UNITED STATES DEPARTMENT OF THE INTERIOR

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Field trip guide to deposition and diagenesis of the Monterey Formation, Santa Barbara and Santa Maria areas, California

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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ILLUSTRATIONS

DEPOSITION AND DIAGENESIS OF THE MONTEREY FORMATION,
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INTRODUCTION

Overlying the Rincon Shale in the Santa Barbara coastal area is the distinctive Monterey Formation, which records deposition in Miocene time spanning about 12-1/2 million years. Depositionally, the Monterey is a hemipelagic deposit in several senses of the term. For example, deposition of the Monterey was strongly influenced by the oceanic or pelagic realm but its deposition was also influenced by nearness to the continent; in addition, sediment was mainly deposited by so-called hemipelagic "rain." Diagenetically, the formation is strongly overprinted by changes during burial. In fact, Monterey strata are practically metamorphosed by the time they have been heated to 100° C: all their silica, the predominant component of most rocks, has been completely dissolved and reprecipitated twice!

In the next two and a half days, we will be examining the deposition and diagenesis of the Monterey Formation in some detail. First we will take a brief look at the Monterey where it is comparatively unaltered diagenetically to fully appreciate its distinctiveness in the Tertiary sequence. Then we will examine its deposition step-by-step through time, from the base of the Monterey in the late early Miocene (c. 18 Ma) to its top in the latest Miocene (c. 5.5 Ma). Finally we will examine the diagenesis of the entire depositional sequence step-by-step with increasing temperature.

The field notes that follow are, for the most part, already available in published papers (particularly the Guide to the Monterey Formation in the California coastal area, Ventura to San Luis Obispo published by the Pacific Section AAPG and hereafter referred to as "1981 Monterey Field Guidebook"). The notes have been restructured, however, so that a wider variety of depositional and diagenetic aspects of the Monterey are addressed at the outcrop. Also a detailed depositional interpretation has been incorporated into the notes from Isaacs (1983), and conclusions of some more recent work are described. Some changes have also been made - for example, new member names are used here to avoid misleading connotations of the old ones. Few figures are included, but many references are made to figures and photos in the 1981 Monterey Field Guidebook.

Maps showing the generalized geology, tectonics, and physiography of southwestern Santa Barbara County are reproduced in figures 1, 2, and 3. Sections we will be visiting are located on figure 4.

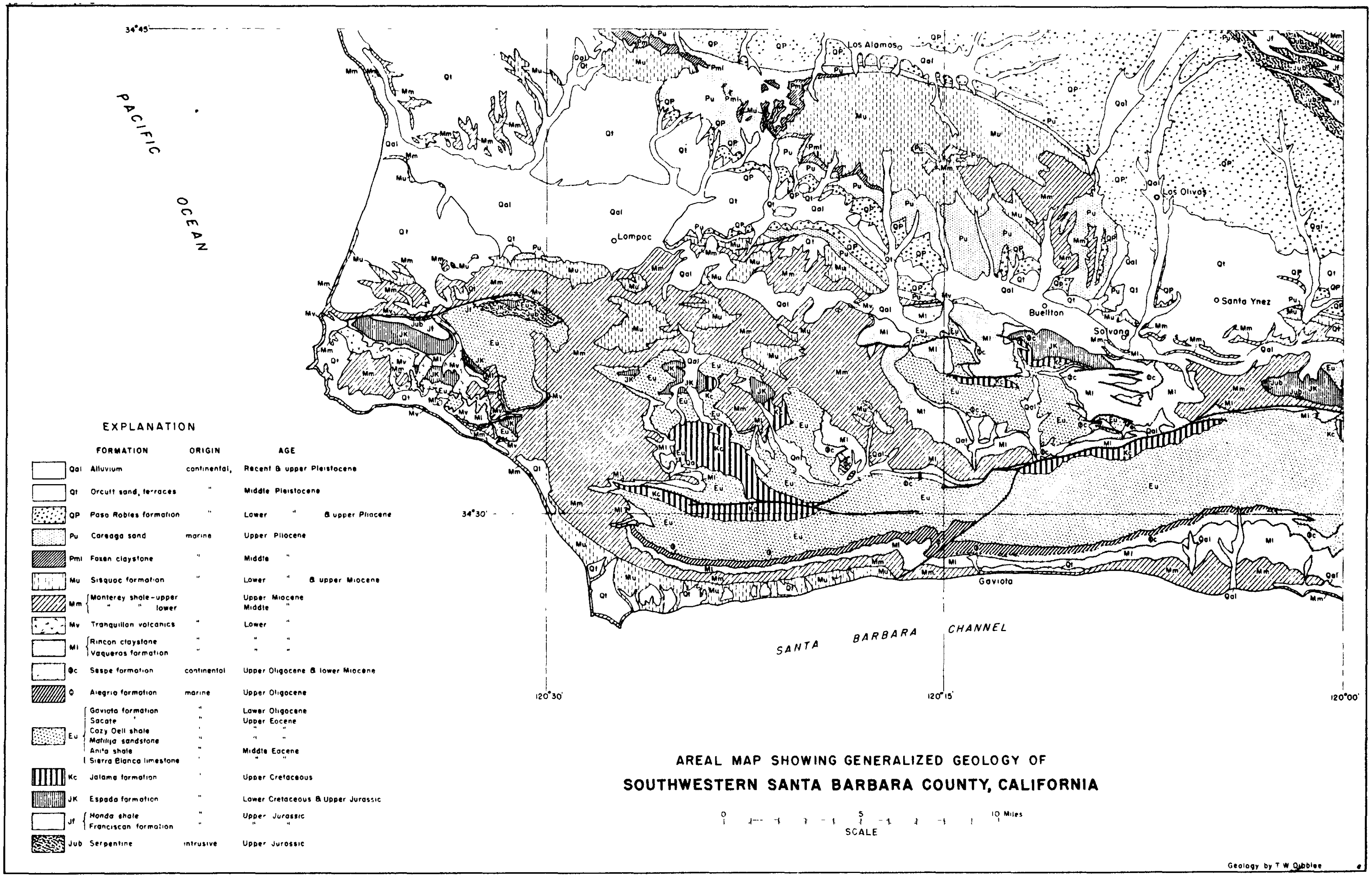

Figure 1. Generalized geology of southwestern Santa Barbara County, California. From Dibblee (1966, plate 6).

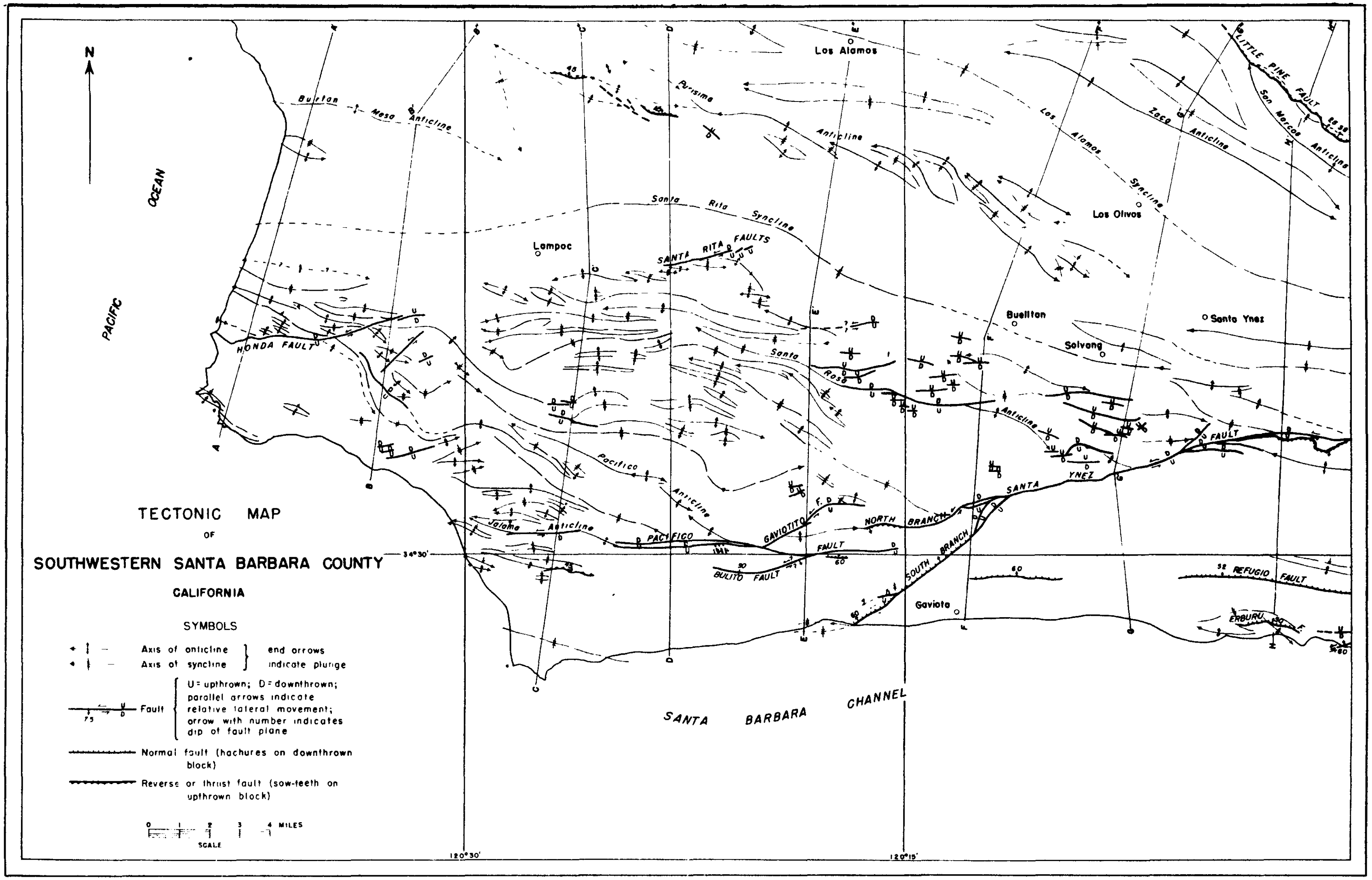

Figure 2. Tectonic Map of southwestern Santa Barbara County, California. From Dibblee (1966, plate 7).

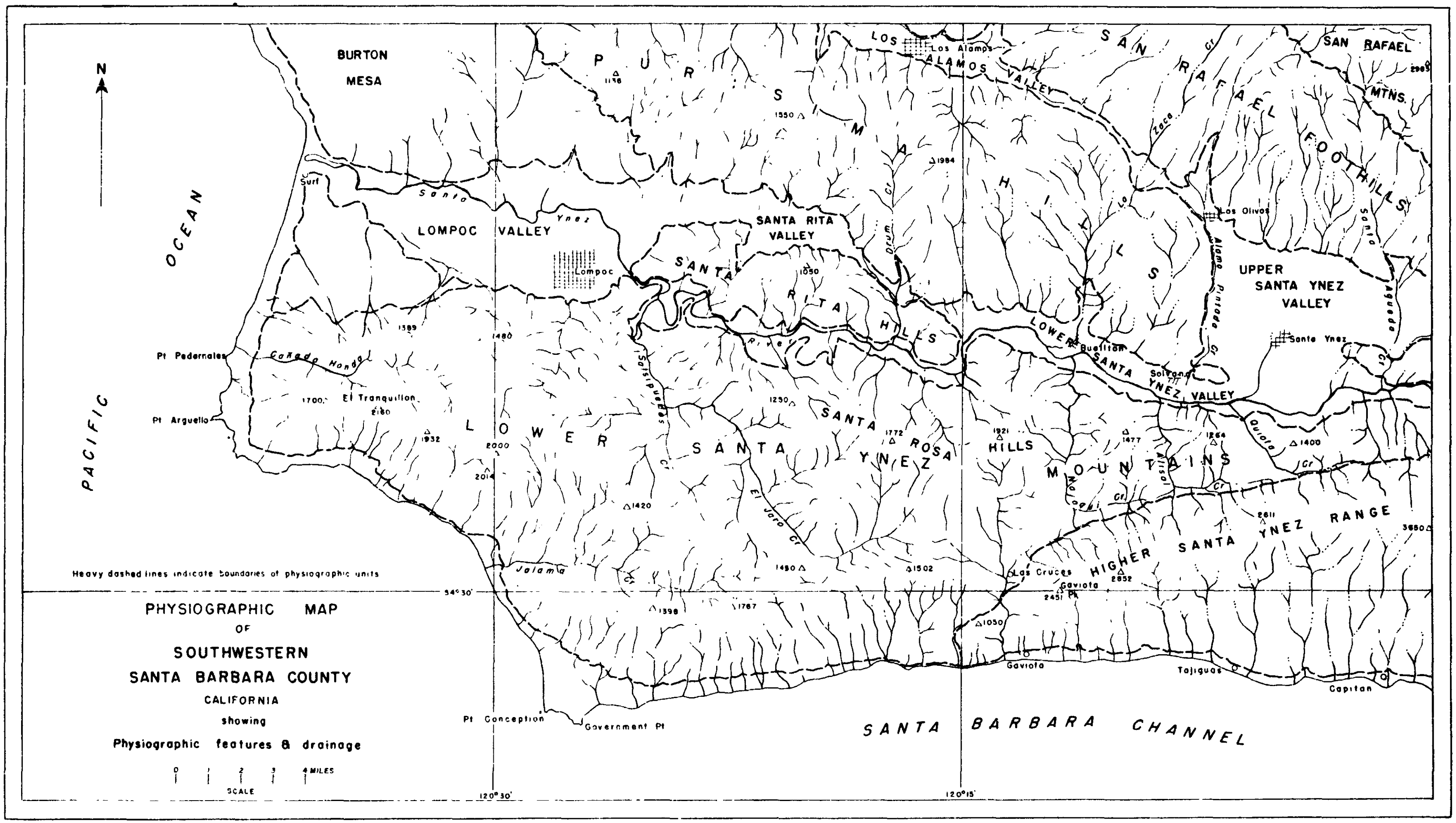

Figure 3. Physiographic diagram of southwestern Santa Barbara County, California. From Dibblee (1966, plate 7).

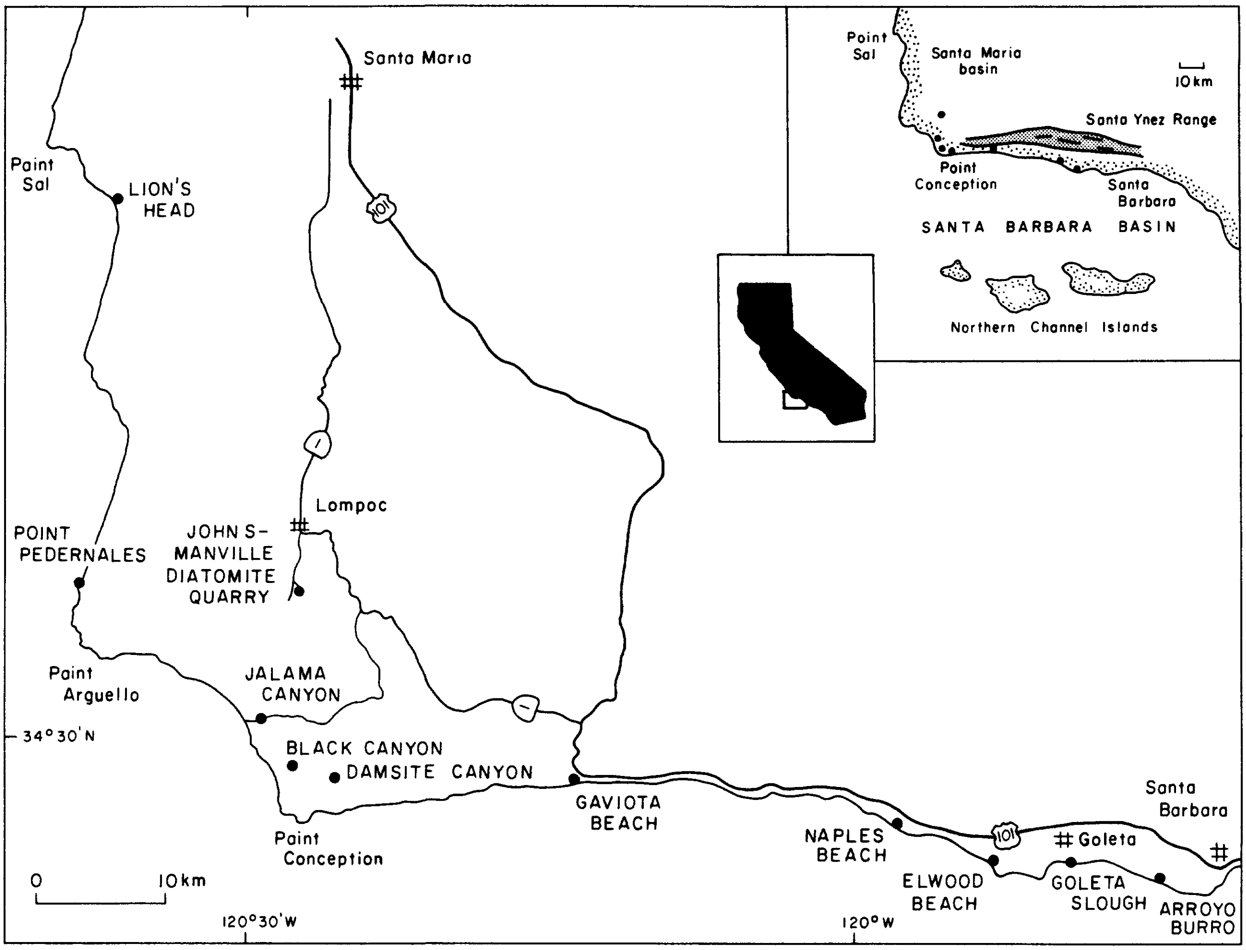

Figure 4. Map showing field trip sections of the Monterey Formation in the Santa Barbara coastal area, California.

JOHNS-MANVILLE DIATOMITE QUARRY

Main objectives: (1) to see the diatomaceous strata of the Monterey where they are extensively exposed, in order to appreciate the distinctively unusual character of the Monterey Formation in the Tertiary sequence of the Coast Ranges; (2) to see the lateral continuity of beds.

Plan: Robert Fullerton, geologist at the Johns-Manville diatomite quarry, will conduct our tour of the quarry (fig. 5).

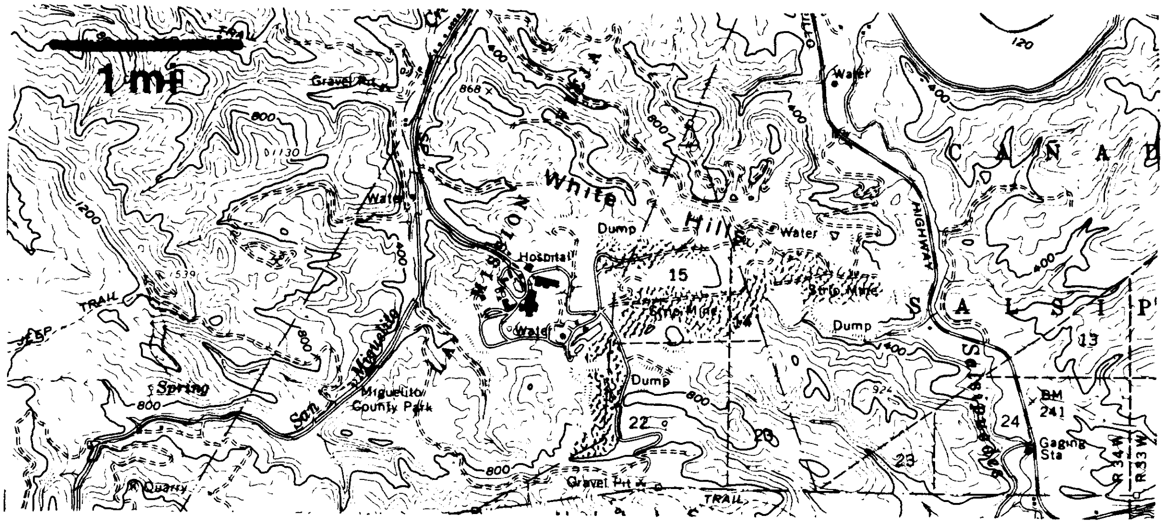

Figure 5. Map showing the vicinity of the Johns-Manville quarry near Lompoc, California. From Lompoc 15 minute quadrangle.

General comments: The part of the section mainly quarried here is the upper Monterey, equivalent in age to the clayey-siliceous member (c. 8-5.5 Ma) of the Santa Barbara coastal area. Note that only selected horizons are quarried here as "ore" and that a considerable proportion of beds in the quarry are regarded as "waste" - that is, containing too much clay to be worth refining. Chemical analyses of a number of samples of "ore" beds indicate that many contain as much as 80-90% SiO_2 and as little as 1.5-3.5% Al_2O_3 (approximately 6-15% aluminosilicates or 8-20% terrigenous detritus; for calculation constants used to estimate detritus, see Isaacs and others, 1983a, table 1.). Many "waste" beds, on the other hand, contain 8-9% Al_2O_3 and are thus predominantly terrigenous detritus.

At the top of the ore zone in the quarry is a pebble conglomerate, marking a disconformity of several hundred thousand years duration (Barron, 1976), which includes bone material and hard phosphate clasts as well as quartzo-feldspathic sand. Strata overlying the conglomerate are reported to be generally detritus-rich ("waste"), poorly bedded, and poorly laminated or massive, whereas underlying strata are predominantly well bedded with some well laminated strata classed as ore. These lithologic differences, as we will discuss in more detail later, define the Sisquoc-Monterey formation boundary. In this area, either a disconformity (or unconformity) is generally present at the contact. For example, a few feet of sand or a thin layer of phosphatic pebbles are present at the base of the Sisquoc Formation in some places in the hills east and west of the quarry (Dibblee, 1950, p. 43), an unconformity marks the boundary in the eastern Santa Rita Hills (about 10 miles east, fig. 3), and silty strata locally with scattered Monterey and Franciscan pebbles and phosphatic nodules are present at the boundary in the eastern Purisima Hills (about 15 miles east, fig. 3) (Woodring and Bramlette, 1950, p. 28).

Note, however, that a pebble conglomerate does not regionally mark the formation boundary, that layers of phosphate pellets are common throughout the formation, and that a conglomerate is widespread near the formation top in the Casmalia Hills (near Lion's Head) (Woodring and Bramlette, 1950). While we are at the quarry, consider how difficult it might be to place the Monterey-Sisquoc boundary where it occurs in diatomaceous strata. Where silica is diagenetic, the lithologic differences between the formations are much more pronounced.

The white color of the diatomaceous strata here - which we know are dark and organic-rich in other localities - is largely due to surface leaching. The base of the leached zone has been quarried, although we will not be able to see it, and comparatively fresh underlying rocks are gray or brown and contain 2-6% organic matter.

The quarry contains many other items of interest which we will probably not have time to see in our brief tour. Among them are thin ash beds, dolomitized layers, opal-CT nodules, and green iron-rich nodules (with as much as 12% iron as Fe_2O_3).

References: On the diatomite deposit, Dibblee (1950, p. 75-79). On diatom biostratigraphy in the deposit, Barron (1976, formation boundary subsequently revised). On layering details of laminated beds in the quarry, Donegan and Schrader (1981).

GOLETA SLOUGH SECTION

Main objectives: (1) to examine briefly, where they are diatomaceous, the upper two members of the Monterey Formation and the Sisquoc Formation of the Santa Barbara coastal area; and (2) to see the spectacular tar seeps in the overlying Pliocene "Pico" sandstones.

Plan: we will walk down into the section from the Southern California Gas Company lands and proceed upsection (east) through the Monterey and Sisquoc Formations to the "Pico" (Figs. 6, 7).

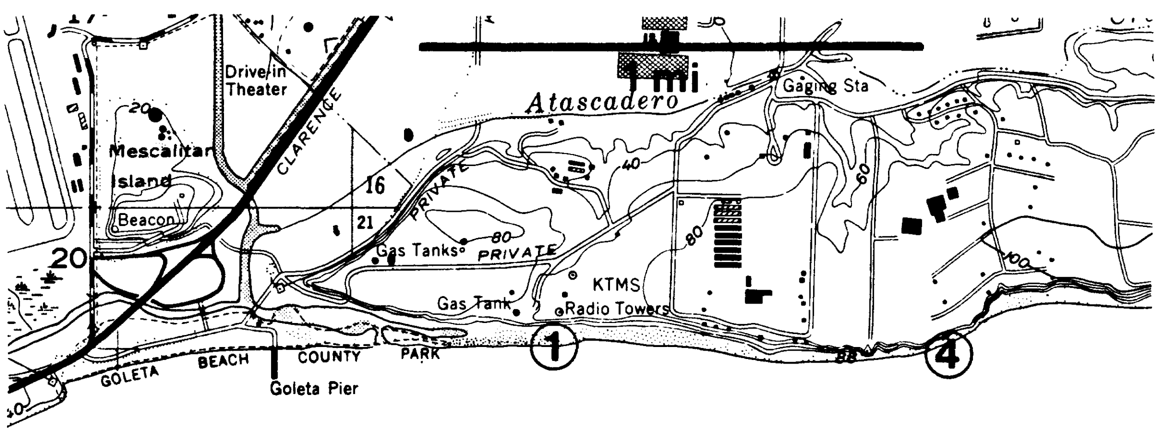

Figure 6. Map showing the location of stops at the Goleta Slough section near Goleta, California. From Goleta 7.5 minute quadrangle.

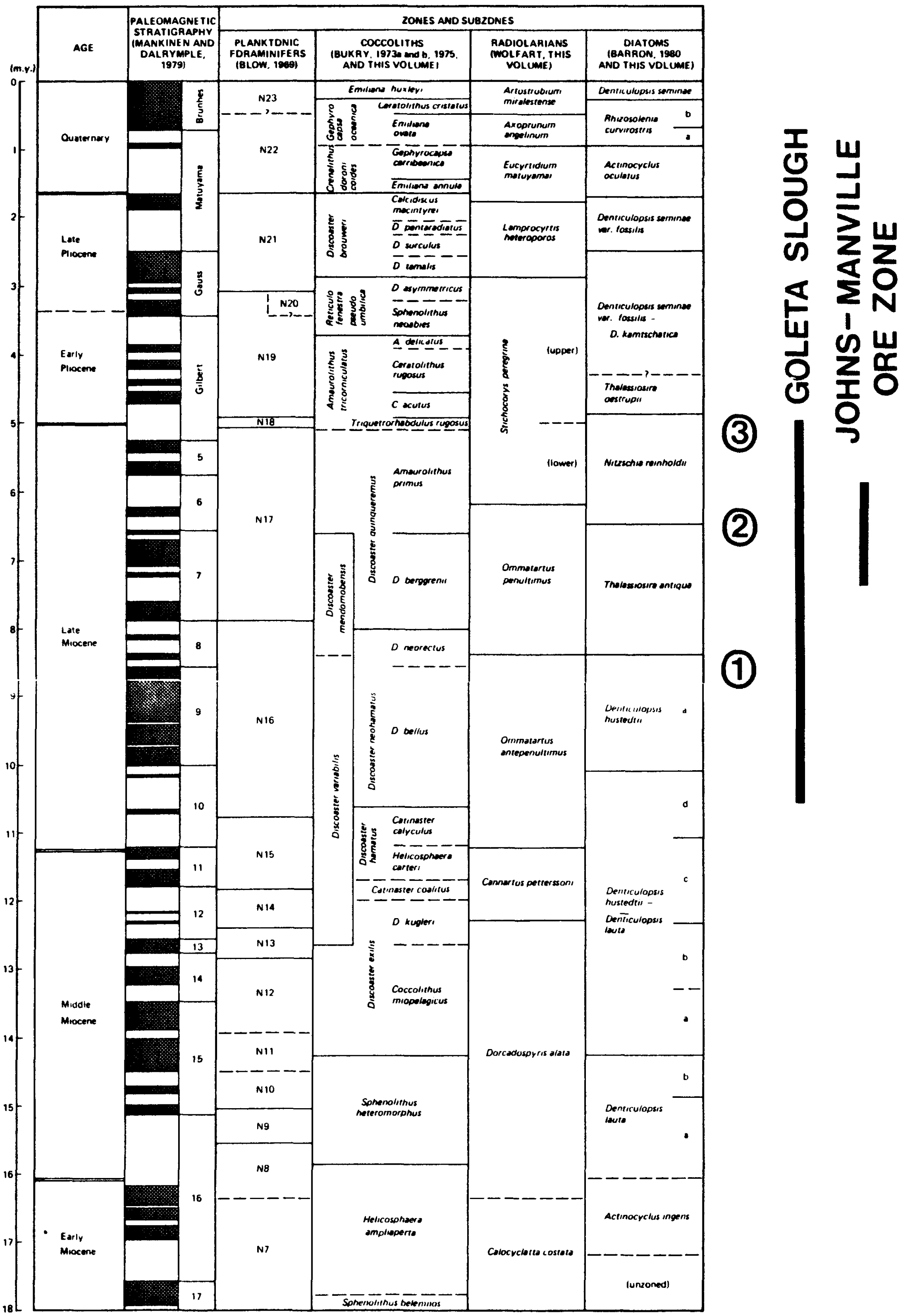

Figure 7. Biostratigraphic framework and time scale used (from Barron and others, 1981), showing diatom correlation of stops in the Goleta Slough section. The total range of the Goleta Slough Section and of the main ore zone in the Johns-Manville quarry is also indicated.

Stop 1: the best fresh exposure of the upper calcareous-siliceous member (c. 9.5-8 Ma) of the Monterey where it is diatomaceous.

o Calcareous diatomaceous rocks

These upper Mohnian strata (fig. 7) are somewhat older than the "ore" diatomite quarried at Lompoc. Underlying strata exposed along the slough cliffs comprise the only known exposure of the transitional marl-siliceous member (c. 11-9.5 Ma) where it is entirely diatomaceous; these beds extend downwards into the early Mohnian benthic foraminiferal stage and have been studied by Keller (1982).

Rocks here are composed of varying mixtures of biogenous silica (principally diatom frustules, also silicoflagellate and radiolarian tests), biogenous calcite (coccoliths and foraminiferal tests), terrigenous detritus (mainly mixed layer illite-smectite with detrital quartz, plagioclase, feldspar, potassium feldspar, mica, etc.), and organic matter (kerogen). The finely laminated diatomaceous rocks, which tend to be lighter in color, are more silica-rich and have less abundant terrigenous detritus (and, commonly, less abundant calcite) than the more massive darker diatomaceous rocks. Organic matter in these beds ranges as high as 10%.

Note particularly that 2-3 foot thick units of well laminated silica-rich rocks tend to alternate with units of poorly laminated (and, in places, bioturbated) detritus-rich rock. We will see this same part of the section at several other localities of higher diagenetic grade where these alternations are more pronounced. Generally speaking, increased diagenesis emphasizes the variations in cohesion among beds so that compositional variations are more obvious to the eye but does not cause the variations. Take a good look at these alternating units here, where silica is still diatomaceous and their original depositional character is clear.

Reference: on underlying strata in this section, Keller (1982).

o Dolostones (a la Roehl)

Brecciated dolostones form prominent resistant beds in this part of the section. As described by Roehl (1981), such breccias form in embrittled rock by a sequence of dilatancy, fluid expulsion, natural hydraulic fracturing, brecciation, hydroplastic flow, injection, and dolomite precipitation.

The presence of these beds interbedded with diatomaceous rocks shows that they can form comparatively early in diagenesis - prior to the silica phase transformations.

References: Redwine (1981), Roehl (1981), and Belfield and others (1983).

o Fracturing

Diatomaceous rocks are usually thought of as unsusceptible to fracturing, but these exposures are extensively fractured. Note that the laminated, more diatom-rich beds are particularly fractured.

Stop 2: the freshest exposure of the clayey-siliceous member (c. 8-5.5 Ma) of the Monterey where it is diatomaceous.

o Diatomaceous rocks

Strata here are similar in composition to underlying diatomaceous strata except in having no biogenous calcite. Rocks are thus principally mixtures of biogenous silica, terrigenous detritus, and organic matter. These strata are equivalent in age (fig. 7) and broadly similar in composition to the part of the Monterey extensively quarried at the Johns-Mansville quarry in Lompoc.

Note that beds alternate between laminated units several feet thick and massive units several feet thick. The laminated units are comparatively rich in biogenous silica and the massive units comparatively rich in clay. We will be discussing the depositional significance of this relation in more detail later in the week, but generally it indicates that periods of high oceanic productivity (silica-rich beds) were also times of very low-oxygen bottom waters (laminated layering) whereas periods of more modest productivity (silica-poor beds) were also times of more oxygenated bottom waters (massive).

Also note the evidence of minor soft sediment disturbances in the diatomaceous strata here. Disruptions of layering in recent diatomaceous sediments on slopes of the Gulf of California are common, even though slopes are quite gentle (e.g., 1-2°) (Soutar and others, 1981).

References: On layering, Soutar and others (1981), Isaacs (1983).

Stop 3: a poor exposure of the Sisquoc Formation (c. 5.5-3.5 Ma).

o Sisquoc strata

The Sisquoc here, although poorly exposed (and not mapped as Sisquoc by Dibblee, 1966), is equivalent in age (fig. 7) and similar in composition and appearance to Sisquoc strata in other nearby sections. Strata are mainly detritus-rich diatomaceous mudstones (massive) with some laminated units which commonly have wide (1-10 mm) laminae or bands.

Much of the Sisquoc in the Goleta Slough section, as in nearby sections, is a shale breccia. Note the various bedding directions even within a single foot of strata. The characteristics of these breccias are more clearly exposed at the Naples Beach section.

Stop 4: the only exposure of Pliocene "Pico" sandstone west of the Ventura area.

o Tar seep

A spectacular tar seep is here exposed in the late Pliocene(?) marine sandstones of the "Pico" Formation. Also at the base of the "Pico" Formation is a twenty-foot thick layer of rock saturated with tar/asphalt. Such deposits were used by the Chumash Indians for "caulking canoes, waterproofing baskets, as adhesive material, and for many other purposes" (Dibblee, 1966, p. 84).

Reference: Dibblee (1966).

o "Pico" sandstones

Unconformably overlying the Sisquoc Formation at this one locality is about 330 feet of fossiliferous dark gray marine sandy siltsone thought to be late Pliocene in age and hence tentatively correlated with the Pico Formation of the Ventura basin (Dibblee, 1966). Where well developed, the Pico Formation (including the lower part locally known as the Repetto Formation) comprises as much as 12,000 feet of sandstone, mainly turbidites, which is a major petroleum reservoir in the onshore and offshore Ventura area. Exposures of the Pico exhibit classic Bouma sequences in the Ventura Anticline and Santa Paula areas.

References: Dibblee (1966), Hsu (1977).

NAPLES SECTION

Major objectives: (1) to examine in detail the stratigraphic sequence of the Monterey Formation in the Santa Barbara coastal area, with emphasis on the depositional and paleoecologic significance of lithologic changes; (2) to see the transitional zone between opal-A (diatomaceous) and opal-CT rocks; and (3) to see the Sisquoc-Monterey boundary where rocks are relatively unaltered diagenetically.

Plan: we will start at the base of the Monterey and work upsection slowly to the Sisquoc, then - if time permits - return through the section examining the sequence downwards, as it is encountered in wells (see figs. 8 and 9).

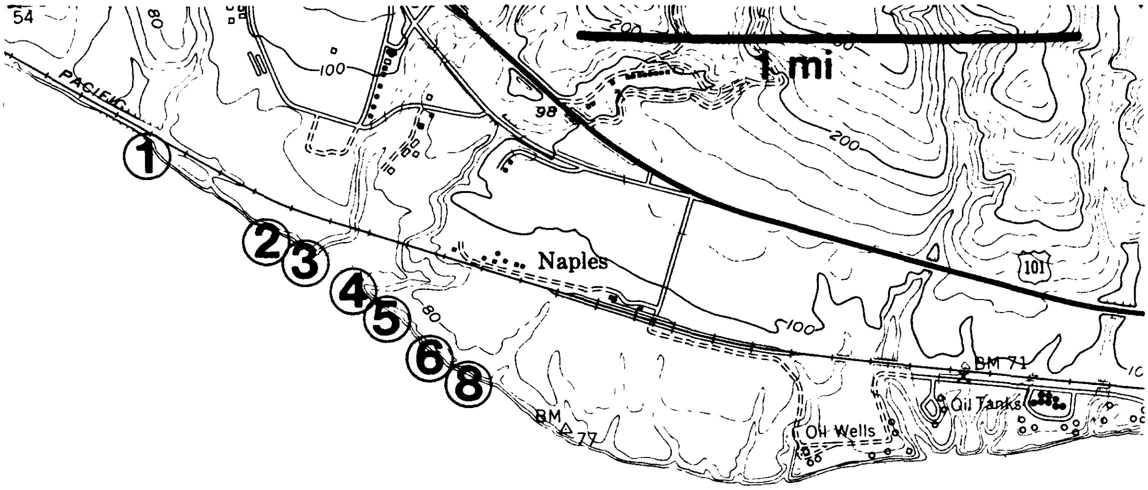

Figure 8: Map showing the location of stops at the Naples Beach section west of Goleta, California, From Dos Pueblos Canyon 7.5 minute quadrangle.

Stop 1: an excellent exposure of the lower part of the lower calcareous-siliceous member (c. 18-15 Ma) of the Monterey where silica is mainly opal-CT.

o Bentonite

This bed defines the base of the Monterey in the Santa Barbara to Point Conception area. The bed was originally mainly volcanic ash but has been altered, at least in adjacent sections, to smectite and clinoptilolite. Although representing a minor proportion of rocks (max 1%), a number of comparatively unaltered ash beds--one as thick as 7" (18 cm)--are also present in overlying strata in this and nearby sections.

The bentonite, although defining the base of the Monterey, does not mark a sharp change in lithology; at most sections, the base of the Monterey would be placed somewhat lower (50-100 feet) in the absence of the bentonite. The age of the base of the Monterey in the Santa Barbara coastal area is uppermost Saucesian, which is late early Miocene; correlations of planktic foraminifers at Naples with the radiometric time scale suggest an age for the base of about 18 Ma.

References: Dibblee (1950, 1966); Isaacs (1980, p. 276-7). On age, see Kleinpell (1938; 1980, p. 91-98), Isaacs (1983, p. 129). On the bentonite, see also 1981 Monterey field guidebook p. 20-21.

o Rincon-Monterey boundary

The Rincon Shale is generally known as a terrigenous mudstone or claystone and the Monterey Formation as a siliceous deposit. What is the

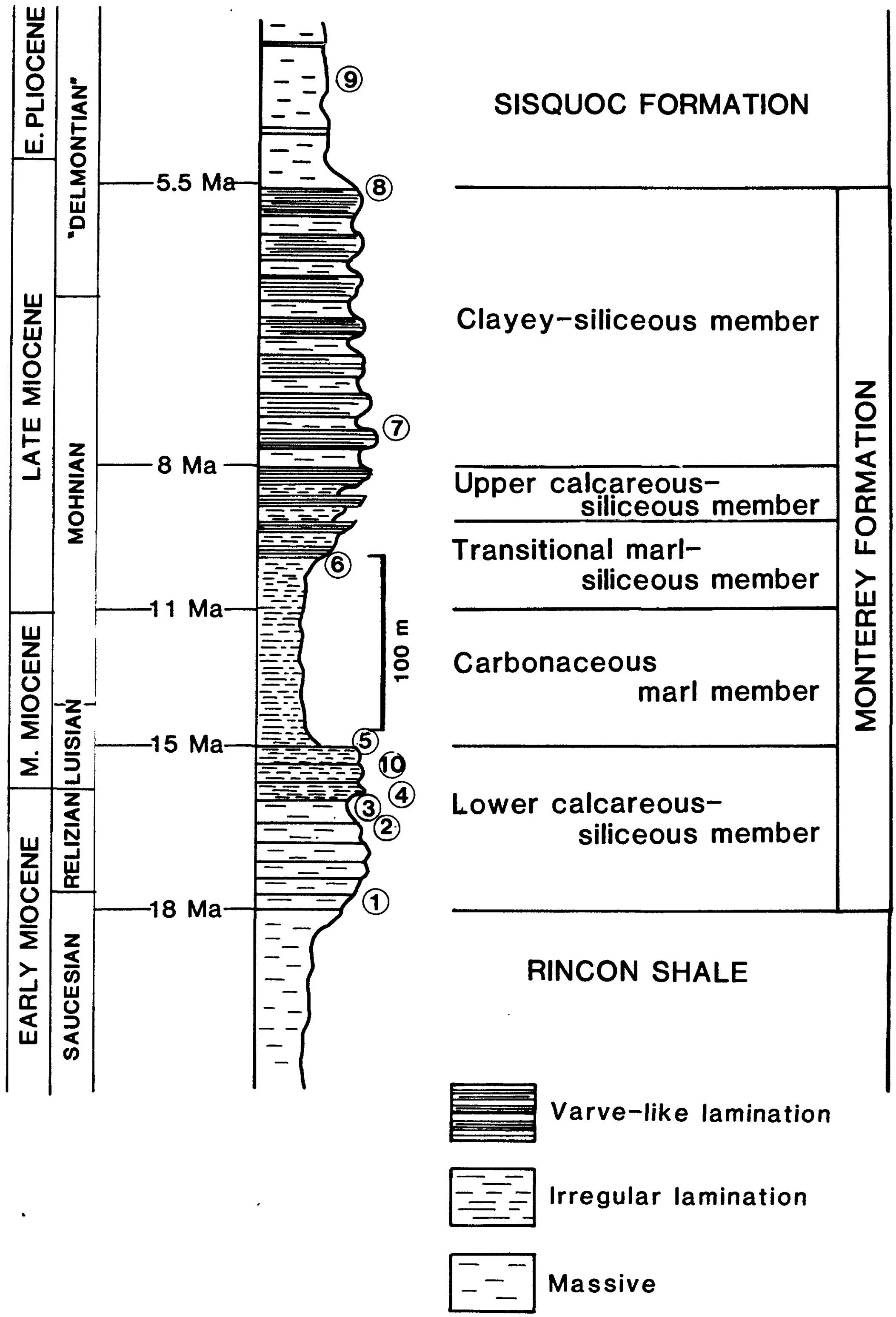

Figure 9. Generalized lithostratigraphic column of the Monterey Formation in the Santa Barbara coastal area (from Isaacs, 1983), showing position of field stops in the Naples Beach section.

depositional significance of this lithologic change? Calculation of total accumulation rates shows that Rincon strata were deposited twice as rapidly as strata at the base of the Monterey and 3-4 times as rapidly as middle Miocene strata in the Monterey. Even if the Rincon is not entirely terrigenous (for example, contains as much as 20% biogenic material), terrigenous detritus was accumulated 6-7 times more rapidly during Rincon deposition than during early Miocene Monterey deposition and 10-15 times more rapidly than during middle Miocene deposition. Thus the base of the Monterey marks a major reduction in the accumulation of terrigenous debris. Does it also mark an increase in the rate of accumulation of biogenous debris? Inasmuch as 20% biogenic silica in Rincon strata would represent the same silica accumulation rate as in the Monterey, present data on rock composition in the Rincon are too sparse for a definite answer, but distinctly siliceous beds present in the Rincon (Carson, 1965; Edwards, 1971) suggest that silica may have been accumulating long before the beginning of Monterey deposition.

The principal "cause" of the Monterey was thus a sharp reduction in the rate of influx of terrigenous debris which would otherwise have diluted the biogenous debris, resulting in a much thicker and less distinctive shale deposit. Important influences on the boundary were thus: (1) rising sea level (which trapped terrigenous debris near shore through most of early and middle Miocene time); and (2) rapid subsidence and basin formation (which produced "sediment-starved" basins), and (3) transgression (which moved the shoreline further away). Note that these influences (and thus the lithologic change marking the base of the Monterey) could easily have varied from place to place.

References: Isaacs (1983). On basin paleodepth, Ingle (1980, 1981). On the Rincon Shale generally, Dibblee (1950, 1966), Carson (1965), Edwards (1971, 1972).

o <u>Lowermost Monterey strata</u>

The composition of the lower part of the Monterey is mixed--as indicated by its designation "lower calcareous-siliceous member". Average composition of the lower half of the member is about 41% silica, 33% calcite (and/or dolomite), 20% terrigenous detritus, and 7% organic matter.

Note that silica is the predominant sediment component, outweighing carbonate by a factor of about 1.2. This relation between silica and carbonate also seems to be true of age-equivalent rocks in the Santa Maria basin known as the "siltstone and shell zone" of the Monterey Formation or the Point Sal Formation, despite the fact that they have been informally described as the "calcareous facies" (Pisciotto and Garrison, 1981). Note that the rocks are thick-bedded and internally massive. These are the characteristics that probably lead to their identification as calcareous rocks inasmuch as their fracture patterns and outcrop characteristics resemble those of thick dolostone beds and differ markedly from those of the thin-bedded and laminated calcareous-siliceous rocks of the upper Monterey.

Depositionally, these strata are regarded as hemipelagic deposits derived mainly from biogenous debris. The predominance of silica in the sediment composition indicates that diatoms (with silica tests) predominated over coccoliths and foraminifers (with calcite tests) in the overlying ocean, a relation indicating relatively high productivity in this late part of the early Miocene (c. 18-15 Ma). The massive layering indicates homogenization by bottom fauna and hence deposition in oxygenated bottom waters above or below the oxygen-minimum zone. Because paleobathymetry derived from benthic foraminifers indicates that the sediment was deposited at 1000-1500 m water depth, far below the top surface of any likely oxygen-minimum zone, these rocks are inferred to have been deposited below the oxygen-minimum zone.

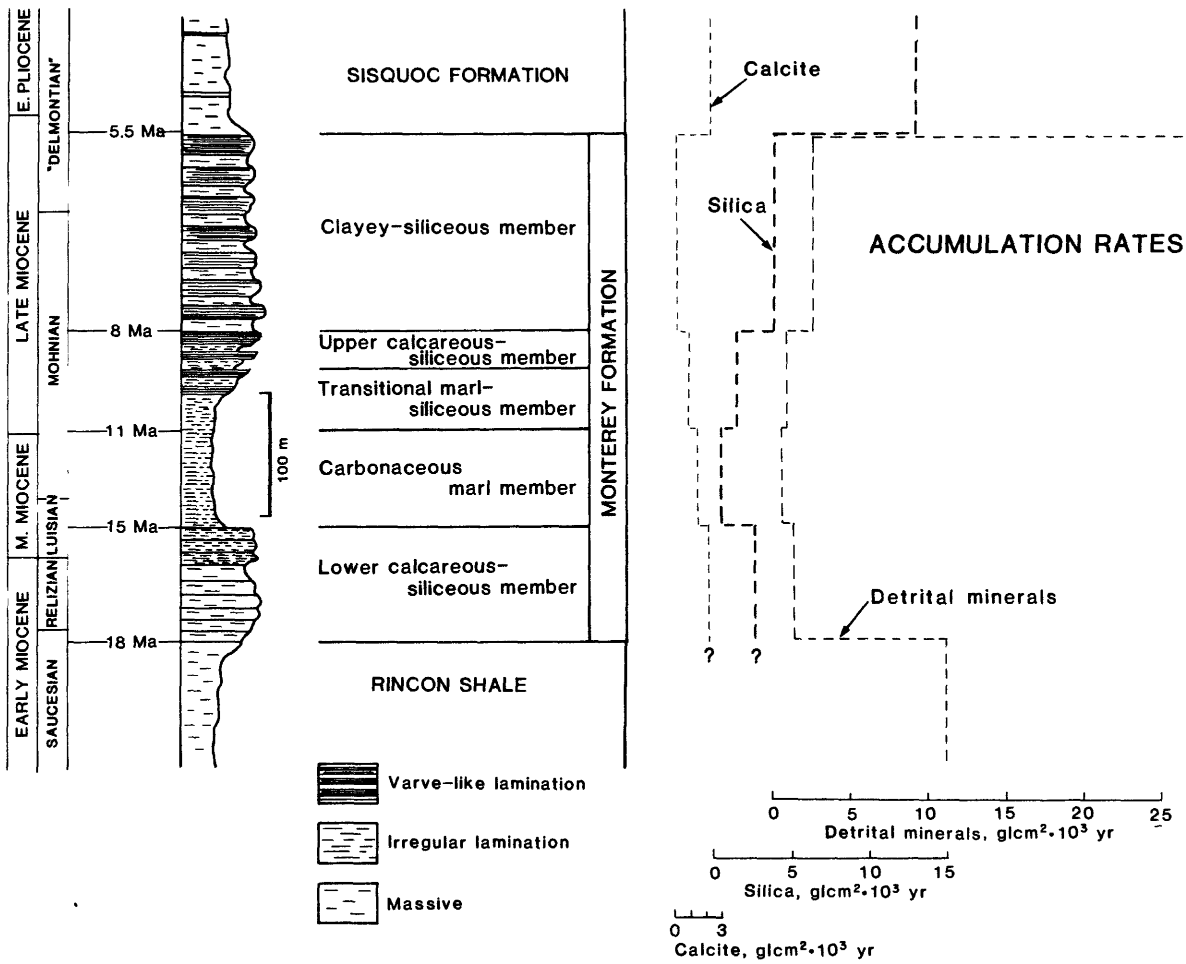

Figure 10. Generalized lithostratigraphic column and accumulation rates of the Monterey Formation in the Santa Barbara coastal area. Values are based on member-average compositions, member-average time intervals, and the average of minimum and maximum thicknesses adjusted for bulk density. From Isaacs (1983).

References: Isaacs (1983). On paleodepth, Ingle (1980, 1981). On layering, Govean and Garrison (1981), Soutar and others (1981). On age, Kleinpell (1938, 1980), Isaacs (1983, p. 129). On composition in the onshore Santa Maria basin, Isaacs and others (1983a, p. 104). See also 1981 Monterey field guidebook p. 45 (fig. 12A) and p. 60 (fig. 10C).

o <u>Variations among beds--lower calcareous-siliceous member</u>

All strata are mixed in composition, but individual beds vary over a wide range of composition: 5-90% silica, 5-75% calcite (and/or dolomite), 5-50% detrital minerals, and 2-18% organic matter. Diagenetically, silica here is diagenetic opal-CT (cristobalite-tridymite), although a few diatom frustule remains are reportedly present in isolated beds. Thus all beds have a crystalline silica framework which has markedly increased cohesion and resistance to erosion.

In general, the most resistant beds are those relatively rich in silica and poor in detrital minerals (that is, rocks with a high silica/detritus ratio), and these beds tend to develop a white weathered surface. Most light-colored hard "fizzy" rocks are thus not limestones, but calcareous porcelanites and cherts. The least resistant beds are those with a low silica/detritus ratio, and such beds are generally calcite-rich and detritus-rich. Descriptively, these beds are marls or chalks and are commonly dark in color. Their low resistance to erosion derives from the fact that their calcite is predominantly in coccoliths and other fossil remains composed of low-magnesium calcite, a material which is geochemically stable and not subject to widespread recrystallization at shallow and moderate burial depths.

References: See 1981 Monterey field guidebook p. 45 (figs. 12A, 13), p. 46 (fig. 14), and p. 60 (fig. 10B).

<u>Stop 2</u>: an excellent exposure of the middle part of the lower calcareous-siliceous member (c. 18-15 Ma), here thicker than in any other section along the Santa Barbara coast.

o <u>Change in layering character</u>

Upsection several hundred feet from the base of the Monterey but still in the Relizian benthic foraminiferal stage (and the early Miocene), distinct layers within beds are more obvious though the layering is not varve-like. The increasing preservation of layering in rocks deposited at a steady water depth suggests either a deepening of the bottom surface of the oxygen-minimum zone OR the creation of a basin sill within the oxygen-minimum zone, producing an oxygen-starved basin.

References: Isaacs (1983). See also 1981 Monterey field guidebook p. 60 (fig. 10D).

<u>Stop 3</u>: a striking exposure of an intraformational shale breccia in the upper Relizian part of the lower calcareous-siliceous member (c. 18-15 Ma).

o Intraformational shale breccia

On the west side of Dos Pueblos Canyon is a shale breccia estimated by Dibblee (1966) to be 115 feet thick. Included as clasts are a number of large fragments of gray tuff beds (some several feet long) as well as numerous fragments and large clasts of calcareous-diatomaceous beds. This deposit is interpreted as a soft sediment chaotic landslide or slump deposit (Martin H. Link, oral communication, 1983). A similar layer about 1 foot thick is well exposed on the east side of Dos Pueblos Creek.

References: Bramlette (1946, plate 17B), Dibblee (1966).

Stop 4: on the east side of Dos Pueblos Canyon, a very fresh exposure of the upper part (c. 16-15 Ma) of the lower calcareous-siliceous member of the Monterey.

o Upper part of lower calcareous-siliceous member

Near the base of the outcrop on the east side of Dos Pueblos Creek is the Relizian-Luisian benthic foraminiferal stage boundary (c. 16-15.5 Ma) in the upper part of the lower calcareous-siliceous member.

Diagenetically, this part of the section consists of a mixture of beds in which silica is mainly diagenetic opal-CT and beds in which diatom frustules are still well preserved. Rocks thus vary considerably, and rock types include calcareous diatomaceous strata (predominant), calcareous cherty rocks, dolostone concretions, and also phosphate-bearing marls which we will examine more thoroughly at the next stop. Also note a tar-filled fracture zone.

Beds here are distinctly laminated, but the lamination is not continuous nor fine (i.e., fractions of a millimeter) like varves in recent sediments from the Santa Barbara Basin or the Gulf of California. Laminae are much further apart (3-10 mm) and are separated by intervals having some wispy or discontinuous layers producing a pronounced planar fabric. Such layering (termed "irregular lamination"), typical of this part of the sequence and the most common type of layering in the Monterey, may indicate marginally oxygenated bottoms waters or periodic incursions of marginally oxygenated bottom waters.

References: on species of benthic foraminifers, Kleinpell (1938, 1980). On layering, Isaacs (1983). See also 1981 Monterey field guidebook p. 19 (fig. 21) and p. 41 (fig. 3 top).

Stop 5:. an excellent exposure of the base (c. 15 Ma) of the carbonaceous marl member.

o Member boundary

The mean composition of strata in the "carbonaceous marl member" is about 16% silica, 23% terrigenous debris, 42% carbonate (mainly calcite), 13% organic matter, and 6% apatite.

Note that the abundance of silica has dropped substantially, to the point that calcite is the predominant sediment component by a factor of about 2-1/2. In addition, organic matter is here nearly twice as abundant as in underlying (and overlying) units, and phosphate nodules are much more common. Compared to other parts of the Monterey, this member is also comparatively homogeneous in lithology. Minor silica-rich beds and dolostones are present, but the majority of rocks are impure chalks or marls rich in organic matter.

Depositionally, the predominance of calcite in these beds indicates a moderately productive ocean during the middle Miocene, much less productive than in underlying strata deposited in the late part of the early Miocene. Calculation of accumulation rates shows that calcite accumulation did not increase across the boundary, that accumulation of terrigeneous debris remained steady, and that silica accumulation sharply decreased (by a factor of 3 to 7). These relations all support a decrease in productivity as the cause of the lithologic change.

Reference: Isaacs (1983). See also Monterey field guidebook p. 18, p. 19 (fig. 19), and p. 60 (fig. 10A).

o <u>Phosphate</u>

In this member and in the upper part of the underlying member, nodules and nodular layers and blebs of apatite are common (as much as 25%) in some beds. Analysis of the apatite shows that it is carbonate fluorapatite (nodules from Lion's Head contain as much as 3.7% fluorine).

Compaction around nodules shows that they formed early in diagenesis - possibly near the sediment-water interface, inasmuch as apatite in modern upwelling areas such as Peru forms in the upper 15 cm of the sediment. Petrographic examination shows that apatite filled and replaced foraminiferal tests, and apatite nodules and blebs commonly show evidence of wholesale replacement of calcareous sediment. The conditions for apatite formation are still debated, but one theory suggests that the intersections of the seafloor with the upper and lower boundaries of the oxygen-minimum zone are ideal in providing a source of abundant phosphate (from organic matter accumulated in low-oxygen water) and its release to pore water (by oxidation during sulfate reduction in oxygenated water). An abundant source of calcium is obviously essential as well.

References: On depositional environment and formation of phosphate, Pisciotto and Garrison (1981). See also 1981 Monterey field guidebook p. 17 (fig. 17B), p. 47 (fig. 17A), p. 48 (fig. 19), and p. 59 (fig. 9).

o <u>Layers of concentrated apatite nodules</u>

High concentrations of apatite nodules occur in some strikingly exposed zones 3-6" thick in the lower part of the carbonaceous marl member. The concentration of discrete nodules and some imbricate structures suggest that these zones represent reworking, possibly due to occasional scouring by currents on the seafloor (R.E. Garrison, oral communication, 1983).

o Weathering characteristics

An important field feature of these sparsely siliceous marls is their low resistance to erosion and their rapid weathering. Note the difference between the dark organic-rich beds exposed in the beach face and the same beds higher in the cliffs where they are light-colored and friable. As these beds contain an average of 13% organic matter (a maximum of 25%) by weight, the percentage of organic matter by solid volume can be as high as 40%. Surface leaching of the organic matter and dissolution of the abundant calcite thus easily destroys the rock framework.

References: see 1981 Monterey field guidebook p. 48 (fig. 19).

Stop 6: a good exposure of the base (c. 11 Ma) of the transitional marl-siliceous member (but a boundary difficult to pinpoint where silica is mostly diatomaceous).

o Member boundary

Gradationally upsection calcareous-siliceous beds are increasingly abundant and organic-rich marls decrease in abundance. Some of the calcareous-siliceous beds contain silica as diagenetic opal-CT, but the majority of beds are still diatomaceous. Because the formation of diagenetic silica affects rock properties so markedly, this change is not--strictly speaking--mappable in a mainly diatomaceous section and hence is not--strictly speaking--a member boundary. In diatomaceous sections, the change can be regarded as "equivalent" to the member boundary defined in more diagenetically altered sections.

The mean composition of strata in the transitional marl-siliceous member along the Santa Barbara coast is about 40% silica, 26% terrigenous detritus, 23% calcite (and/or dolomite), 10% organic matter, and 1% apatite. Note that silica is more than twice as abundant here as in the underlying member. Calculation of accumulation rates shows that silica accumulation was 3-4 times faster and carbonate accumulation about half as fast as in underlying strata. The boundary therefore mainly marks an increase in oceanic productivity.

In age, the increase in silica accumulation rates seems to have occurred in the late early Mohnian or at about 11 Ma. This boundary lithologically correlates in the Santa Maria basin approximately with the base of the cherty zone as used by Canfield (1939), the base of the middle member of the Monterey as used by Woodring and Bramlette (1950), and the upper part of the "phosphatic facies" as used by Pisciotto (1981a,b).

Depositionally, this boundary also approximately correlates with a decrease in sea-surface temperature and a change from subtropical-tropical to subarctic biofacies (Ingle, 1981, p. 168). Realize, however, that a decrease in surface temperature per se does not cause greater silica productivity. The main factor affecting the productivity of diatoms is nutrients, and diatoms will dominate high-nutrient waters whether comparatively cool (as in the Antarctic) or warm (as in the Gulf of Califoria). Because upwelling is the main factor influencing nutrient levels and upwelling also brings cooler water to the surface, temperature changes may correlate with productivity changes - but not in a cause-and-effect relationship, rather as proxy indicators. That is, both changes are caused by changes in a third factor - oceanic circulation reflected in upwelling levels.

References: On composition and age, Isaacs (1983). On temperature changes, see Ingle (1981, p. 168), Keller and Barron (1983). On temperature influence, see Tont (1981, p. 196). See also 1981 Monterey field guidebook p. 17 (fig. 16) and p. 22 (fig. 24).

o Variations among beds

The compositions of beds in the transitional marl-siliceous member and the upper calcareous-siliceous member are as heterogeneous as compositions at the base of the Monterey. The range of composition is: 5-90% silica, 5-65% detritus, 2-75% carbonate, 0-20% apatite, and 2-20% organic matter.

Differences in composition among beds seem to result mainly from oceanographic variations rather than from influxes of detritus due to tectonism or to climatic changes. That is to say, detritus-rich beds apparently resulted from lower silica accumulation rates rather than from high rates of detritus influx. This conclusion is inferred from two lines of evidence: (1) that detritus abundance tends to correlate with calcite abundance, indicating that detritus-rich rocks were deposited during periods of moderate productivity and hence at slower accumulation rates; and (2) diatom assemblages in silica-rich beds are dominated by species characteristic of strong upwelling (*Thalassionema nitzschiodes* and *Thalassiothrix longissima*), whereas in detritus-rich beds upwelling species are rare, diatom frustules are poorly preserved generally, and the assemblage is dominated by solution-resistant species (e.g., *Coscinodiscus marginatus*) (John Barron, written communication, 1983).

Differences in composition closely correlate in this part of the sequence with layering styles. Silica-rich beds generally have varve-like lamination whereas detritus-rich/calcite-rich beds are generally irregularly laminated. Depositionally, this relation indicates that periods of high productivity (silica-rich beds) were also periods of intense low-oxygen bottom waters (varve-like lamination), whereas periods of more moderate productivity (silica-poor beds) were also periods of more oxygenated bottom water (irregular lamination). At the next stop, we will return to this relationship and discuss some of its practical implications.

References: Isaacs (1983). See also 1981 Monterey field guidebook p. 14-5 (figs. 10 and 14), p. 36 (fig. 21), and p. 59 (fig. 8).

o Organic matter

The abundance of organic matter shows considerable variation among beds, with a total range in the Monterey of about 1 to 25%. The distribution of organic matter shows several main relations: its abundance strongly positively correlates with the abundance of detritus, moderately positively correlates with calcite in the calcite-bearing part of the sequence, and strongly negatively correlates with the abundance of silica. These relations could be due to a number of factors--for example, preferential preservation of organic matter by adsorption on clays or higher accumulation rates of silica-rich beds (steady accumulation of organic matter would result in a lower weight percentage of a more rapidly deposited bed). Whatever the mechanism, organic matter is NOT most abundant in beds with varve-like laminae (presumed to be deposited in very low-oxygen conditions) but is actually least abundant in such beds. Inasmuch as average organic matter contents in the lower (massive) member of the Monterey are practically the same as averages in the upper three (laminated and partly laminated) members, the oxygen content of bottom water, as inferred from layering character, had a debatable influence on preserving organic matter.

Reference: Isaacs (1983, p. 124-5).

Stop 7: a good cliff exposure of the lower part of the clayey-siliceous member (c. 8-5.5 Ma) where silica is partly opal-A and partly opal-CT.

o Member boundary

The clayey-siliceous member differs from the underlying upper calcareous-siliceous member in having virtually no disseminated carbonate. Analyses of rocks indicate <0.1% carbonate except in dolostone layers. (Foraminifers are abundant on some bedding planes, but these are arenaceous foraminifers, with skeletons made of agglutinated sand and silt particles; arenaceous foraminifers are also visible as white flecks perpendicular to bedding.)

Depositionally, this boundary probably resulted from calcite dissolution rather than from non-deposition of calcite. The boundary seems to represent a widespread rising of the CCD or introduction of corrosive bottom water.

Biostratigraphy shows that this boundary is in the late Mohnian benthic forminiferal stage, a substage at least 3 million years long. Because of the sparsity of foraminifers at this horizon--and the dolomitization of calcite in many sections--this important boundary is impossible to date at most localities. Where diatom frustules have not been destroyed by silica diagenesis, as at Naples and nearby localities, an age of about 8 Ma is indicated.

References: On age, Isaacs (1983, p. 129). See also 1981 Monterey field guidebook p. 6 (CCD), p. 11-13, p. 59 (fig. 7B).

o Silica diagenesis

This member (as well as most underlying strata in the Monterey at Naples Beach) consists of a mixture of opal-CT-bearing rocks and opal-A-bearing rocks. What is the significance of this mixture?

Although the transformation from opal-A to opal-CT is well documented as a solution-precipitation process (Murata and Larson, 1975; Kastner and others, 1977; Murata and others, 1977), opal-CT strata do not generally form by simple cementation (addition of silica). In fact, several studies have shown that this silica phase transformation is, for the most part, a nearly in situ reaction (e.g., Hein and others, 1978). Compositional analysis at this and other nearby localities shows that the beds that still retain diatomaceous silica (opal-A) are the more detritus-rich (and silica-poor) beds whereas the beds in which silica is diagenetic opal-CT are the more detritus-poor (and silica-rich) beds. Evidently detritus retarded the formation of opal-CT in the Monterey, a relation also noted in diatomaceous strata in the Bering Sea (Hein and others, 1978). Experimental studies suggest that the abundance of smectite is the influencing factor as smectite competes with opal-CT for nucleation centers (Kastner and others, 1977).

Although composition influenced some of the details of silica diagenesis, it was not the most important influence. The transformation from amorphous opaline silica to crystalline opal-CT (cristobalite-tridymite) is not an equilibrium reaction, for the stable phase of silica at near-surface temperatures is quartz. Apparently opal-CT forms metastably because silica derived from the dissolution of amorphous silica is excessively saturated with respect to quartz (Murata and Larson, 1975; Kastner and others, 1977). The rate-determining step in the opal-A to opal-CT transformation is the nucleation of opal-CT, a process that can be promoted by a number of factors, the most important of which is temperature. Estimates of the transformation temperature from isotope data are based on many problematic assumptions, but empirical evidence (overburden thickness combined with present geothermal gradients) generally indicates that opal-A transforms to opal-CT in the Monterey in the range 45°-55° C (Murata and others, 1977; Pisciotto, 1981a; Isaacs and others, 1983b).

Reference: Isaacs (1982), Keller (1982). See also 1981 Monterey field guidebook p. 32 (fig. 12A).

o Porosity reduction

A major reduction in porosity is associated with the silica phase transformation from opal-A to opal-CT in the Monterey. Moderately and abundantly diatomaceous rocks in the Santa Barbara coastal area have porosities in the range 55-70% and dry bulk densities in the range 0.7-1.1 g/cm^3. Compositionally equivalent rocks in which the biogenic silica has transformed to diagenetic opal-CT have porosities mostly in the range 25-35% and dry bulk densities mostly in the range 1.4-1.7 g/cm^3.

Differences in silica diagenesis among beds show that the porosity reduction directly resulted from the silica phase transformation rather than from generally increased temperature/burial. For example, diatomaceous beds here retain porosities of typical diatomaceous rocks, and diatomaceous rocks with porosities as high as 60% lie hundreds of feet below the opal-CT strata here. Considerable evidence shows, however, that in individual beds - or in thick, compositionally homogeneous sections - porosity loss is abrupt. This abruptness apparently results from the rapidity of the solution-precipitation process during the transformation from opal-A to opal-CT. Because of low compressibility and minor dissolution during burial to several hundred meters, abundantly diatomaceous rocks retain unusually high porosities (over 70%) supported by a framework of diatom frustules (Hamilton, 1976). During the transformation from opal-A to opal-CT, when rapid frustule solution is promoted by precipitation of opal-CT, the framework of the rock is inferred to weaken, thus permitting rapid compaction, as shown by marked reduction in member thickness and average varve-like laminae thickness across the transformation zone.

The diagenetic boundary marking the formation of opal-CT is well known as a prominent acoustic reflector from Deep-Sea Drilling sites in the Bering Sea (Hein and others, 1978). Because the diagenetic boundary is controlled primarily by temperature, in many places is is oblique to stratigraphic bundaries (and is called, in the Bering Sea, a bottom simulating reflector or BSR). Most rocks at the silica phase transformation temperature (about 45°-55° C) in offshore areas of central and southern California are detritus-rich rocks younger than the Monterey (e.g. Isaacs and others, 1983a). For this reason, the diagenetic boundary is probably not as pronounced here as in the Bering Sea.

References: Murata and Larson (1975), Isaacs (1981).

Stop 8: an excellent exposure (at the right time of year) of the Sisquoc-Monterey boundary (c. 5.5 Ma) on the beach face.

o Rock types and layering variations, clayey-siliceous member

Compositions of rocks (excluding dolostones) in the clayey-siliceous member ranges from 15-90% silica, 10-80% detritus, and 2-12% organic matter. Rocks tend to occur in alternating units of "massive" siliceous mudstone (recessive units) and laminated porcelanite (resistant units). This alternation is typical of this member and indicates that bottom waters were very low in oxygen (laminated) during deposition of beds with abundant silica (porcelanites and cherts) and that bottom waters were aerobic (massive) during deposition of beds with sparse silica (siliceous mudstones). In addition, as discussed at the last stop, evaluation of diatoms from similar alternating units at Goleta Slough shows that the silica-rich beds have abundant upwelling species, whereas the clay-rich beds have few upwelling species, generally poorly preserved diatom debris, and an abundance of solution-resistant species.

These relations have important implications for detailed chronostratigraphy in the Monterey because they imply that massive beds were deposited much more slowly than laminated beds. A rough approximation of how much more slowly can be made by assuming a constant rate of detrital influx; for example, a bed with 20% detritus would have been deposited about 2-1/2 times more rapidly than a bed with 40% detritus and 16 times more rapidly than a bed with 80% detritus. Massive beds cannot, therefore, be presumed to represent simply the homogenized equivalent of beds with varve-like lamination - inch for inch, massive beds probably represent 2-10 times more geologic time.

References: Govean and Garrison (1981), Soutar and others (1981), Isaacs (1983, p. 127). See also 1981 Monterey field guidebook p. 12 (fig. 6) and p. 59 (fig. 7A).

o <u>Rock types</u>

The formation boundary is marked here by the predominance of detritus-rich diatomaceous/siliceous mudstone in the Sisquoc. Note the thin conglomerate beds and layers of sparse phosphate clasts present at a number of horizons in the upper part of the Monterey and basal Sisquoc. Most of these layers continue for hundreds of feet along strike.

References: see 1981 Monterey field guidebook p. 11 and p. 59 (fig. 7A).

o <u>Accumulation rates of detritus</u>

An important change in composition, first reflected in the clayey-siliceous member, is an increase in the abundance of terrigenous detritus. Note that the clayey-siliceous member averages nearly 40% detritus, compared with 20-25% in underlying Monterey strata, and that the Sisquoc averages over 60% detritus. For the clayey-siliceous member, more abundant detritus partly reflects the dissolution of calcite (which left a greater proportion of detritus in the sediment) but may also reflect higher rates of background detritus influx. For example, in the clayey-siliceous member cherty porcelanites ($\sim$ silica/detritus > 4) are not common and cherts ($\sim$ silica/detritus > 8) are virtually non-existent, but such beds represent about 30% of strata in the lower and upper calcareous-siliceous members. Assuming that the age of the top and bottom of the clayey-siliceous member are the same at diagenetically altered sections (where no diatom frustules or foraminiferal tests remain) as at diatomaceous localities, detritus influx is as much as four times faster in this member than in the underlying three members. For the Sisquoc, higher abundance of detritus clearly reflects more rapid accumulation of detritus--at least 10-40 times more rapid than in the middle part of the Monterey.

This increase in detritus influx could reflect two factors: sea level lowering (which would cause regression of the shoreline and allow "escape" of terrigenous material trapped nearshore during the earlier sea level rise and high stand) or regional tectonism (which would increase the terrigenous supply due to erosion of uplifted areas). Both factors probably contributed inasmuch as the increase in detrital influx corresponds with a moderately low stand of sea level (Vail and Hardenbol,

1979) and an unconformity in some adjacent areas. Evidence of regional tectonism is most apparent in the Santa Maria basin, where the boundary between the Sisquoc and Monterey is locally marked by an angular unconformity of as much as 40° (Woodring and Bramlette, 1950).

References: Canfield (1939), Woodring and Bramlette (1950), Dibblee (1950, 1966), Isaacs (1983).

o Silica accumulation rates

An interesting complexity in our picture of the Sisquoc is that silica accumulation rates as well as detritus accumulation rates seem to have increased towards the end of Monterey deposition and markedly into the Sisquoc. Silica actually accumulated 3-14 times faster in the Sisquoc than in the middle Miocene part of the Monterey! This relation illustrates clearly that high silica accumulation rates are not sufficient to form a highly siliceous deposit; restriction of detritus influx is equally essential.

References: Ingle (1980), Isaacs (1983).

Stop 9: an excellent exposure of the Sisquoc Formation (c. 5.5-3.5 Ma) when the beach sand is stripped.

o Layering character

Sisquoc strata, although most commonly massive or indistinctly layered, are in many places distinctly laminated. Laminated units generally have a characteristic type of lamination, not present in the Monterey, termed "wide" lamination. It consists of thick (about 1 mm) continuous laminae within broad (about 1 cm) homogeneous bands, characteristics suggesting fluctuating oxygenation of bottom water during deposition. Because benthic assemblages indicate a shallowing of the Sisquoc in this area to water depths of about 700 m (Ingle, 1980, 1981), deposition may have been mainly above the oxygen-minimum zone or near its upper boundary. Note that Sisquoc strata have a grayish cast unlike the Monterey. Organic matter in the Sisquoc is also commonly much lower (1-2%).

References: Ingle, (1980, 1981), Isaacs (1983)

o Shale breccia

As at Goleta Slough, much of the Sisquoc here is highly contorted and brecciated by soft sediment landsliding or slumping. According to Dibblee (1966, p. 51), this shale breccia is as much as 300 feet thick.

Stop 10: on our return after examining the Sisquoc Formation, again at the top (c. 15 Ma) of the lower calcareous-siliceous member.

o Influence of calcite on silica diagenesis

The Naples section illustrates that the presence of calcite per se did not have a marked influence on promoting the formation of opal-CT. Here, over 500 stratigraphic feet below the clayey-siliceous member (where opal-CT has formed in about 50% of beds), are thick sequences of calcareous-diatomaceous rocks in which diatom frustules are well preserved and no opal-CT is present.

Detailed compositional analysis shows that in the vast majority of Monterey rocks, the presence of calcite had no effect on the kinetics of silica diagenesis at all - neither on opal-CT formation nor on quartz formation. This general pattern has, however, two important exceptions which seem to involve only calcareous strata with extremely sparse clay (silica/detritus > 8): (1) early formation of quartz nodules, as we will see at Gaviota and Jalama; and (2) early formation of minor diagenetic quartz in opal-CT cherts, illustrated here, where as much as 6-7% of some opal-CT beds (interbedded with diatomaceous strata) consists of diagenetic quartz. This type of low-temperature quartz formation is important to note when evaluating silica diagenetic grade as its presence is easily misinterpreted as an indication of advanced diagenesis.

References: Isaacs (1980, 1982). See also 1981 Monterey field guidebook p. 33 (figs. 14 and 15).

GAVIOTA BEACH EAST SECTION

Main objectives: (1) to see the lithostratigraphic sequence of the Monterey at the diagenetic grade most typical of onland sections - where silica is diagenetic opal-CT. (2) to examine the depositional features of the upper two members of the Monterey in more detail.

Plan: We will start in the clayey-siliceous member and walk downsection (east) to the upper part of the lower calcareous-siliceous member (figs. 11 and 12).

Stop 1: An excellent exposure of the the clayey-siliceous member (c. 8-5.5 Ma) where silica is opal-CT.

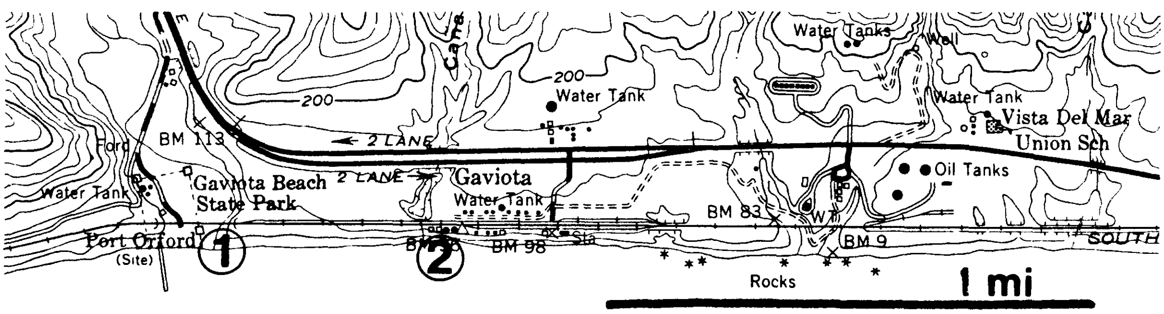

Figure 11. Map showing the location of stops at the Gaviota Beach East section near Gaviota, California. From the Gaviota 7.5 minute quadrangle.

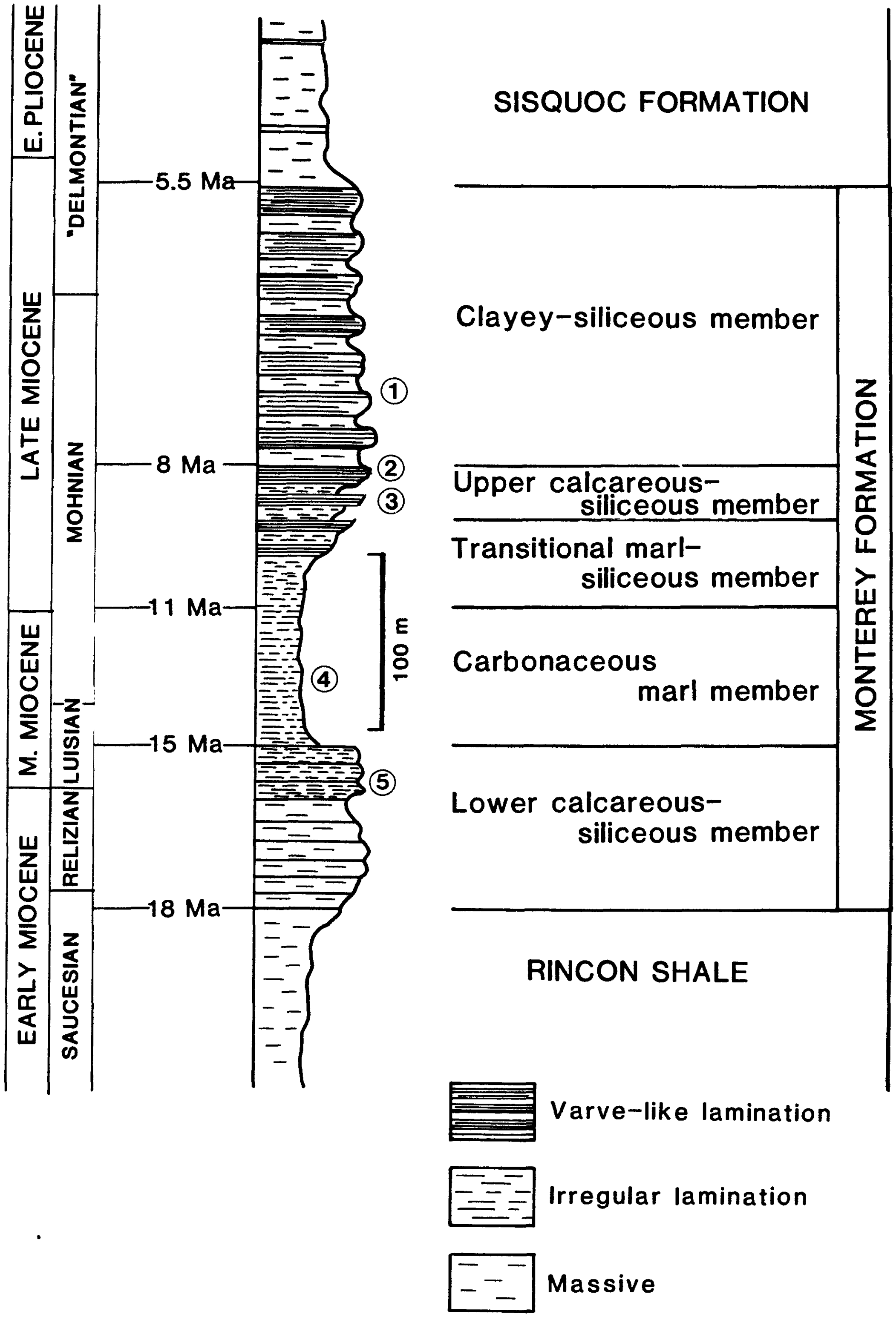

Figure 12. Generalized lithostratigraphic column of the Monterey Formation in the Santa Barbara coastal area (from Isaacs, 1983), showing position of field stops in the Gaviota Beach section.

o Dolostone nodules

Although this member has almost no disseminated carbonate, carbonate is present in discrete dolostone nodules. These nodules most typically occur in clay-rich beds and commonly form stratiform layers, as in this exposure. Isotope data show that dolomite in the Monterey has a complex history and continues to form at various times during diagenesis. Note compactional features around the nodules indicating comparatively early formation of these nodules.

References: On dolomite, Murata and others (1969), Pisciotto (1981c). See also Monterey field guidebook p. 13 (fig. 8).

o Alternation of massive and laminated units

The alternation of laminated porcelanite and massive siliceous mudstone, typical of the clayey-siliceous member, is particularly well exposed at this locality. Porcelanite units are more resistant to erosion, commonly form resistant ledges and prominent dip-slope exposures, have a white weathered surface, and clink when hit with a hammer. Siliceous mudstone units, on the other hand, are recessive, are commonly darker on weathered surfaces, and thud when hit with a hammer. Also note the difference in surface texture - porcelanites resemble a matte photograph, whereas siliceous mudstones are more grainy.

As discussed at Naples, the composition of beds indicates that bottom waters were very low in oxygen (preserving laminations) during the more rapid deposition of beds with abundant silica (porcelanites and cherts) and that bottom waters were aerobic, allowing extensive bioturbation by benthic organisms (resulting in bioturbated or massive sediment), during the slower depositon of beds with low abundance of silica (siliceous mudstones). Note some vague layers and structures in "massive" units.

The cliff exposure here is an excellent place to see the detailed forms of arenaceous foraminifers along bedding planes.

References: Isaacs (1983). See also Monterey field guidebook p. 12 (figs. 5-7) and p. 61 (figs. 11A and 11B).

Stop 2: boundary (c. 8 Ma) between the clayey-siliceous member and the upper calcareous-siliceous member of the Monterey where silica is opal-CT.

o Member boundary

The boundary between the overlying clayey-siliceous member and the underlying upper calcareous-siliceous member is gradational over 5-10 feet. Note a color change in the cliffs here--the weathered surface of the carbonate-free rocks have a pinkish brown cast whereas the underlying strata have a yellowish cast. Calcareous rocks also tend to have smoother edges, pocks on their weathered surfaces, and yellow-pink mottling internally. Also note a prominent limestone/dolostone bed.

References: see Monterey field guidebook p. 61 (fig. 12A).

o Silica phase

Silica in both members exposed here is almost entirely opal-CT. Strata equivalent in age and composition are entirely diatomaceous at Goleta Slough and mixed opal-CT and opal-A at Naples Beach. Note the much greater cohesion and resistance to erosion of strata here but the similarity of layering features.

Reference: see 1981 Monterey field guidebook p. 12 (fig. 5), p. 13 (fig. 9), and p. 61 (figs. 11 and 12A).

Stop 3: an excellent exposure of the upper calcareous-siliceous member (c. 9.5-8 Ma) where silica is opal-CT and carbonate mainly calcite.

o Variations among beds

Compositional differences are easier to recognize here, where silica is diagenetic, than in sections where this member is diatomaceous (Goleta Slough, Naples Beach). Just as in the overlying clayey-siliceous member, clay-poor silica-rich beds are much more resistant to erosion, form ledges, ring when hit with a hammer, and tend to have white weathered surfaces, whereas calcite-rich detritus-rich beds are recessive and thud when hit with a hammer.

Examine here, where strata are opal-CT-bearing, the characteristic style of bedding in the upper calcareous-siliceous member--units 2-3 feet thick grading upward from irregularly laminated beds which are carbonate- and detritus-rich to silica-rich beds having varve-like lamination. We examined these same depositional units at Goleta Slough and Naples, but they are more pronounced here where silica is diagenetic. Incidentally, most of the prominent white bands in these beds are not phosphate but are concentrations of calcareous microfossils, in some beds dolomitized.

References: see Monterey field guidebook p. 62 (fig. 12B).

o Formation of disseminated dolomite

Many individual beds in this member contain disseminated dolomite rather than calcite. Rock types thus include - in addition to calcareous cherts, calcareous porcelanites, and calcareous siliceous shales - dolomitic (or partly dolomitic) equivalents. Dolomitic rock types are quite similar to their calcareous equivalents except in being somewhat more cohesive and resistant to erosion. Dolomitic siliceous rocks also resemble some dolostones in having an orange or ochre color where weathered.

Compared to the origin of dolostones, the origin of disseminated dolomite has been virtually ignored. In the Monterey as a whole, however, the total volume of dolomite disseminated in beds is probably much greater than its volume in discrete dolostones. We will discuss disseminated dolomite further at Damsite Canyon and Jalama Canyon where dolomitic rock types predominate in parts of the section.

Reference: see 1981 Monterey field guidebook p. 46.

Stop 4 an excellent fresh exposure of the carbonaceous marl member (c. 15-11 Ma) where silica is mainly opal-CT.

o Veined quartz chert

Although diagenetic quartz generally formed at lowest temperatures in clay-rich silica-poor beds (a relation we will discuss more at Damsite Canyon), this diagenetic pattern had several exceptions in calcareous strata. One exception, discussed at Naples, was formaton of minor diagenetic quartz in calcareous-siliceous rocks with very sparse detritus (silica/detritus > 8) at about the same time as opal-CT formed.

Another exception was formation of quartz in cherty nodules and veined cherty nodules which are present locally, as at this locality, in opal-CT strata. Judged from compaction around nodules (which we will see more clearly at Black Canyon and Lion's Head), such quartz apparently formed at about the same time as widespread opal-CT (i.e., 45°-55° C). Oxygen isotope ratios determined by Haimson and Knauth (in draft) on such quartz - including this bed - generally confirm a low formation temperature.

References: Isaacs (1982). See also 1981 Monterey field guidebook p. 33 (and fig. 16).

o Layers of concentrated apatite nodules

Similar to layers we examined in the same part of the sequence at Naples Beach, these layers are particularly well exposed in dip-slopes along the beach here.

Take a careful look at the nodule beds and note the cohesion of the blebby phosphatic marls here. In the canyon, where we will go next, the same beds are so friable and weathered that they are easily mistaken for diatomaceous shales.

Reference: see 1981 Monterey field guidebook, p. 47 (fig. 17).

Stop 5: the upper part of the lower calcareous-siliceous member (c. 18-15 Ma), a rare exposure of (friable) sandstone interbedded with calcareous-siliceous rock.

o Interbedded sandstones

In this exposure are a few beds of sandstone, a rock type present in the lower Monterey at only a few localities along the Santa Barbara coast. The sandstone is medium-grained and well sorted, with mainly quartzo-feldspathic grains and some volcanic and metavolcanic rock fragments indicating a mixed plutonic, volcanic, and metamorphic source (Hugh McLean, written communication, 1983).

Note the poor cementation of these sandstone beds; their friability shows clearly that silica does not necessarily migrate extensively and form cement during diagenesis.

Reference: for lower part of the member, see Monterey field guidebook p. 62 (fig. 14).

GAVIOTA CANYON

Main objectives: (1) to examine the same section exposed at Gaviota Beach in weathered outcrops of the adjacent canyon, to gain appreciation of the effects of weathering and to prepare ourselves for sections at Point Conception; and (2) to see the extreme friability of opal-CT-bearing carbonaceous marls where they have been deeply weathered and can be easily mistaken for diatomaceous shales.

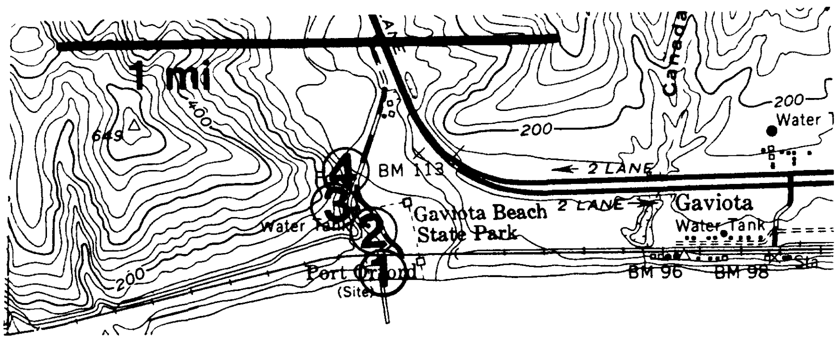

Figure 13. Map showing the location of stops at the Gaviota Canyon section near Gaviota, California. From the Gaviota 7.5 minute quadrangle.

<u>Stop 1</u>: a good exposure of the clayey-siliceous member (c. 8-5.5 Ma) in a weathered roadcut.

o <u>Clayey-siliceous member</u>

Alternations of laminated porcelanite (resistant) units and massive siliceous mudstone (recessive) units are clearly exposed here. The siliceous mudstone is characteristically spheriodally weathered and stained by jarosite (yellow stains) whereas the porcelanite is flaggy, has a white surface, and is stained by limonite (orange).

Reference: see Monterey field guidebook p. 63 (fig. 16B).

o <u>Upper calcareous-siliceous member</u>

Exposed in outcrop underneath the trestle, this member is not prominent in the canyon but can be distinguished (with careful examination) by the presence of moderate calcite and the characteristic yellowish weathered surface and internal mottling of beds.

Take a careful look at the outcrop style of this unimposing member - at the next canyon (Damsite), it will be extremely resistant to erosion and the part of the Monterey most prominently exposed!

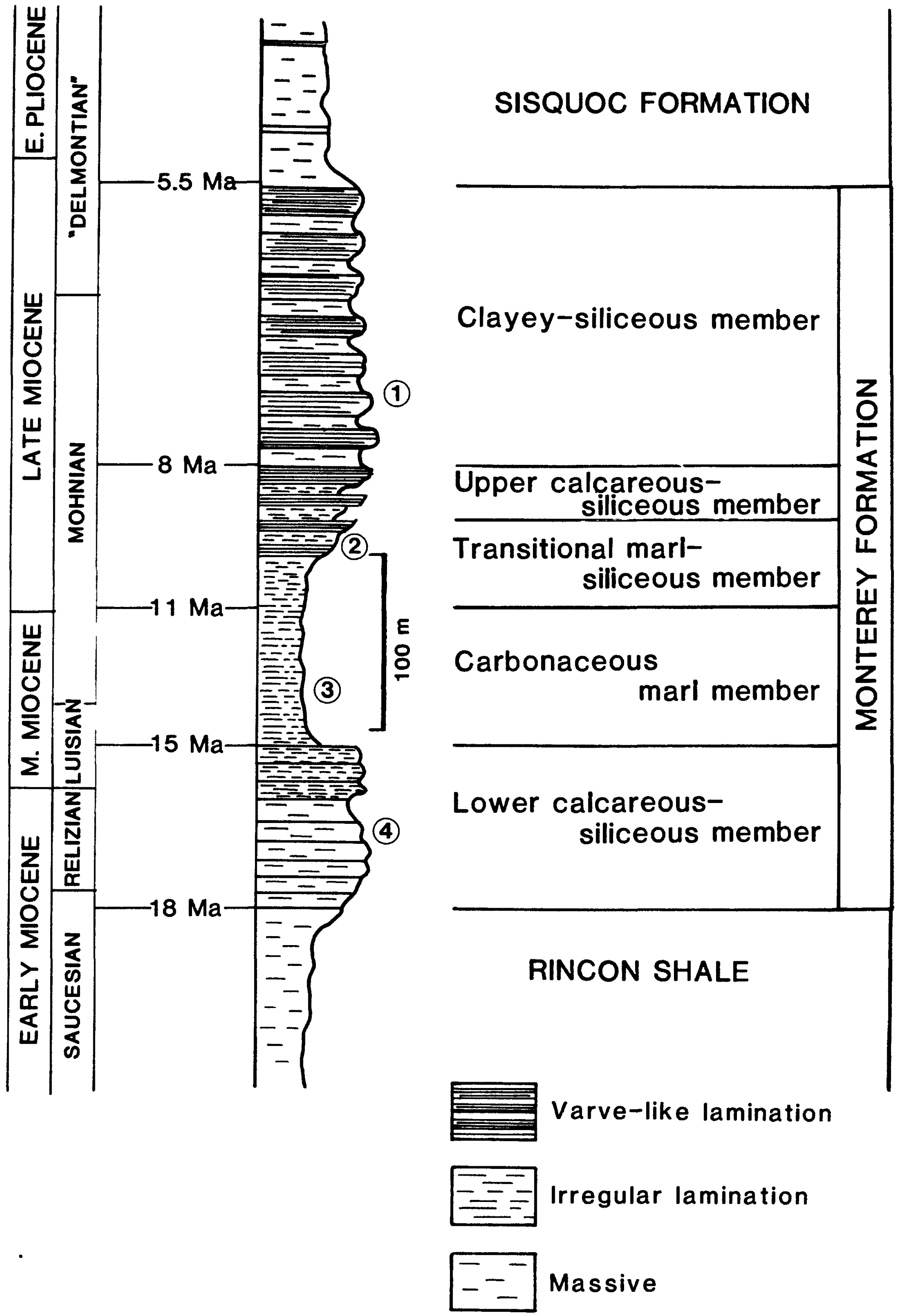

Figure 14. Generalized lithostratigraphic column of the Monterey Formation in the Santa Barbara coastal area (from Isaacs, 1983), showing position of field stops in the Gaviota Canyon section.

Stop 2: a good exposure of the transitional marl-siliceous member (c. 11-9.5 Ma) in a weathered roadcut.

o Transitional marl-siliceous member

Exposed in the roadcut behind the park store, this member has abundant recessive phosphatic marls (here light in color) and more resistant beds of calcareous-siliceous rock. More prominent are several ledges of diagenetic limestone/dolostone. This outcrop is the most complete exposure of this member in canyons along the Santa Barbara coastal area.

Reference: see Monterey field guidebook p. 64 (fig. 17)

Stop 3: a much better-than-average exposure of the carbonaceous marl member (c. 15-11 Ma) in weathered roadcut.

o Carbonaceous marl member

Exposed in roadcut along the Hollister Ranch access road is a remarkably good exposure of this member, complete with 3-6" thick horizons of concentrated apatite nodules, just as we saw on the beach. Note the pale color and friability of the rocks - they crumble easily and seem to totally lack cementation. As discussed at Naples, the reasons these rocks are so friable where weathered are: (1) 25-40% of their solid volume is organic matter, here almost completely leached out; (2) calcite, the dominant component of the beds, has not recrystallized to form a cohesive rock framework and is also partly leached during weathering; and (3) silica, the component of the rock which forms a strong framework in most Monterey rocks, is sparse (5-20%).

The friability of these rocks makes them easily mistaken for diatomaceous shales, but they contain no diatom frustules - silica is mainly opal-CT and in some beds is partly diagenetic quartz! (Moral: beware of published descriptions including zones of diatomaceous shales - they may be weathered marls.)

Reference: see Monterey field guidebook p. 47 (fig. 17) and p. 64 (fig. 18).

Stop 4: a typical exposure of the lower calcareous-siliceous member (c. 18-15 Ma) in weathered outcrop.

o Lower calcareous-siliceous member

The few beds exposed along the creek here show the characteristic thickbeddedness of these calcareous-siliceous rocks. Silica here is mainly opal-CT but in clay-rich rocks is entirely diagenetic quartz.

Reference: see Monterey field guidebook p. 64 (fig. 19).

DAMSITE CANYON

Main objectives: (1) to see that the same lithostratigraphic sequence we examined on the beach at Naples and Gaviota is present in the Point Conception area; (2) to examine the Sisquoc-Monterey boundary in a section where silica is diagenetic; and (3) to examine the diagenetic transitional zone where silica is partly opal-CT and partly quartz.

Plan: we will walk downsection (north) through the Sisquoc Formation to the base of the Monterey Formation.

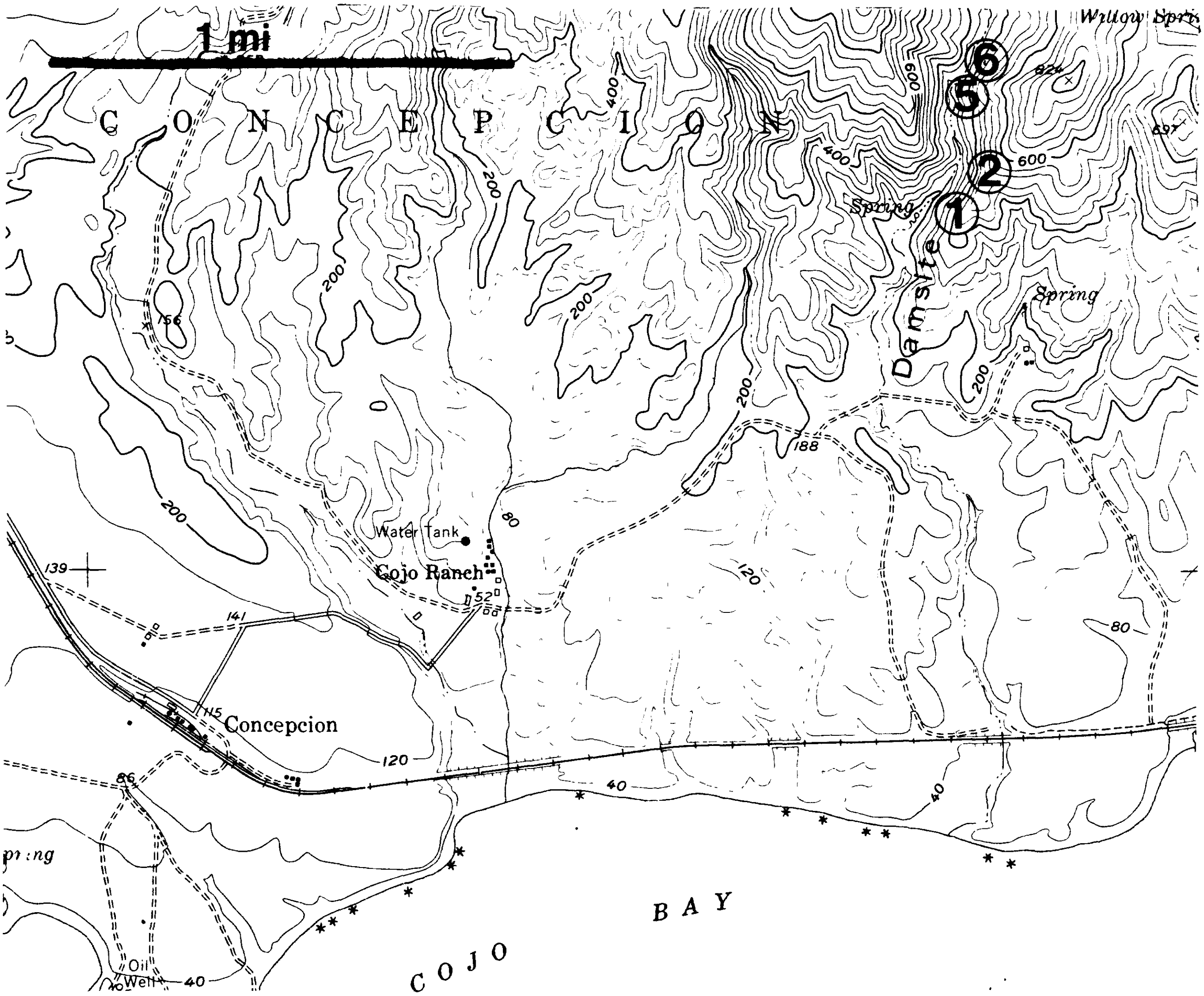

Figure 15. Map showing the location of stops at the Damsite Canyon section near Point Conception, California. From the Point Conception 7.5 minute quadrangle.

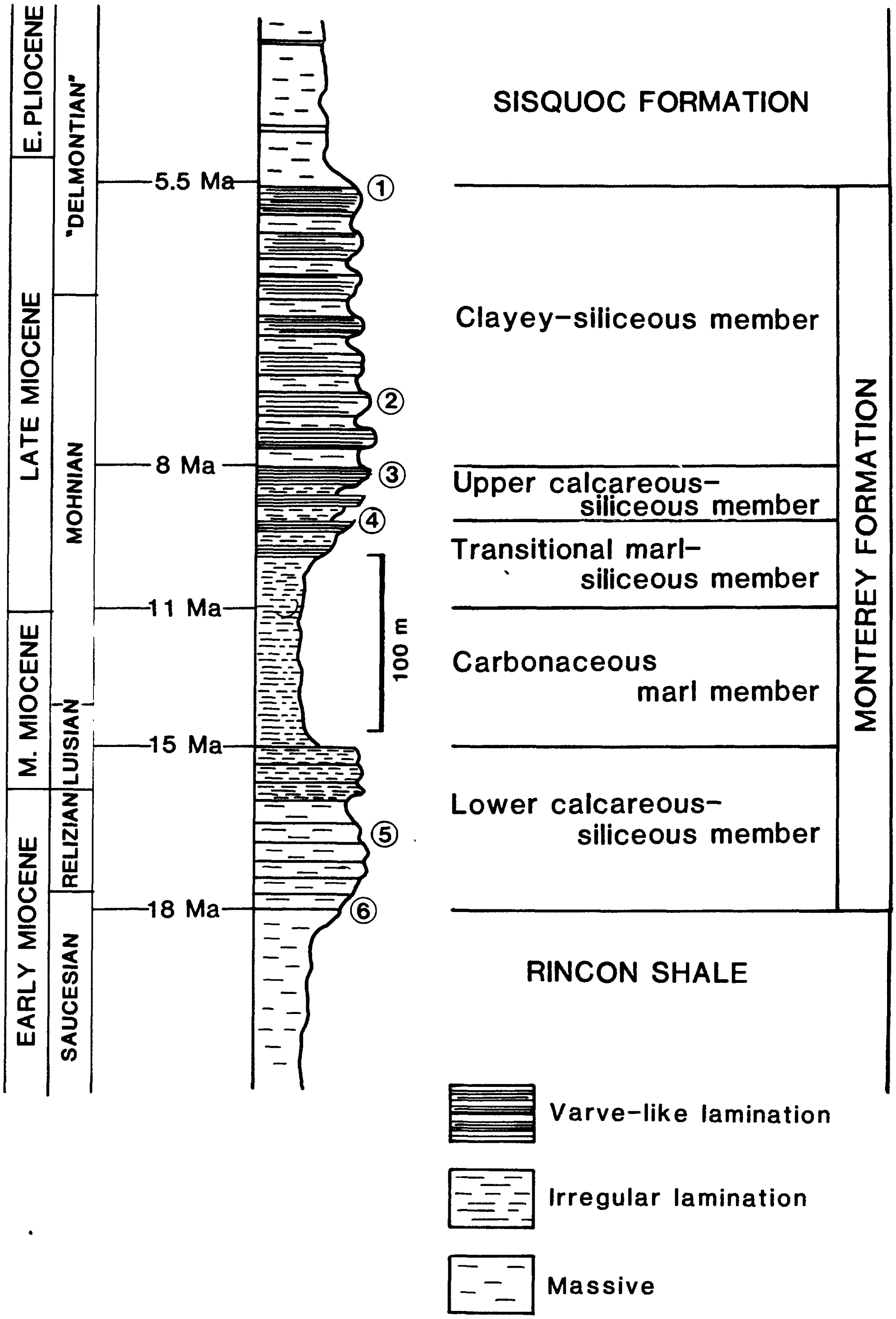

Figure 16. Generalized lithostratigraphic column of the Monterey Formation in the Santa Barbara coastal area (from Isaacs, 1983), showing position of field stops in the Damsite Canyon section.

Stop 1: a good exposure of the Sisquoc-Monterey boundary (c. 5.5 Ma) as exposed in canyons along the coast between Gaviota and Point Conception.

o Sisquoc-Monterey boundary

The terrace at Point Conception, as much as 2 miles wide, is underlain by the Mio-Pliocene Sisquoc Formation. As measured by Bramlette (1946) along the northern side of the point, strata now assigned to the Sisquoc are at least 3300 feet thick and the top of the formation is not even exposed. Because silica in that section is nearly all opal-CT (some beds contain diagenetic quartz and a few beds contain opal-A), its solid thickness (and original thickness) is similar to that of the thick diatomaceous sections in the Santa Maria basin. For example, 5000 feet of diatomaceous strata in the Purisima Hills, assuming an average porosity of 60% (40% solids), translates to 2000 feet of solid material--nearly the same as the solid thickness of 2150 feet at Point Conception, assuming an average 35% porosity (65% solids).

Strata in the Sisquoc Formation, which is not nearly as resistant to erosion as the Monterey, are mainly detritus-rich siliceous shales/mudstones with some interbedded porcelanites. Dolostone concretions are also present.

The contact itself, although described generally as a disconformity in the southwestern Santa Ynez Range (Dibblee, 1950), seems to be gradational at Point Conception, marked by the upward change from a predominance of hard platey porcelanite to a predominance of detritus-rich siliceous shale/mudstone. Whether the formation boundary, as herein lithologically defined, is exactly the same age everywhere could be debated inasmuch as the sparsity of calcareous fossil remains makes microfossil dating almost useless where silica is diagenetic. However, within the limits of diatom zonation, ages are the same at Lompoc (only a few miles distant) as at Goleta, a relation suggesting that the formation boundary does not vary greatly.

References: Bramlette (1946, p. 7 and plate 2; upper strata in the Monterey here subsequently reassigned to the Sisquoc Formation), Dibblee (1950), Isaacs (1980). On age, see Isaacs (1983, p. 129-30). For Sisquoc composition in the onshore Santa Maria basin, see Isaacs and others (1983a, p. 104).

Stop 2: a good canyon exposure of the clayey-siliceous member (8-5.5 Ma) where silica is a mixture of opal-CT and quartz.

o Silica diagenesis

At this locality, the clayey-siliceous member consists of a mixture of beds containing silica mainly as diagenetic opal-CT and beds containing silica mainly as diagenetic quartz. Compositional analysis shows that beds containing silica exclusively as diagenetic quartz are the most detritus-rich rocks and that the percentage of silica which is diagenetic opal-CT is progressively larger in more silica-rich rocks. Rocks with diagenetic quartz here are thus principally the detritus-rich siliceous mudstones, which have grainy textures and do not at all resemble glassy cherts.

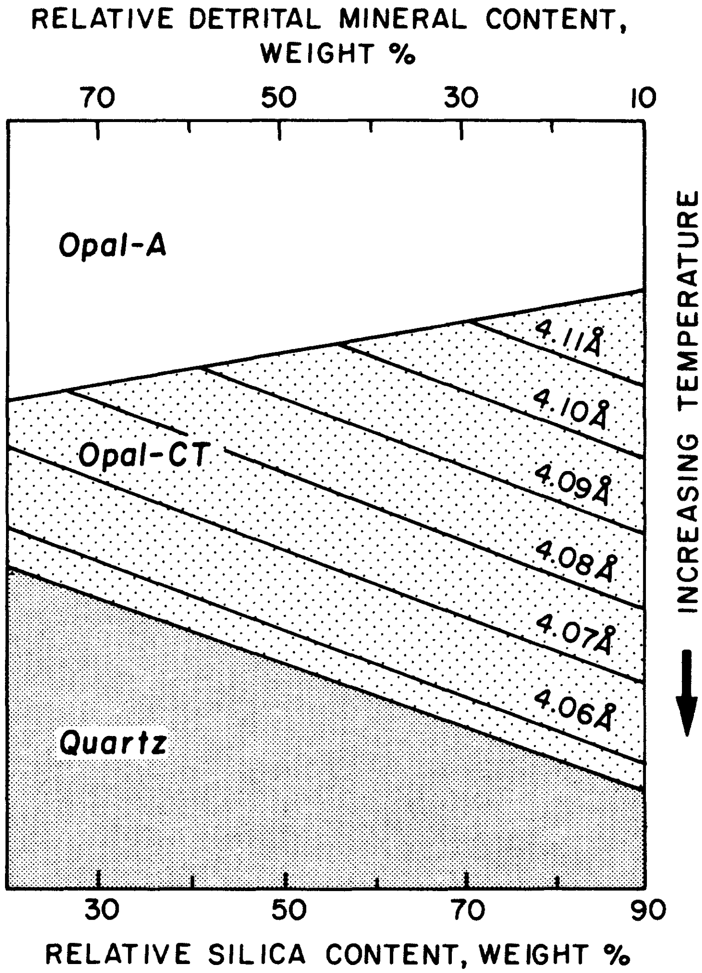

Figure 17. Idealized scheme showing relation between detrital mineral content, kinetics of silica phase transformations, and opal-CT d-spacings as burial temperature and depth increase in the Monterey Formation. Silica and detrital mineral contents are calculated as a percent of the sum of silica + detrital minerals. From Isaacs and others (1983b).

The relation between detritus content and temperature of diagenetic quartz formation is not fully explained by current experimental geochemical models, but empirical relations suggest that the kinetics are determined by the character of the opal-CT when first formed. Opal-CT d-spacings, which seem to reflect the proportion of cristobalite and tridymite layers, are initially higher (have more tridymite layers) in silica-rich clay-poor rocks than in clay-rich silica-poor rocks. Assuming that a specific d-spacing is required before diagenetic quartz can form, as suggested by Murata and Larson (1975), this d-spacing was achieved - and hence diagenetic quartz formed - at lower temperatures in detritus-rich rocks than in interbedded silica-rich rocks.

The mechanism of the silica phase transformation from opal-CT to quartz was widely regarded as a solid-solid reaction a decade ago, but more recent studies have shown that it is actually a solution-precipitation process. Murata and Larson (1975) and Murata and others (1977) showed, for example, that oxygen isotope ratios in silica change abruptly across the transition from opal-CT to quartz rocks, a relation indicating re-equilibration of the silica with pore waters. Porosity reduction (see below) also indicates solution and/or precipitation. Compositional analysis laterally across the transitional zone here in the Point Conception area has ruled out systematic silica transfer (for example, from siliceous mudstones as silica-donor beds to cherts as silica-receiver beds) as a volumetrically significant process. Nearly in situ solution-precipitation seems to be the predominant mechanism of the phase transformation.

References: Isaacs (1982). See also Monterey field guidebook p. 32 (fig. 12B), p. 32-35, and p. 66 (fig. 21).

o Porosity reduction

Differences in silica diagenesis among individual beds show that porosity reduction directly resulted from quartz formation. For example, siliceous mudstones at Gaviota Beach, where silica is still opal-CT, have dry bulk densities in the range 1.5-1.6 g/cm^3 (porosities in the range 30-35%). At Damsite Canyon, compositionally equivalent beds with silica entirely diagenetic quartz have dry bulk densities in the range 1.9-2.0 g/cm^3 (porosities in the range 18-22%). Interbedded strata here which still contain silica mainly as opal-CT also still retain comparatively low bulk densities (as low as 1.5 g/cm^3). The increase in bulk density is thus directly associated with the formation of diagenetic quartz rather than with a general increase in burial depth.

The mechanism of porosity reduction during the opal-CT to quartz transformation is not as easy to decipher as the mechanism during the opal-A to opal-CT transformation because volume reduction is much smaller (70% solid to 85-90% solid). Note that a solid-solid silica phase transformation (without compaction or addition of silica) would leave dry bulk densities the same and increase porosities, inasmuch as quartz is denser (at 2.65 g/cm^3) than opal-CT (at 2.30 g/cm^3). Judged from the fact that opal-CT completely dissolved without appreciable silica transfer, compaction (possibly due to weakening of the rock structure during dissolution) is concluded to be the principle mechanism of porosity reduction.

References: Murata and Larson (1975), Isaacs (1981).

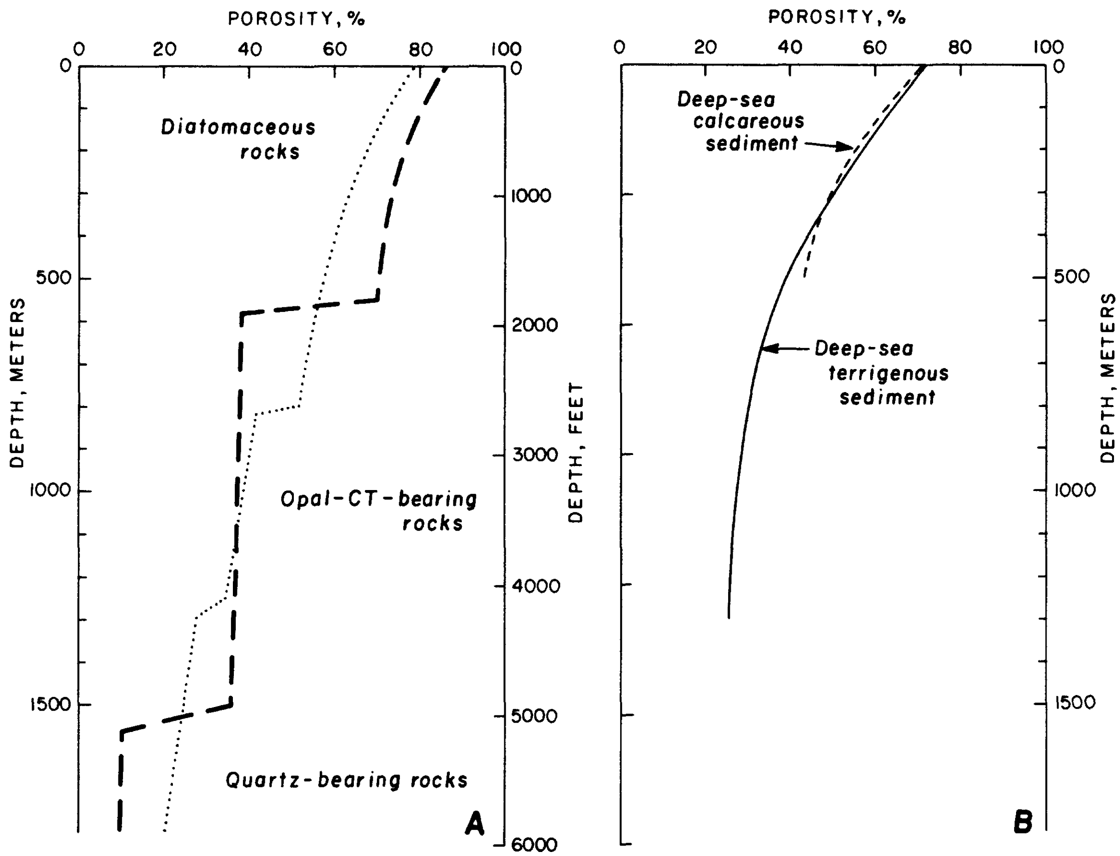

Figure 18. (A) Pattern of porosity reduction for highly diatomaceous rocks and their diagenetic equivalents (dashed line), showing two abrupt reduction steps corresponding to the two silica phase transformations (after Isaacs, 1981). The dotted line shows the pattern for sparsely siliceous calcareous rocks of the Monterey Formation. Depths are illustrative only. (b) Patterns of porosity reduction for terrigenous and calcareous deep-sea sediments (from Hamilton, 1976). From Isaacs and others (1983b).

Stop 3: a good canyon exposure of the upper part of the upper calcareous-siliceous member (9.5-8 Ma) where silica is a mixture of opal-CT and quartz.

o Outcrop character

This part of the section is equivalent (in age, layering, composition, etc.) to the unimposing rocks exposed under the railroad trestle in Gaviota and to the calcareous diatomaceous rocks at Goleta Slough. Note its extreme resistance to erosion and outcrop prominence. In all canyons between Cojo Canyon (about 1/2 mile to the east) and Gaviota Canyon, this part of the section is no more prominent than at Gaviota, but it forms highly resistant cliffs at Cojo Canyon and Jalama Canyon (where disseminated dolomite is widespread) and several other canyons in the area.

Reference: see 1981 Monterey field guidebook p. 67 (fig. 23A).

o Thick glassy quartz chert

A bed of black glassy chert 2-3 feet thick is prominently exposed here. Around this bed, which is extremely resistant to erosion and somewhat irregular in shape, siliceous shales show differential compaction indicating comparatively low temperature.

Similar beds can be seen in the carbonate-bearing part of the sequence where silica is diagenetic opal-CT (Agujas, San Augustine, and Bulito Canyons between Gaviota and Point Conception; Jalama Canyon; Point Pedernales Beach) and where silica is diagenetic quartz (Lion's Head Beach). The distribution of these beds is not systematic (e.g., they do not consistently increase in abundance with increasing silica diagenetic grade), and the conditions leading to their formation are so far a mystery. Note that their black color does not result from an abundance of organic matter; organic matter in such beds is generally less than 1%. The black color apparently results from the presence of organic matter in a translucent matrix.

Reference: Isaacs (1980, 1982). See also Monterey field guidebook p. 67 (fig. 23B).; on color, p. 48.

o Rock types

Strata adjacent to the thick chert bed, which are less weathered and better exposed in the creek bed, all contain dolomite. Rock types here thus include dolomitic cherty porcelanite, dolomitic porcelanite, and dolomitic siliceous shale as well as dolostone.

Distribution of dolomitic strata indicates that the formation of disseminated dolomite is not simply related to increased temperature as inferred from silica diagenesis. For example, in Wood Canyon to the west, where silica diagenetic grade is slightly greater than at Damsite Canyon, stratigraphically equivalent strata are mainly calcareous. In Jalama Canyon to the north where silica diagenetic grade is less even than at Gaviota Beach, stratigraphically equivalent strata are entirely dolomitic.

Like the overlying clayey-siliceous member, this member consists of a mixture of rocks containing silica mainly as opal-CT and rocks containing silica mainly as diagenetic quartz. The quartz-bearing rocks are the siliceous shales, here dolomitic.

Reference: Isaacs, 1980. See also Monterey field guidebook p. 68 (fig. 23C).

Stop 4: a rare canyon exposure of the base (c. 9.5 Ma) of the upper calcareous-siliceous member, where silica is a mixture of opal-CT and quartz.

o Rock types

Here carbonate is mainly calcite, although some rocks contain a mixture of calcite and dolomite. Bedding is characteristic of this member, with units of irregularly laminated moderately siliceous rock several feet thick grading upward into units of finely laminated silica-rich rock several feet thick. Recall the same depositional units as we saw them at Goleta Slough where all strata were diatomaceous and comparatively similar. Note the grainy surface texture of the calcareous siliceous shales which are the quartz-bearing beds.

Reference: see Monterey field guidebook p. 14 (fig. 10), p. 15 (fig. 13).

o Member boundary

Although rocks are extremely weathered in this roadcut, the base of the member is well defined. Downward is an increasing abundance of calcareous-dolomitic siliceous shales and silica-poor phosphatic marls. Note the friability of the phosphatic rocks - most of these beds contain silica exclusively as diagenetic quartz!

Reference: see Monterey field guidebook p. 15 (fig. 14) for representative section of member boundary.

o Phosphatic marls

The carbonaceous marl member (c. 15-11 Ma) is not exposed along the road but fresh rock is present at several places along the creek. Silica in these marls is diagenetic quartz, and dry bulk densities here and in Wood Canyon to the west (where the member is well exposed) are in the range 1.75-2.0 g/cm^3.

Incidentally, because of the abundance of organic matter (which has a specific gravity of about 1.0 g/cm^3), grain densities of these rocks are as low as 2.36 g/cm^3 despite the predominance of quartz (at 2.65 g/cm^3), calcite (at 2.72 g/cm^3), and apatite (at about 3.1 g/cm^3). Porosities calculated from well logs assuming a standard grain density of 2.65-2.72 g/cm^3 are thus overestimated by as much as 10-11 porosity %.

References: Isaacs (1980; 1981, p 260).

Stop 5: a typical canyon exposure of the lower calcareous-siliceous member (c. 18-15 Ma), where silica is a mixture of opal-CT and quartz.

o Rock types

In this part of the section, calcareous-siliceous rocks predominate, just as in age-equivalent strata farther east. Note that most rocks are vaguely laminated but that varve-like laminae are not evident.

Also note here an unusual bed composed mainly of large calcareous foraminifers and phosphatic ooids. This is the last exposure of the lower part of the Monterey that we will see as this lower part of the Monterey is faulted out at Black Canyon.

Silica in the lower calcareous-siliceous member here is both diagenetic opal-CT and diagenetic quartz. Opal-CT predominates only in the most silica-rich rocks, and some diagenetic quartz is present in all beds. In Wood Canyon (to the west), where this member is well exposed along the creek, silica in this member is entirely diagenetic quartz.

Reference: 1981 Monterey field guidebook p. 19 (fig. 20), p. 69 (fig. 24).

Stop 6: a poor roadcut exposure of the tuff/tuffaceous rock at the base (c. 18 Ma) of the Monterey.

o Base of the Monterey

Poorly exposed along the road (better exposed in the creek) is an altered volcanic tuff/tuffaceous sedimentary rock which marks the base of the Monterey. In the Point Conception area this basal bed is as much as 75 feet thick (as at Wood Canyon) and is generally altered to clinoptilolite.

Reference: Dibblee (1950), Isaacs (1980).

BLACK CANYON

Main objectives: (1) to see the upper two members of the Monterey where silica is entirely diagenetic quartz; (2) to examine lensoid quartz nodules well exposed in calcareous strata.

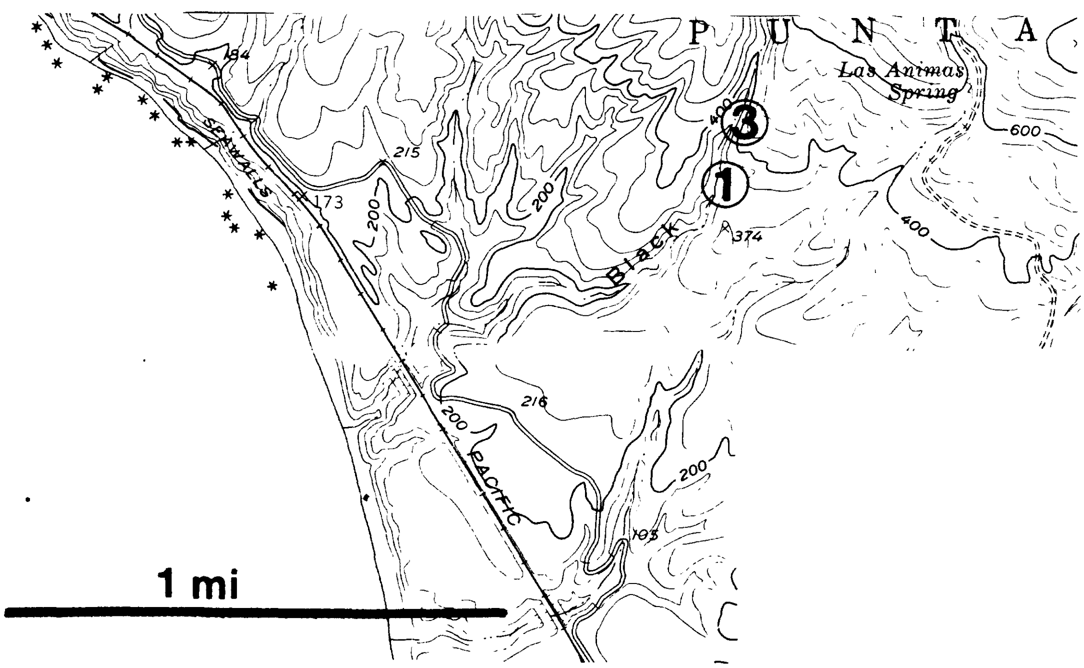

Figure 19. Map showing the location of stops at the Black Canyon section near Point Conception, California. From the Point Conception 7.5 minute quadrangle.

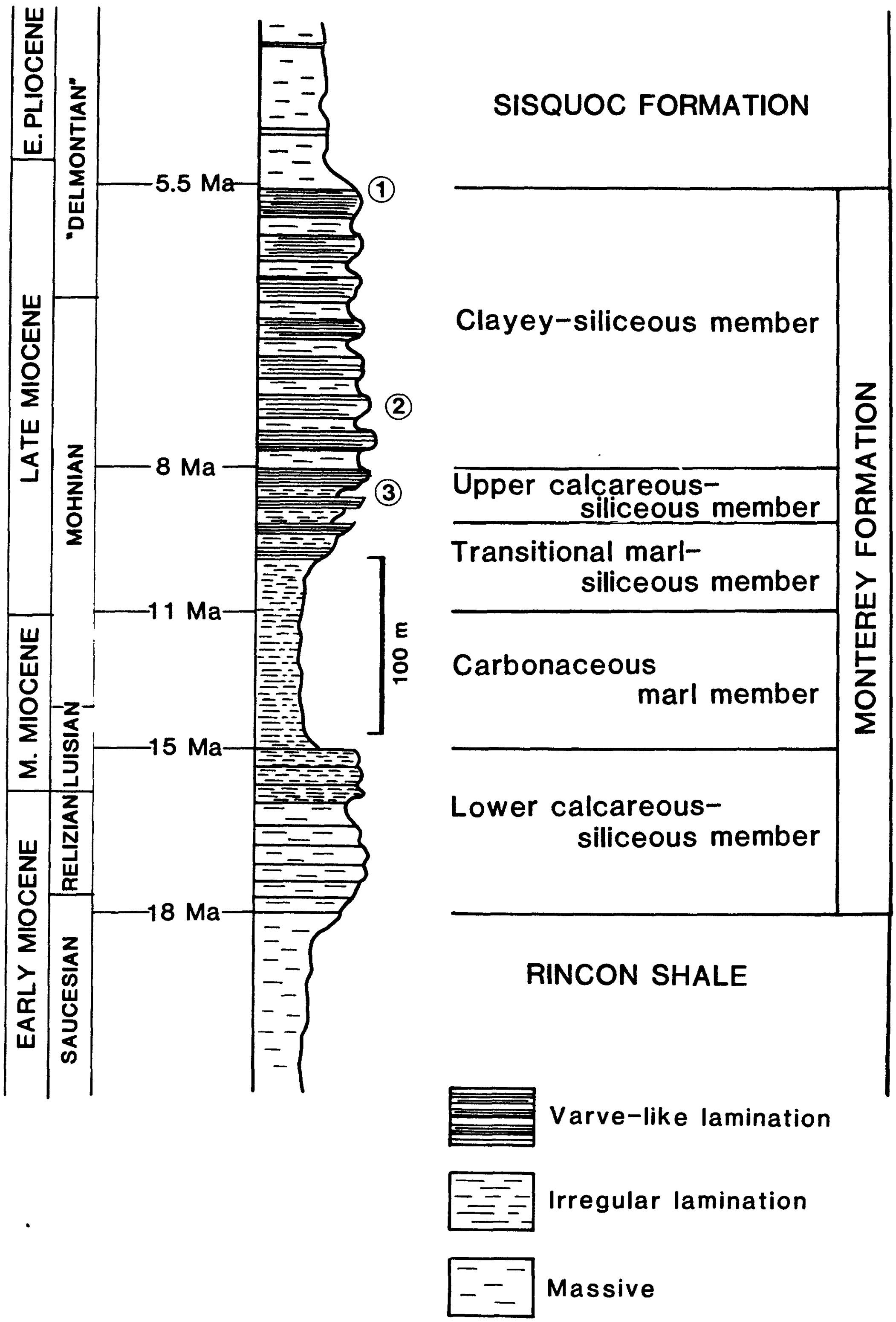

Figure 20. Generalized lithostratigraphic column of the Monterey Formation in the Santa Barbara coastal area (from Isaacs, 1983), showing position of field stops in the Black Canyon section.

Plan: we will walk along a crude roadcut downsection (north) through the Monterey-Sisquoc boundary into the upper calcareous-siliceous member.

Stop 1: a good exposure of the Sisquoc-Monterey boundary (c. 5.5 Ma) where it is clearly gradational and silica is almost entirely quartz.

o Sisquoc-Monterey boundary

The boundary between the Sisquoc and Monterey Formations, a gradational contact here, is defined by the predominance of siliceous mudstone and siliceous shale units in the Sisquoc.

Note that all strata are quartzose - no diagenetic opal-CT remains. As we walk through the section, note the similarities between these rocks and the opal-CT rocks in the same part of the sequence at Gaviota and Damsite: flagginess, matte surface texture, brown color, white weathering, etc. For those of you who have not seen the thick section of quartzose rocks at Chico Martinez Creek in the San Joaquin Valley, these rocks are extremely similar.

Stop 2: the best canyon exposure of the clayey-siliceous member (c. 8-5.5 Ma) where silica is quartz.

o Quartzose rocks types

All the rocks at this unimposing outcrop are quartzose, despite the fact that almost none of the beds is glassy. Note the variety of rock types - quartzose siliceous mudstone, quartzose porcelanite, and quartzose chert - and their similarity to opal-CT rock types. In fact, it is impossible to tell that the silica here is quartz without X-ray diffraction. Two clues can help: these rocks are much more cohesive than opal-CT rocks, and they are much denser. Note that the infamous tongue test (which identifies opal-CT rocks by their adherence to the tongue when licked) is not entirely reliable - many of these rocks where weathered adhere somewhat to the tongue.

Reference: see 1981 Monterey field guidebook p. 42 (table 1) and p. 69 (fig. 26).

o Porosity reduction

Rocks in this part of the sequence have dry bulk densities in the range 1.9-2.5 g/cm^3 (and porosities in the range 1-20%). Density tends to be higher (and porosity lower) in quartzose rocks with less detritus and more silica. In Quail Canyon, less than a mile to the east, dry bulk densities in this part of the section are as low as 1.5 g/cm^3 in silica-rich rocks, which still have abundant opal-CT; compositionally equivalent strata here have densities of 2.2-2.5 g/cm^3, quite a major increase for only a few degrees of temperature.

The close association between porosity reduction and quartz formation shows that the mechanism of the phase transformation involves solution. As discussed at Damsite Canyon, this same conclusion is also drawn from the abrupt change in oxygen isotope ratios of the silica across the diagenetic boundary, a change which shows that the silica re-equilibrated with pore waters during formation of quartz (Murata and Larson, 1975; Murata and others, 1977). Note here textural features, lateral continuity of beds, low matrix permeabilities (<0.01 md), and absence of veining which all indicate little movement of silica between beds. Quartz is concluded to form generally by an almost in situ solution-precipitation process.

Reference: Murata and Larson (1975), Isaacs (1981).

Stop 3: the best canyon exposure of the lower part of the upper calcareous-siliceous member (9.5-8 Ma) where silica is quartz.

o Rock types

These rocks are all quartzose but also contain moderate amounts of calcite, as in stratigraphically equivalent parts of the sequence elsewhere. Rock types thus include calcareous chert, calcareous porcelanite, and calcareous siliceous shale--as well as some dolostone beds.

Note the greater cohesion and density of these rocks compared to equivalent opal-CT rocks.

Reference: Monterey field guidebook p. 70 (fig. 27B).

o Oxygen isotopes of calcite

Just as unstudied as the formation of disseminated dolomite in the Monterey is the recrystallization of calcite in typical marls and calcareous-siliceous rocks. As shown by Scholle (1977), the low-magnesium calcite in chalks generally recrystallizes with increasing burial as a result of overburden stress (not primarily as a function of temperature). Incremental changes in oxygen isotope ratios result from this partial recrystallization.

A preliminary analysis of patterns of oxygen isotopes in marls and calcareous-siliceous rocks showed rather complex results. One interesting pattern emerged, however: oxygen in calcite is somewhat lighter in diatomaceous rocks ($\delta^{18}O$ =+0.1 to +1.1) than in opal-CT rocks ($\delta^{18}O$= -0.7 to +0.2) but is markedly lighter ($\delta^{18}O$= -5.2 to 0.0) in some quartz-bearing rocks. This relation possibly suggests that compaction caused only a little recrystallization of calcite during formation of the relatively porous opal-CT framework but that restructuring of the rock during quartz formation caused extensive recrystallization.

o Quartz chert nodules

In a few layers of clay-poor calcareous-siliceous rock are black cherty nodules composed almost entirely of diagenetic quartz. These nodules provide the clearest field evidence of the early formation of quartz chert in that surrounding rock has compacted around the nodules. Measurements show that the surrounding rock had about 50-55% porosity at the time the nodules formed, a porosity indicating that silica was diatomaceous or transforming to opal-CT.

Reference: Isaacs (1980, 1982).

JALAMA CANYON

Main objectives: (1) to see "atyical" quartz cherts in an opal-CT section; (2) to examine strata where all carbonate is dolomite (mainly disseminated dolomite); and (3) to examine the Sisquoc-Monterey boundary where well exposed in the road.

Plan: we will walk through part of the upper calcareous-siliceous member, then walk upsection (west) to the Monterey-Sisquoc boundary on the beach side of the ridge crest.

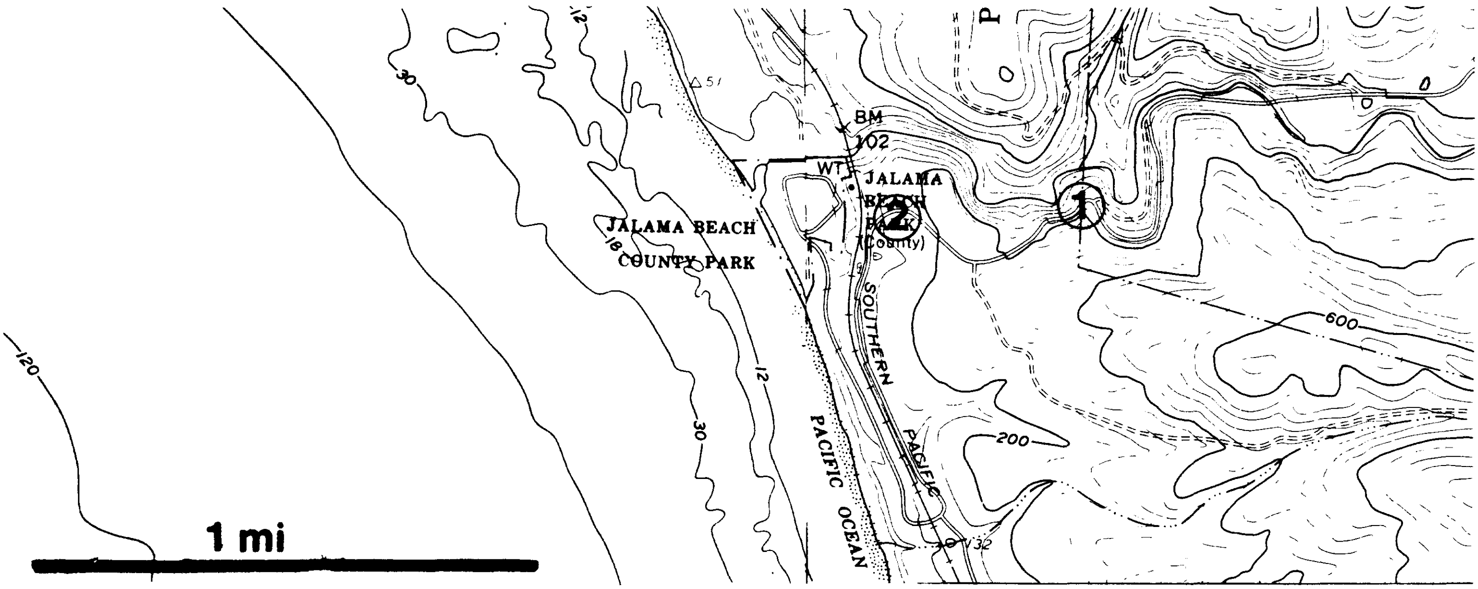

Figure 21. Map showing the location of stops at Jalama Canyon near Jalama Beach, California. From the Lompoc Hills 7.5 minute quadrangle.

Stop 1: the most accessible exposure of the upper calcareous-siliceous member (c. 9.5-8 Ma) where carbonate is entirely dolomite and silica is opal-CT.

o Thick quartz chert

This bed, which is much folded, is mainly diagenetic quartz with some lighter-colored bands mainly opal-CT. Sparse (1-2%) calcite or dolomite is present in some of these types of beds, but ghosts of foraminifers indicate that the cherts formed by wholesale replacement of the pre-existing bed.

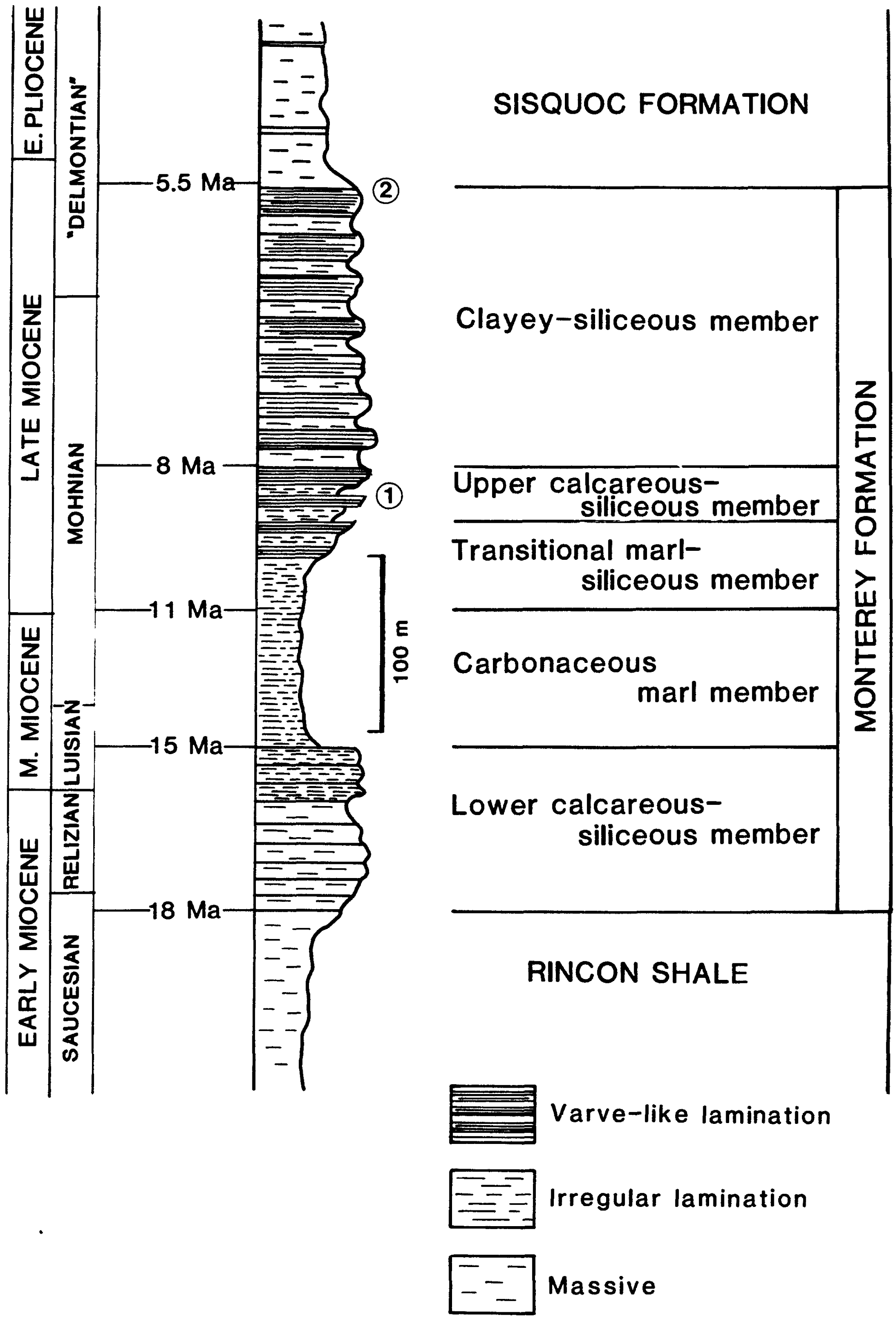

Figure 22. Generalized lithostratigraphic column of the Monterey Formation in the Santa Barbara coastal area (from Isaacs, 1983), showing position of field stops in the Jalama Canyon section.

The presence of this quartz chert in an opal-CT section (in which opal-CT is, incidentally, comparatively "disordered") demonstrates that such quartz did form at a relatively low temperature compared to typical quartz. Oxygen isotope ratios of the silica (Haimson and Knauth, in draft), confirm a comparatively low temperature for formation of quartz in these beds.

References: Murata and others (1977), Isaacs (1982). See also Monterey field guidebook p. 32-3 (and fig. 16), p. 65 (fig. 20B).

o Rock types

As in other exposures of this member, rocks here tend to occur in grading upward sequences which here resemble alternating units, 1 to 3 feet thick, of porcelanite/cherty porcelanite and siliceous shale/mudstone. The porcelanite/cherty porcelanite units are commonly well laminated and have a light-colored weathered surface with limonite stains, whereas the siliceous shale/mudstone units are much less distinctly laminated and have a yellow or gold color.

Both rock types are dolomitic (containing 10-40% disseminated dolomite), and the thick siliceous mudstone/shale units are easily mistaken for dolostones because of their color, cohesiveness, and thick-beddedness. Nearly all rocks, however, contain abundant opal-CT.

Reference: see Monterey field guidebook p. 65 (fig. 20A).

o Other varieties of atypical quartz cherts

Also present here is a bed of opal-CT cherty porcelanite with a veined quartz chert core and a number of cherty (quartzose) nodules. Note that these quartz cherts all formed in detritus-poor carbonate-bearing rocks, an association also true of disseminated diagenetic quartz formed at low temperatures (at about the same time as widespread opal-CT), as discussed at Naples. Comparatively low temperature formation of quartz has been widely recognized in clay-poor calcareous rocks and may result from the combination of low silica solubility at low temperature and alkalinity produced by calcite (Kastner and others, 1977).

Reference: Isaacs (1980, 1982).

Stop 2: a good roadcut exposure of the Sisquoc-Monterey boundary where silica is opal-CT.

o Monterey-Sisquoc boundary

The Monterey-Sisquoc boundary is here placed at the top of the platey white-weathering porcelanites. Sisquoc strata are detritus-rich siliceous shales/mudstones which here have a pencilly or splinterey weathering pattern very characteristic of weathered outcrops.

References: Dibblee (1950). See also Monterey field guidebook p. 11 (fig. 4 top).

JALAMA BEACH

Near the county park both to the north and south is one of the most accessible exposures of the Sisquoc Formation where silica is opal-CT. Exposures to the south continue for several miles, nearly to Point Conception. Note particularly:

- o Dolomite concretions (more resistant gold or orange beds).
- o Striking examples of soft sediment deformation in laminated horizons (when sand conditions are right).
- o Typically wide laminae or banding in laminated units.
- o Gray color of fresh strata.

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PART 11

COMMENTS ON
THE LITHOSTRATIGRAPHY OF THE MONTEREY FORMATION,
SANTA MARIA AREA

INTRODUCTION

In contrast to the Santa Ynez Mountains, where the Monterey Formation lies within a thick sequence of Cretaceous to Pliocene sedimentary strata, in the Santa Maria basin Neogene strata generally lie on Franciscan or Cretaceous basement. Considerable controversy surrounds the structure in this area, at the juncture of the Transverse Ranges and Coast Ranges. A major structural break is generally accepted, with 90°-120° clockwise rotation of the Transverse Ranges advocated by Luyendyk and others (1980) and the formation of a pull-apart basin along a transform fault (figs. 1 and 2) advocated by Hall (1981). The stratigraphic column in the southern Santa Maria basin (fig. 3) and cross-sections across the Santa Ynez Mountains north from Point Conception and Point Arguello (fig. 4) illustrate the different pre-Monterey sequences in the two areas.

Earliest Tertiary rocks in the Santa Maria basin, only locally present, are nonmarine sandstones of the Lospe Formation, of early Miocene or older age (Woodring and others, 1943; Dibblee, 1950; Woodring and Bramlette, 1950). The Point Sal Formation marks the first recorded marine incursion into the area at the time of the Relizian benthic foraminiferal stage, during late early Miocene time. The Point Sal Formation - also known as the siltstone and shell zone of the Monterey Formation - is evidently mainly shale or mudstone (with moderate biogenic silica and calcite) interbedded with siltstones and sandstones. It is age-equivalent with the lower part of the Monterey (lower calcareous-siliceous member) in the Santa Barbara coastal area. The Monterey itself, locally with a sandy zone near the base (the "oil sand zone" of Canfield, 1939), has been divided by various schemes into members and zones which generally correlate lithologically with divisions of the Monterey in the Santa Barbara coastal area (fig. 5).

A major difference between the Monterey in the two areas is detritus abundance in the lower parts. Preliminary evaluation of cores from the Union Newlove 51 well in the Orcutt Field suggests nearly twice as abundant detritus there as in the Santa Barbara coastal area well into upper Miocene strata (Isaacs and others, 1983). The evident nearness of land to lower Monterey deposition in the Santa Maria area explains its richness in detritus. Somewhat in contrast is the lower Monterey in the Tranquillon Mountain area where it is reported by Dibblee (1950) as generally comprising cherty shale difficult to distinguish from the upper Monterey.

We will have time to examine only a few parts of the Monterey north of Point Conception. At Point Pedernales we will see the base of the Monterey where it interfingers with the Tranquillon Volcanics, and at Lion's Head we will see the age-equivalent of the middle part of the Santa Barbara coastal Monterey (here termed the lower and middle member of the Monterey by Woodring and Bramlette, 1950).

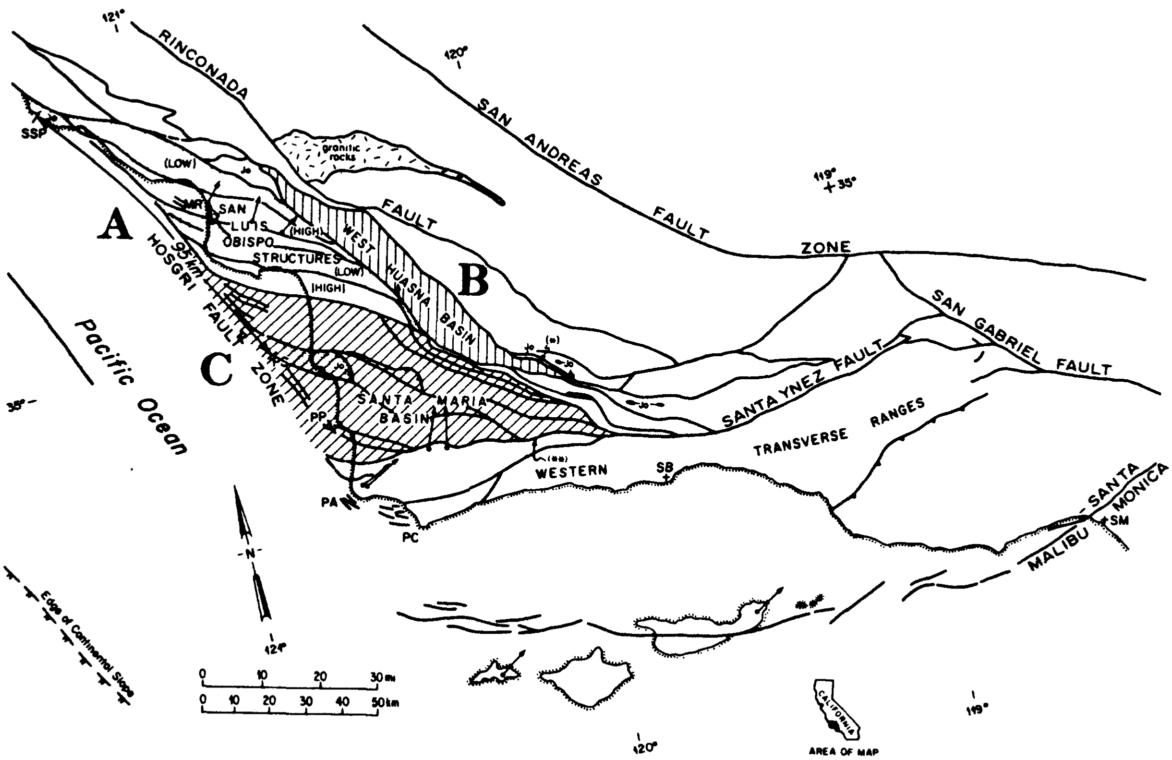

Figure 1. Generalized geologic map of the southwestern part of the Coast Ranges and the western part of the Transverse Ranges, California, depicting three structural regions: (a) San Luis Obispo structures (stippled pattern and intervening blank area), consisting of horst-graben-like pull-apart structures between faults. (b) West Huasna basin (depicted by vertically ruled pattern), a pull-apart structure. (c) Santa Maria basin (diagonally ruled pattern). The distance between the midpoints of stratigraphic sequences near San Simeon Point (SSP) and Point Sal (PS) is 95 km. Abbreviations are Morro Rock (MR), Purisima Point (PP), Point Arguello (PA), Point Conception (PC), Santa Barbara (SB), and Santa Monica (SM). Jurassic ophiolite is Jo. A, B, and C refer to the accompanying diagrams in figure 2. Paleomagnetic declination vectors (arrows) are from Luyendyk and others (1980). The double asterisk shows the approximate location of clasts of coarse crystalline gabbro, with anorthite altered to prehnite, in the Sespe Formation. These clasts are identical in lithology to a gabbro facies in Jurassic ophiolite at the single asterisk to the north. From Hall (1981, p. 1026).

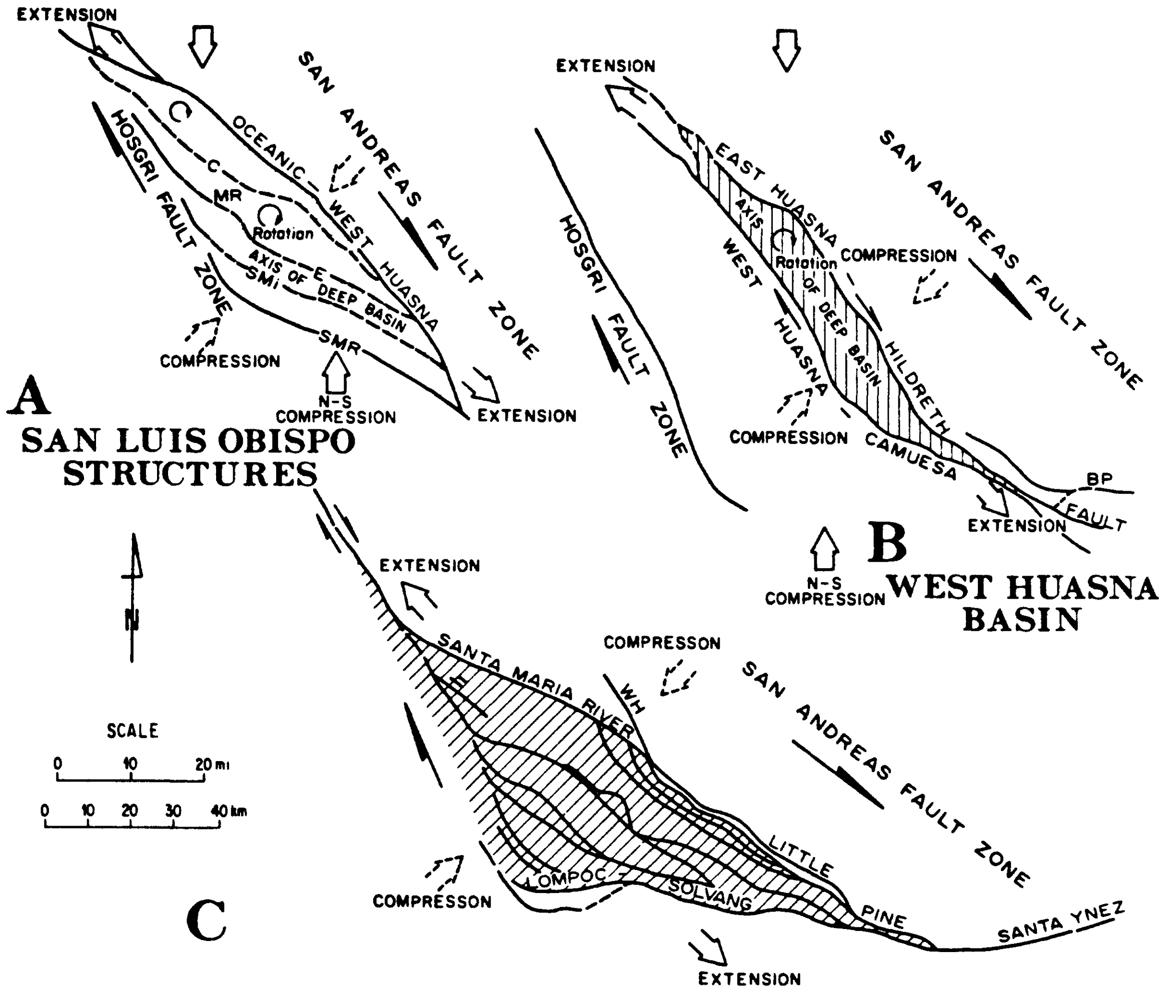

Figure 2. Sketch maps to accompany Figure 1, showing models for the development of pull-apart structures with attendant extension and rotation within the structures. Abbreviations are Morro Rock (MR), Oceanic (O), Cambria (C), West Huasna (WH), San Miguelito (SMi), Santa Maria River (SMR), Big Pine (BP), Little Pine (LP), and Santa Ynez (SY) faults and Edna and Los Osos fault zone (E). From Hall (1981, p. 1028).

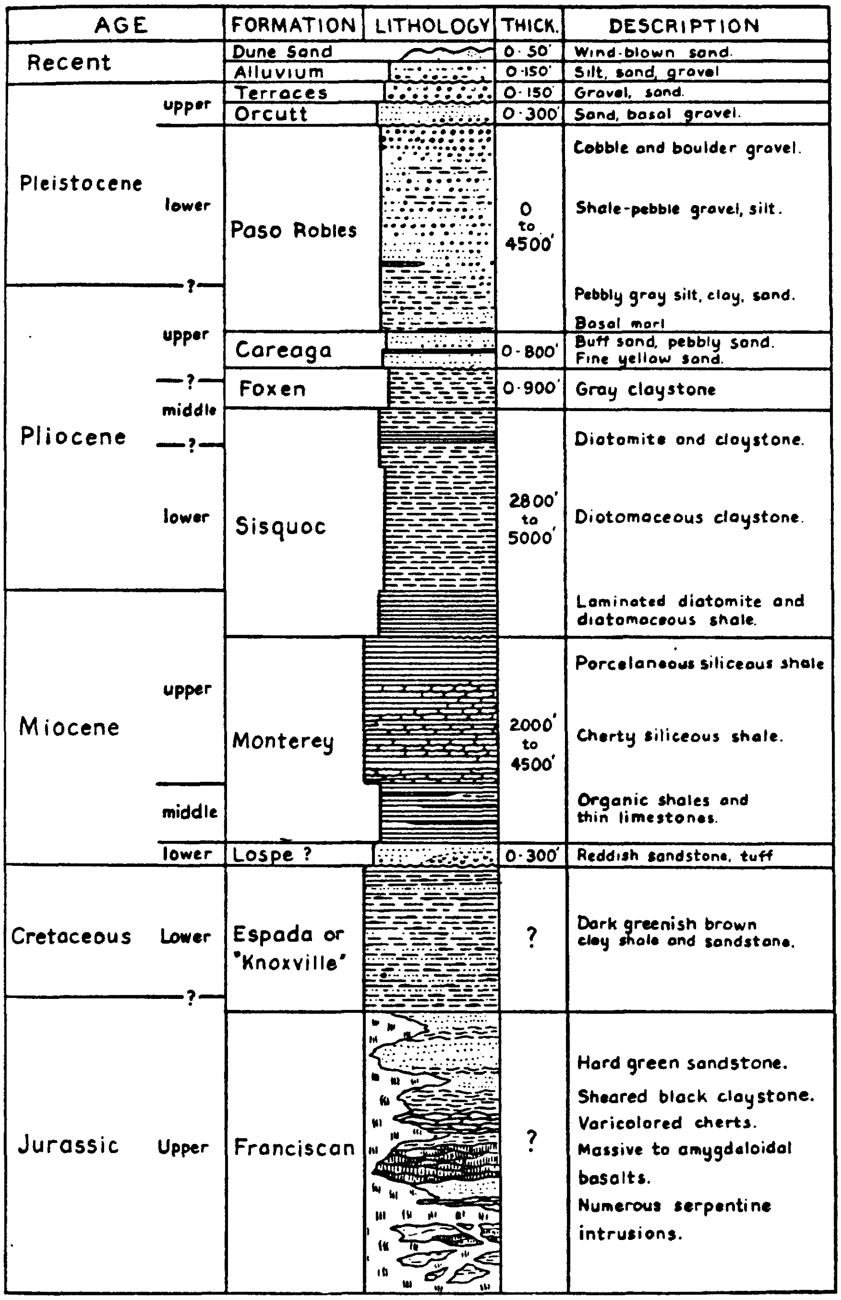

Figure 3. Stratigraphic column of the southern Santa Maria basin, California. From Dibblee (1950, p. 39).

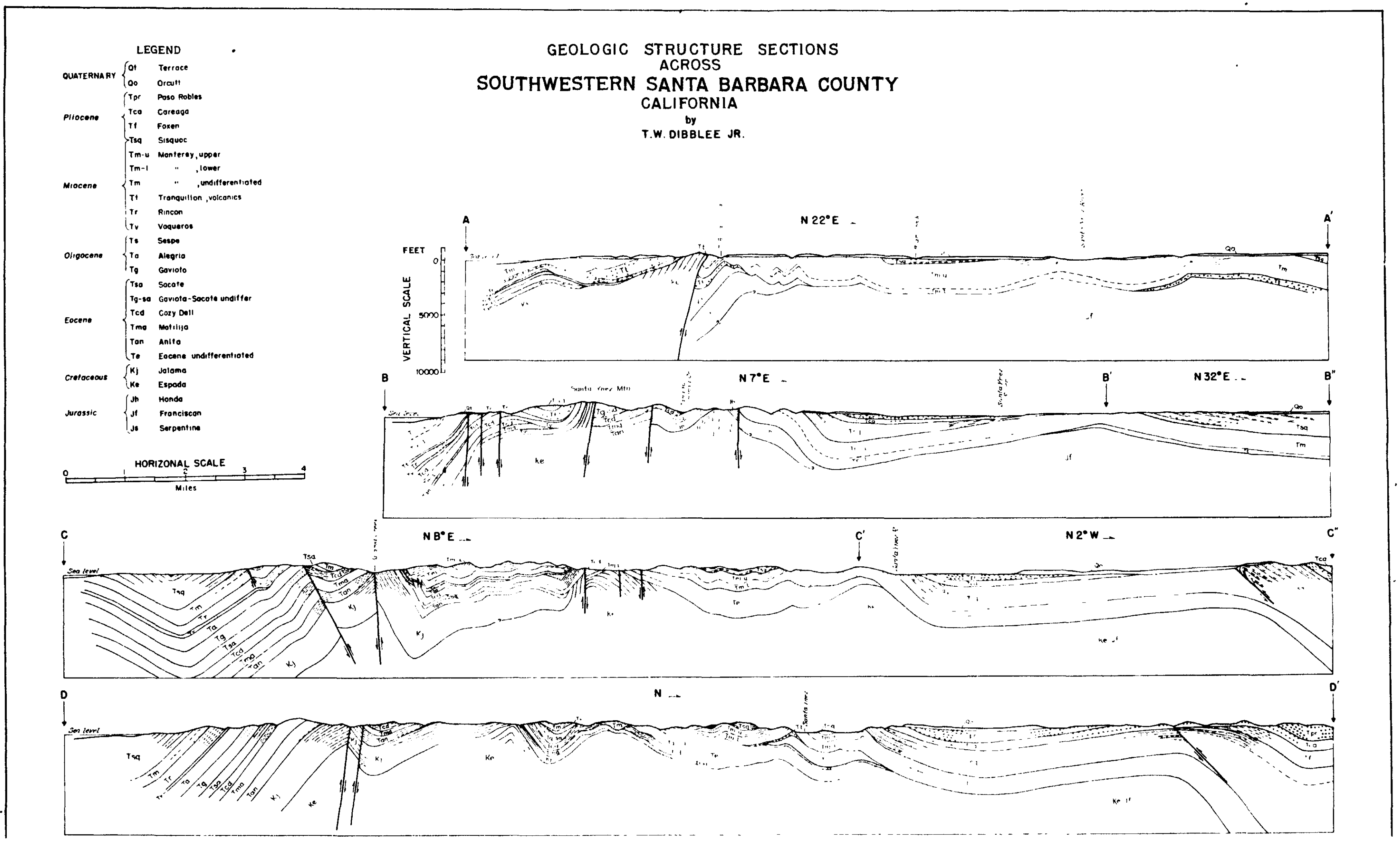

Figure 4. Geologic structure sections across southwestern Santa Barbara County, California. Position of sections shown in map p. 28 (this volume). From Dibblee (1950, plate 5).

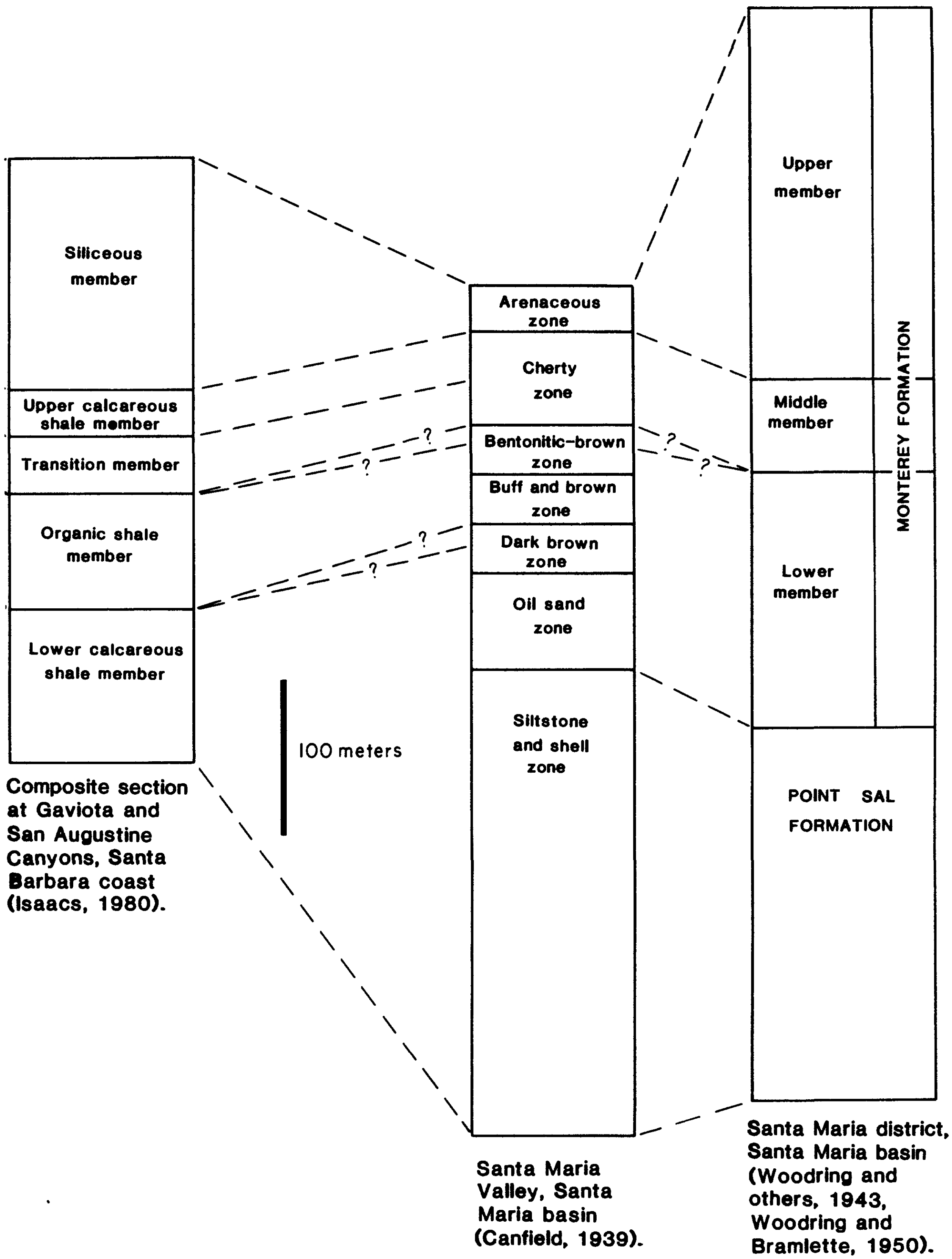

Figure 5. Approximate lithologic correlation of parts of the Monterey in the Santa Barbara coastal area and the Santa Maria basin. From 1981 Monterey field guide book (p. 22).

LION'S HEAD SECTION

Main objectives: (1) to see the part (c. 16-9 Ma) of the Monterey Formation overlying the Point Sal Formation in the Santa Maria area - Woodring and Bramlette's (1950) lower and middle members; (2) to see a completely quartzose section, in which diagenesis is at higher grade than in any other accessible exposure; and (3) to examine folding and fracturing in the "tiger-striped" cherts.

Plan: we will start from the base of the section near the Lion's Head fault and walk upsection (south) along the beach.

Stop 1: the base of the most accessible and extensive exposure of Woodring and Bramlette's (1950) lower member (c. 16-12 Ma), with silica as diagenetic quartz.

o Siliceous shales and marls

From here we can see the Franciscan where it is faulted against the Monterey. The Monterey strata exposed here along the beach belong to the lower part of Woodring and Bramlette's (1950) lower member. This member as a whole represents the upper Relizian and Luisian benthic foraminiferal stages and is thus age-equivalent with the upper half of the lower calcareous-siliceous member and the entire carbonaceous marl member of the Santa Barbara coastal area. Strata here at the base are Relizian and thus age-equivalent to the upper half of the lower calcareous-siliceous member in the Santa Barbara coastal area (e.g., 1981 Monterey field guidebook p. 60, fig. 10D).

Rocks are generally foraminiferal siliceous shales; typical beds contain about 45-50% silica, 35-40% terrigenous detritus, about 10% calcite, and 2-6% organic matter. Although more detritus-rich than age-equivalent strata in the Santa Barbara coastal area, rocks at Lion's head are generally similar in having more abundant silica than calcite. Most of the light-colored layers in these rocks contain abundant apatite and represent zones of concentrated calcareous foraminifers.

References: Woodring and Bramlette (1950, p. 18-20), Pisciotto (1978, 1981), Grivetti (1982).

o Sandstone interbeds and breccia

Interbedded with the siliceous shales here are a number of sandstone beds, some as thick as 4-5". Even the thicker beds are fine-grained, with grains mainly quartzo-feldspathic from a plutonic or recycled Eocene-Cretaceous source (Hugh McLean, oral communication, 1983). Note the load structures at the base of the beds. A few very thin sandstone beds which pinch and swell along bedding are composed largely of pyrite.

A breccia and conglomerate 2-1/2 to 3 feet thick is also present slightly upsection. According to Woodring and Bramlette (1950, p. 20-1), this conglomerate contains, in a matrix of foraminiferal shale, angular pebbles of chert, sandstone, greenish igneous rock, and pebbly limestone as well as shell fragments of *Aequipecten*, *Amusium*, *Ostrea*, and *Balanus*.

Reference: Woodring and Bramlette (1950).

o Dolostone nodules

Also prominent in this outcrop are dolostone beds and layers of dolostone concretions. Isotope values of carbonate determined by Pisciotto (1978, p. 305) in four beds described as "dolomitized phosphatic shale" from Lion's Head yielded a wide range of values ($\delta^{18}O$= -7.0 to +2.5 PDB), suggesting temperatures of formation ranging from 17° to 67°. (For comparison, one sample of siliceous shale contains calcite which is presumably only partly recrystallized having $\delta^{18}O$= -2.40 PDB.) Carbon isotope ratios in the dolostones also vary ($\delta^{18}O$= -10.0 to +2.7 PDB) but not systematically with respect to the oxygen isotope ratios (Pisciotto, 1978, p. 305). Note carbonate-filled veins as thick as 1-1/2" in some of the dolostone beds.

Reference: Pisciotto (1978).

Stop 2: the middle part of Woodring and Bramlette's (1950) lower member.

o Siliceous rocks

To the south along the beach is a unit of highly siliceous rocks (cherts and porcelanites) interbedded with the siliceous shales and marls. Silica in all rocks is diagenetic quartz (except possibly for some opal-CT in chert rims according to Grivetti, 1982). This is one of the most accessible fresh exposures of a section at quartz diagenetic grade, and many of these beds would be characterized as cherts, although only a few as glassy cherts.

Note the nodular shape of the few dark glassy cherts. These are similar to the "atypical" nodules present in carbonate-bearing parts of the Monterey along the Santa Barbara coast (e.g., at Black Canyon). As discussed at Damsite and Black Canyons, both the compaction and oxygen isotope ratios of the silica in these nodules suggest comparatively low-temperature formation of the quartz, possibly at about the time of widespread opal-CT formation.

o Phosphate-bearing rocks

Note as we walk upsection the well-exposed phosphatic shale. Nodules analyzed from Lion's Head contain as much as 36% P_2O_5 and 3.7% fluorine.

Stop 3: an excellent exposure of Woodring and Bramlette's (1950) middle member, with silica as diagenetic quartz.

o Rock types

A wide variety of rocks are exposed here, including siliceous shales (recessive), carbonate-bearing cherts (resistant), brecciated dolostones (resistant), and glassy cherts (extremely resistant). Carbonate is largely dolomite in all beds here.

o Folded cherts

Most prominent of the rock types are the glassy cherts, similar to those we examined at Damsite and Jalama Canyons but here more abundant. According to Grivetti (1982), the black-and-white banded cherts (termed "tiger-striped chert") are composed of quartz (black) and dolomite (white) layers. Note particularly that the cherts are much more intensely folded than surrounding strata. According to Grivetti (1982), these folds are not sedimentary slump folds but are probably parasitic (drag) folds.

Reference: Grivetti (1982).

POINT PEDERNALES SECTON

Main objectives: (1) to see the base of the Monterey where it is underlain by the Tranquillon Volcanics; and (2) to examine fractures.

o Tranquillon-Monterey boundary

The Tranquillon Volcanics interfinger with the base of the Monterey which here is mainly marl/siliceous-calcareous rock with some dolostones. According to Dibblee (1950), the Tranquillon is as thick as 1200 feet in the vicinity of Tranquillon Mountain, where it is composed mainly of a large rhyolite flow. At Point Pedernales, rhyolite agglomerate and tuff predominate.

Underlying the Tranquillon Volcanics on the south side of Tranquillon Mountain is the Rincon Shale and the Vaqueros Formation (latest Oligocene shelf sandstone) disconformably overlying Eocene and Cretaceous marine sedimentary rocks. On the north side of Tranquillon Mountain the Rincon Shale rests directly on the Cretaceous Espada Formation.

References: Dibblee (1950), Grivetti (1982).

o Fracturing

Some beds at the base of the Monterey here are highly fractured (almost shattered) in places. Open fractures are particularly characteristic of siliceous nodules/concretions.

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