up the shells of diatoms and radiolarians; metastable opal-CT (hydrous silica with crystal structure similar to mixed cristobalite and tridymite) which forms with increased temperature or time from dissolved opal-A; and the stable end-product, diagenetic quartz, which forms by another dissolution/reprecipitation step with further burial or time. Field and geochemical evidence indicates that cherts can form earlier than porcelanite (Murata & Nakata, 1974; Behl & Garrison, 1994: Behl, 1998). In addition to temperature and time, compositional variations in clay, organic matter, and calcium carbonate content are also important in controlling the rates of silica diagenesis. The presence of clay and organic matter retards the opal-A to opal-CT transformation (Fig. I-04; Kastner *et al*., 1977; Isaacs, 1981a, 1982; Hinman, 1990), whereas the presence of calcium carbonate increases the rate of opal-CT nucleation (Kastner *et al*., 1977) and possibly quartz.

Chert and porcelanite are distinguished by their physical characteristics as observable in the field or in core. Chert is identified as the pure, fine-grained siliceous rock that is hard and dense, has a smooth, conchoidal or splintery fracture, and a glassy or waxy luster. It is usually composed of >90% diagenetic silica (Behl & Garrison, 1994). In contrast, porcelanite is the rock composed of 50 to 85% diagenetic silica that is less hard and dense than chert, has a blocky to splintery fracture and a matte surface texture similar to that of unglazed porcelain (Isaacs, 1981b). The principal difference between chert and porcelanite is clay content and/or porosity (Isaacs, 1981b, 1982; Dunham & Blake, 1987; Behl & Smith, 1992; Behl & Garrison, 1994). Identification of a rock as chert or porcelanite is made independently of the silica phase, i.e., a dense vitreous chert can be composed of either, or both, opal-CT or quartz silica phases, and a porcelanite, similarly, can contain either opal-CT and/or quartz phases.




Day 3. View north from Mussel Rock (A), and view south to Mussel Rock.

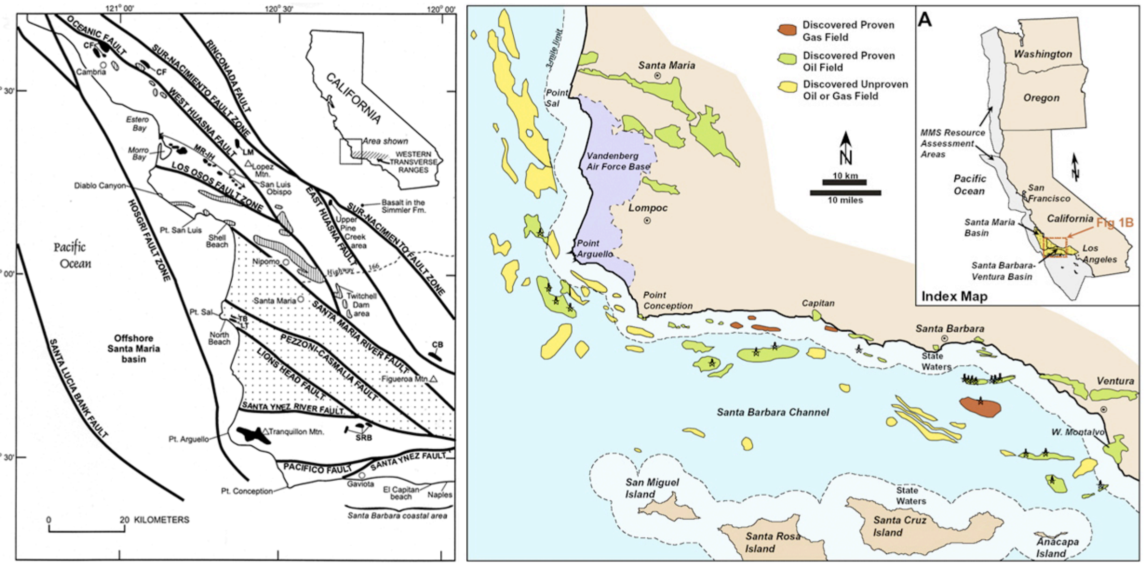



Figure I-02. Major faults of field trip area (left), and related oil fields (right).

| GENERALIZED LITHOLOGY (After Isaacs (1980)) | WOODRING ET AL. (1943); WOODRING & BRAMLETTE (1950) | | PISCIOTTO (1978) (informal) | | ISAACS (1984) | |
|---|---|---|---|---|---|---|
| SILICEOUS ROCKS: Diatomites, changing down-section to rythmically-bedded, laminated and massive chert, porcelanite and siliceous mudrocks (variable carbonate) | MONTEREY FORMATION | UPPER MEMBER | MONTEREY FORMATION | SILICEOUS FACIES | MONTEREY FORMATION | CLAYEY-SILICEOUS MEMBER |
| | | | | | | UPPER CALCAREOUS-SILICEOUS MEMBER |
| PHOSPHATIC ROCKS: Phosphatic (P), organic-rich shale and mudstone with cyclic alternations with siliceous rocks near the top (variable carbonate) | | MIDDLE MEMBER | | PHOSPHATIC FACIES | | TRANSITIONAL MARL-SILICEOUS MEMBER |
| | | LOWER MEMBER | | | | CARBONACEOUS MARL MEMBER |
| CALCAREOUS ROCKS: Foraminifer and coccolith shale and mudstone with abundant biogenic and authigenic carbonate | POINT SAL FORMATION | | PT. SAL | CALCAREOUS FACIES | | LOWER CALCAREOUS-SILICEOUS MEMBER |

Figure I-03. Comparison of lithostratigraphic zonations (informal members) of the Monterey Formation in the Santa Barbara-Santa Maria areas (after Pisciotto, 1981).

Figure I-04. (next page) Diagrams and scanning electron microscope (SEM) photomicrographs depicting steps in silica diagenesis. A. Mixed clay and diatom fragments (opal-A) in a muddy diatomite. B. Nearly pure opal-A diatomite (penate diatoms). C. Large centric diatom simultaneously being dissolved and infilled with opal-CT lepispheres. D. Close-up of opal-CT lepispheres ("spheres of blades"). E. Nearly completely cemented opal-CT chert showing lost intercrystalline microporosity and remaining moldic porosity. F. Silica phase diagram (Keller and Isaacs, 1985 as modified by Behl and Garrison, 1994) showing that the transition of opal-A to opal-CT and opal-CT to quartz is a function of both temperature and composition. Note that the purest cherts form at considerably lower temperature than the silica phase transitions in less-pure porcelanite and siliceous mudrocks. G. Sequence of diagenesis for the timing of formation of various siliceous rocks (Behl and Garrison, 1994).

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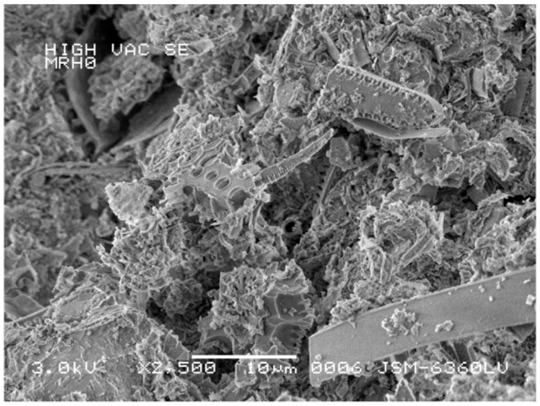
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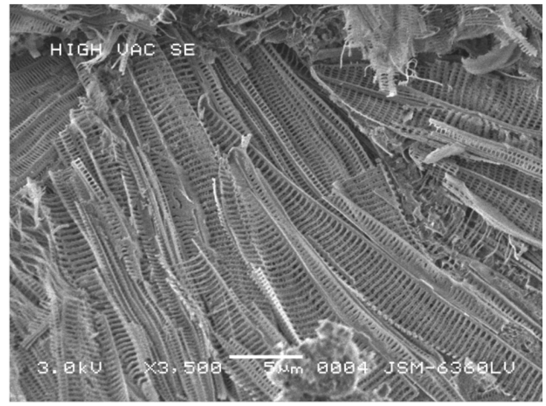
**B.**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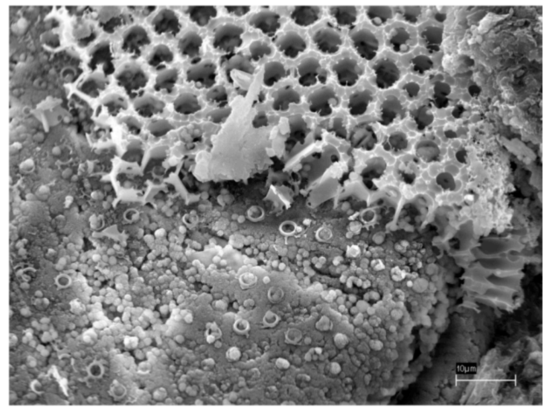
**C.**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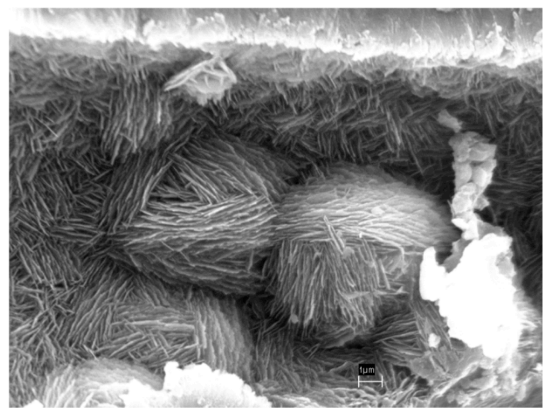
**D.**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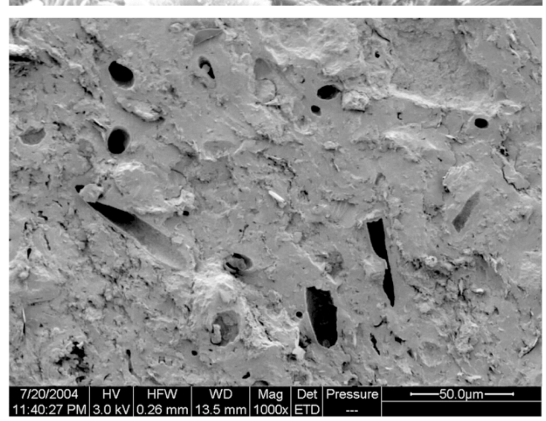
**E.**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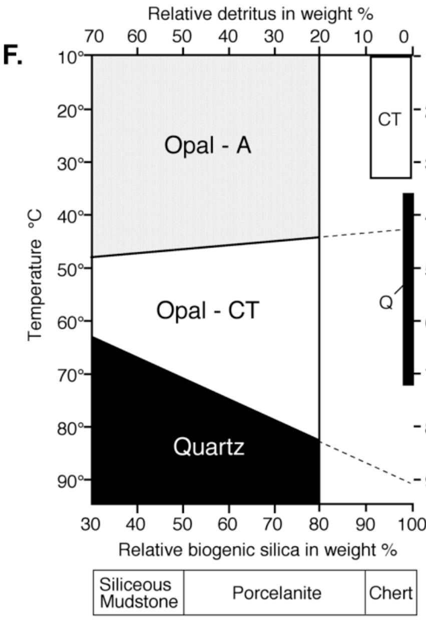
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Relative biogenic silica in weight %
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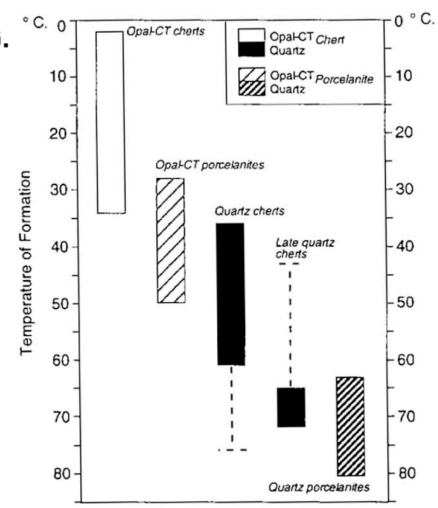
Porcelanite
Chert

**G.**


° C.
Opal-CT cherts
Opal-CT porcelanites
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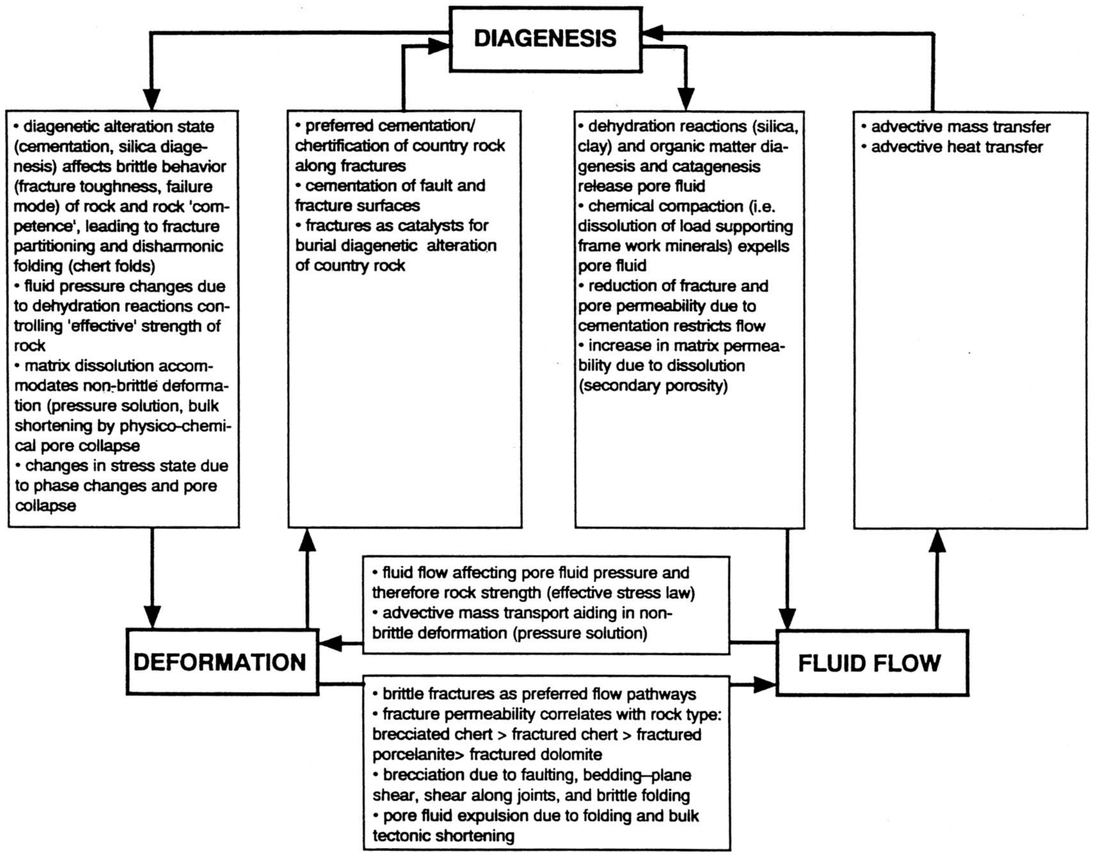



Figure I-05. Potential relationships between diagenesis, deformation, and fluid flow as inferred from observations of the Monterey Formation (Eichhubl & Behl, 1998).

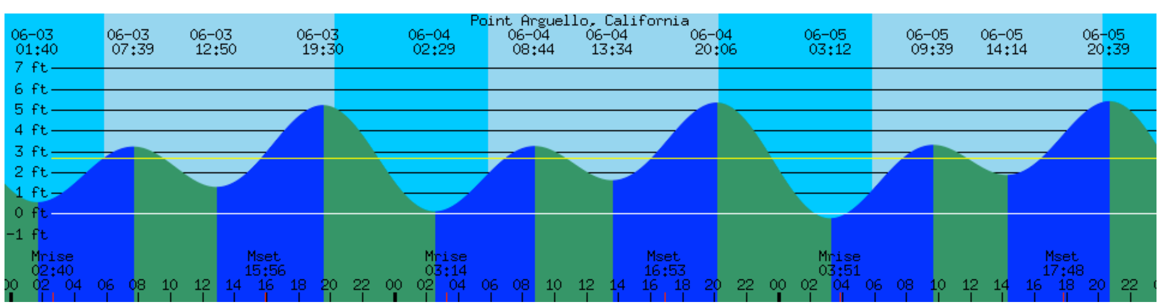



Figure I-06. Tide table for the field trip. Daylight hours shown in light blue.

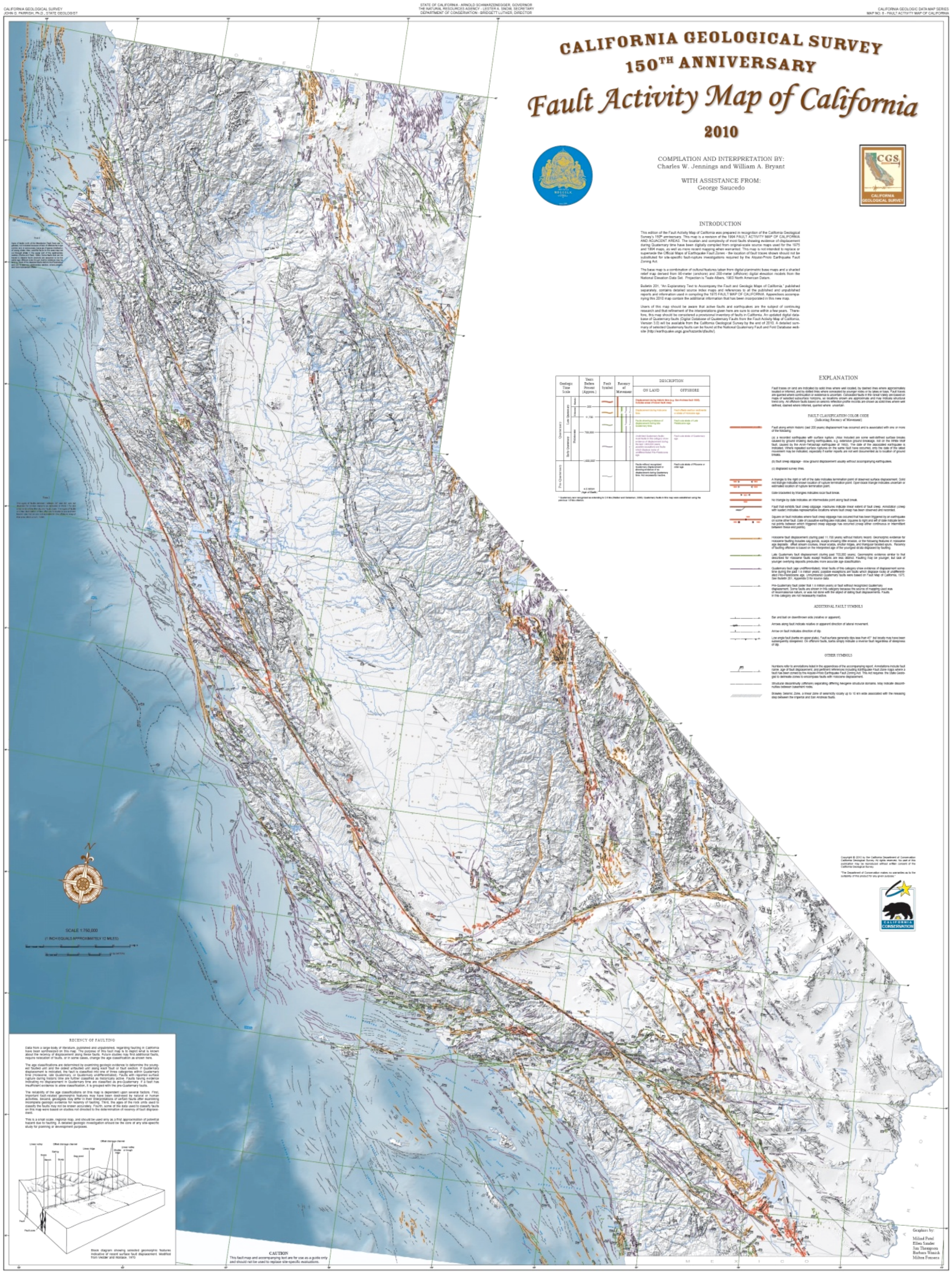



Figure I-07. Map of active faults in California (California Geological Survey). The San Andreas Fault (SAF) is a right-lateral transform the marks the boundary between the Pacific and North American tectonic plates. Estimate the locations of Bakersfield, Santa Barbara and field stops.

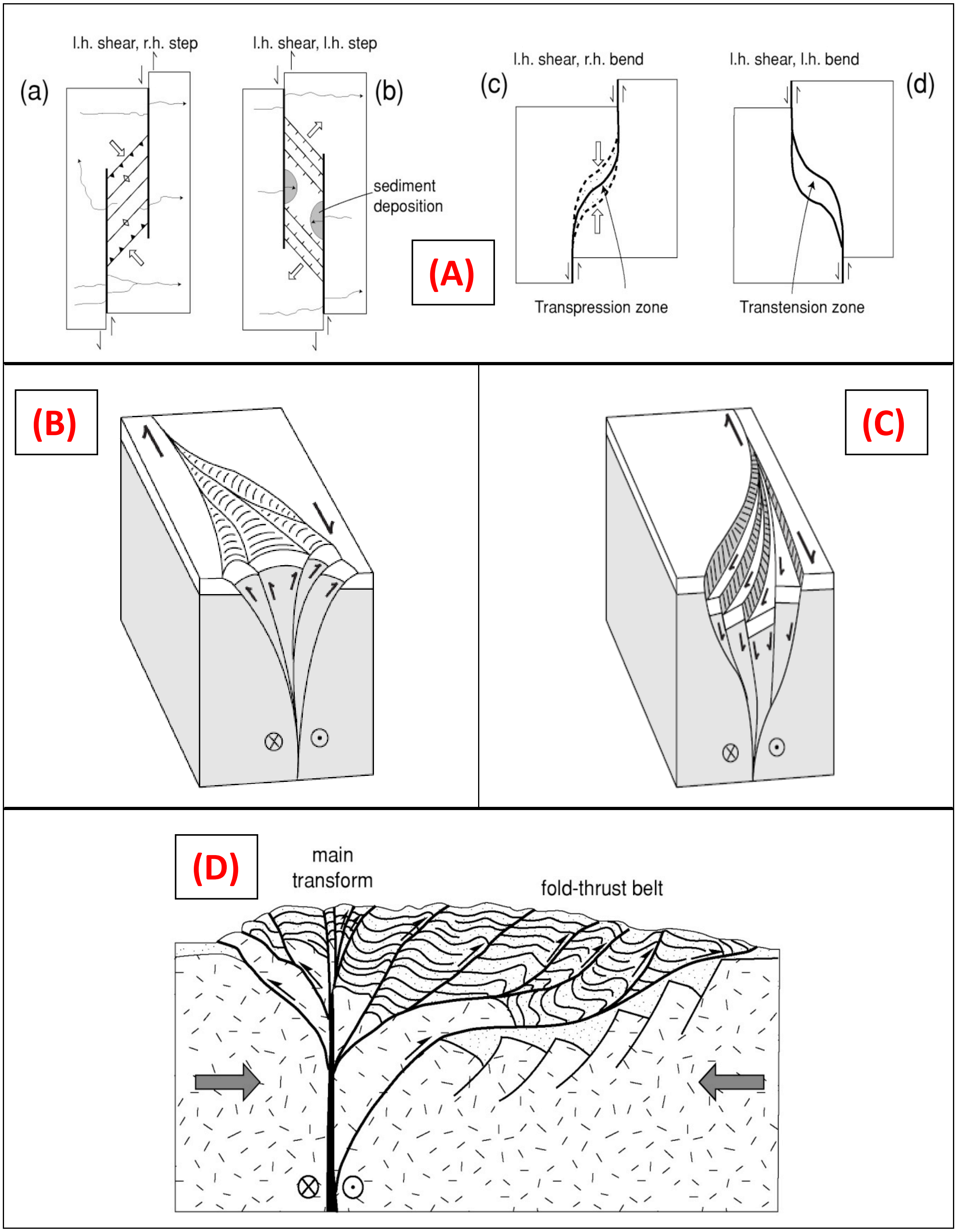



Figure I-08. Deformation associated with strike slip faults. (A) Bends and en-echelon step-overs in strike-slip faults resulting in localized contraction and extension (Ramsay and Huber, 1987); (B) Contractional strike-slip duplex ("positive flower structure"); (C) extensional strike-slip duplex ("negative flower structure")(B & C from van der Pluijm and Marshak, 2004); (D) Contractional fold and thrust belt adjacent to plate boundary transform, due to transform-normal tectonic shortening (Marshak and Wilkerson, 2004).

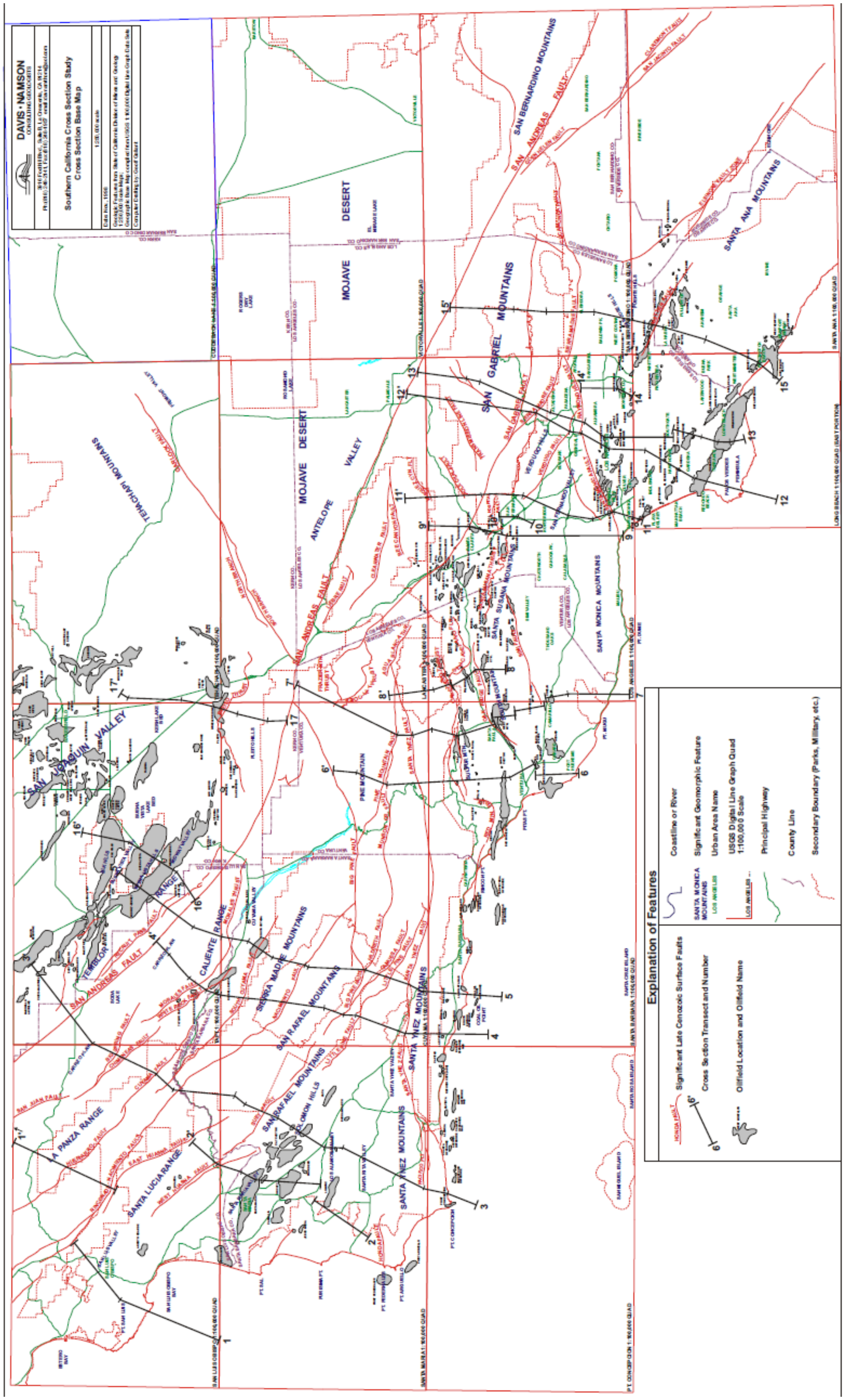



Figure I-09. Base map for Namson and Davis USGS cross sections. Main faults shown in red and oil fields shaded gray.

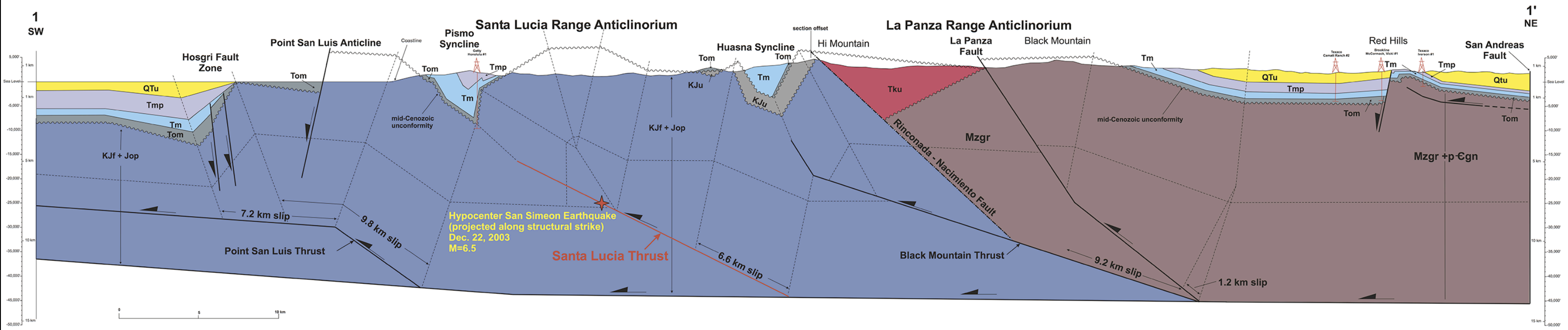



Figure I-10..Namson and Davis USGS cross section #1 (1988).

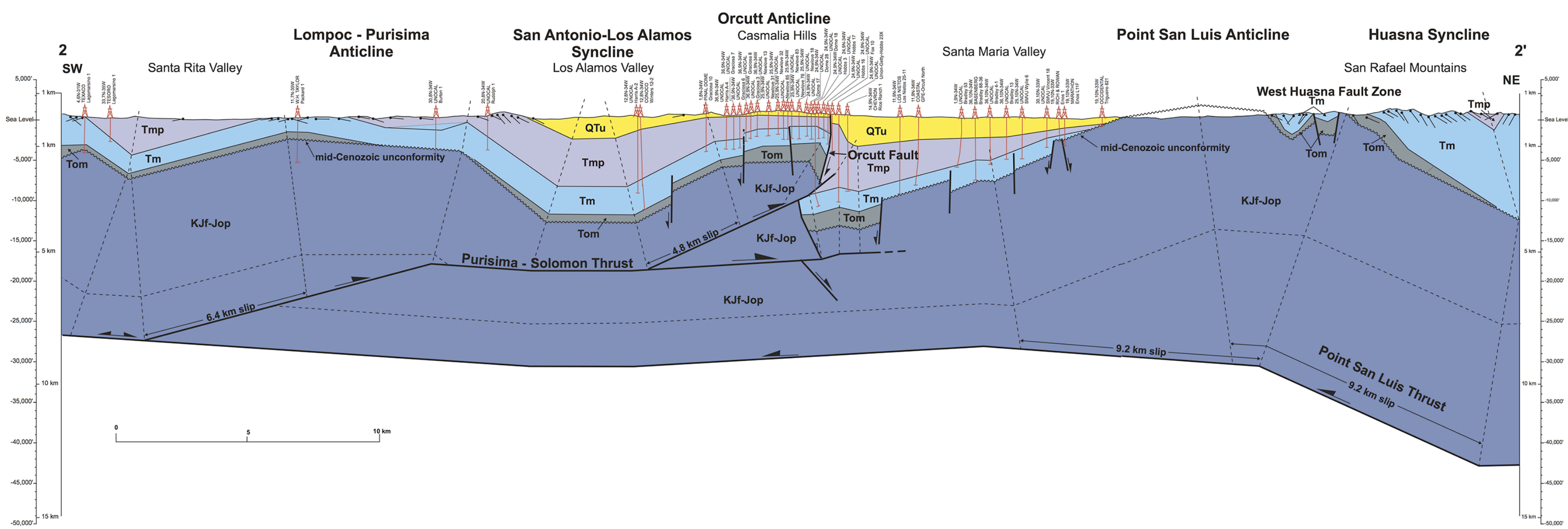



Figure I-11..Namson and Davis USGS cross section #2 (1988).

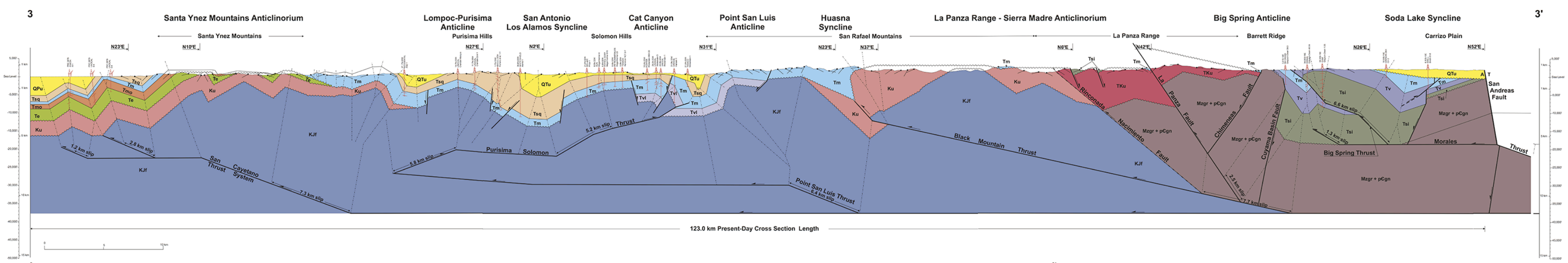



Figure I-12..Namson and Davis USGS cross section #3 (1988).

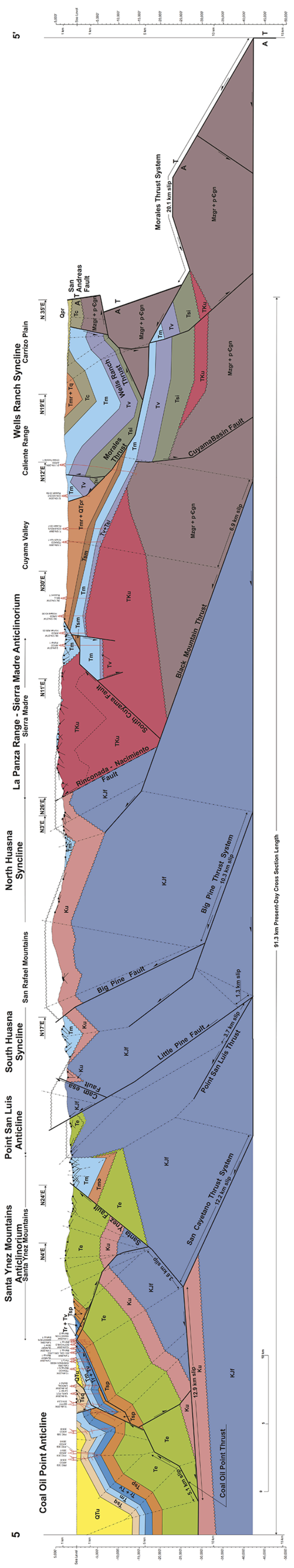



Figure I-13..Namson and Davis USGS cross section #5 (1988).

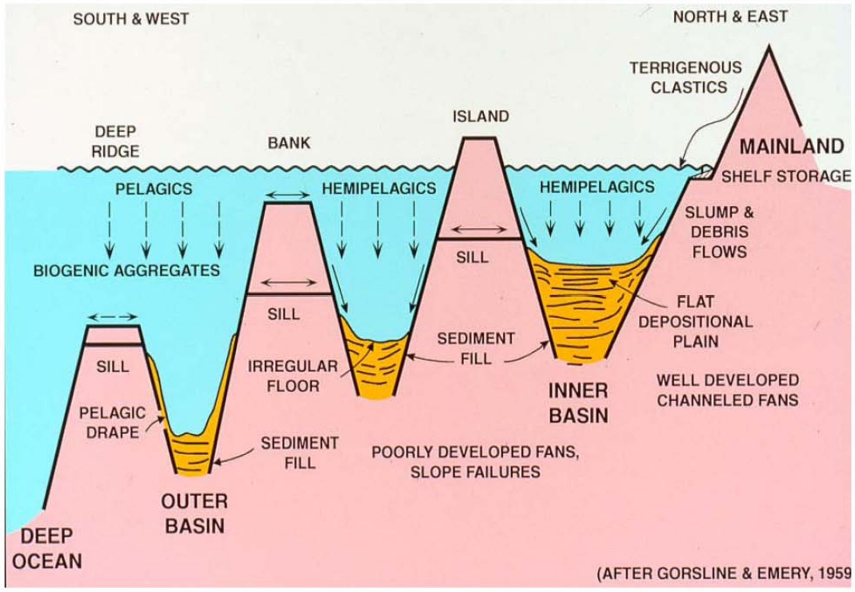



*Figure 2. Schematic cross section of margin configuration of the California Continental Borderland after Gorsline and Emery (1959). Blake (1981) suggested this topographic arrangement could account for many characteristics of Monterey Formation depositional systems.*

Figure I-14. Depositional setting for Monterey Formation basins (from Schwalbach et al, 2009).

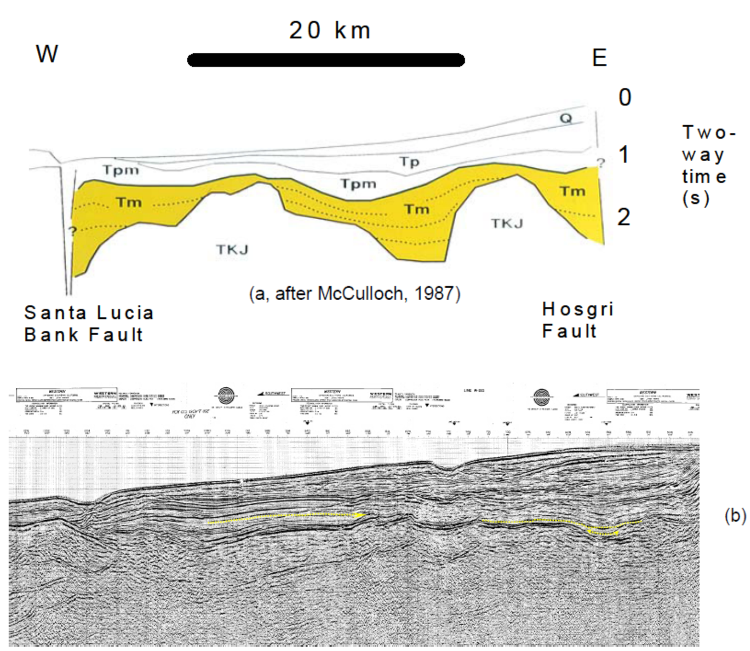



*Figure 3. (a) Seismic line drawing after McCulloch (1987) from offshore Santa Maria Basin the illustrates onlap of lower units filling basin topography and generally planar, parallel reflectors for younger Monterey strata (Tm). (b) Migrated seismic data from offshore Santa Maria Basin - different location and scale from (a). Similar onlap and depositional geometry as depicted in line drawing. Neither example shows evidence of seismic-scale progradation.*

Figure I-15. Seismic expressions of offshore Miocene basins (from Schwalbach et al, 2009).

# Introduction Part 2: Fracture & Mechanical Stratigraphy

Throughout the course of our field trip we will relate specific field observations to four main themes related to brittle deformation. Our goal is to initiate discussions that will incorporate the fracture patterns and geometries we observe in outcrop with the expertise and experience of the field trip participants. The four main themes are:

**1.) The relationship between fracture development and structural style (i.e., regional tectonics, fold geometry and stress fields).**

Fracture development is strongly controlled by regional tectonics and the style of structural deformation. The large folds and faults that define many hydrocarbon traps are a product of regional deformation, thus their geometries and internal strains often reflect a broader tectonic framework (Fig. I-16). Mechanisms of fold development, in turn, will have a profound influence on fracture development, both in terms of orientation and intensity (Fig. I-17).

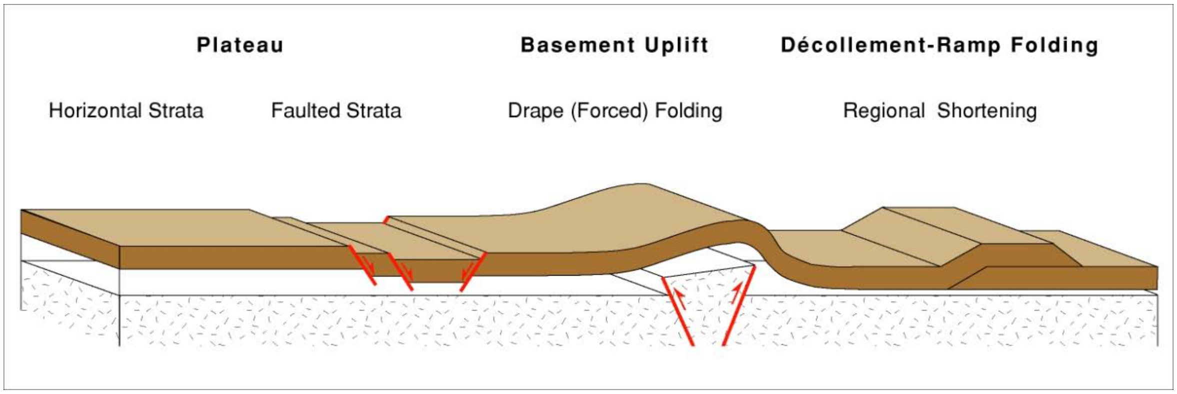



**Figure I-16.** Various tectonic settings that lead to regional fracture development.

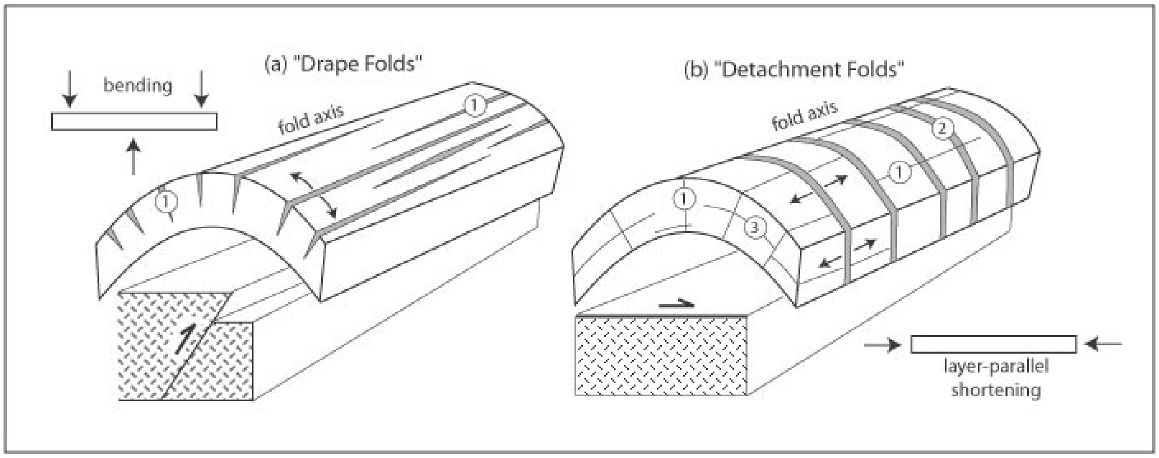



**Figure I-17.** Dependence of fold-related fracture development on folding mechanism. For drape folds (a) the dominant opening-mode fracture set is often hinge-parallel, whereas for detachment folds (b) the most prominent set is perpendicular to the fold hinge. The main fracture sets are (1) hinge (strike) parallel, (2) hinge (strike) perpendicular, and (3) bed parallel. The numbers do not imply relative timing.

*Questions to consider:*

- What is the dominant fracture set observed in the Monterey Formation with respect to regional and local folding?
- How are these fractures related to fold geometry and tectonic contraction?
- Why and how is extension accommodated by brittle fracturing in the Monterey Formation?
- What is the magnitude of this fracture-related extension, and how does it contribute to porosity and permeability?

**2.) The influence of mechanical stratigraphy on fracture development and distribution**

Mechanical stratigraphy refers to the elements within a stratigraphic section that control structural deformation. In our case, we focus primarily on brittle deformation, though you will note that intraformational folding in the Monterey Formation is also strongly controlled by mechanical stratigraphy. Important elements within the mechanical stratigraphy that influence fracture development and distribution in the Monterey Formation include lithology, bed thickness and bed boundaries.

In the Monterey Formation, fracture type (faults versus joints) is often dependent upon lithology. The more competent beds such as cherts, porcelanites and dolostones tend to develop joints and veins, whereas the less competent beds such as mudstones and shales often fail by faulting (Fig. I-18a). This dependence of failure mode on lithology is referred to as "fracture partitioning". Portions of the stratigraphic section therefore display a different type of fracture in alternating beds (Fig. I-18b).

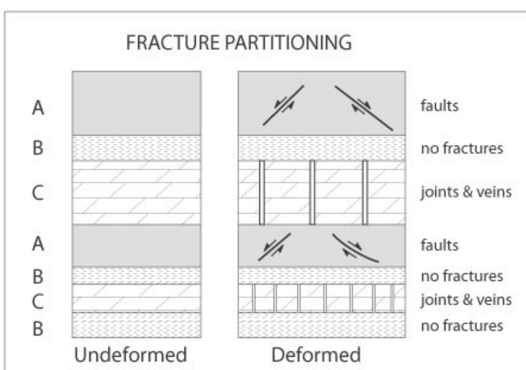



**Figure I-18a**. The concept of fracture partitioning, where the type of fracture (faults versus joints) is controlled by lithology (from Gross, 1995).

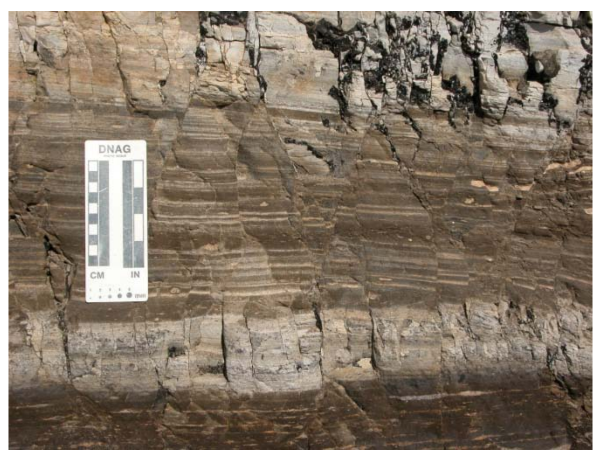



**Figure I-18b**. Photo of Monterey Fm at Arroyo Burro with small faults in laminated mudstone and joints in the porcelanite.

The boundaries between mechanical units, referred to as mechanical layer boundaries, have a profound influence on fracture development in the Monterey Formation. Fractures often terminate at discrete bed boundaries, thus restricting their vertical dimensions and leading to highly elliptical fracture shapes. The fracture height, which often corresponds to the thickness of one or several stratigraphic beds, thus defines the mechanical layer thickness (Fig. I-19). Fractures confined to discrete mechanical units are observed at a variety of scales in outcrop, core and image logs.

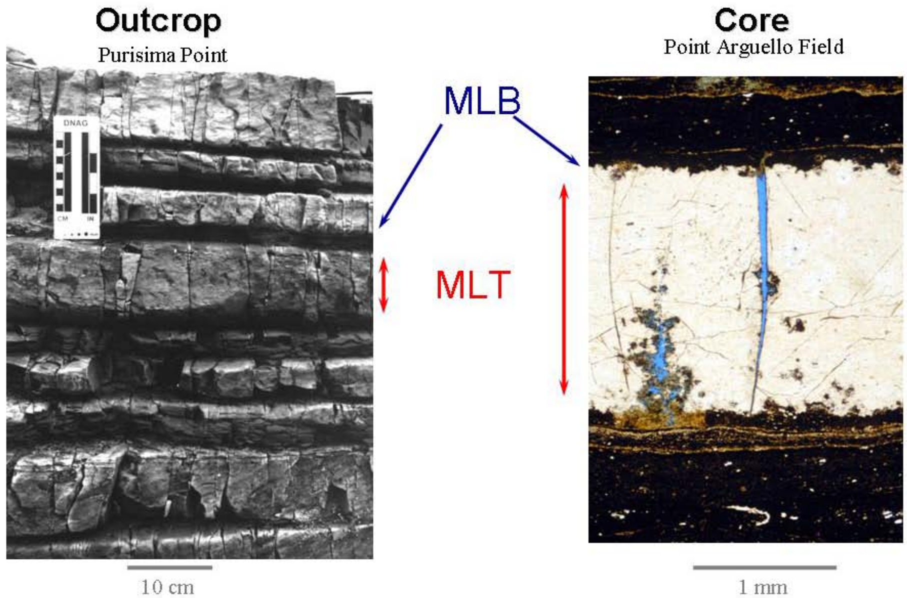



**Figure I-19**. Bed-confined fractures in outcrop and core of the Monterey Formation. Note discrete mechanical layer boundaries (MLB) and how the fracture height defines the mechanical layer thickness (MLT). From Gross et al (1995).

Mechanical stratigraphy is also one of several factors that control fracture spacing in the Monterey Formation. Several studies of bed-confined fractures in the Monterey Formation have shown a strong correlation between fracture spacing and bed thickness (Narr and Suppe, 1991; Gross et al., 1995). The linear relationship is thought to result from the stress reduction shadow that develops in the vicinity of a pre-existing fracture, whose dimensions scale with fracture height. Thus, thin beds tend to have more closely-spaced fractures, whereas fracture spacing is greater in thicker beds (Fig. I-20). Other factors that control fracture spacing include structural position (strain magnitude) and lithology (mechanical properties).

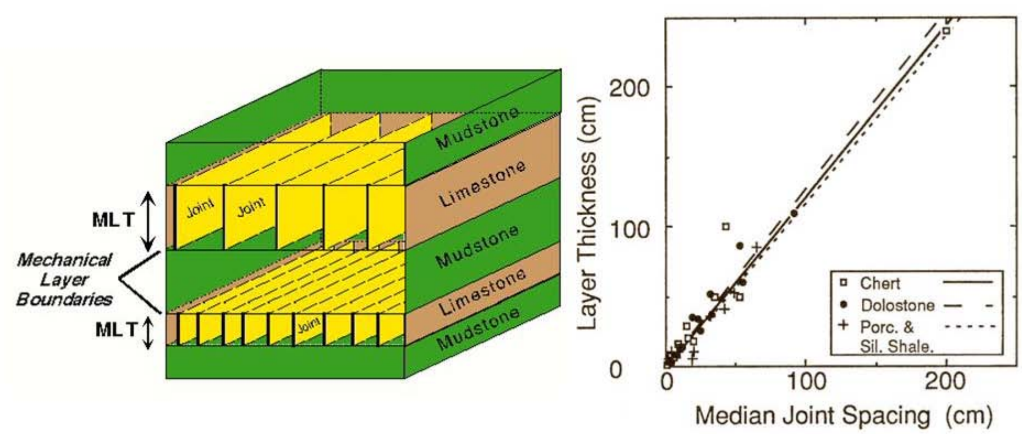



**Figure I-20**. Schematic to left showing relationship between fracture spacing and mechanical layer thickness (Gross et al., 1995). On right, plot of layer thickness versus joint spacing for fractures measured in the Monterey Formation (from Narr and Suppe, 1991).

*Questions to consider:*

- How important is mechanical stratigraphy for characterizing and modeling fractures at the reservoir scale?
- What methods can be used to quantify effects of mechanical stratigraphy on fracture distribution in the Monterey Formation?
- What kind of impact does fracture partitioning (alternating units of faults and joints) have on fluid flow?

**3.) Fracture scaling in the Monterey Formation.**

Fractures in the Monterey Formation occur at a variety of scales. For example, opening-mode fractures belonging to the same set (i.e., fractures of the same orientation that formed in response to the same episode of deformation) can be observed at the microscale in thin section, confined to single beds, spanning multiple beds and as throughgoing features that extend across the entire outcrop. A similar scaling relationship is observed for faults. The result is a hierarchical fracture-fault architecture consisting of "nested" fractures that correspond to mechanical units of varying dimensions (Fig. I-21).

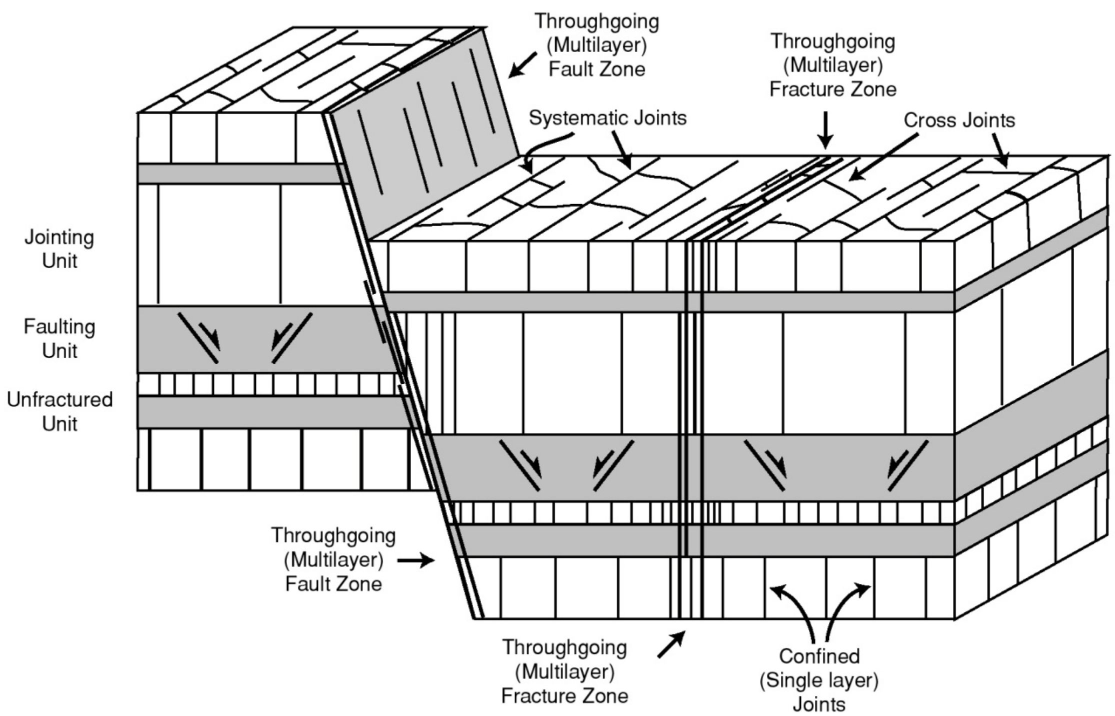



**Figure I-21**. Schematic of fracture architecture commonly observed in layered sedimentary rocks such as the Monterey Formation (from Gross and Eyal, in press).

The photographs in Figure I-22 show opening-mode fractures in the Monterey Formation at different scales.

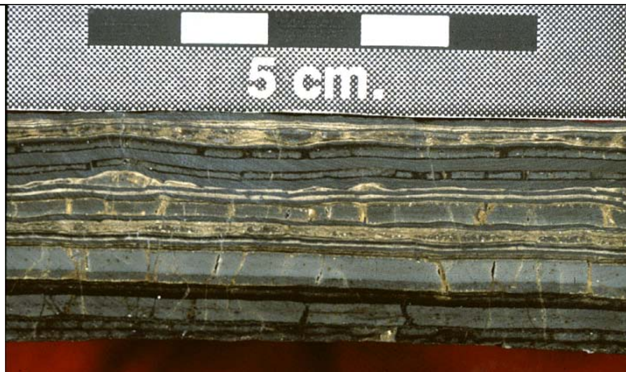



**Figure I-22a.** Small fractures confined to thin laminae of the Monterey Formation. Sample taken from well in Point Arguello field.

**Figure I-22b.** Bed-confined fractures at Point Buchon. Note alternating fractured and unfractured beds.

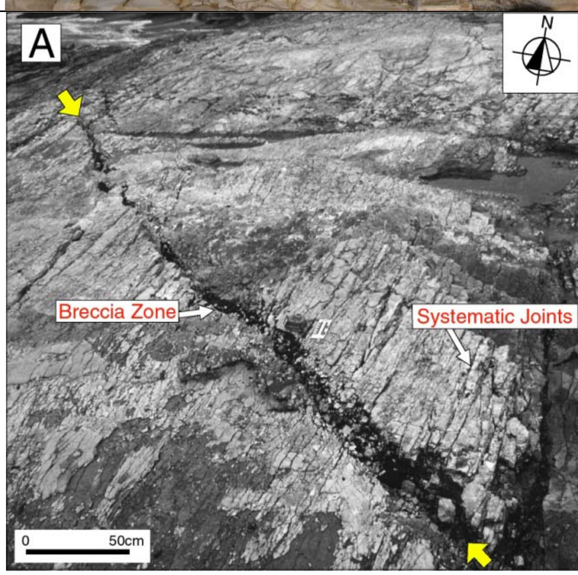



**Figure I-22c.** A multi-layer, tar-filled breccia zone (between arrows) at Lompoc Landing. These are intermediate-size structures that provide access to hydrocarbons stored in the smaller bed-confined fractures. In the Monterey Formation they have heights ranging from 10-25 feet and lengths from 50-80 feet. (From Finn et al., 2003).

**Figure I-22d.** Large, throughgoing fractures at Point Buchon. These represent major pathways for fluid flow and provide vertical connectivity among fracture populations confined to smaller mechanical units.

*Questions to consider:*
● At what scale do fractures and faults become significant hydrologic features?
● Can populations of the more abundant, small fractures contribute to our understanding of the larger fractures? How?
● How is fracture connectivity achieved among the various mechanical-flow units?
● What is the mechanism for the formation of multilayer faults and fractures, and are they genetically related to the smaller bed-confined features?

**4.) Reservoir characterization and extrapolating field observations to the subsurface.**

The first step in modeling fractured Monterey reservoirs involves developing a conceptual model of how the fractures and faults are distributed with respect to mechanical stratigraphy (Fig. I-23), and incorporating subsurface data from core and well logs that shed light on fracture orientations and intensity. Primary data required to characterize fracture populations include fracture type (faults, joints, fracture zones, etc.), fracture intensity (e.g., spacing or its inverse frequency, clustering), fracture orientation (to determine major trends and division into discrete sets), fracture aperture, mineral fill, timing of fracture set development (with respect to other fracture sets and structural/tectonic history), dimensions (length and height to estimate aspect ratio) and porosity.

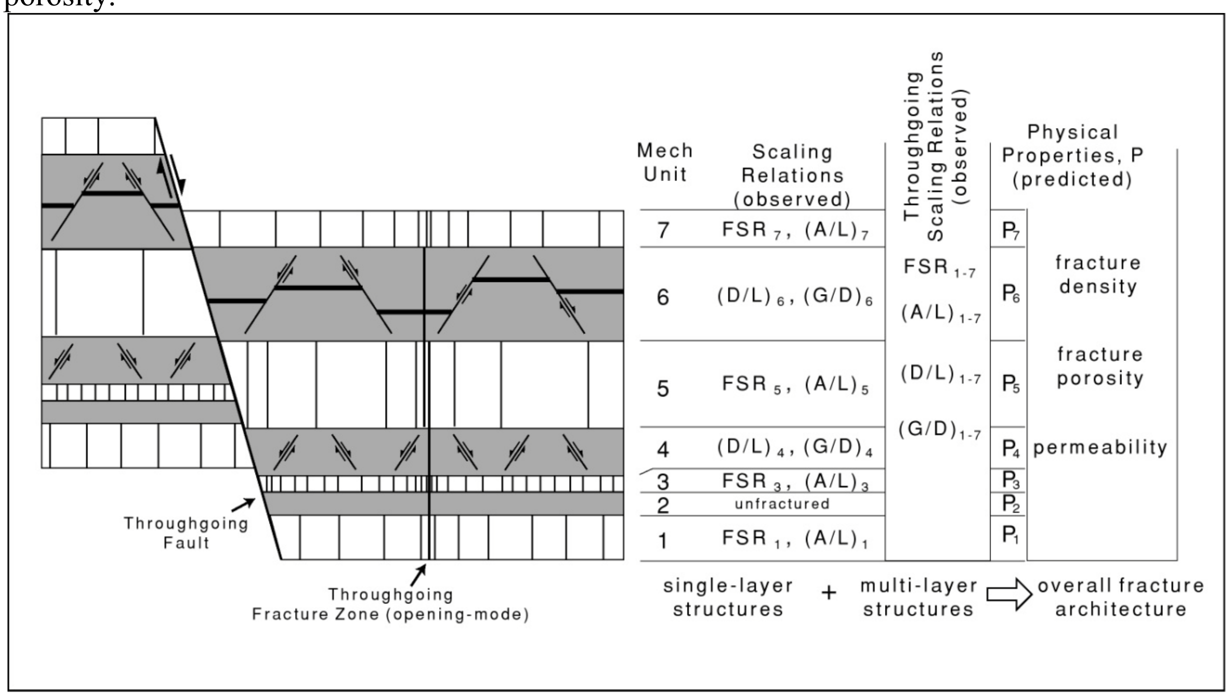



**Figure I-23.** A very basic conceptual model for a Monterey Fm fractured reservoir based on outcrop observations, showing how fracture scaling relations can be used to estimate petrophysical properties.

Outcrop analogs offer considerable insight for understanding fractured reservoirs, especially important concepts such as mechanical stratigraphy, scaling of fracture populations and associations with structural geometry and tectonics. In frontier settings results from outcrop surveys may formulate the strategy for initial exploratory drilling.

However, in production settings there is no substitute for collecting fracture data directly from the reservoir. In the latter case, the outcrop analogs serve as a framework for building the conceptual model based on the inherently limited datasets derived from subsurface data sources. It is therefore useful to incorporate as much subsurface techniques and data as possible, including sonic logs, image logs, well tests, tracer tests mud loss/lost circulation, production logs, core and seismic. Knowledge of the structure (geometries, mechanisms and kinematics) and state of stress (orientations and magnitudes) will provide valuable constraints.

*Some specific examples from core and image logs:*

Cores provide the highest level of detail about fractures in the subsurface. The example in Figure I-24 illustrates the different expression of fracture features in rock units of different composition. The slabbed cores are 4 inches wide. The core on the left is mostly biogenic silica (opal CT) and the highest fracture density occurs in the most siliceous interval. Many of the smaller bed-bounded fractures terminate in the darker, clay-rich layer. The core on the right has a much higher clay content, has poorly developed fracture sets, and contains a slickensided surface (broken core face on lower right). Therefore, cores are very valuable for establishing mechanical stratigraphy in the subsurface, in this case the dependence of failure mode (faulting vs. jointing) on lithology (see Figure I-18 and related text).

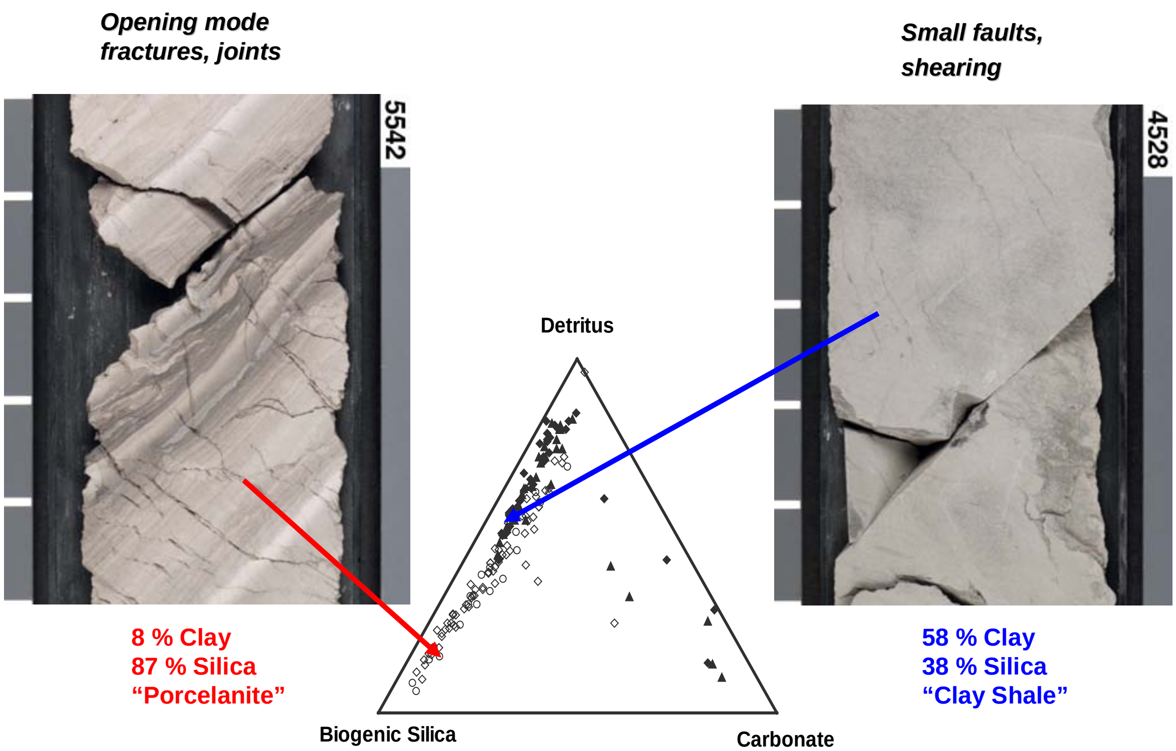



**Figure I-24.** An example of “fracture partitioning” observed in core of the Monterey Fm.

Cores, however, suffer from one significant limitation. Often cores are only obtained over a limited part of the interval being studied. And, particularly in highly-fractured intervals, recovery is often not complete. Over the past decade the addition of image logs to well logging suites has significantly improved our ability to characterize fractures in the reservoir. Perhaps the biggest benefit has come from horizontal wells. The example in Figure I-25 is from a horizontal well in the Monterey Formation that drilled approximately parallel to bedding. The brighter colors on the image represent the more siliceous lithology (porcelanite, more resistive), the darker colors represent the rocks with higher clay content (more conductive). Notice the fracture distribution and that many of the bed-bounded fractures terminate at the clay-rich bed boundaries. Image logs in horizontal wells are also valuable for measuring spacing between fractures.

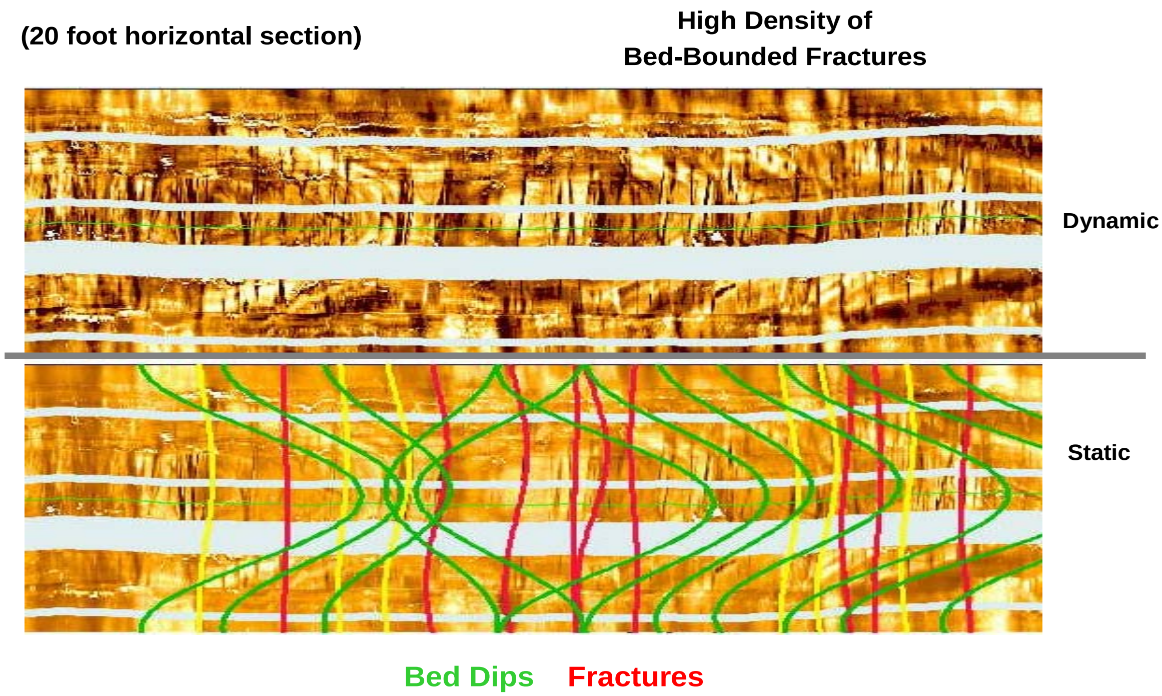



**Figure I-25.** An image log from a horizontal well in the Monterey Fm showing termination of fractures at clay-rich bed boundaries.

The final example (Figure I-26) is an image log from a horizontal well that crossed a cemented dolomite zone (bright on static image), likely analogous to the partially-cemented faults and breccias viewed at Arroyo Burro. In the subsurface these can be point-sources of extremely high flow to the well bore (either oil/gas or water!). Wells drilled into pressure-depleted parts of the reservoir have lost circulation and thousands of barrels of drilling mud.

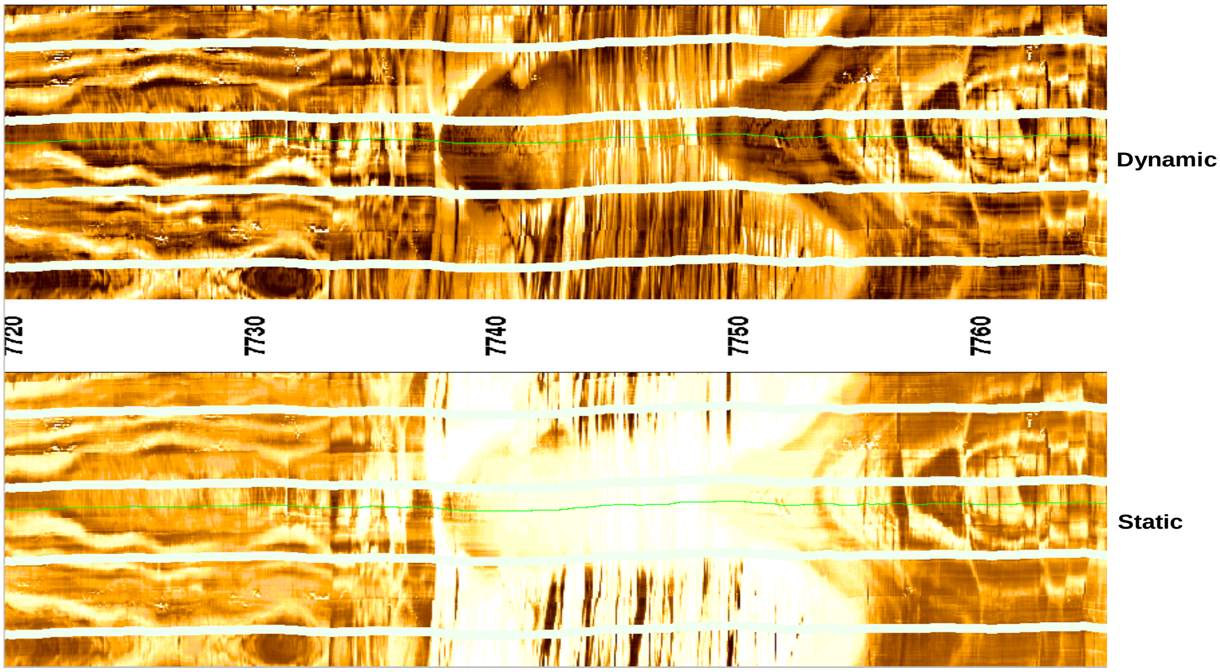



**Figure I-26.** An image log from a horizontal well in the Monterey Fm showing a dolomite-cemented fracture zone. Note high intensity of fracturing between 7740 and 7750 ft.

*Questions to consider:*

● How many of the fractures observed in outcrop are actually found at depth under reservoir pressures, and how many represent near-surface weathering processes?

● What are the dimensions of the fractures and mechanical units that can be used to generate discrete fracture models at the reservoir scale, and what do they look like in outcrop?

● What is the contribution of the numerous small fractures and faults to overall porosity and permeability of the formation, and how can it be captured in reservoir models?

● What kind of techniques have been used successfully by field trip participants to characterize fractured reservoirs (e.g., seismic anisotropy, sonic logs, scaling relations)?

## Day 2: Montaña de Oro State Park

***Basin:*** Pismo (Pismo-Huasna)

### *Formation/Members:*

Pismo,

- Miguelito Member (basal), upper Miocene (10-6.4 Ma)
- Equivalent to, and originally assigned to, the upper of Monterey Formation
- Reference: M. A. Keller (1992) in Schwalbach and Bohacs, PS-SEPM Volume 70, "Sequence Stratigraphy in Fine-Grained Rocks: Examples from the Monterey Formation."

### *Notes and Questions:*

- State park - No sampling without a permit!
- Visit outcrops in Spooner Cove and beach platform exposures below headland to the north of cove (Keller's stops 1, 2, and 3).
- Stratigraphy consists mainly of interbedded porcelanite, siliceous shale, mudstone, and chert, but includes clay shale, nodular and stratified dolostone (bones!), sandstone and phosphatic rocks.
- Nearly all siliceous rocks here are in the opal-CT phase. There may be some diagenetic quartz.
- Greater than 2,200' of stratigraphic section
- Dated by diatoms extracted from early diagenetic dolostone beds and concretions.
- Thinly interbedded porcelanite and siliceous shale with thicker beds of dolostone and some mudstone strata.
- Even spacing of dolostone beds may reflect cyclic changes in sediment accumulation rate associated with sea-level fluctuation.
- Laminated siliceous rocks and commonly burrowed mudstones.
- Bathyal depositional environment.
- Distinguish between joints (opening-mode displacement) and faults (shear displacement) - what are their observed geometrical and inferred hydrologic properties?
- Can you distinguish between fractured and unfractured rock beds? If yes, how are they different in terms of lithology and mineralogy?
- Can you observe different fracture populations based on fracture orientation, fracture dimension, and fracture geometry?
- Sketch your interpretation of mechanical and fracture stratigraphy at this outcrop.
- How would you drill a horizontal wellbore through this section?

*Watch for surf and slippery rocks!!!*

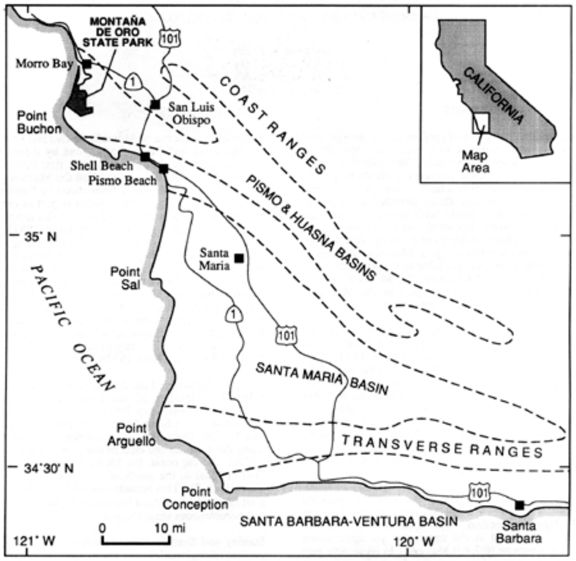



Figure **1-01.** Location Map of Montana de Oro State park and Neogene basins (Keller, 1992).

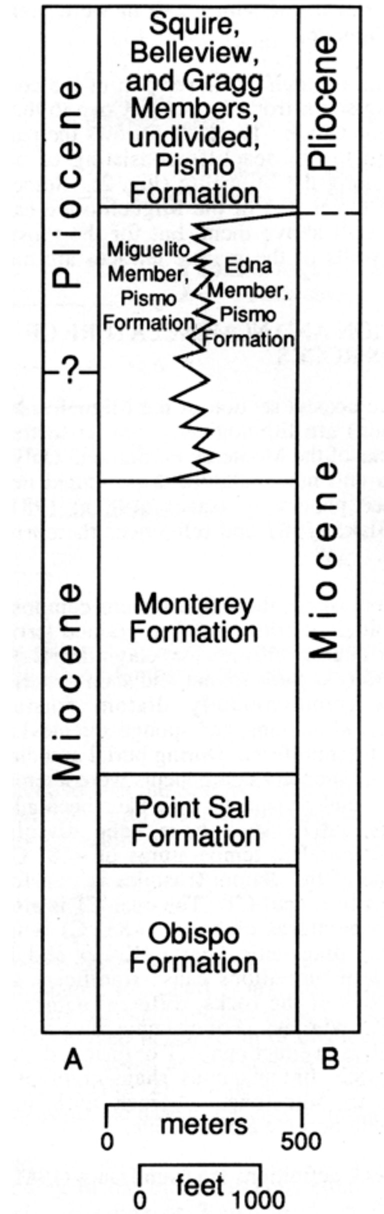
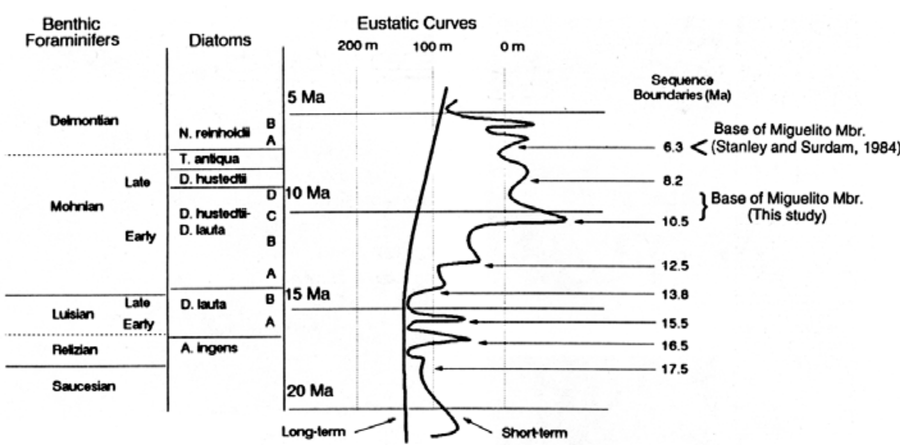



Figure **1-02**. Stratigraphic chart of Miocene and Pliocene series in the Pismo basin after Hall (1973), from Keller (1992). Upper and laterally equivalent members of the Pismo formation are producing sandstone reservoirs.

Figure **1-03.** Eustatic sea level curves of Haq et al. (1987) integrated with benthic foraminiferal and diatom biostratigraphy for this section (Keller, 1992)



## POINT BUCHON & MONTANA DE ORO

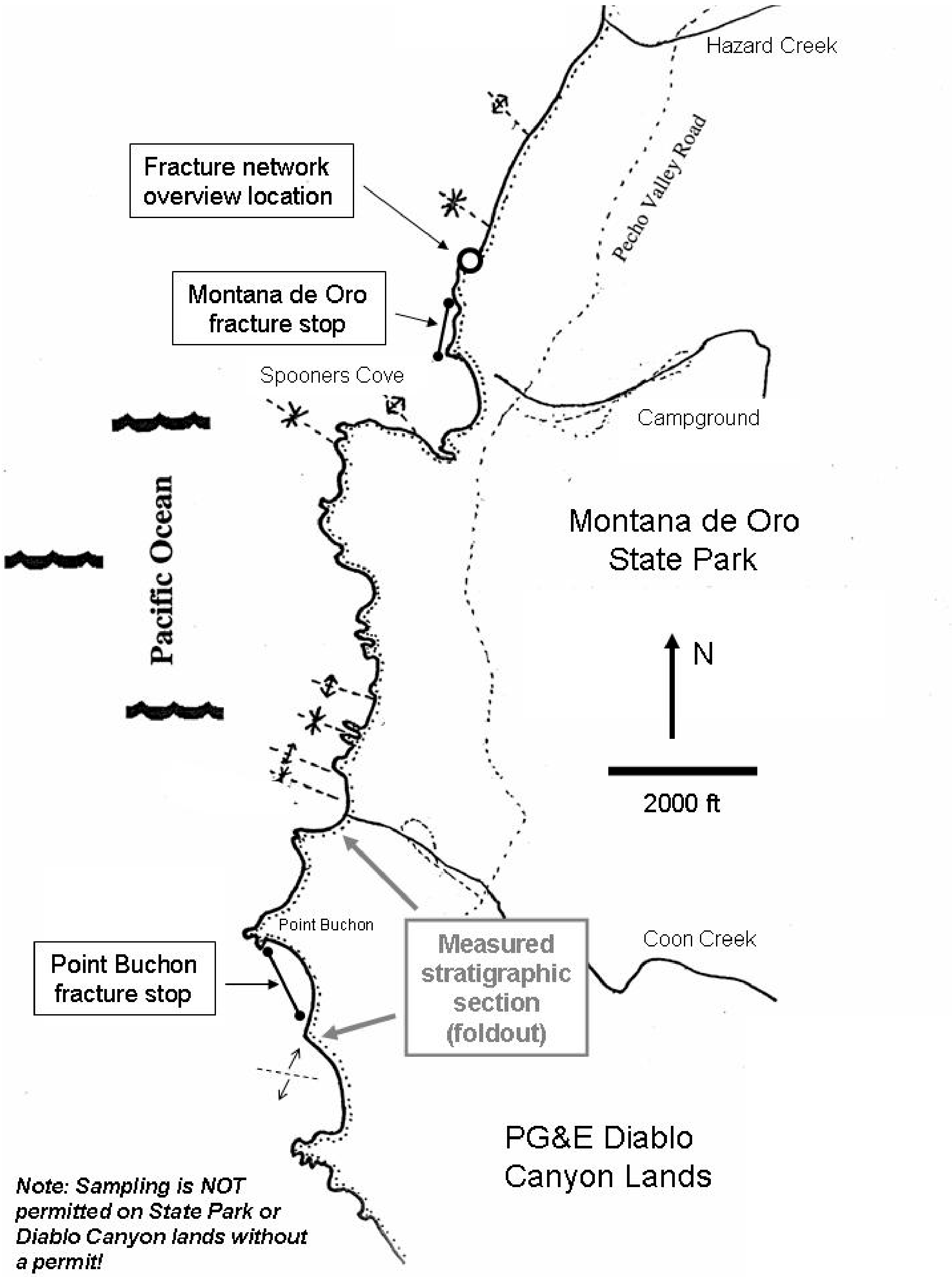



**Figure 1-4.** Map of field stops for Point Buchon (optional) and Montana de Oro on Day 1 of the field trip.

# Fracture Architecture and Mechanical Stratigraphy in the Monterey Formation and its Relationship to Sedimentary Cycles at Montaña de Oro, California

**Strickland, Heather; Behl, Richard J.; and Gross, Michael**
*hstrick06@gmail.com*

The Monterey-equivalent Miguelito Member of the Pismo Formation at Montana de Oro State Park displays four orders of fracture length that can be related to stratigraphic position in primary sedimentary cycles of bed-thickness and composition. Characterization of fractures such as these is crucial to understanding reservoir behavior in low-permeability, fine-grained rocks that require natural or induced fractures for economic hydrocarbon production. We define the fracture network and mechanical stratigraphy – the subdivision of a rock section into discrete units defined by mechanical layer boundaries – at scales from cm's to 10's of m.

A ~200-m-thick interval of the upper Miocene Miguelito Member consists principally of rhythmically interbedded porcelanite, mudstone and dolostone; sedimentary cycles in porcelanite:mudstone ratio, bedding thickness and dolostone occurrence are quantitatively defined by spectral gamma ray and ground-based three-dimensional LiDAR (light detection and ranging). We hypothesize that primary sedimentary cyclicity influences subsequent fracture and fault development (and the resulting mechanical stratigraphy) in the Miguelito Member and likely other thin-bedded siliceous successions. and therefore may be used as a predictive tool for fracture frequency and length in conjunction with other geologic information such as tectonic strain and structural position. We are mapping the dimensions of fractures and faults and calculating their frequencies in relation to the overall stratal stacking pattern and variations due to sedimentary cyclicity. As fracture type and frequency are known to be directly related to lithology in the Monterey Formation on a single-bed scale, intervals where strata are thinner-bedded and have a higher silica:mudstone ratio are predicted to develop a higher number of both bed-confined fractures and multilayer features than intervals that are thickly-bedded and have a lower silica to mudstone ratio. Mechanical layer boundaries also occur at a number of thickness scales and terminate different size structural features, but predominantly occur at distinct changes in stratal stacking pattern. We have also found that thick-bedded dolomite horizons and thin volcanic tuff can be effective mechanical layer boundaries.

*AAPG Search and Discovery Article #90162©2013 Pacific Section AAPG, SPE and SEPM Joint Technical Conference, Monterey, California, April 19-25, 2013*

**Stop 1 – Montana de Oro Fracture Outcrop (wave-cut platform)**

- Short hike from Spooners Cove area along bluff trail, we will take the trail down to the wave cut platform just north of the cove (Fig. 1-4).
- Beds dip uniformly ~25° to the NNE without any folding. The lack of structural complexity allows us to focus on the architecture of the fracture network.

**STOP 1A: Major Units 9 and 8**

- Major Unit 9 is an approximately 30 meter-thick interval of porcelanite and mudstone with minor dolostone and tuff horizons.
- Unit 9 is subdivided in units 9A, 9B and 9C based on changes in mudstone to porcelanite ratios and bed thickness.
- All porcelanite beds are in the opal-CT phase.
- Note the orientations of the fractures with respect to bedding strike. Are you becoming convinced that the dominant fracture sets are perpendicular to bedding strike and local/regional fold axes?
- All 4 orders of fractures are present in this unit, bed-confined to mature multilayer features with offset. (Fig. 1-5). What do you notice about the large, multilayer features? Can you identify any cross-cutting relationships? How do the large feature orientations compare to the bed-confined fractures?
- Can the conceptual model of fracture scaling and mechanical stratigraphy shown in Fig. 1-11 be applied here? Which techniques can observe outcrop-scale fractures in the subsurface (Fig. 1-12)?
- 
- There are both structural and stratigraphic mechanical layer boundaries that arrest fractures that span multiple layers. Can you identify them?
- Imagine a horizontal well was drilled through this outcrop. What would the core and image logs look like? (See Fig. 1-6).

**STOP 1B: Major Units 8, 7 AND 6**

- Major unit 8 is approximately 25 meters-thick, consisting of porcelanite and mudstone with some dolostone horizons. It has been subdivided into units 8A-8G.
- Major unit 7, at 7 meters thick, is the smallest "major unit" defined in the field area. This unit is a mud-dominated interval of porcelanite and mudstone, with no dolomite or tuffs present.
- To the north of unit 7, major unit 6 consists of subunits 6A-6F. As you walk north from subunit 6F to 6A, what stratigraphic observations can you make along this transect?
- There is a tuff layer at the bottom of major unit 6 that acts as mechanical layer boundary to several multilayer features. How do the large features/fractures behave as they approach the mechanical layer boundary?
- Note the alteration of rock matrix adjacent to the fractures, and that the width of alteration zones seems to correlate with the development of the fractures/fracture zones (see Fig. 1-7). What are the implications for fracture-matrix interaction?
- Look at the photos in Figs. 1-7 to 1-9, and try to find examples in the outcrop. Where would they fit into the conceptual model?

- From our studies of fractures in the Monterey Fm and other sedimentary rocks, we infer a systematic evolution of multilayer, throughgoing fractures from incipient to mature stages (Fig. 1-5). In thin-bedded rocks, these potential conduits for fluid flow develop through the linkage and coalescence of pre-existing, bed-confined fractures.

**STOP 1C: MAJOR UNIT 6 and 5**

- Unit 5 consists of subunits 5A and 5B that have very different mudstone to porcelanite ratios and bed thicknesses.
- There are thick mudstones near the top of unit 6 and in unit 5 that have basal pebble phosphate horizons and also show evidence of burrowing. What does this tell us about the depositional environment? Is there any difference in the mechanical behavior in these mudstone units than the porcelanite or other mudstone beds?
- Do you find the same features in unit 6 as you do unit 5? Why do you think there may be a difference between the two based on your knowledge of mechanical stratigraphy?
- There is a swarm of large fractures in the wall just to the north of unit 5 below the unconformity. Do you find them in units 5 or 6? Why or why not?

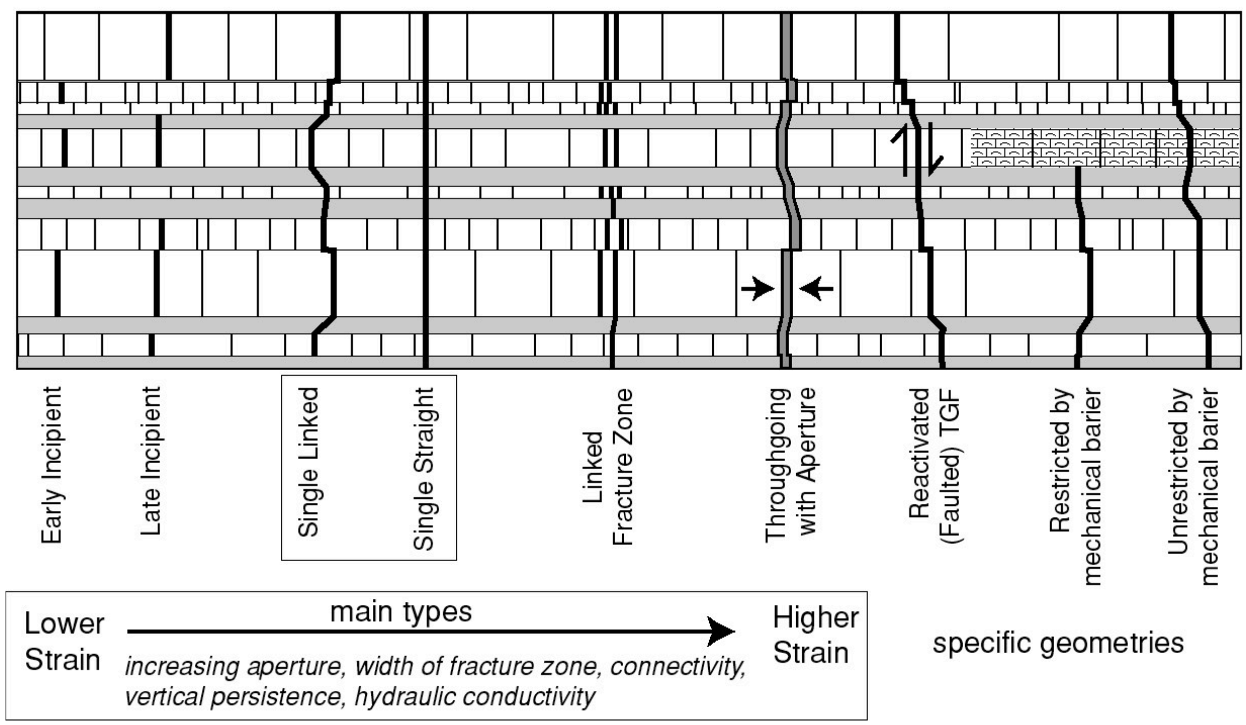



**Figure 1-5.** Classification and morphologies of multi-layer, throughgoing fractures in thin-bedded carbonate rocks as viewed in cross section, perpendicular to bedding (from Gross and Eyal, 2007).

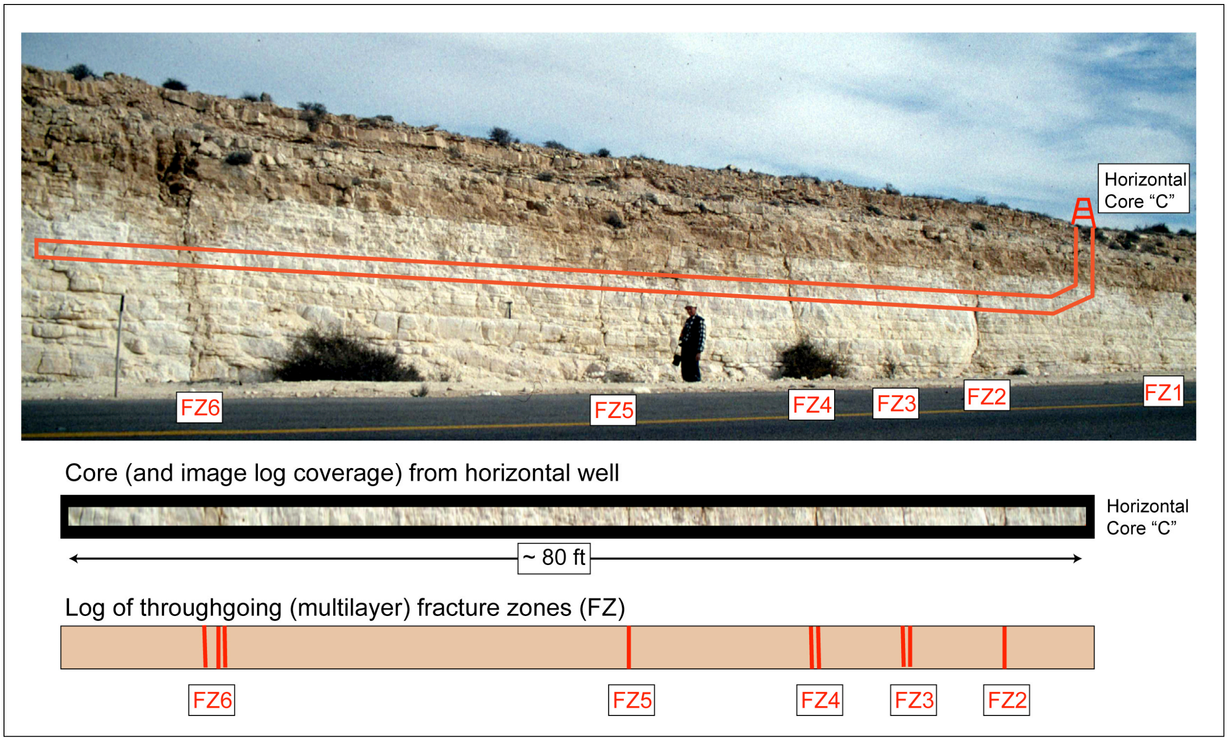



**Figure 1-6.** An imaginary horizontal well drilled through multilayer fractures in thin bedded limestone. Note where the wellbore intersects throughgoing fracture zones. What would a horizontal wellbore look like here?

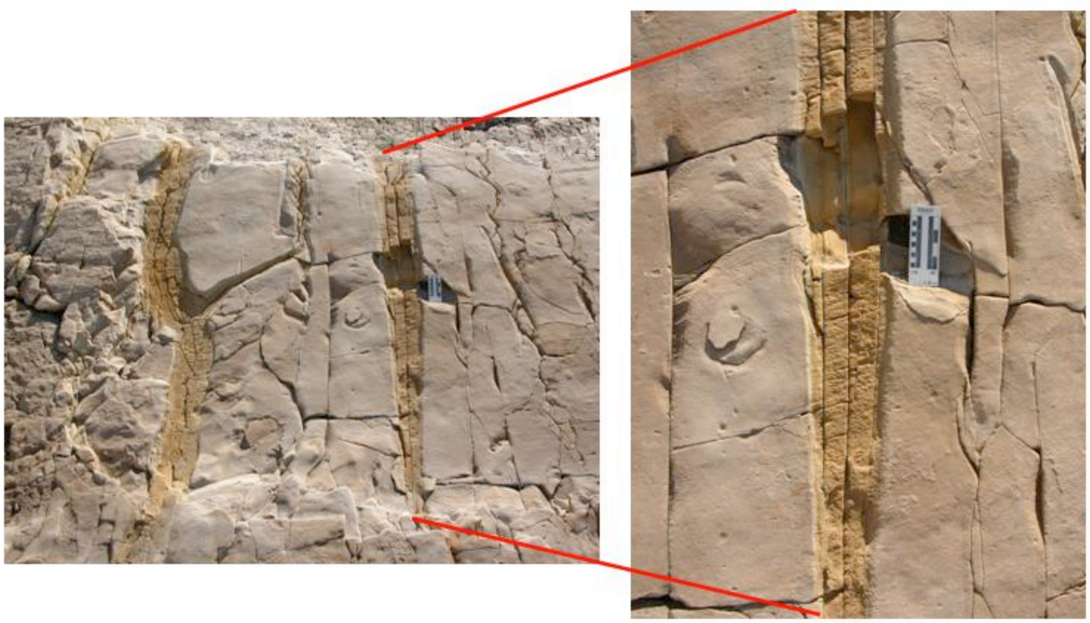


**Figure 1-7.** Photos of multilayer fractures at Montana de Oro showing zone of alteration in adjacent rock matrix. Refer to figures from Arroyo Burro GIS study.

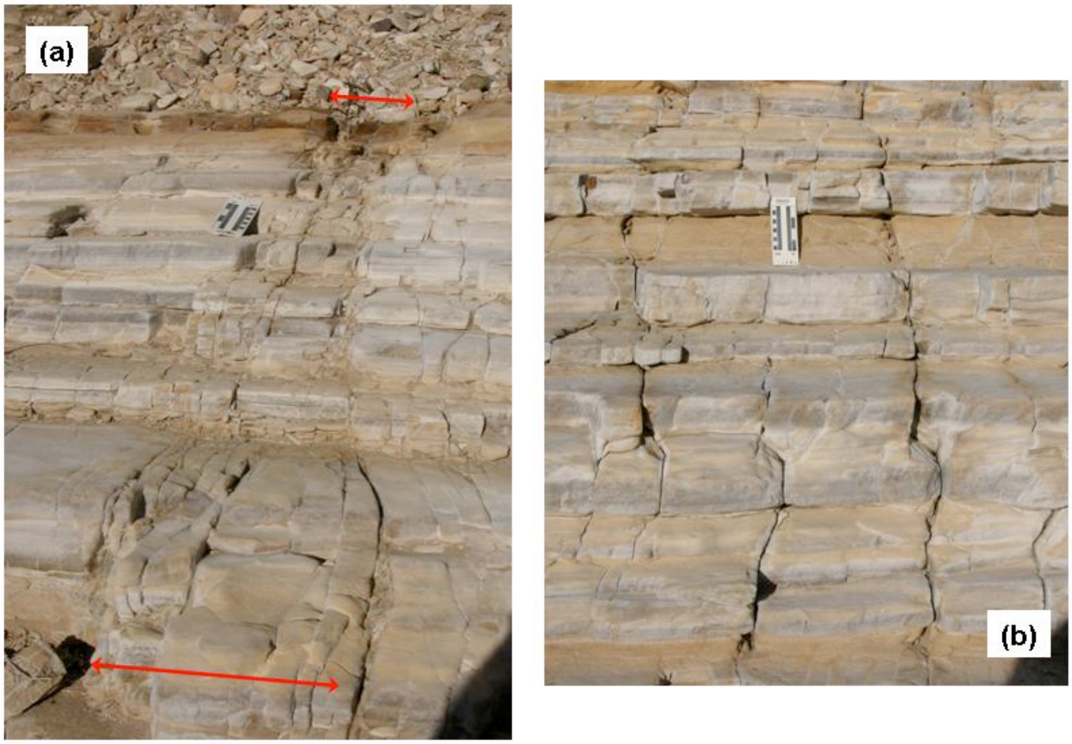



**Figure 1-8.** Photos of multilayer fractures at Montana de Oro showing different stages of development (a) a multilayer fracture zone consisting of closely-spaced fractures, sometimes referred to as a “fracture cluster”; (b) initially linked multilayer fractures.

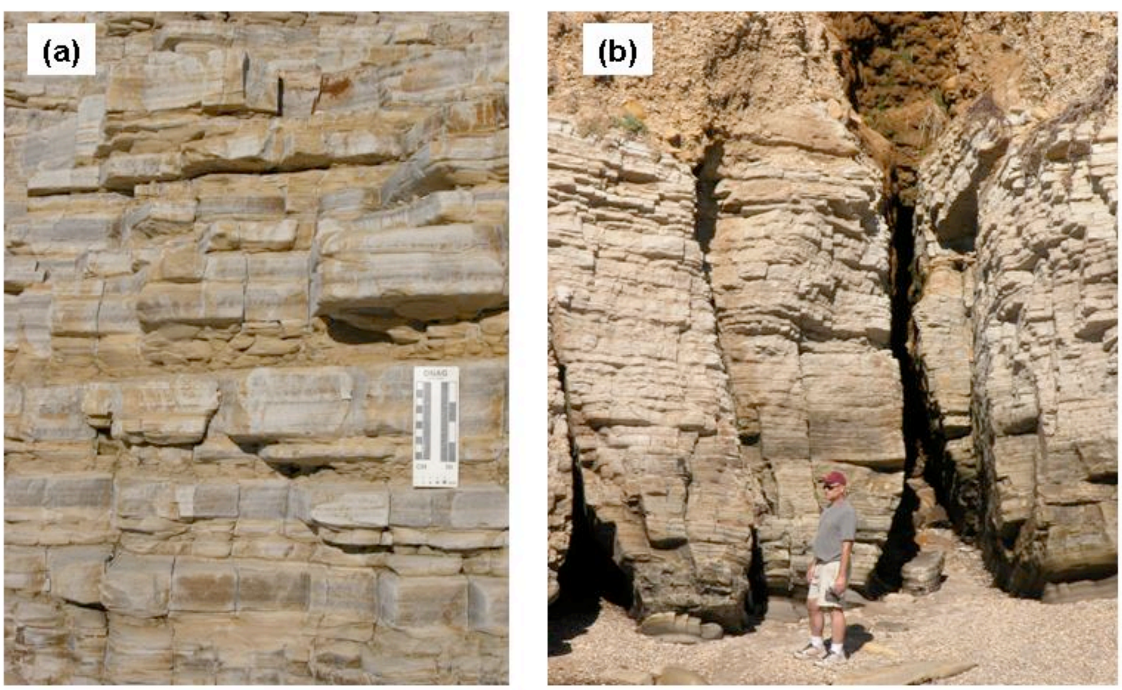



**Figure 1-9.** Photos of fractures at Montana de Oro showing different stages of development (a) single layer, bed-confined fractures (b) throughgoing fracture zones, perhaps representing a localized region of high strain.

## Stop 2 – Montana de Oro Overview (view from cliff above)

- Begin from the second parking lot north of Spooners Cove, along Pecho Valley Road.

- Hike along path (less than ¼ mile) towards coast, when trail splits, head north a few hundred yards to overlook of major units 1-4 from the top of sand dunes.

- The wave cut platform below illustrates the relation between well-developed, multi-layer fractures and the regional fold axis. At least two sets of multi-layer fractures are present, whose trends are roughly perpendicular to bedding strike and local/regional fold axes (Figure 4-6). These features are enhanced by weathering and wave action. At Stop 1 we had the opportunity to examine the character and morphology of these features in more detail. **This is a great view of a Monterey Fm fractured reservoir!**

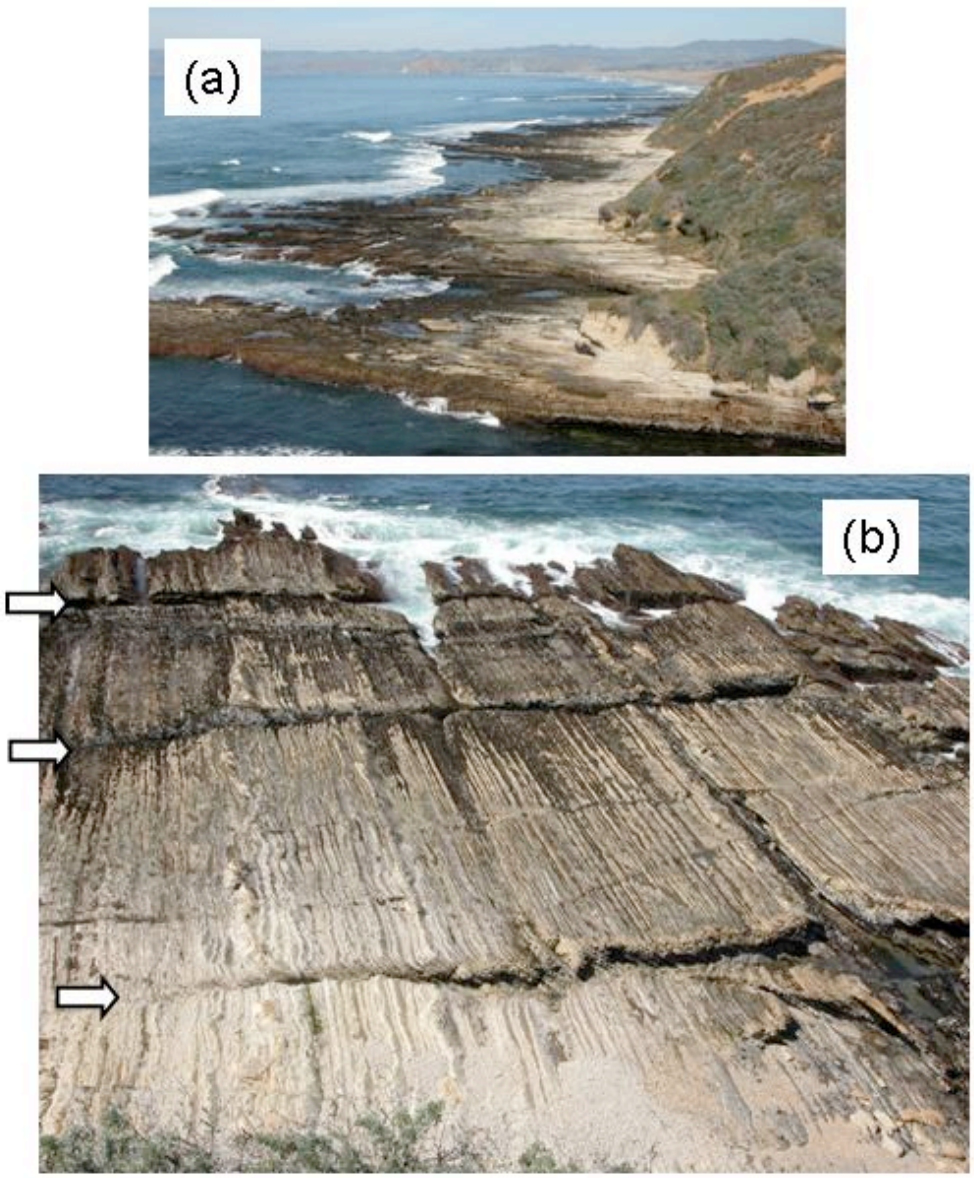



**Figure 1-10.** Photos of wave-cut platform from Stop #2. (a) overview; (b) multi-layer fractures (arrows).

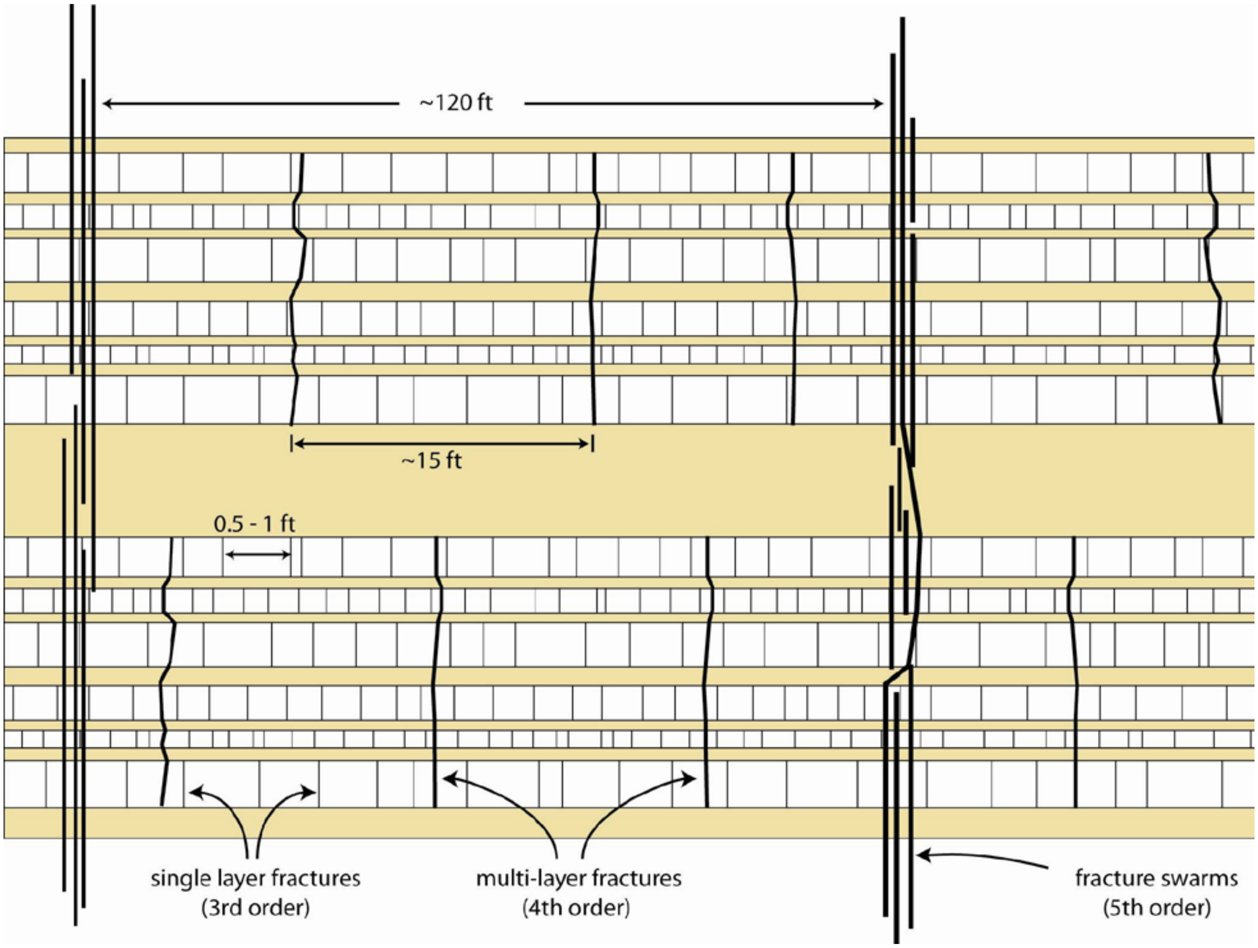



**Figure 1-11.** A conceptual model for fracture distribution and scaling in the Monterey Formation. What do you think based on your observations at this field stop?? This figure was originally devised based on core and image log analysis from Elk Hills.

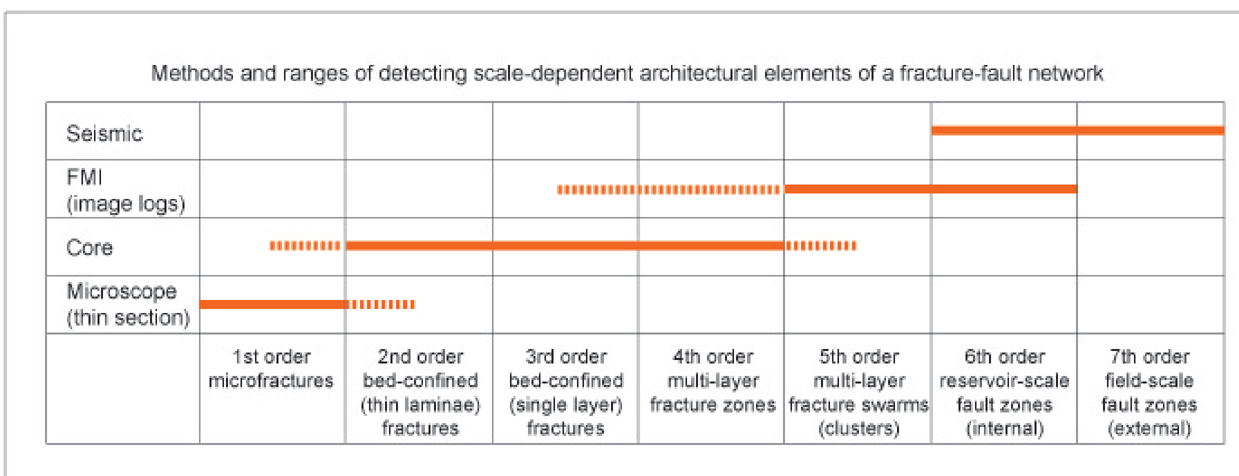
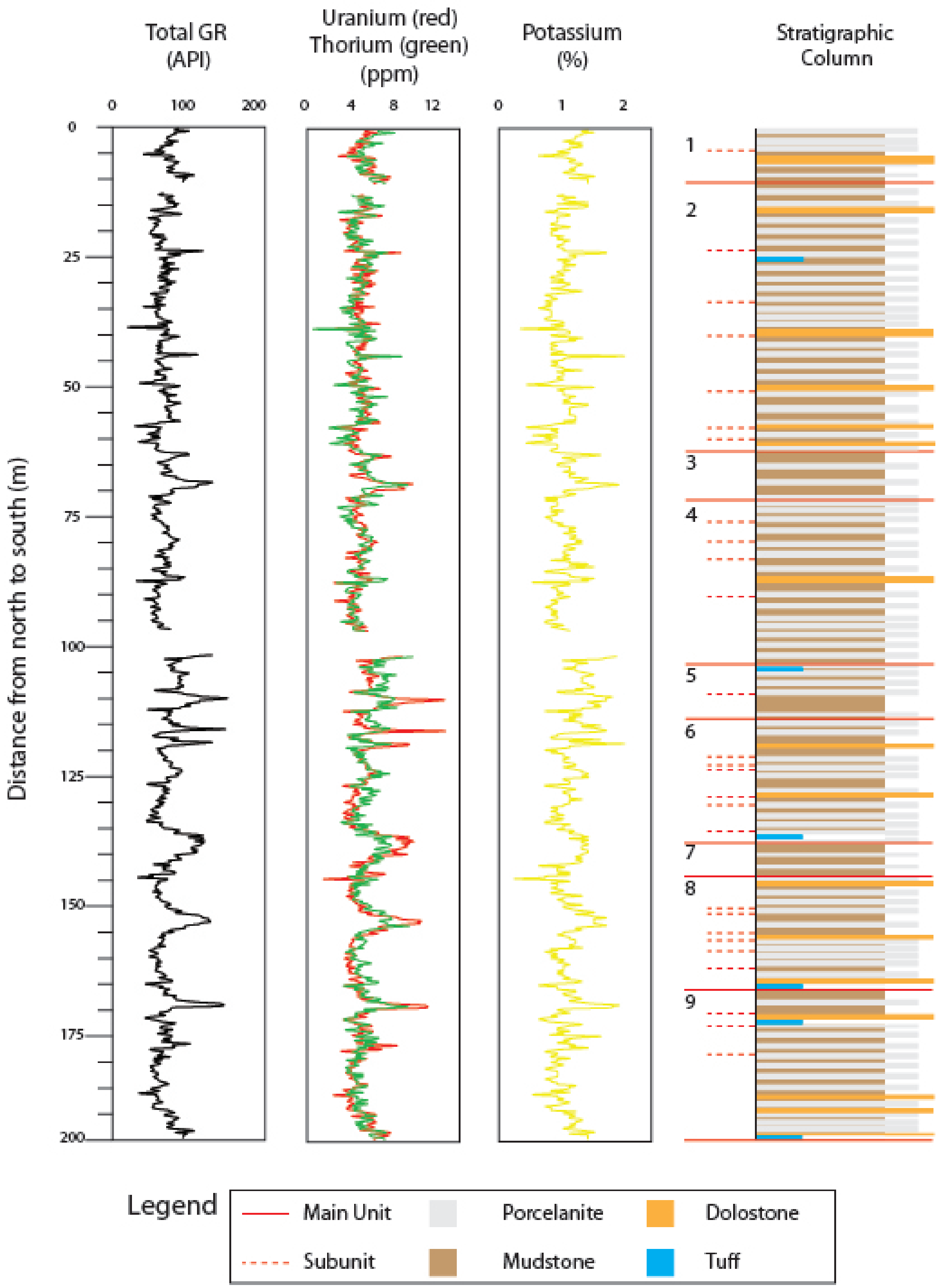
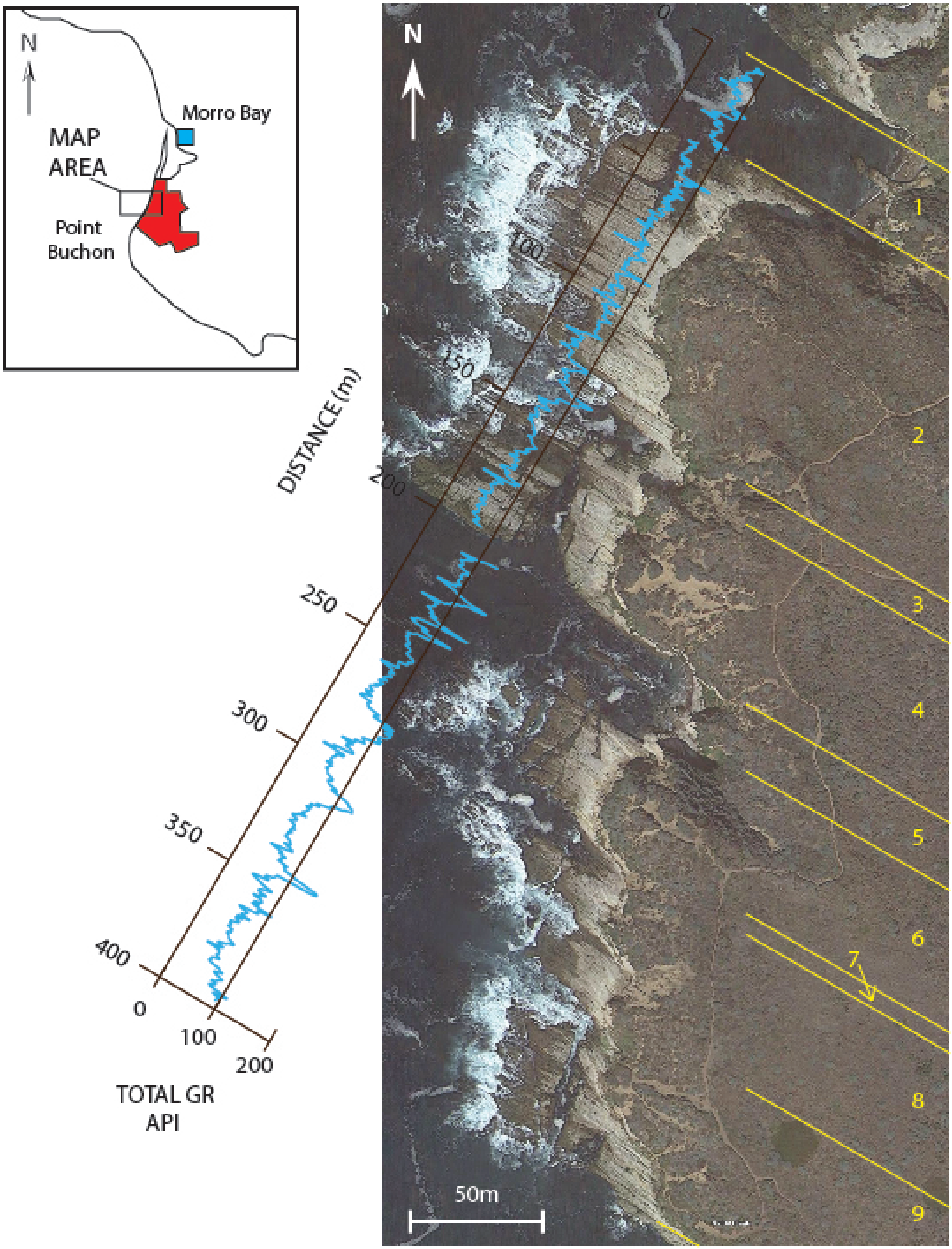


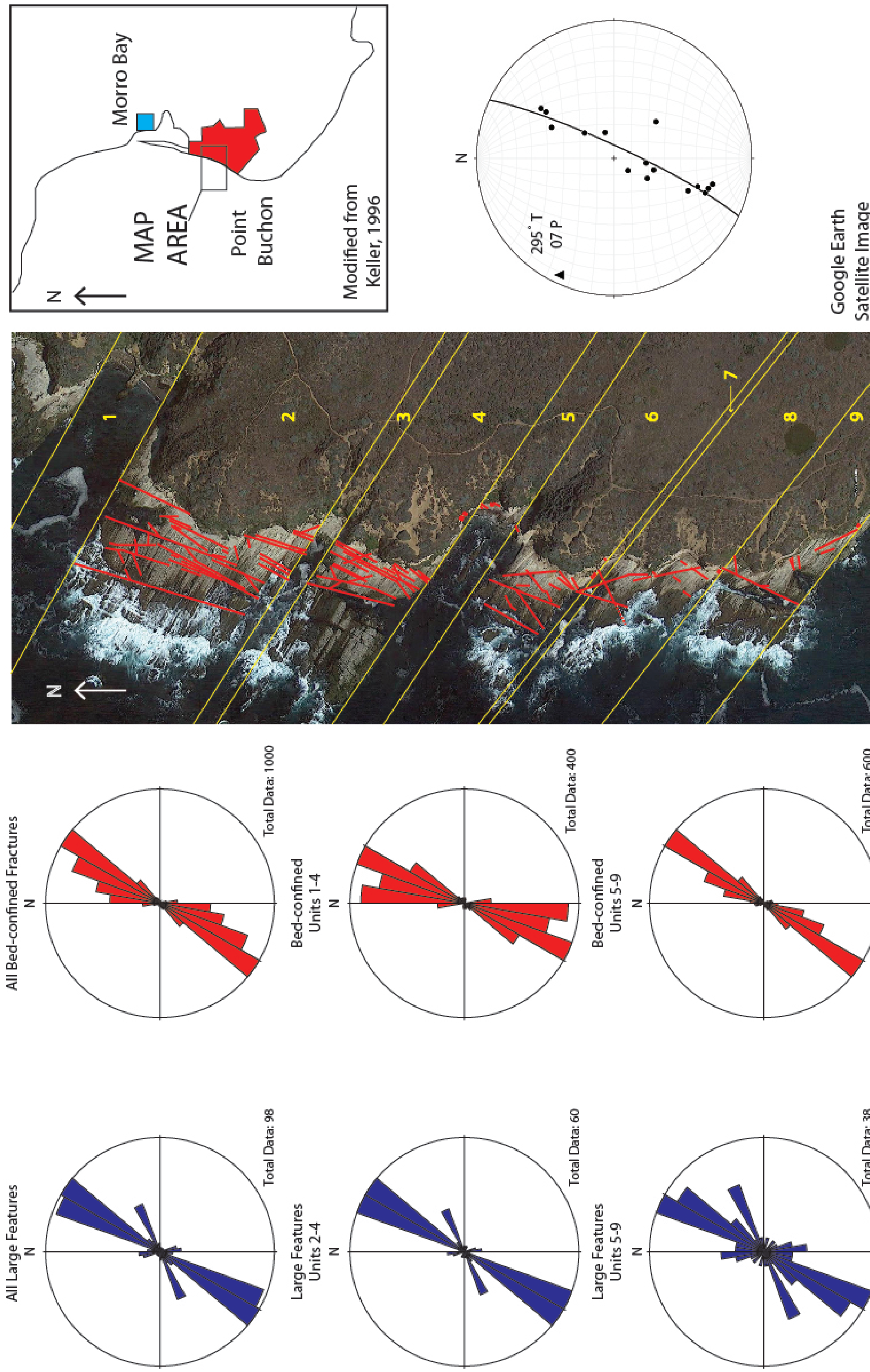

**Figure 1-12.** Fracture type as a function of scale of observation, according to technique of observation. Are sub-seismic scale fractures important in the Monterey Formation? How can they be characterized and quantified?

# Combined Stratigraphic Section with Gamma-Ray



# Total gamma-ray on Google Earth Satellite Image

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Morro Bay
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AREA
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1
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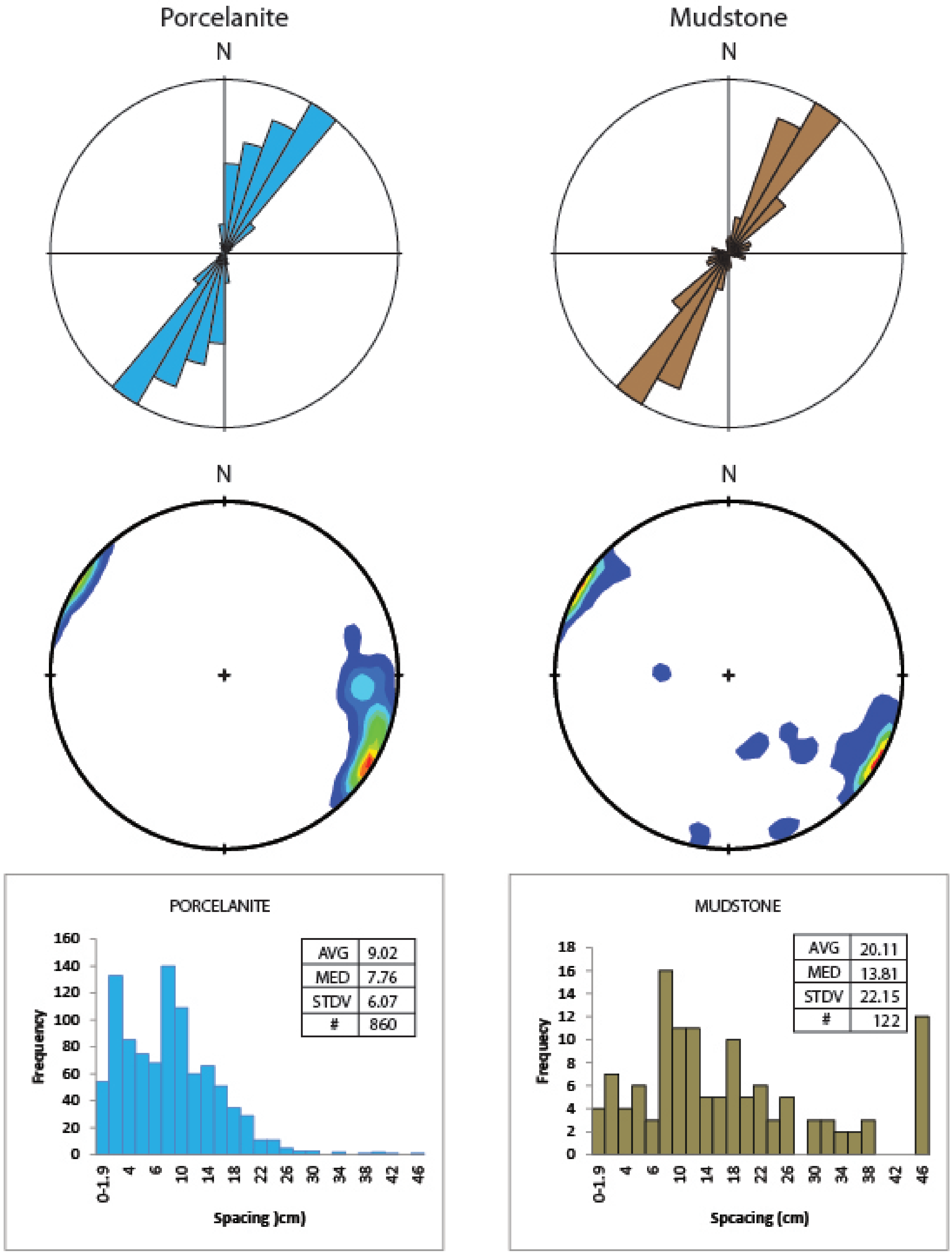
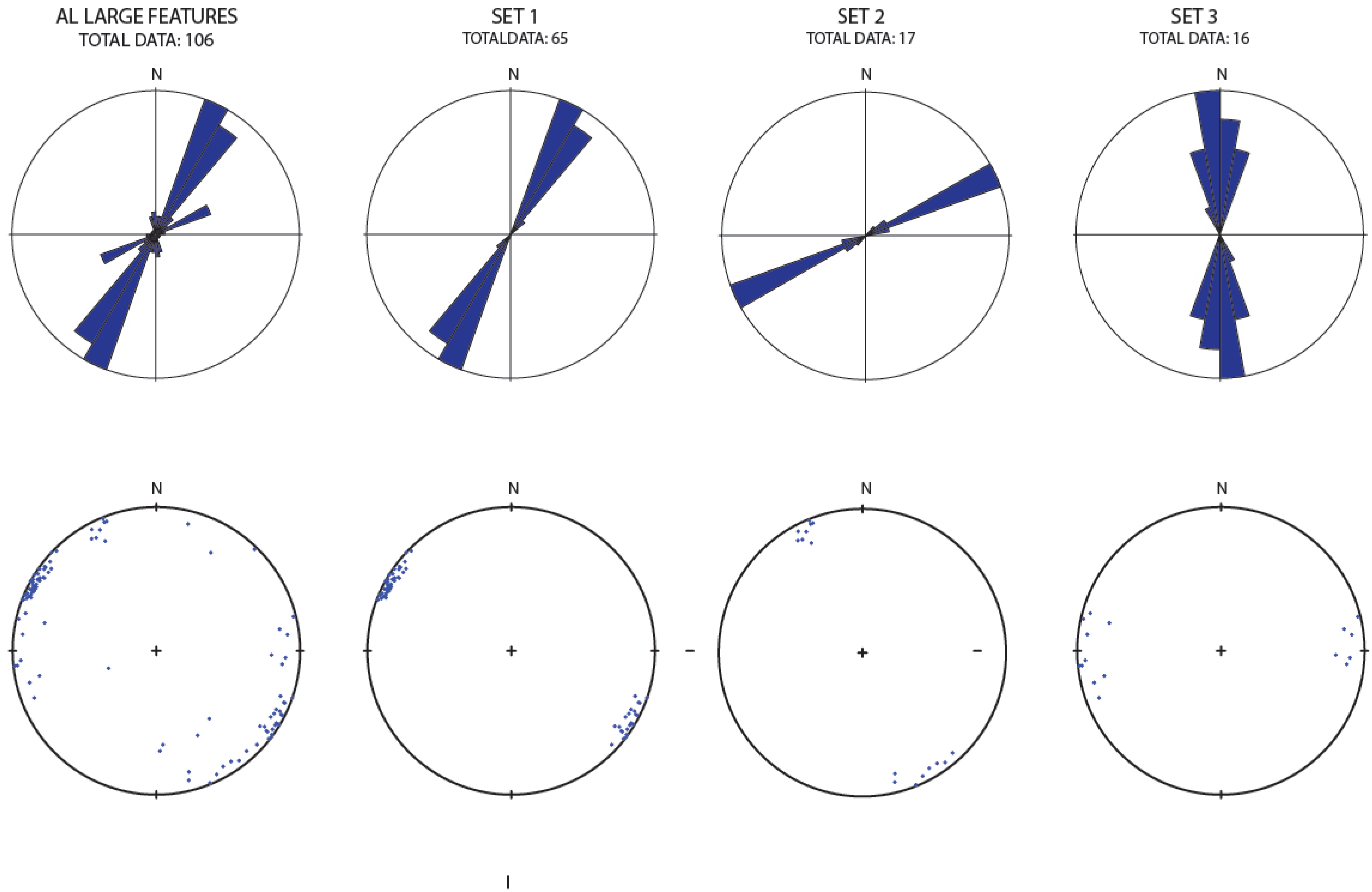
5
6
7
8
9
Google Earth
Satellite Image
All Bed-confined Fractures
N
Total Data: 1000
Bed-confined
Units 1-4
N
Total Data: 400
Bed-confined
Units 5-9
N
Total Data: 600
All Large Features
N
Total Data: 98
Large Features
Units 2-4
N
Total Data: 60
Large Features
Units 5-9
N
Total Data: 38

# Bed-confined Fracture Summary by Litholgy



# LARGE FEATURE ORIENTATION ANALYSIS



## Day 3: Mussel Rock / Guadalupe Dunes

***Basin:*** Santa Maria

### *Formation/Members:*

Sisquoc

- Uppermost Miocene-Pliocene diatomaceous siltstone and mudstone with basal conglomerates

Monterey

- Clayey-siliceous (upper siliceous)
- Uper calcareous-siliceous member (massive chert)

Key references,

- Woodrin and Bramlette (1950)
- Pisciotto (1981)
- Grivetti (1982)
- Garrison, Ingle, et al. (1985), Global Geochemistry Report

### *Notes and Questions:*

- Santa Barbara County beach - sampling is OK.
- Hike 2 miles south along beach, then downsection through the Sisquoc and Monterey formations.

- Sisquoc consists of massive (bioturbated) diatomaceous mudstone (opal-A) and debris-flow deposits of reworked Monterey clasts (chert, phosphate, dolomite).

- Upper, clayey-siliceous member of the Monterey Formation consists of laminated muddy diatomite (opal-A), then opal-CT phase porcelanite, chert, and minor dolomite.

- Note soft-sediment deformation in diatomaceous deposits.

- Silica phase transition within muddy diatomite marked by development of nodular cherts and ribbon-bedded chert, shale, and porcelanite. Extreme diagenetic enhancement of primary compositional variability.

- Note heavy oil on joints of brittle lithologies (porcelanite and dolomite).

- Middle Monterey Formation (upper clayey-siliceous member) consists of interbedded quartz phase black chert, opal-CT and quartz phase buff to white porcelanite, dolomite and organic-rich shale.

- Note lithologic control of degree of fracturing of the oil/tar-saturated chert, porcelanite, and dolomite breccias.

*Watch for high surf and slippery rocks!!!*

## SANTA MARIA BASIN

(extracted in part from Charlotte Deason's thesis)

The Santa Maria region experienced rapid subsidence and volcanism from 18-16 Ma (Tranquillon Volcanics) and a subsequent slower subsidence phase from ~16-7 Ma. The rapid phase was probably associated with extreme local extension during the onset of coastal rotation just south of the southern Coast Ranges and Santa Maria Basin (McCrory, et al. 1995) (Figure 2-01). The slower phase was probably associated with thermal subsidence due to cooling of young oceanic lithosphere (McCrory, et al. 1995; Compton, 1991). Offshore contractional deformation beginning about 5-6 Ma (latest Miocene to earliest Pliocene) overlapped in time with onshore faulting beginning about 4 Ma (Pliocene) (McCrory, et al. 1995), and intense shortening occurred at approximately 3 Ma (Pleistocene) (McCrory, et al. 1995; Behl and Ingle, 1998). Recognized local events include uplift of the Santa Ynez Mountains during the early Pliocene and reorganization and uplift of much of the California borderland during the Pleistocene (Woodring and Bramlette, 1950; Ingle, 1981). Continued shortening is accommodated by a fold-and-thrust belt reflected in the Casmalia and Purisima Hills (Namson and Davis, 1990) that formed structural traps in the Orcutt, Casmalia and Lompoc oil fields, among others (Fig 2-02 and 2-03).

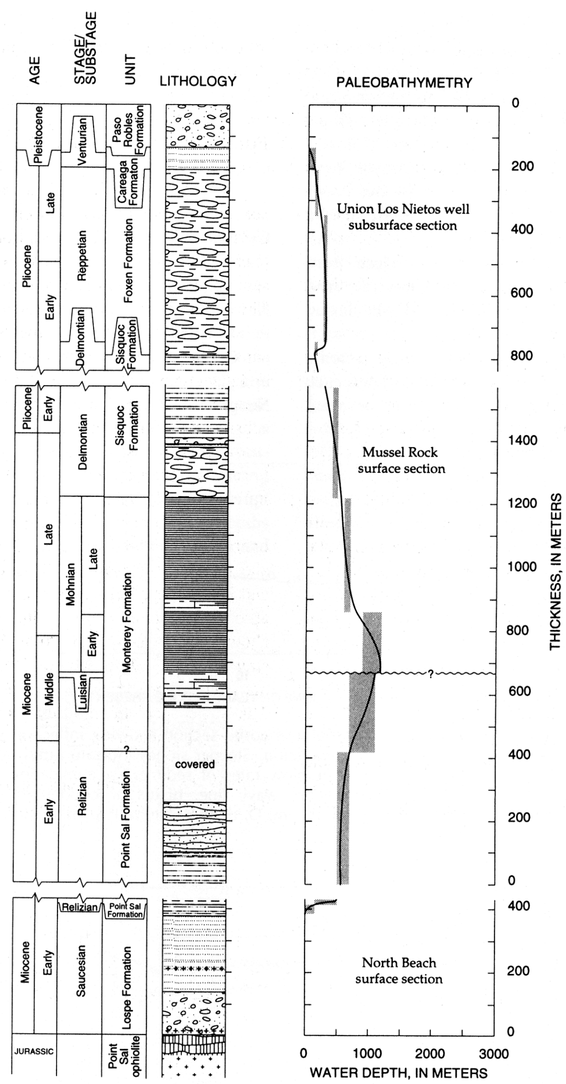



Figure 2-01. Stratigraphy and paleobathymetry after McCrory et al. (1995)

Hence, complex fault geometry and Pliocene and Pleistocene regional compression has overprinted much of the original Neogene geologic structures, uplifting and intensely deforming the Monterey Formation and other rocks along the south and central California coast. Along the beach from Guadalupe Dunes to Mussel Rock, we will walk downsection through the north flank of the Orcutt-Casmalia anticline where it intercepts the coast (and extends offshore towards the Hosgri fault zone).

Figure 2-02. Map of the Santa Maria province showing major faults and outcrops of igneous rock. After Cole and Stanley (1998).

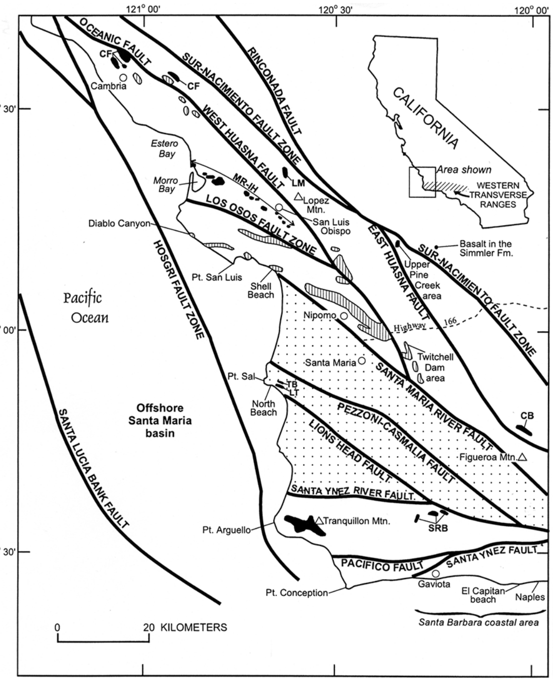



Figure 2-03. North-south balanced cross-section through the onshore Santa Maria basin showing major structures and oil fields (Namson and Davis, 1990).

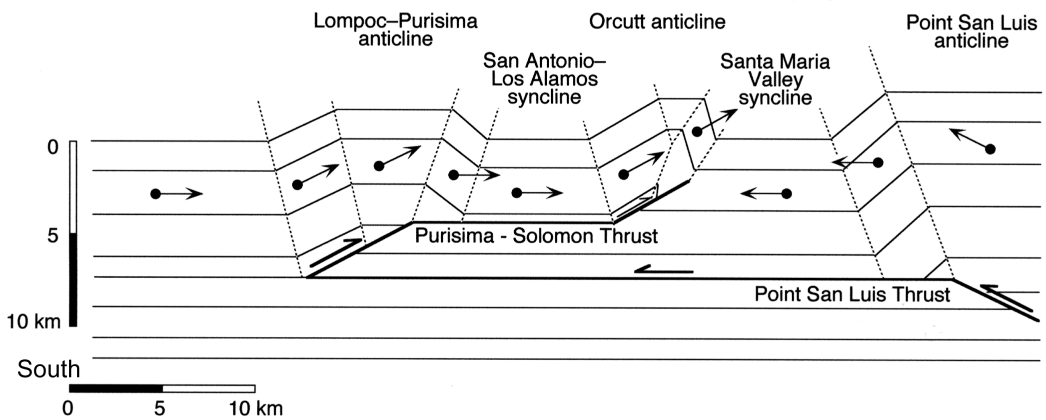
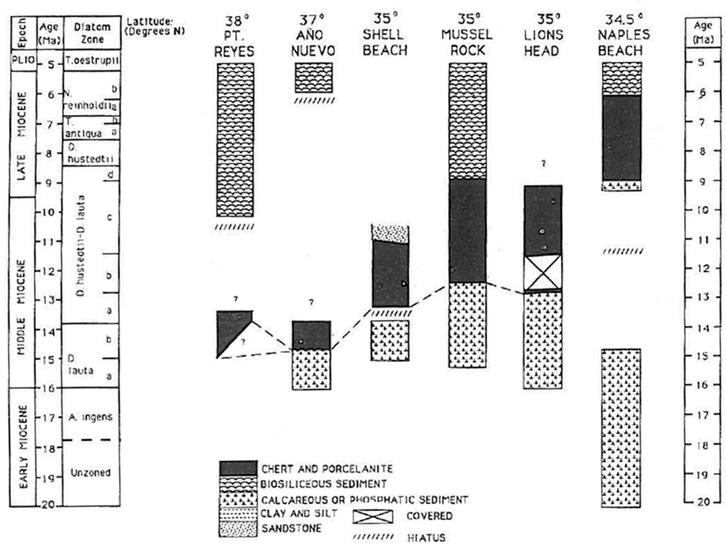



Figure 2-04. Chronostratigraphic correlation of Miocene sections from northern to southern California. Mussel Rock is the most continuous and extensive section. From White et al. (1992).



## COASTAL MONTEREY FORMATION LITHOSTRATIGRAPHY

In central coastal California, the Monterey Formation consists chiefly of three lithofacies; a calcareous facies, a phosphatic facies and a siliceous facies recording deposition on outer shelf to basin environments (Pisciotto and Garrison 1981). Woodring and Bramlette (1950) divided the three facies into the upper, middle, and lower members in Santa Maria region. Isaacs (1980; 1981a, 1983) divided the three facies into five informal members along coastal Santa Barbara. MacKinnon (1989) divided the coastal and offshore Monterey in the Santa Maria basin into 4 informal members (Figure 2-05).

Isaacs (1981a) stressed the lateral homogeneity of lithostratigraphic members (as well as ages of beds). In contrast, the facies interpretation by Piscotto and Garrison (1981) and Föllmi et al. (1991) emphasized the time-transgressive component of the Monterey Formation. At different localities, member-scale facies record extremely varied water-depth and distribution in time. The youngest Monterey strata range from 6.9 Ma in Palos Verdes Hills, southern California, to 5 Ma in the Berkeley Hills, northern California (Behl 1999). The complete sequence is not present on any location in California (Pisciotto and Garrison 1981).

Fine-grained, carbonate-bearing shales, mudstones and claystones of the basal calcareous facies overlie clastic rocks and locally interbedded volcanics and indicate the beginning of deep basin sedimentation along the California margin. This facies includes the most clastic-rich Point Sal Formation. Locally, dolomite beds and concretions are common, whereas dolomite crystals and calcareous microfossils are dispersed through the matrix of many of the fine-grained rocks. The middle facies is composed of phosphatic shales and mudstones interbedded with limestone or dolostone beds and concretions and minor sandstone layers. The upper siliceous facies and is the thickest and most characteristic of the Monterey Formation. Principal rock types are laminated diatomite, porcelanite, chert, siliceous mudrock and shale. A gradational or unconformable contact with younger clastic rocks continues the record of basin filling (e.g. Woodring and Bramlette 1950; Isaacs 1980, 1981a; Pisciotto and Garrison 1981). In the Santa Maria and Santa Barbara basins, the diatomaceous/siliceous Sisquoc Formation overlies the Monterey.

The Monterey Formation reaches much greater thickness in Santa Maria Basin than in the adjacent Santa Barbara Basin; a total of 500-800 m (Compton and Siever 1984a) versus an average of 400 m (Isaacs 1980; Isaacs 1981a), respectively. Other differences include greater abundance of dolostone beds and nodules in Santa Maria Basin, with remaining beds significantly less calcareous (Compton and Siever 1984a).

## MUSSEL ROCK FIELD LOCALITY

The Mussel Rock field area, Santa Barbara County, central California, can be reached from US 101 by taking Highway 166 (Main Street) west through Santa Maria to Guadalupe Dunes Preserve (Figure 2-06). The stratigraphic section studied for this research is located approximately 2.1 miles south from the beach parking lot at the end of the road and can only be reached by foot (Figure 2-06). Here – tide and surf permitting – the Sisquoc and Monterey Formation are magnificently exposed with beds that dip nearly vertically in cliff outcrops along the beach. Although there is a constant battle with sand erosion and avalanches that erode trails, the wave-washed exposures at the base of the cliffs are spectacular.

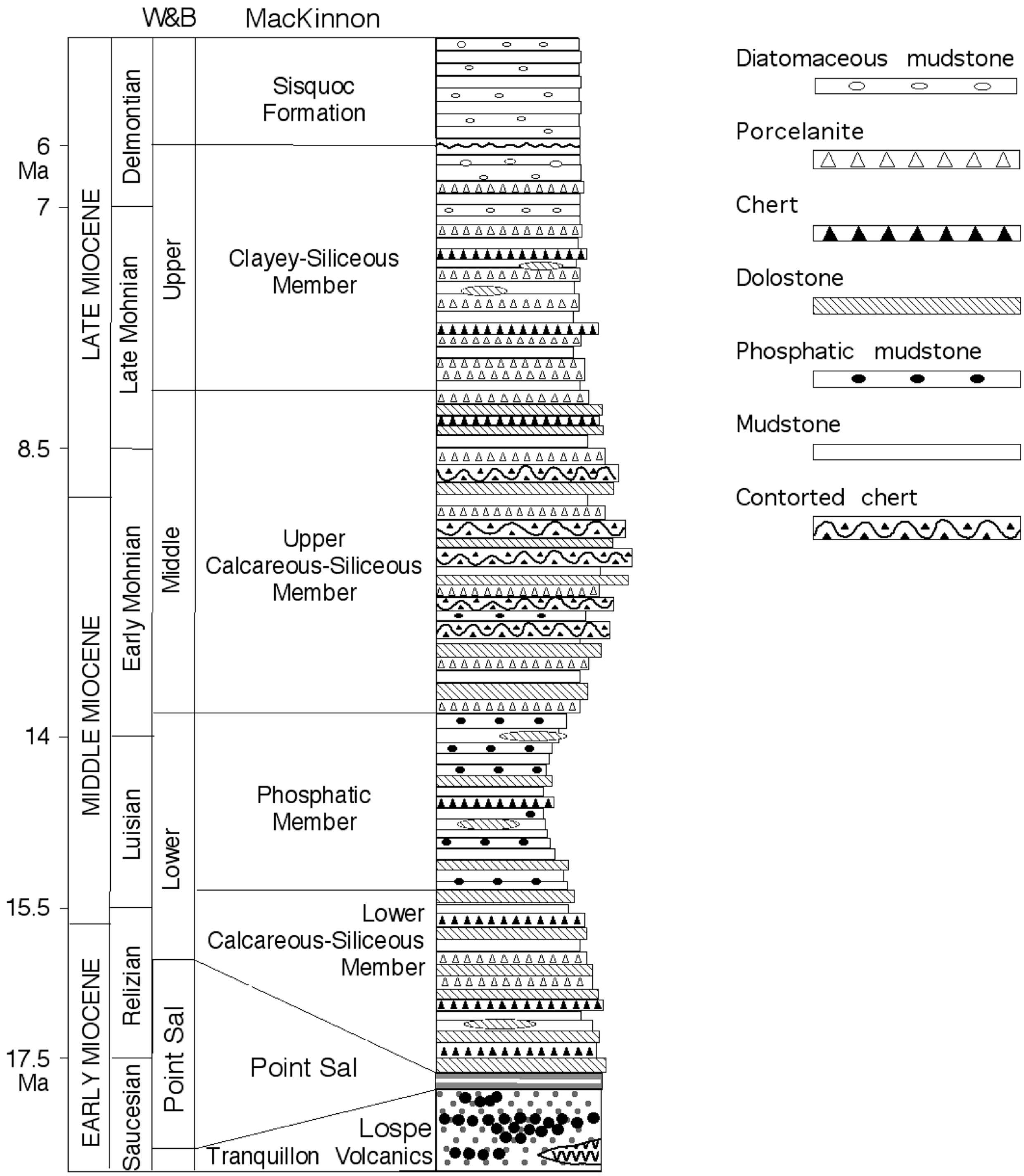



Figure 2-05. Coastal and offshore Santa Maria basin stratigraphy, slightly modified from MacKinnon (1989).

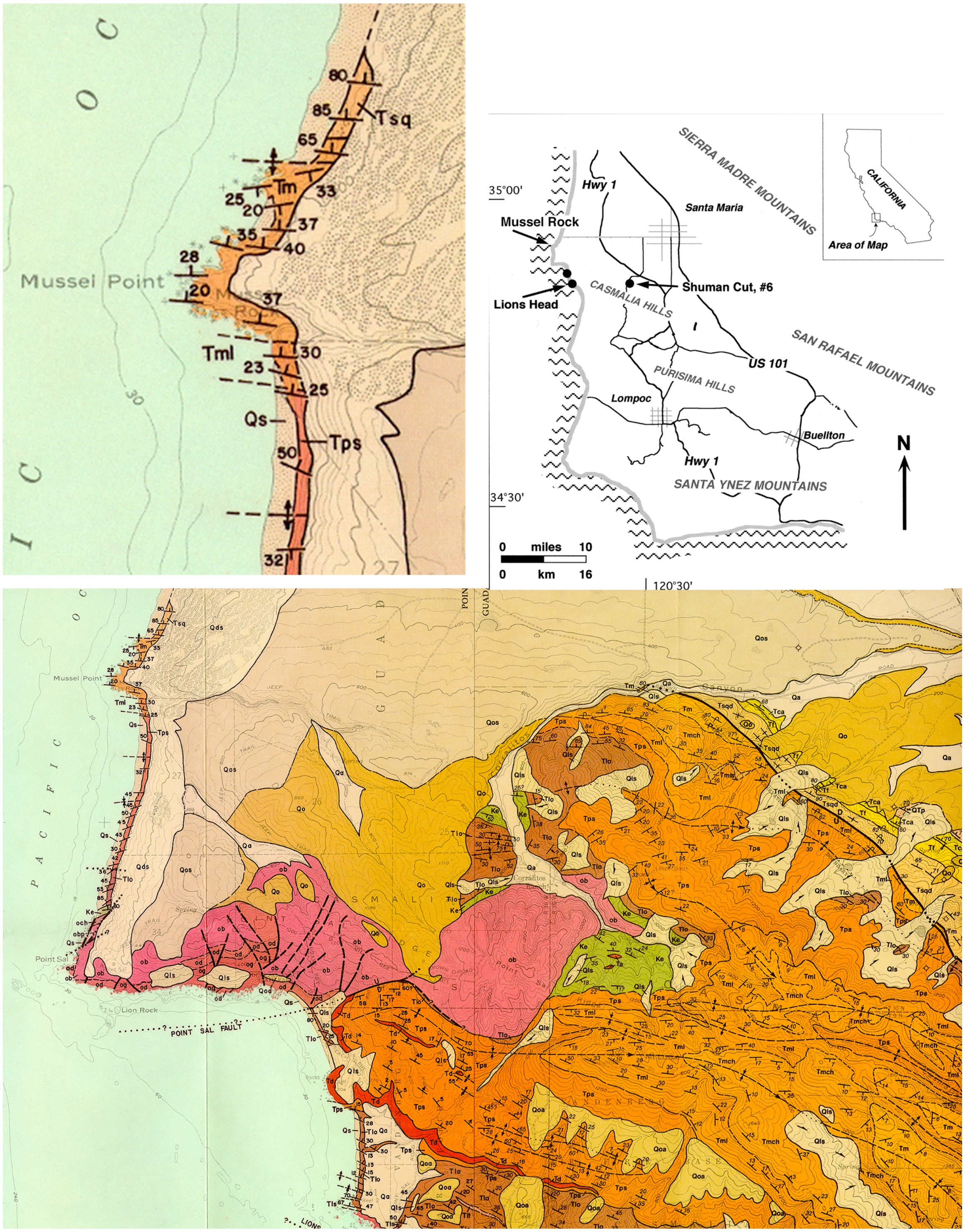



Figure **2-06.** Location map for Mussel Rock and other nearby Monterey exposures. Geology by Dibblee (1989), Point Sal and Guadalupe quadrangles.

## STRATIGRAPHY

The stratigraphy and sedimentology of the succession at Mussel Rock has been investigated by Canfield (1939), Woodring and Bramlette (1950), Pisciotto (1978,1981), Grivetti (1982), and by Garrison and Ingle (1985). This is the most complete sections exposed at the surface in the Santa Maria basin, in fact, one of the most complete in the entire state (Fig 2-04). It extends northward from the Jurassic Point Sal Ophiolite at its type locality through a short interval of Great Valley Sequence deposits, Lospe Formation, Point Sal Formation (Miocene), Monterey and Sisquoc formations. Depending on sand cover, >350 m of Sisquoc is exposed and ~800 m of Monterey, athough there are some structural difficulties imposed by faulting and folding, and some sections are not generally exposed. It is only a few miles south and southwest of the Guadalupe and Santa Maria Valley oil fields. It has served as the basis of a major confidential study by Global Geochemistry completed by Bob Garrison, Jim Ingle, Miriam Kastner and others, and their data forms the basis of the stratigraphic discussion. It was also the major regional succession for geohistory analysis (Point Sal Composite Section) by McCrory et al. (1995) (Fig. 2-01). A map of the coastal outcrops from the GGC study is shown in Figure 2-07. The stratigraphy follows in Figure 2-08.

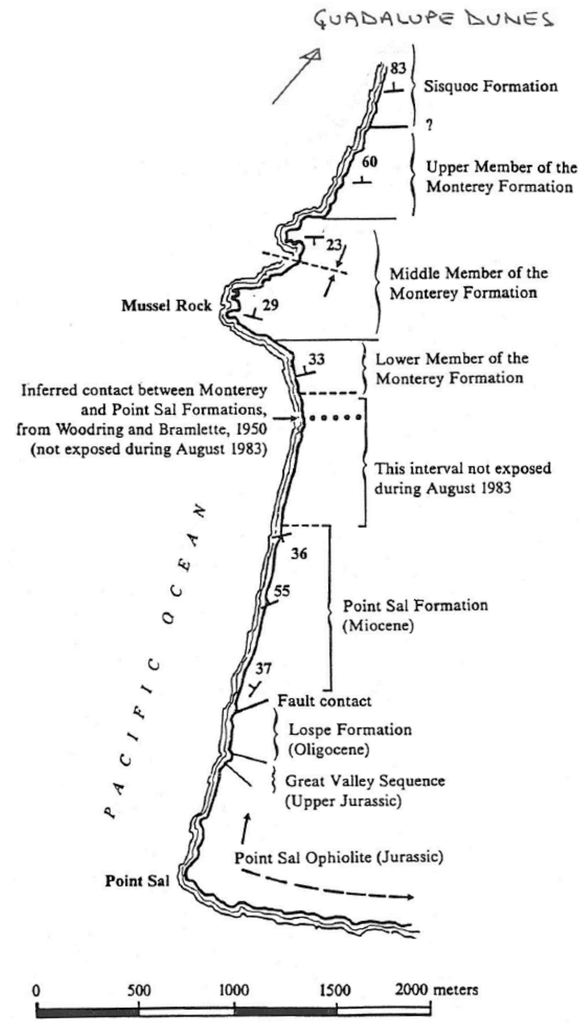



Figure 2-7. Geologic map of coastal outcrops by Garrison and Ingle for GGC (1985).

The Point Sal Formation (not visited on this trip) is about 420 meters thick and overlies the ophiolite and a thin section of Great Valley Sequence. Is is chronostratigraphically correlative with rock elsewhere assigned to the Lower Calcareous member of the Monterey Formation. it consist predominantly of black to gray mudstone/shale and turbiditic sandstone. The mudrocks are organic-rich (2-3% TOC) and are interbedded with dolostone concretions and layers.

The Lower Member of the Monterey (not visited on this trip) is greater than 200 meters thick, but is poorly exposed on “Paradise Beach” south of the Mussel Rock promontory. It consists largely of phosphatic, calcareous mudrocks, or carbonaceous marlstone. TOC averages 6.7 %.

The Middle Member of the Monterey Formation is approximately 200 meters thick, but is complicated by folding and faulting. The highly siliceous rocks form the wave resistant promontory of Mussel Rock (Mussel Point). It contains cycic interbeds of carbonaceous

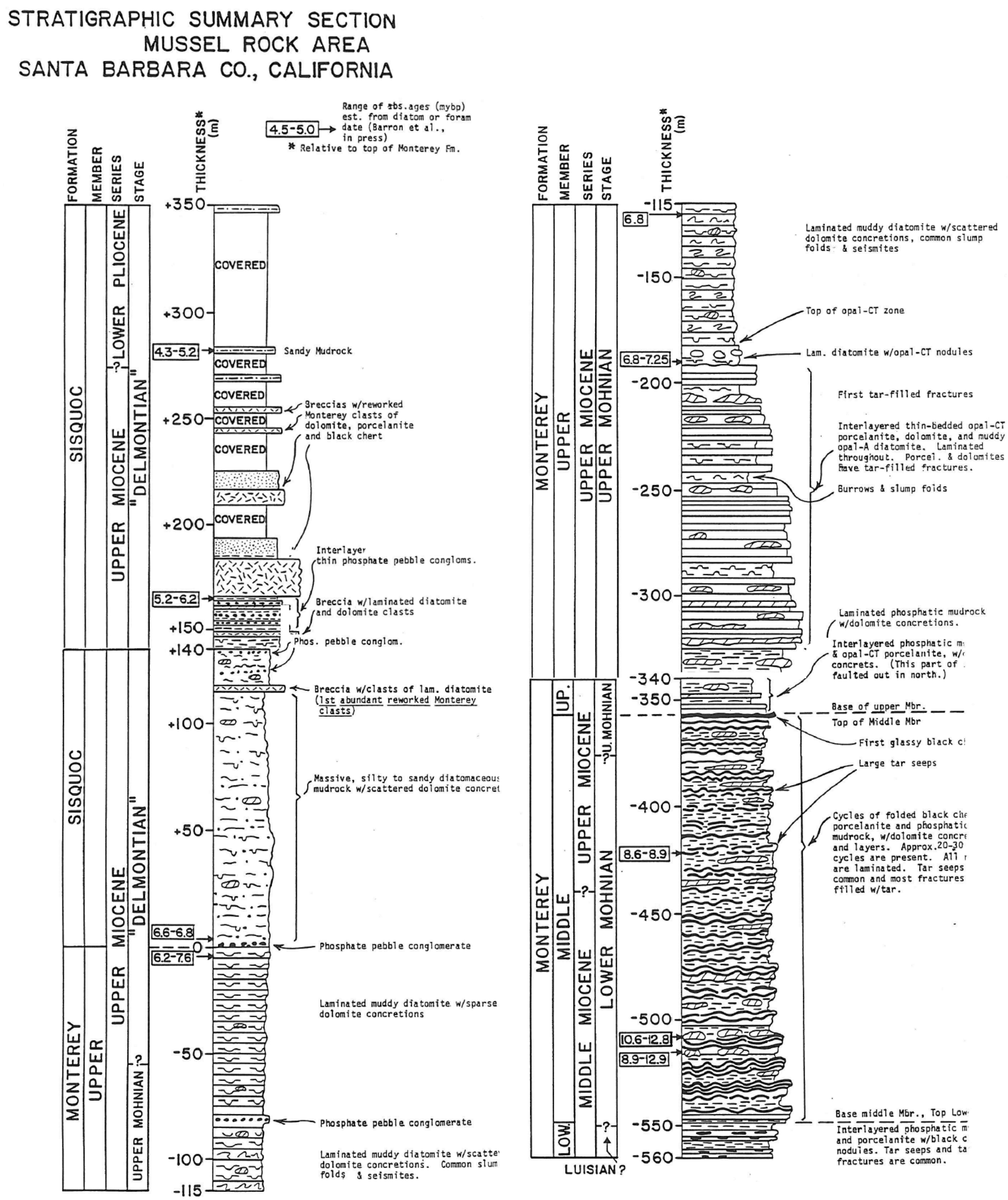



Figure 2-08. Stratigraphy of the Mussel Rock section. From Garrison and Ingle (GGC, 1985).

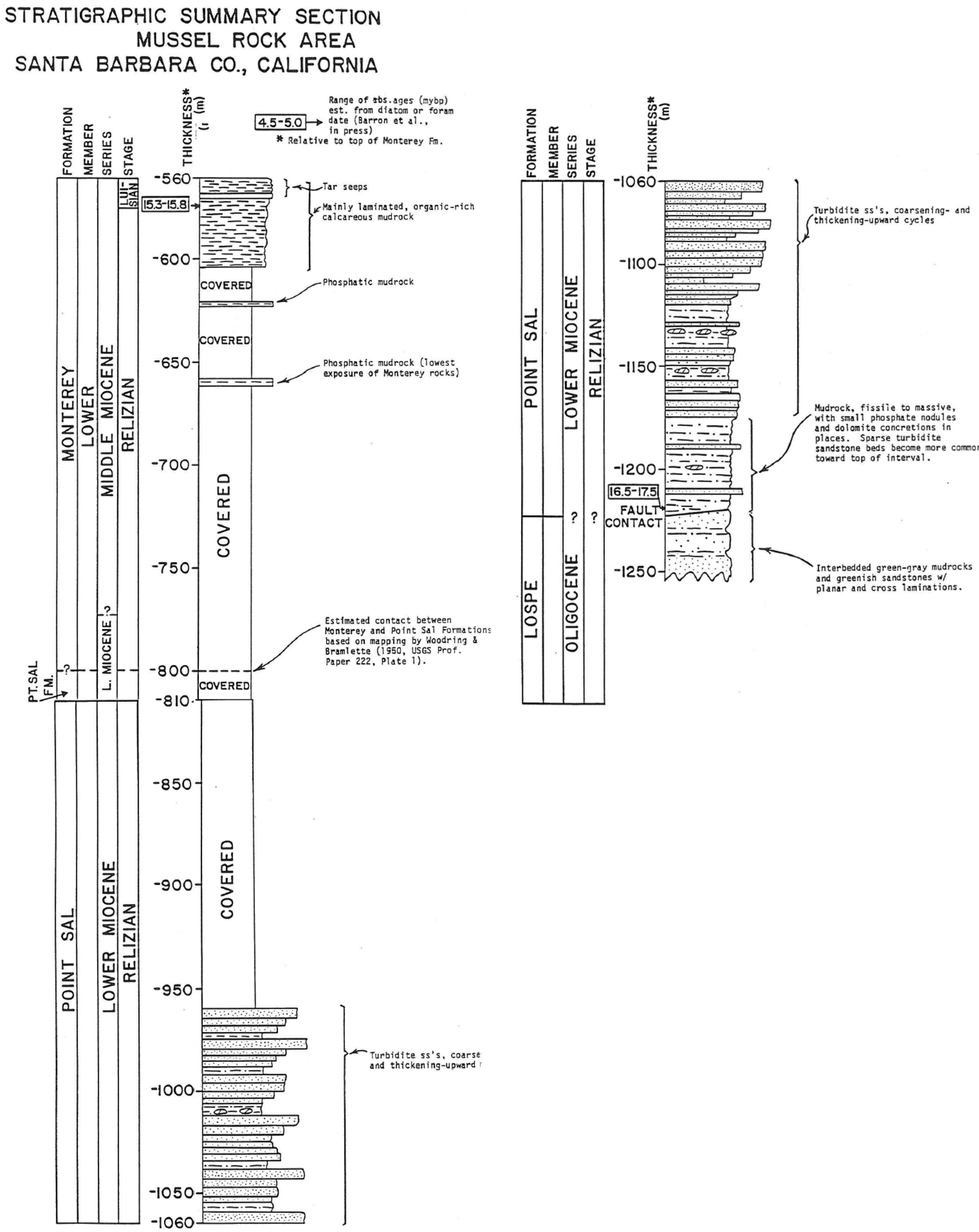



Figure 2-08. Stratigraphy of the Mussel Rock section (continued).

marlstone, porcelanite and chert, with interspersed dolostone beds. The chert, porcelanite and dolostone are highly fractured and oil/tar saturated. This is an exhumed petroleum reservoir similar to these exploited at the Point Pedernales and Point Arguello fields directly offshore. The chert is in the quartz phase, the porcelanite contains both quartz and opal-CT.

The ~350-m-thick Upper Member (Upper Siliceous) of the Monterey Formation at Mussel Rock contains the transition from opal-A muddy diatomites to opal-CT phase porcelanite and chert. This is discussed in more detail below. This member actually contains a broad diversity of lithologies and runs from being dominated by phosphatc calcareous mudstone and dolostone at its base (much like the Lower Member) to interbedded muddy diatomite and porcelanite, to laminated, but thick-bedded diatomite and muddy diatomite in the upper part. There is an abundance of synsedimentary intraformational folds and breccias.

The contact with the overlying Sisquoc Formation is marked by a phosphatic conglomerate that separates laminated from generally massive, silty diatomaceous rocks. The top of the Sisquoc is not exposed, but there is about 350 meters of discontinuous outcrop along the beach. Interbedded with the diatomaceous sediments are a series of meter- to several-meter-thick conglomerates and breccias deposited as sharp-based gravity flows. These contain clasts of Monterey porcelanite, chert, dolomite, phosphate, many with pholad clam borings.

## SEDIMENTOLOGY OF OPAL-A to OPAL-CT TRANSITION ZONE

An 80 m thick section across the opal-A to opal-CT silica phase transition of the Upper (clayey-siliceous ) Member of the Monterey Formation was measured. The section includes roughly 40 m of biogenic opal-A diatomites and an equal thickness containing lithologies with diagenetic silica (Figure 2-08). The uppermost occurrence of opal-CT is present in siliceous nodules, and this horizon was defined as the zero datum for stratigraphic reference. This point is approximately 180 m stratigraphically below the Sisquoc Formation contact to the north (Garrison and Ingle, 1985) at longitude N34.94° and latitude W120.66°.

The stratigraphic section is uniquely continuous and undeformed compared to other exposures of the Monterey Formation along the coast. Some faulting is present, but is mainly bedding-parallel along mudstone beds. The maximum observed decrease in section thickness due to faulting is approximately 30 cm. Large-scale folding is absent in the studied section although the entire sequence lies on the steeply dipping northern flank of the Casmalia anticline; at most, diagenetic lithologies exhibit undulating beds.

In general, the section is fine-grained (clay and silt size) with thin, pin-stripe lamination and soft-sediment deformation present throughout. Mineralogy is dominated by biogenic silica, clay, quartz, and feldspar, with minor presence of hematite. Dolomite beds are rare. Macrofossils are absent, limited to scattered fish scales.

Lamina commonly measure 0.5-2 mm in thickness, but variation exists from less than 0.5 mm up to 5 mm, and are only absent in a few thicker mudstone beds. Abundant soft-sediment deformation includes micro-folds and micro-faults with less abundant decimeter-thick slump folding. Slumps are at times extremely chaotic. Small shale olistoliths are present at a few locations. Shallow scoured surfaces are present at the base of thicker detrital-rich lamina or thin silty beds. Smaller scale sedimentary features, in particular laminations, are excellently preserved in cherts and porcelanites in the lower part of the studied interval.

In the following, the section is described from diatomaceous to diagenetic grades of siliceous rocks, i.e. from young to old rocks to better emphasize diagenetic changes.

Minimally altered opal-A diatomites vary from light buff and grey color to grey-brown and dark grey. Differences in colors are mainly dependent on the influence of detrital components, with the lighter laminations being purer diatomite. Rarely, light color is due to weathering of partially dolomitized beds. Five to 20 cm thick laminated sections grade from purer siliceous to more argillaceous in overall composition. Several horizons contain noticeably more abundant clay.

There is an abrupt transition to opal-CT nodules (Figure 2-08) and a more gradual transition into beds with discontinuous and irregular silicification fronts. The complete thickness of this transition zone is approximately 6 m. The uppermost continuous bed on outcrop scale occurs within this zone, though continuity beyond outcrop scale is unknown. Nodules are mainly thin and elongate. The color, grain size, and sedimentary structures of apparently unaltered host diatomites in the transition zone look identical to diatomites above zero datum.

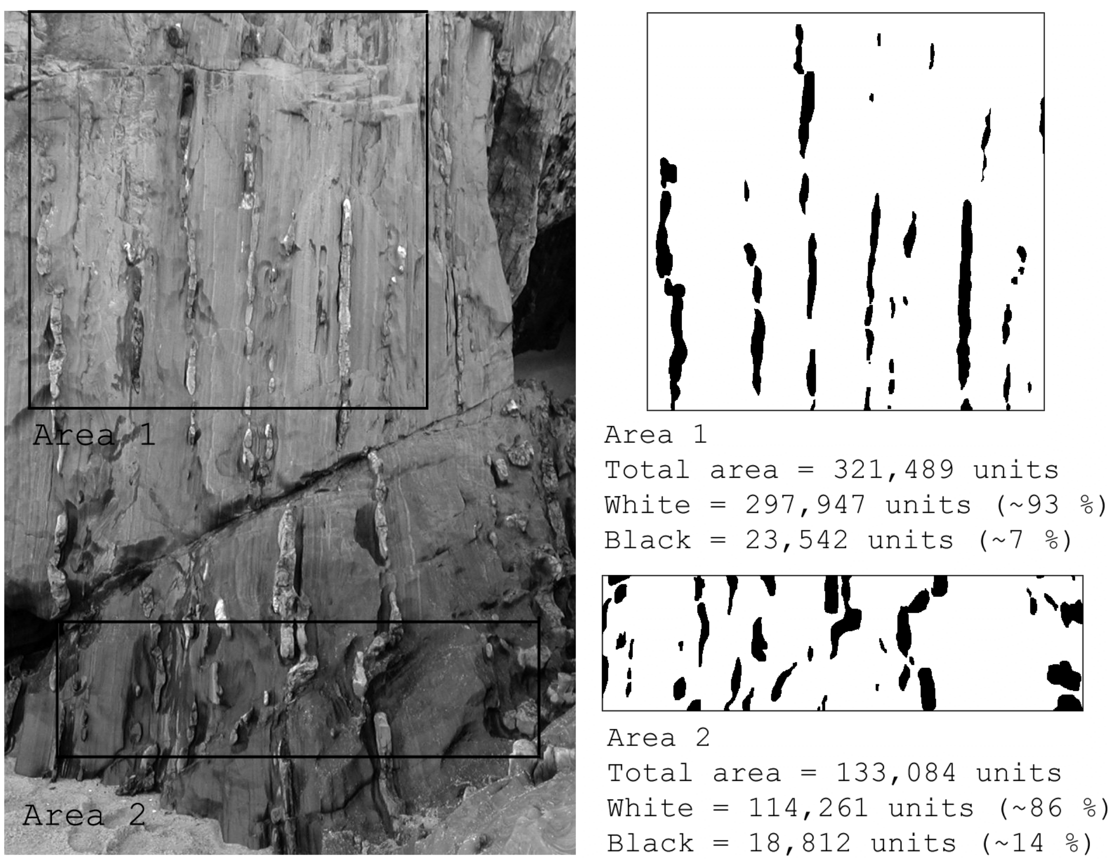



Figure **2-08.** Estimates for percentage of siliceous nodules in the opal-A to opal-CT transition. Nodules occupy from 7-14 percent of the area.

Stratigraphically below the nodular zone, a 3 m section of 1-7 cm thick pinch-and-swell chert beds are followed by a 10 m thick zone of well-developed ribbon beds (figure 2-089. The ribbon-bedded opal-CT cherts or porcelanites, and siliceous mudrocks or shales are stratigraphically above a less distinctly bedded section of argillaceous porcelanite-shale couplets.

This alternation from well-bedded to less well-bedded pattern repeats itself in the lower part of the measured section. Approximately 7 m of well-bedded, undulating porcelanite-shale couplets are stratigraphically above a 10 m thick section composed mainly of siliceous mudstones and argillaceous porcelanites.

Beds below zero datum are generally 5-10 cm thick. It should be pointed out that the thicknesses of each component of the cherty-shaley couplet are very difficult to measure in the field for two reasons. First, the appearance between unweathered, sand-blasted exposures and weathered outcrops are very different. Examination of fresh outcrops indicates very gradational contacts between beds, such as seen in most cores. Second, bedding surfaces are at times poorly defined due to extremely thin shale layers.

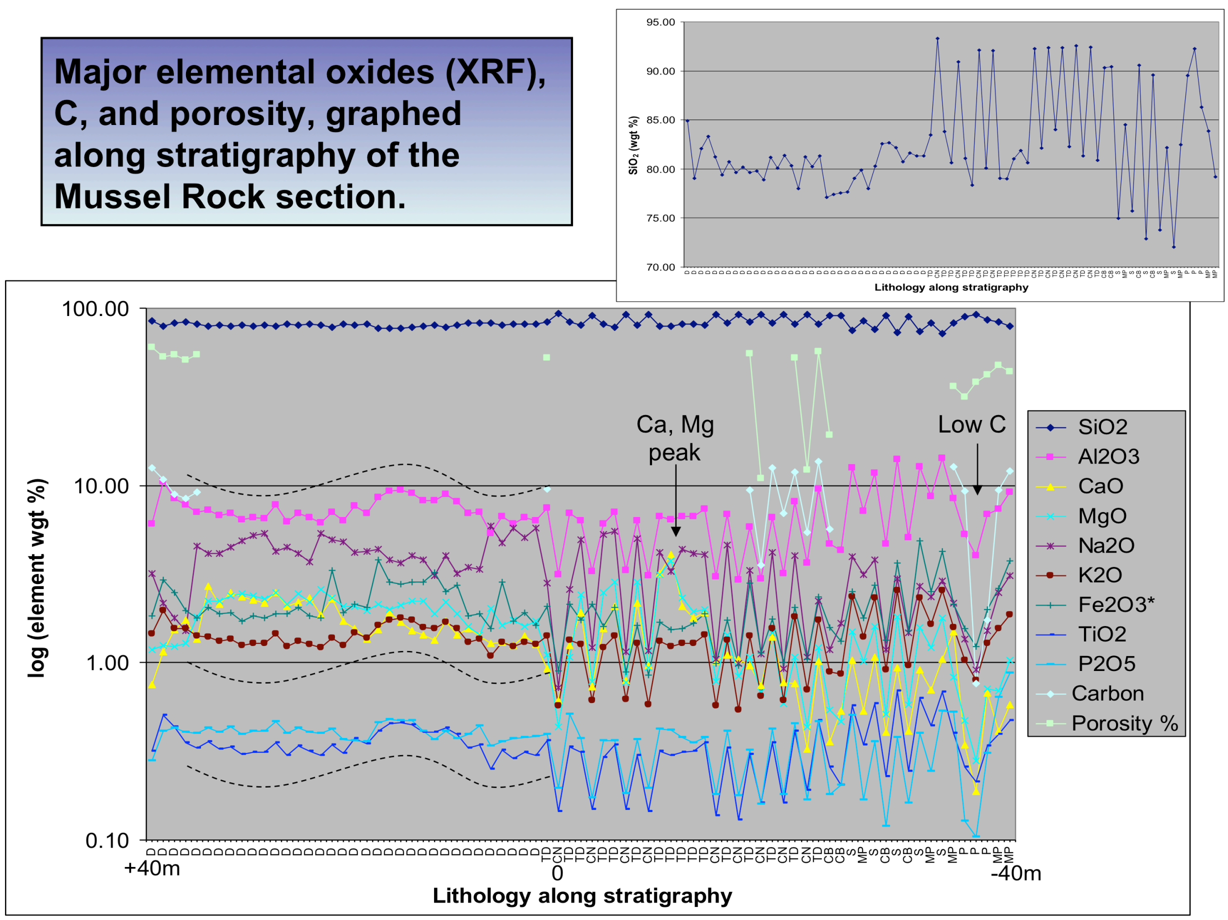



Figure **2-09**. Geochemical segregation at the opal-A to opal-CT boundary with the development of chert nodules and porcelanite beds. (Deason, MS research).

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