DL 9

FIFTH ANNUAL FALL FIELD FROLIC

AUGUST 1987

POINT CONCEPTION AND WESTERN SANTA YNEZ MOUNTAINS

COMPILED BY JON SLOAN

WELCOME TO THE 1987 GEOLOGICAL SCIENCES DEPARTMENT FALL FIELD FROLIC. THIS TRIP IS GOING TO BE A BIT DIFFERENT THAN TRIPS IN THE PAST. IN THE PAST THE LEADERS KNEW A LITTLE ABOUT THE ROCKS THROUGH WHICH THEY WERE LEADING. BUT WE ARE BRAVE. THE HIGH POINT IN THE TRIP WILL BE REFUGIO PASS AND THE LOW POINT SEA LEVEL. AS PROMISED TO SOME, ASPECTS OF THE NATURAL SCIENCES MORE FLEETING THAN ROCKS WILL BE KEPT TO A LEVEL AS LOW AS WILL POWER ALLOWS.

OVERVIEW - Friday

- Leave CSUN at 0900
- Morning drive up the coast to Gaviota Beach where we will have lunch
- Afternoon on Hollister ranch with Tom Dibblee, Helmut Ehrenspeck, and Paul Huebner.
- Spend night at the Julian Ranch

Saturday

- A morning hike on the Julian Ranch and diatomite quarry.
- In the Afternoon a loop drive on Santa Rosa Road and Nojoqui Falls.
- Spend night at Julian Ranch

Sunday

- Drive over Refugio Pass Road
- Arrive back at CSUN by mid-afternoon.

ROAD LOG - FRIDAY MORNING - RESEDA BLVD. TO GAVIOTA BEACH

0.0 Reseda Blvd. (on Ventura Fwy)

West center of San Fernando Valley. At this point most of this side of the Santa Monica Mountains (SMM) is composed of the soft upper Miocene Modelo Formation. The Los Angeles River flows (at times) just a few blocks to the north; the drainage has been moved to this off-centered position due to a greater source of sediment and fan formation from the Santa Susana Mountains which border the northern edge of the valley.

2.0(2.0) Winnetka Blvd.

Just after the overpass we climb over "chalk hill" which is part of the Tarzana Fan. Most of this fan is under the San Fernando Valley but the uplift of the SMM lifted these deep marine, foram-rich, slope-face, Modelo siltstones and shales to the surface. These rocks are the youngest of any which surround the San Fernando Valley, uppermost Miocene to Pliocene.

At Canoga Blvd. houses on the hills to the left are on the Tarzana Fan.

The Simi Hills (Cretaceous Chatsworth Formation) can be seen at about 3:00.

6.1(4.1) Valley Circle Blvd. North end of San Fernando Valley.

SEE FIGURE 1 FOR FORMATION NAMES AND STRATIGRAPHIC RELATIONSHIPS OF ROCKS IN THIS END OF THE SMM.

The rolling hills ahead are the proximal turbidites of the Calabasas Formation of Yerkes and Cambell (1979). I mention this because you will not find this name on the L.A. sheet or in the Sharps Guide to this area. The deep marine Calabasas Formation complexly overlies the middle Miocene Conejo Volcanics and are in turn unconformably overlain by the Modelo Formation.

10.0(3.9) Malibu Creek (Las Virgenes Road) is the only drainage which cuts through the SMM.

14.0(4.0) Kanan Road. The ruged exposures to the left are composed of Conejo Volcanics which form most of the western SMM. Dr. Weigand will tell us a little about these volcanic rocks at our first stop.

25.3(11.3) Base of the Conejo grade. From the end of the San Fernando Valley to this point most of the topography on the south (left) is controlled by the Conejo Volcanics. On the north (right) topography is controlled by the erosional nature of the Calabasas Formation.

26.6(1.3) **STOP** 1 - LARGE AREA JUST AFTER THE TRUCK STOP

On a clear day we will get a good view of:

- Oxnard plain
- Conejo Volcanics
- mountains in distance (proximal to distal)
  * Camarillo Hills and Las Posas Hills
  * South Mountain Ridge and Big Mountain on Oak Ridge
  * Santa Clara River
  * Topatopa Mountains
  * San Rafael Mountains
  * Sierra Madre Mountains

* Santa Ynez Mountains

Time to armwave about Transverse Ranges, rotation (see figures 2 and 3 on paleomagnetics by Hornafius and others), seas came in and seas went out, Conejo Volcanics, students working in these mountains, etc. etc...

27.6(1.0) Continue down the west side of Conejo grade. Look back and see a large dike with poorly developed columnar jointing.

41.0(13.1) Santa Clara River drains much of the central Transverse Ranges including the eastern slope of the San Gabriel and the western slopes of the Sierra Pelona. In 1928 it drained the contents of St. Frances Dam rather quickly when a wall of water 6 meters high passed this point which is more than 50 miles downstream from the damsite.

46.1(6.1) Just before Seaward Ave. the cliff to the right is an abandoned sea cliff. This cliff marks the sea edge as recently as a few centuries ago.

49.3(3.2) At the junction of Rts. 33 and 101 look up the Ventura River and see the facilities associated with the Ventura oil field, the fourth largest in California. The drilling is associated with the Ventura Anticline.

50.4(1.1) On reaching the ocean turn off on old Hwy 1. As we drive along the beach note the marine terraces and the inclined beds which are marine Pliocene and Pleistocene formations (Pico, San Pedro, and Santa Barbara).

56.0(5.6) **STOP 2** - Oil platforms and post-Miocene rocks.
See Figure 4 on Santa Barbara Channel oil fields.
We have driven past the first of the three "rincons", Pitas Point, and Punta Gorda is in front of us. The trace of the Rincon Anticline is marked by the line of oil platforms out to sea.

57.3(1.3) Get back on freeway and get another view of the oil platforms. It was one of these that blew in 1969 and created havoc on shore with more lasting damage to offshore drilling off California.

59.8(2.5) Banana plantation on right.

Just before Rincon Point the Rincon Fault goes out to sea. Miocene rocks are lifted up on its north side.

60.5(.7) At Bates Road, outcrop on right. Middle Miocene Monterey Formation. The reddish tint to the rocks is caused by near-surface combustion of these organic-rich shales.

There are Pleistocene brea (tar) deposits near Carpinteria State Beach Park. We will stop here if time permits Sunday afternoon.

75.5(15.0) At stop lights in Santa Barbara. Hill to the left-ahead is composed of the Santa Barbara Formation. In some areas this is a bryozoan marl very rich in micro- and macrofossils.

80.0(4.5) Mountains on right are the Santa Ynez. We will drive through them on Sunday.

82.0(2.0) Beyond Goleta are two points, Goleta Point (site of the University of California at Santa Barbara) and Coal Oil Point, both of these points are on trend with the Rincon Anticline. Oil and tar seeps are abundant on the crest of the anticline, much of it washing onto the beaches.

92.6(10.6) Dos Pueblos Canyon. Middle Miocene Monterey Formation on beach (cannot be seen from the road), Rincon Formation forming the rolling grass covered hills, with Oligocene and Eocene units supporting the west side of the Santa Ynez Mountains.

109(16.4) **STOP 3** - MONTEREY FORMATION AT GAVIOTA BEACH

Get off freeway at Gaviota Beach State Park to look at features of several members of the Monterey Formation. The field trip guide to this stop, which follows, has been unabashedly stolen. George Freitag attended that field trip and will aid in interpreting these rocks.

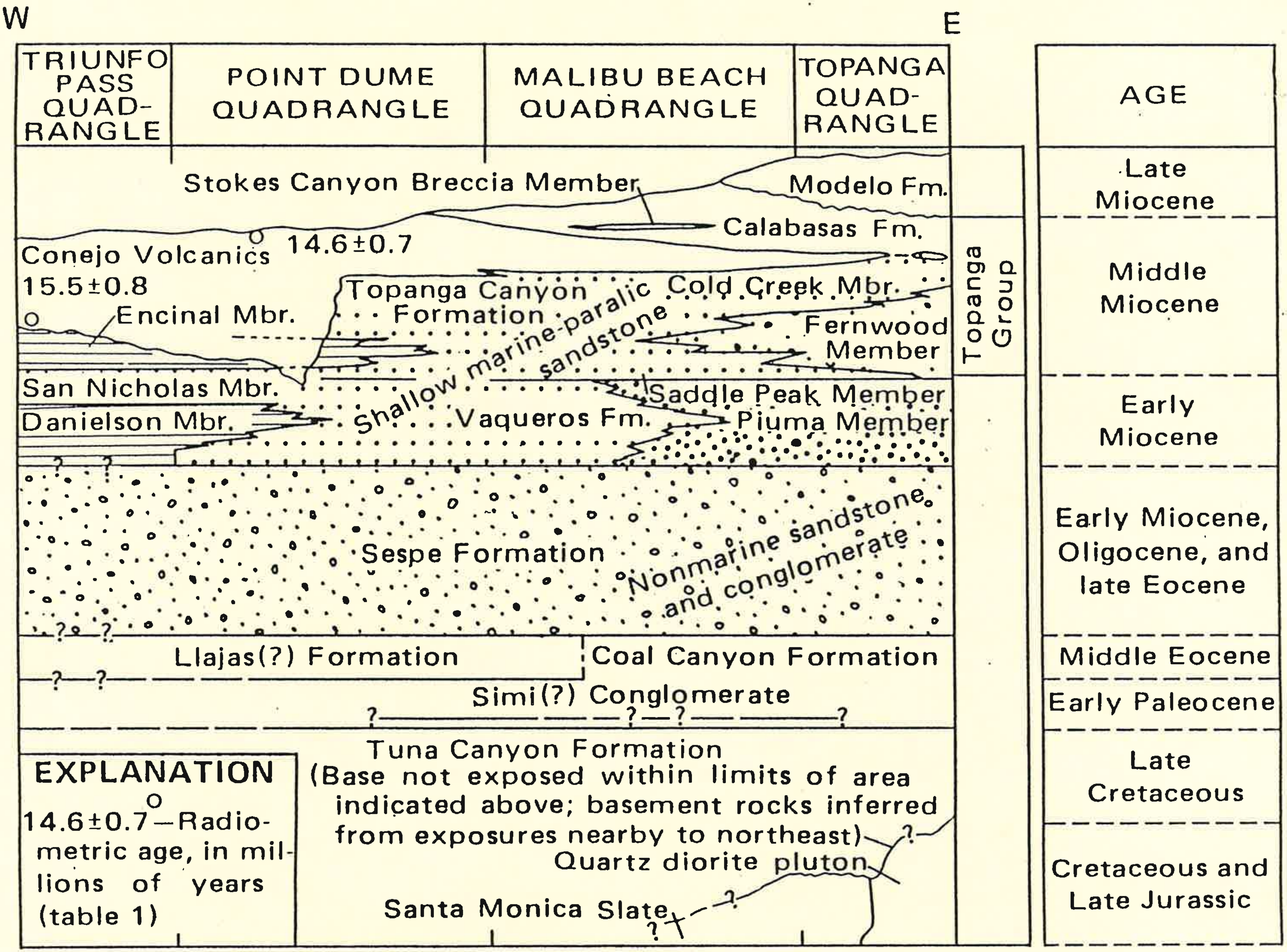
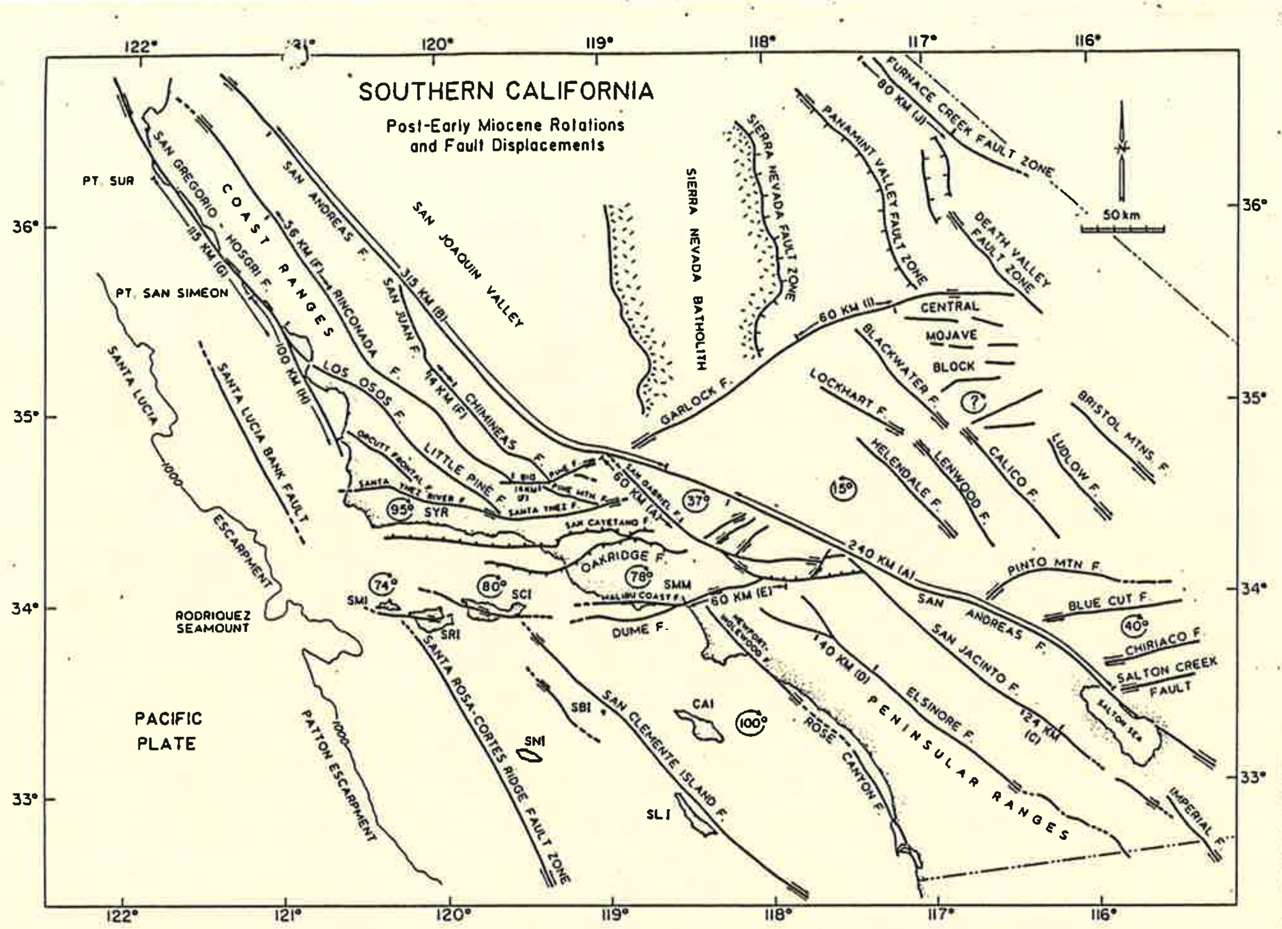
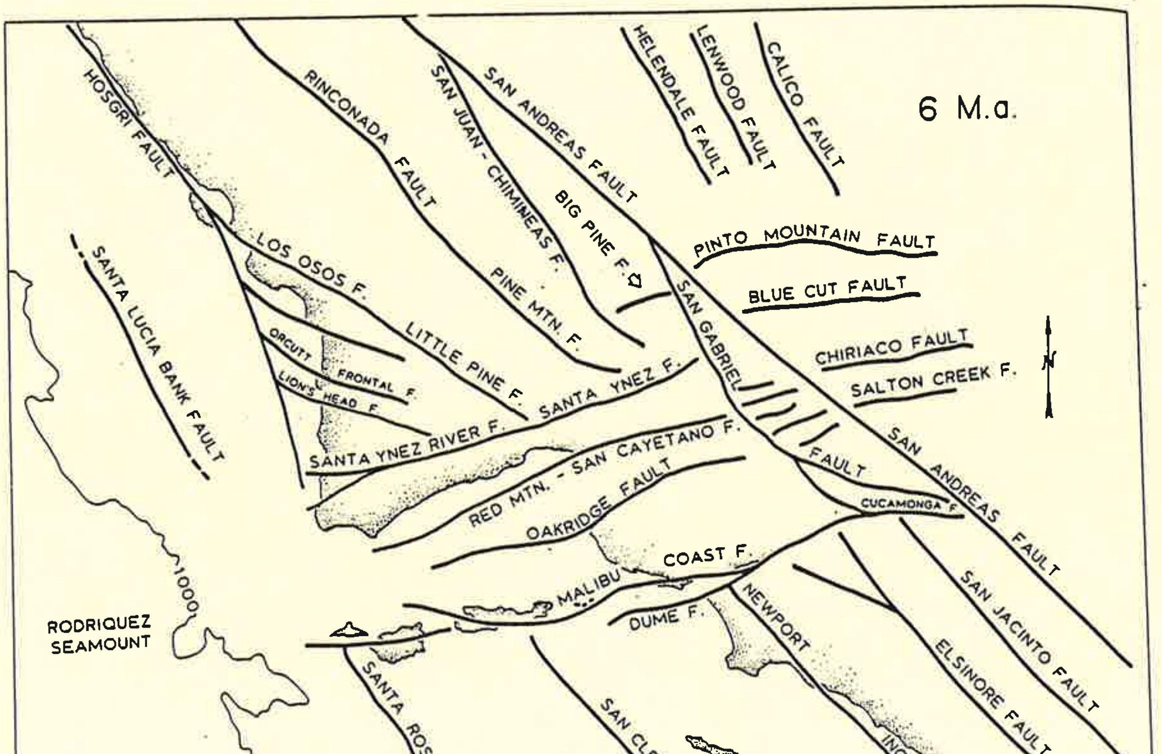


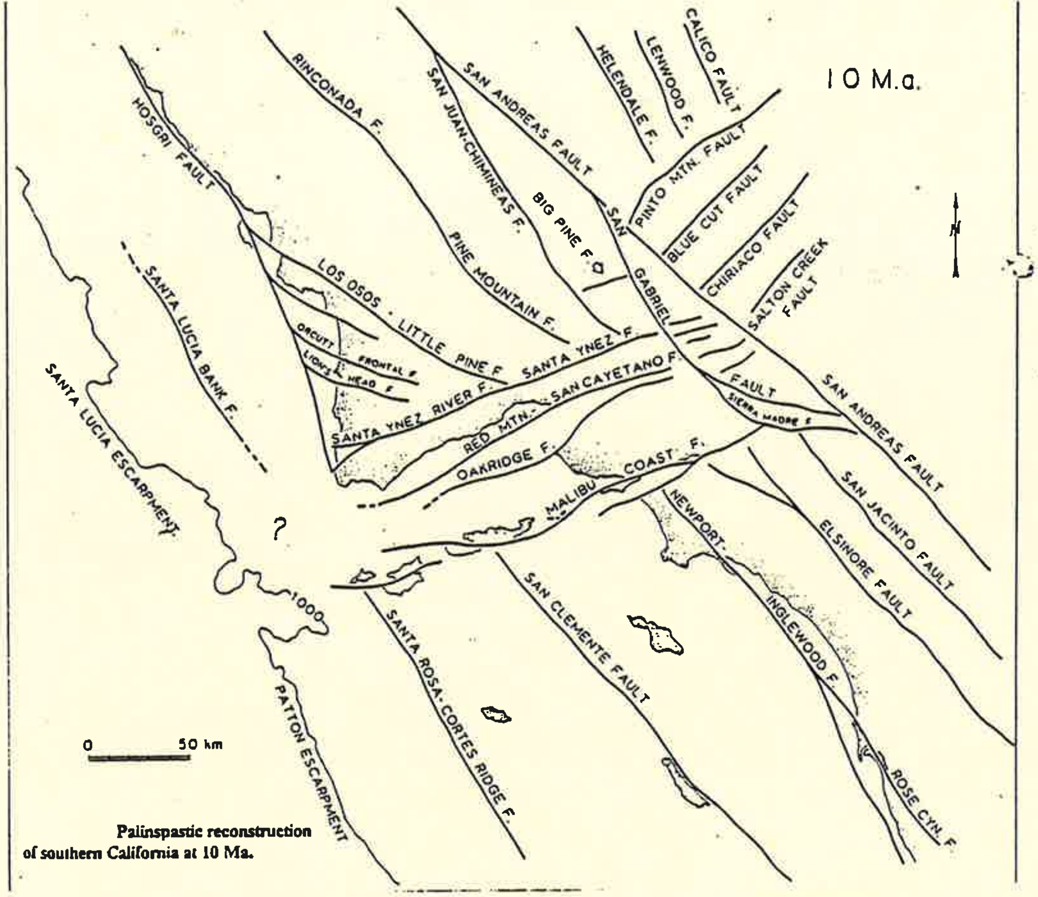
FIGURE 1—Correlation diagram of units north of the Malibu Coast fault (except for those restricted to the upper plate of the Malibu Bowl fault).





Palinspastic reconstruction of southern California at 6 Ma.

Figure 2



Palinspastic reconstruction of southern California at 10 Ma.

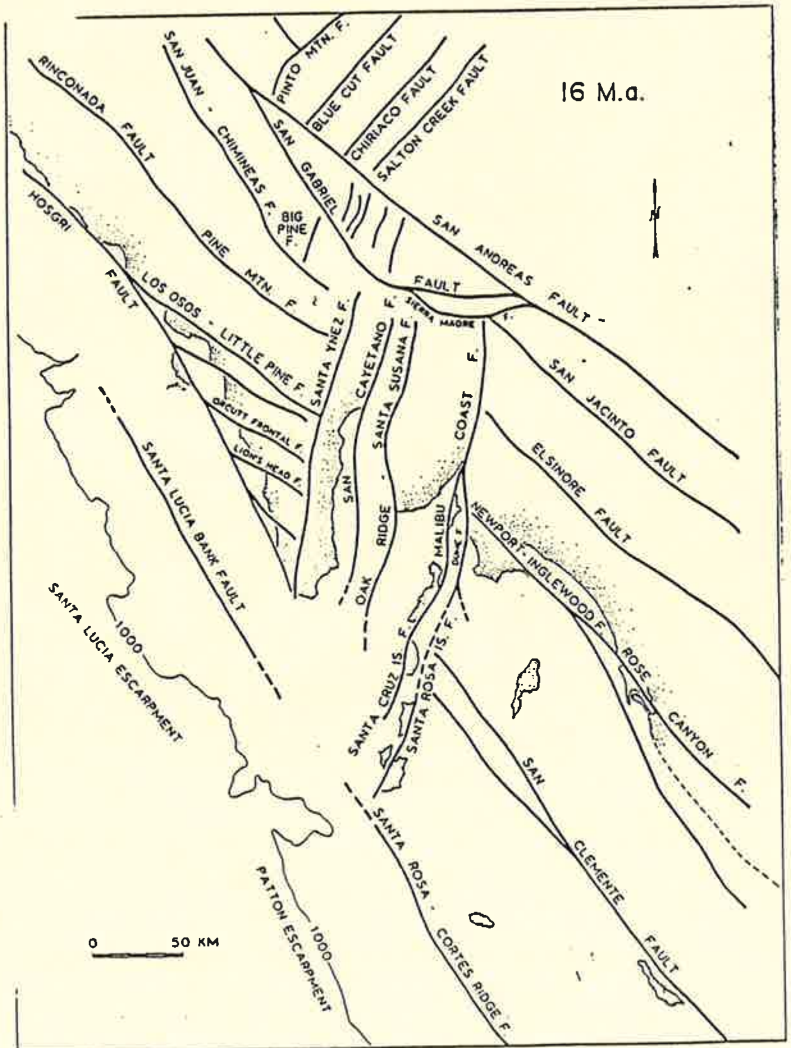
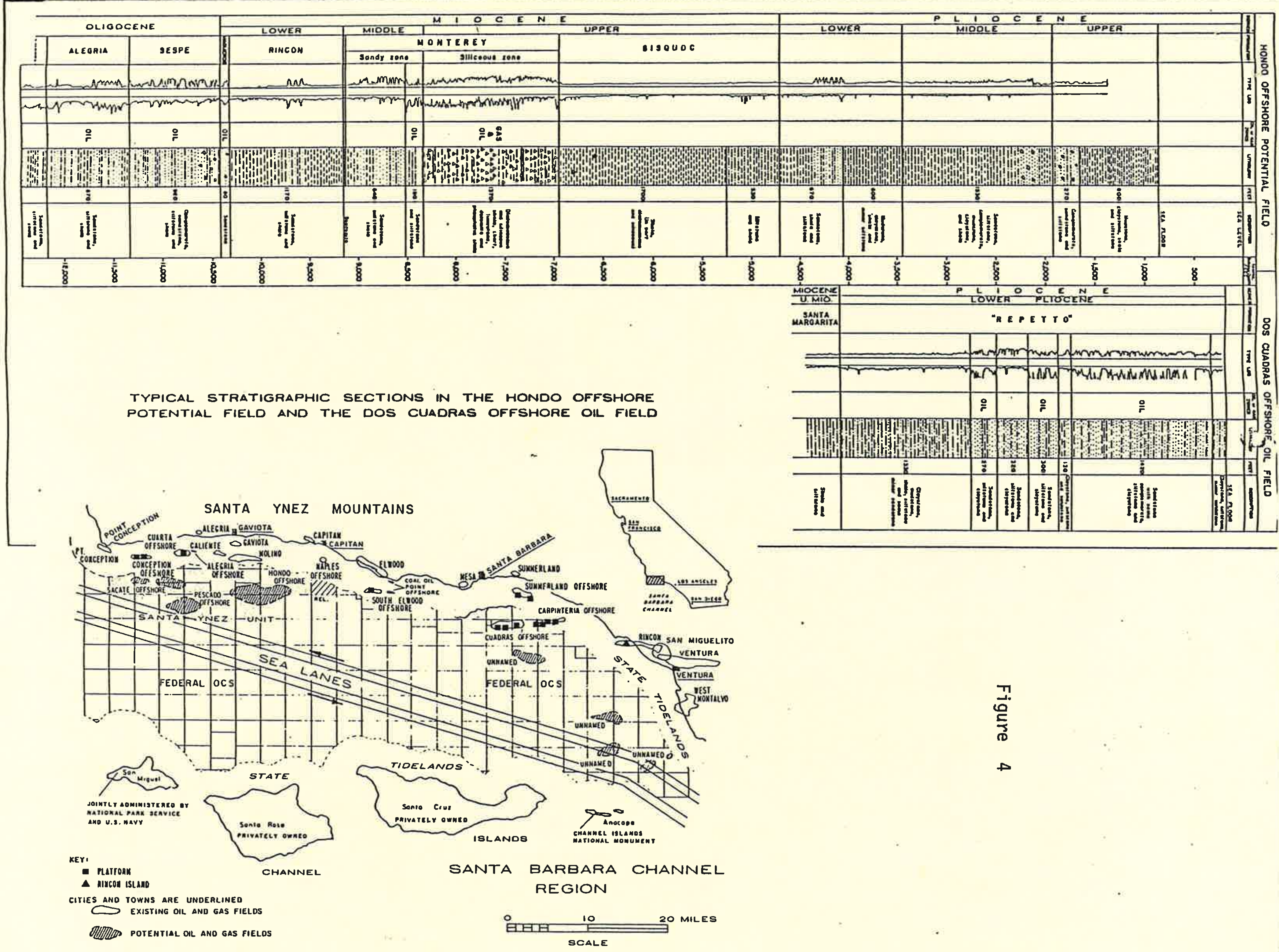


Figure 3

Palinspastic reconstruction of southern California at 16 Ma. Present-day shorelines are shown for geographical reference.



TYPICAL STRATIGRAPHIC SECTIONS IN THE HONDO OFFSHORE POTENTIAL FIELD AND THE DOS CUADRAS OFFSHORE OIL FIELD

Figure 4

PREFACE

On this field trip, we will have time to see only a few aspects of the Monterey Formation. First (at Gaviota East section), we will take a look at the Monterey where it is most typical diagenetically and see some of the depositional features of the upper part of the section. Then we will examine a tar-filled conglomerate that represents a Miocene submarine canyon. Then we will take a brief look (at Goleta Slough section) at the Monterey where is is less diagenetically altered - still diatomaceous. Finally, at Arroyo Burro section, we will look at fracturing in the Monterey.

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). Other references are included at the end of the notes.

Maps showing the generalized geology, tectonics, cross-sections, and stratigraphic column for the Santa Barbara area are reproduced in Figures 1-4. Sections we will be visiting are located on Figure 5.

OVERVIEW

Why is the Monterey Formation interesting and important to geologists?

- Major oil source. The Monterey is generally regarded as the principal source of oil in California, an area with about 20 billion barrels of cumulative production. Much controversy surrounds the Monterey's organic geochemistry. Monterey oil tends to be heavy (viscous) and sulfur-rich, and recent research suggests that it is generated at lower temperature than conventionally thought possible. Commonly used "maturity" indicators such as vitrinite reflectance and rock-eval parameters are thus problematic in the Monterey.

- Important oil reservoir. In the Santa Maria and Santa Barbara-Ventura areas, the Monterey is a major oil reservoir, with reserves discovered in the last 15 years of about 2 billion barrels (Fig. 6). The Monterey is almost unique as a combination source and reservoir of oil. Moreover, the Monterey is unusual in being a fractured reservoir - in which permeability is derived from fractures rather than matrix porosity.

- Unusual and variable lithotypes. Monterey strata have an unusually abundant biogenous component and when deposited were mainly diatomaceous and coccolithic-foraminiferal oozes. Major sedimentary components are silica (diatom frustules), carbonates (coccoliths, forams, dolomite), terrigenous detritus (clays, feldspars, detrital quartz), apatite, and organic matter. These components combine in widely varying amounts - and at various stages of diagenesis - to form diatomites, diatomaceous mudstones/shales, porcelanites, siliceous mudstones/shales, cherts, a wide variety of calcareous rocks (including calcareous cherts, calcareous porcelanites, calcareous siliceous shales/mudstones, marls, and limestones), a wide variety of dolomitic rocks (including dolomitic cherts, dolomitic porcelanites, dolomitic siliceous shales/mudstones, and dolostones), phosphorites, oil shales, and many gradational lithotypes. One of the most confusing aspects of the Monterey is the fact that rock compositions are extremely variable - and, moreover, not clustered around specific compositions (Fig. 7).

- Oil exploration problems. Fractured reservoirs of the Monterey Formation are a relatively recent exploration target outside the onshore Santa Maria basin. In fact, major discoveries before 1980 were mainly inadvertent - that is, made by sheer luck and/or total mistake. Recent interest in the Monterey has shown that the problems with conventional exploration techniques are many: (1) usual signs of an oil discovery are commonly lacking in fractured reservoirs so that discoveries have been missed or "cased in"; (2) many conventional well-log techniques are not very helpful in the Monterey because they are designed to locate porous zones (which are not the productive zones in fractured reservoirs), because they misidentify lithotypes, and because they integrate over too great a thickness for the commonly thin-bedded Monterey.

- Diagenesis. Patterns of diagenesis in the Monterey are also atypical, mainly because of the unusual characteristics of diatomaceous strata - e.g., high porosity (>65%), low permeability, and chemical instability. The amorphous silica (opal-A) synthesized by diatoms is unstable at near-surface conditions and converts with increased temperature/burial first to metastable opal-CT (cristobalite-tridymite) at about 50°C and then to stable quartz at about 85°C (Fig. 8). The two phase transformations generally occur by a process of solution-precipitation, so the silica in quartz strata has completely dissolved and reprecipitated twice at temperatures less than 100°C! During the process, porosity is reduced in two abrupt steps coincident with the phase transformations (Fig. 9) - a pattern which produces, in diatomaceous areas such as the Bering Sea, distinctive seismic reflectors approximating isothermal surfaces.

  Carbonate diagenesis is also important - particularly the formation of dolomite both in nodular and disseminated form. Dolomite formation involves carbon derived from organic matter diagenesis and incorporation of magnesium from seawater, but the details remain controversial and existing models do not account for the amount of dolomite in some parts of the Monterey.

- Record of Miocene ocean history. Because the Monterey is largely biogenous (composed of microfossils and organic debris), it represents a detailed record of ocean history along the margin of the eastern Pacific. Of special interest to paleoceanographers is evidence of increased thermal stratification in the Pacific water mass structure as a result of the formation of the Antarctic ice cap about mid-Miocene time. During the trip, we will be examining some of the sedimentologic features that resulted from oceanographic changes.

PALEOGEOGRAPHIC SETTING

Surprisingly, the paleogeography of the Monterey Formation in the Santa Barbara area is not at all clear. A major problem is that the structural history of the area is both complex and controversial - the Santa Maria basin just to the north is regarded by some researchers as a Miocene pull-apart basin, whereas other researchers have considerable evidence of major rotations and rearrangements of structural blocks in the area (Hall, 1981; Hornafius, 1985). How the pieces fit together during deposition of the Monterey is thus still problematic - and basin outlines, orientations, etc. are impossible to estimate at present.

One aspect of the depositional framework that is better known is the paleobathymetric history in the immediate area. Marine transgression began in the late Oligocene (about 25 Ma) and the seafloor deepened rapidly, probably to about 2000 m by the Miocene-Oligocene boundary (about 22.5 Ma). By the beginning of Monterey time (about 18 Ma), the seafloor was at a depth of about 1000-1500 m (lower middle bathyal).

Models of the Monterey derive mainly from analogous presentday environments - the Santa Barbara Basin and the Gulf of California (Fig. 10). A major feature of both environments is the oxygen-minimum zone, a midwater feature in which bottom-water oxygen is so sparse that (1) organic matter is easily preserved from oxidation; and (2) sediments are not disturbed because bottom-dwelling creatures are mainly excluded. Theoretically, the result is organic-rich laminated sediments. Surprisingly, however, organic matter in the Monterey of the Santa Barbara area is not more abundant in laminated rocks where they are interbedded with massive (more oxygenated) strata - in fact, just the reverse! Like other components, organic matter abundance is extremely variable in the Monterey, and its distribution is more closely related to sediment composition than to layering characteristics (Fig. 11).

What is the depositional "cause" of the Monterey? It is widely attributed to climatic changes which encouraged upwelling, the bringing to the surface of nutrient-rich water which encourages biologic productivity (especially diatoms). Recent work on accumulation rates, however, suggests that biologic productivity was high much earlier than the Monterey and did not change markedly at the base of the Monterey. In fact, the Monterey was not apparently marked by unusually high silica rates when compared with either subjacent and superjacent strata - what is distinctive about the Monterey is an unusually slow influx of terrigenous debris that would otherwise have diluted the biogenous components (Fig. 12). The principal "cause" of the Monterey was thus apparently a sharp reduction in the rate of influx of terrigenous debris. Important influences on the boundary thus may have included: (1) rising sea level (which could have trapped terrigenous debris near shore through most of early and middle Miocene time); (2) subsidence and basin formation (which produced "sediment-starved" basins); and (3) transgression (which moved the shoreline further away).

Incidentally, the top of the Monterey, when examined in the context of accumulation rates, is even more surprising - it seems to represent a simultaneous <u>increase</u> in both silica and terrigenous detritus rates! Silica accumulated about 25 times faster - and detritus about 40 times faster - in the Sisquoc than in the mid-Miocene. These changes probably reflect three unrelated circumstances: (1) a major change in the oceanwide pattern of opal deposition about uppermost Miocene or early Pliocene time (Leinen, 1979); (2) local tectonism; and (3) global sea level lowering.

GAVIOTA BEACH SECTION

Main objectives: (1) to see 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 some detail; and (3) to see the brea conglomerate.

Plan: We will start in the clayey-siliceous member and walk downsection (east) to the carbonaceous marl member, then return to the conglomerate west of the pier (Figs. 13 and 14).

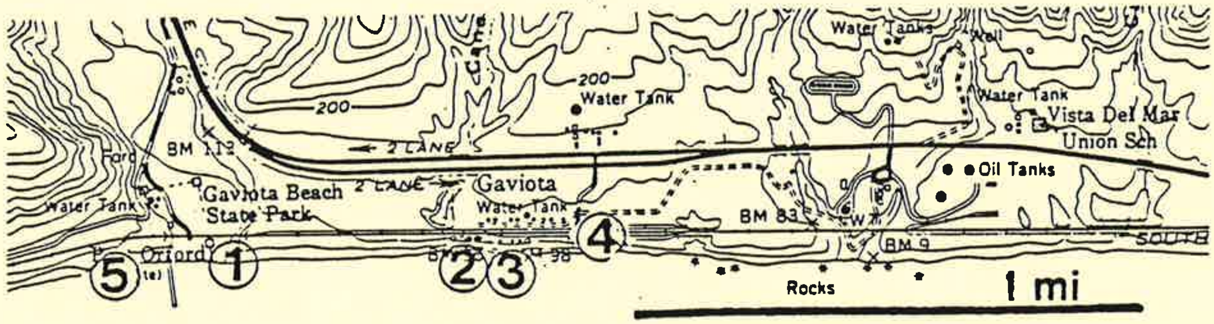


Figure 13. Map showing the location of stops at the Gaviota Beach section. From the Gaviota 7.5 minute quadrangle.

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

- 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.

- Rock types and 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 (more siliceous) 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 (more clay-rich) 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

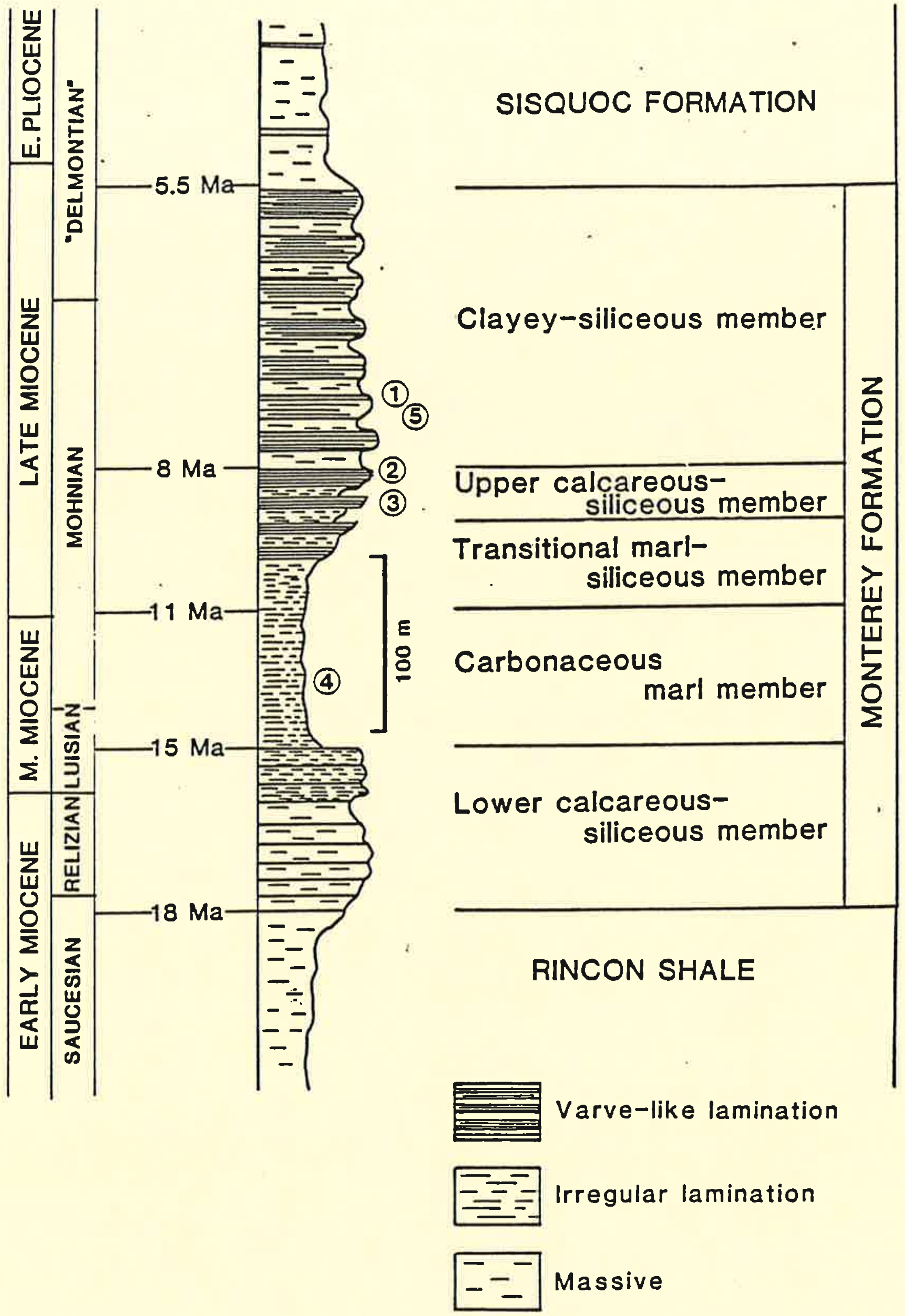


Figure 14. Generalized lithostratigraphic column of the Monterey Formation in the Santa Barbara coastal area (from Isaacs, 1983), showing position of field stops in the Gaviota Beach section.

resemble a matte photograph, whereas siliceous mudstones are more grainy.

Compositions of rocks (excluding dolostones) in the clayey-siliceous member ranges from 15-90% silica, 10-80% detritus, and 2-12% organic matter. The alternation of "massive" siliceous mudstone (recessive units) and laminated porcelanite (resistant units) 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, 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 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.

The cliff exposure here is an excellent place to see the detailed forms of arenaceous foraminifers along bedding planes. Arenaceous foraminifers have skeletons made of agglutinated sand and silt particles - they are also visible as white flecks perpendicular to bedding.

o Accumulation rates of detritus

The clayey-siliceous member represents the most abundant terrigenous detritus in the Monterey Formation. 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 (Fig. 12). For the overlying Sisquoc Formation, 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).

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.

- 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.

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. In underlying rocks throughout the Monterey Formation, nearly all beds contain carbonate minerals - with an average of 22% carbonates in the upper calcareous-siliceous member.

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 Carbonate Compensation Depth (CCD) or introduction of corrosive bottom water.

- 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.

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.

- Variations among beds

The compositions of beds in the upper calcareous-siliceous member vary considerably. The range of composition is: 5-90% silica (av. 47%), 5-65% detritus (av. 25%), 2-75% carbonate (av. 22%), 0-20% apatite (av. 0%), and 2-20% organic matter (av. 6%). Except for the addition of ubiquitous carbonate and thinner bedding, lithotypes in this member are similar to those in overlying strata. 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 silica-poor 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.

Incidentally, most of the prominent white bands in these beds are not phosphate but are concentrations of calcareous microfossils, in some beds dolomitized.

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).

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.

o *Organic matter*

The abundance of organic matter shows considerable variation among beds, with a total range in the Monterey of about 1 to 35% (Fig. 11). The distribution of organic matter shows several main relations: its abundance (1) strongly positively correlates with the abundance of detritus, (2) moderately positively correlates with calcite in the calcite-bearing part of the sequence, and (3) 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.

o Compositional changes downsection

Gradationally downsection organic-rich marls are increasingly abundant and calcareous-siliceous beds decrease in abundance. 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. 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 upsection.

In time, the increase in silica accumulation rates seems to have occurred in the late early Mohnian or at about 11 Ma. 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 California). 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.

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

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 (Fig. 12). In addition, organic matter is here nearly twice as abundant as in underlying and overlying units, and phosphate nodules are much more common. Depositionally, the predominance of calcite in these beds indicates a moderately productive ocean during the middle Miocene, much less productive than in overlying and underlying strata.

o Phosphate

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.

o Layers of concentrated apatite nodules

High concentrations of apatite nodules occur in some strikingly exposed zones 3-6" thick in 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 Veined quartz chert

Although diagenetic quartz generally formed at lowest temperatures in clay-rich silica-poor beds, this diagenetic pattern had several exceptions in calcareous strata. One 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 can be seen 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.

Stop 5 the brea conglomerate west of Gaviota pier.

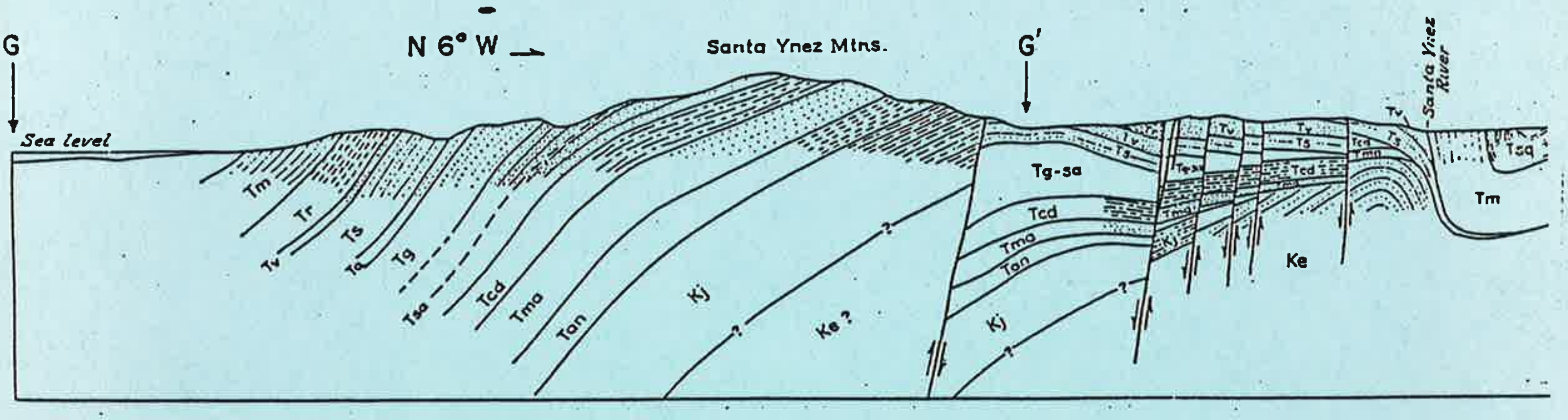
o Conglomerate. Exposed here is one of several conglomeratic canyon complexes found in the upper part of the Monterey Formation in this vicinity. Environments identified by Ward (1984) include channel axis, mid channel bar, channel margin, levee, crevasse splay, secondary channel, and overbank deposits (Fig. 15). Paleocurrent directions are southerly.

Cobbles in the conglomerate include many opal-CT porcelanite, dolostone, and quartz chert clasts derived from the Monterey. Also in the conglomerate are reworked igneous, sedimentary, and metasedimentary pebbles and cobbles probably derived from the Oligocene Sespe Formation (Ward, 1984).

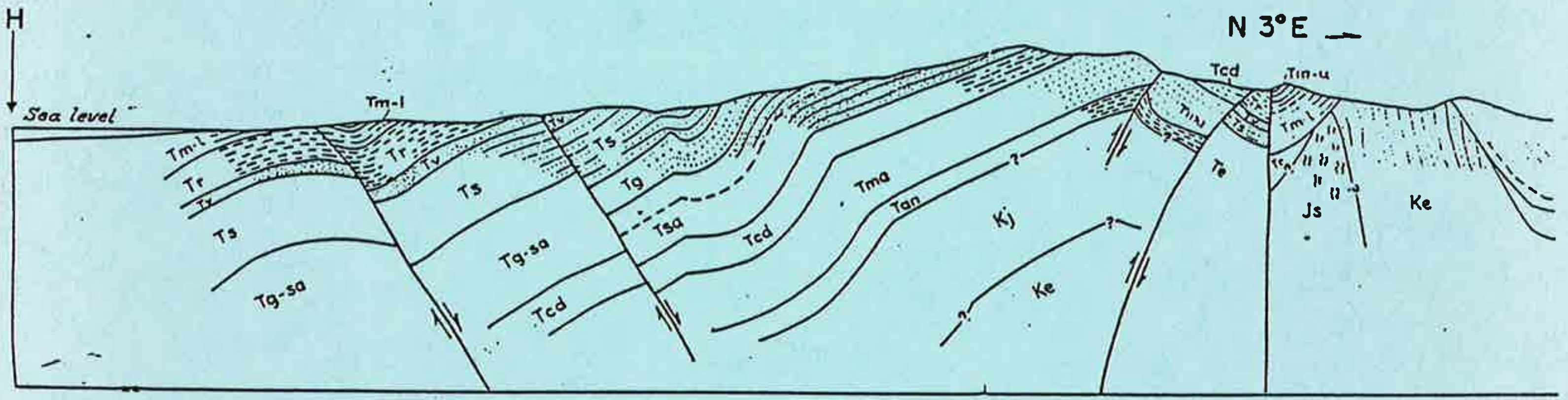
ROAD LOG - SUNDAY MORNING - JULIAN RANCH OVER REFUGIO PASS TO THE BEACH

0.0(0.0)	Turn left off route 1 onto 101 Freeway.
5.0(5.0)	To the left is a new unit we have not seen. The Sierra Blanca Formation. An algal limestone which is often the oldest Cenozoic unit in Southern California which rests on Mesozoic rocks. Here it is found in the axis of an anticline.
7.8(2.8)	Santa Rosa Road. On the freeway we have been going through Cretaceous Espada and Jalama Formations, which are unconformably overlaid by the Sespe Formation which can be seen to the left as we cross Santa Rosa Road.
8.0(0.2)	Cross Santa Ynez River. Note the river we have been following is not the Santa Ynez. It continues west and reaches the ocean north of Point Conception after going through Lompoc.
8.3(0.3)	Turn off Freeway at Buellton and right onto Route 246. Continue on Route 246, through Solvang.
14.3(6.0)	Turn right onto Refugio Pass Road.
15.2(0.9)	**STOP** - Before bridge on left. A view of where we are going. The San Rafael Mountains are behind us across the valley. This is a good place to talk about the geology of the central Santa Ynez mountains.

During this traverse of the Santa Ynez Mountains we will again see most of the rock types making up this range of mountains. As we drive up we will be on the north flank of a predominately homoclinal structure. In this area the Santa Ynez Mountains are a strike ridge with the axis of the mountains parallel to and south of the Santa Ynez fault (see X-section below). If the road was a little to the west or to the east we would cross the roleover "anticline" in Cretaceous rocks but they did not build the road for geologists. The road, the "anticline", and the Santa Ynez Fault meet in about the same place on this side of the mountain range.



X - SECTION TO THE WEST



X - SECTION TO THE EAST

Mileage will note formational contacts, at least where I could recognize them. There will be several stops as we enter different formations. Compare these outcrops with the same formations on the Julian Ranch. We will also stop at the top and get a good view of the ocean to the south and mountains to the north (fog permitting).

DRIVERS: THIS IS A WINDING ONE LANE ROAD, DRIVE WITH CARE

17.1(1.9) Cross an anticline with Vaqueros Formation in the center. The Vaqueros forms the cliff to the right.

17.6(0.5) We are nearing the Santa Ynez Fault. To the left the highest ridge (cliff) are Tranquillon Volcanics. From here until we reach the fault, at the base of the mountains, there are several fault splinters with Miocene (Rincon, Vaqueros), Oligocene (Sespe), and Eocene (cozy dell, Matilija) rocks exposed.

18.7(1.1) Cross the main trend of the Santa Ynez Fault. The fault is in the drainage (forms?) to the left. As we cross the fault we enter the Eocene Matilija(?) Formation from the Oligocene Sespe Formation. Cretaceous rocks (Jalama Formation), the oldest rocks we see in this traverse, are ahead and two the right. This piece of Matilija is caught in a fault splinter and we leave it at

19.7(1.0) and enter the Anita Shale just (1/4 Mile) before the hard right switchback. We may stop here and try to find the foram-rich, thin, red, "Poppin" shale for 403.

20.7(1.0) Re-enter the Matilija(?) sandstone.

20.9(0.2) Matilija(?) / Cozy dell shale

21.3(0.4) Cozy Dell / Sacate sandstone-shale

22.1(0.8) Refugio pass - turn left

BOTANICAL NOTE: The red trunked trees here are not manzanita (*Arctostaphylos* spp.) but madrone (*Arbutus menziesii*).

23.2(1.1) **STOP** - Overlook, a short hike up the hill to the ridge. Here is a good place to discuss the depositional environments of these Eocene rocks (read abstract and see Figures 5 and 6 from Engle, 1980).

24.3(1.1) Turn around and return to Refugio Pass and turn left down the paved road.

??? Pass the presidents driveway - if he is here it is often marked by demonstrators.

27.4(3.1) A good pull-out on the right to view the ocean. Most of this side of the mountain range is composed of the Eocene Sacate Formation. The **BRUSH** covered slopes in the foreground are those of the Sacate, Gaviota, Alegrea, Sespe, and Vaqueros Formations. The **GRASSY** slopes in the distance and to the beach are those of the Monterey and Rincon Formations. Off to the east and to the south can be seen the massive Gaviota, which is dominantly a sandstone in this area. To the east the Gaviota thins, has a shallow water aspect, and ultimately becomes the basal conglomerate of the Sespe Formation to the east. We leave the Eocene and enter the Oligocene at about
28.2(0.8) where there is a dude guest ranch (Circle Bar B). This is the approximate contact between the Sacate and the Gaviota Formations.

28.7(0.5) Gaviota / Alegria (corn field). The Alegria is very thin and crops out for the next 0.1 Mile only. The sespe is thickening eastward and has become the dominant formation stratigraphically above the Gaviota.

28.8(0.1) Alegria / Sespe

29.4(0.6) Sespe / Vaqueros

29.7(0.3) Vaqueros / Rincon

30.9(1.2) Rincon / Monterey

31.7(0.8) Freeway underpass. We are on a small anticline in the Rincon Formation. Turn left and go home.

p.·163–195, 1980

CENOZOIC PALEOBATHYMETRY AND DEPOSITIONAL HISTORY OF SELECTED SEQUENCES WITHIN THE SOUTHERN CALIFORNIA CONTINENTAL BORDERLAND

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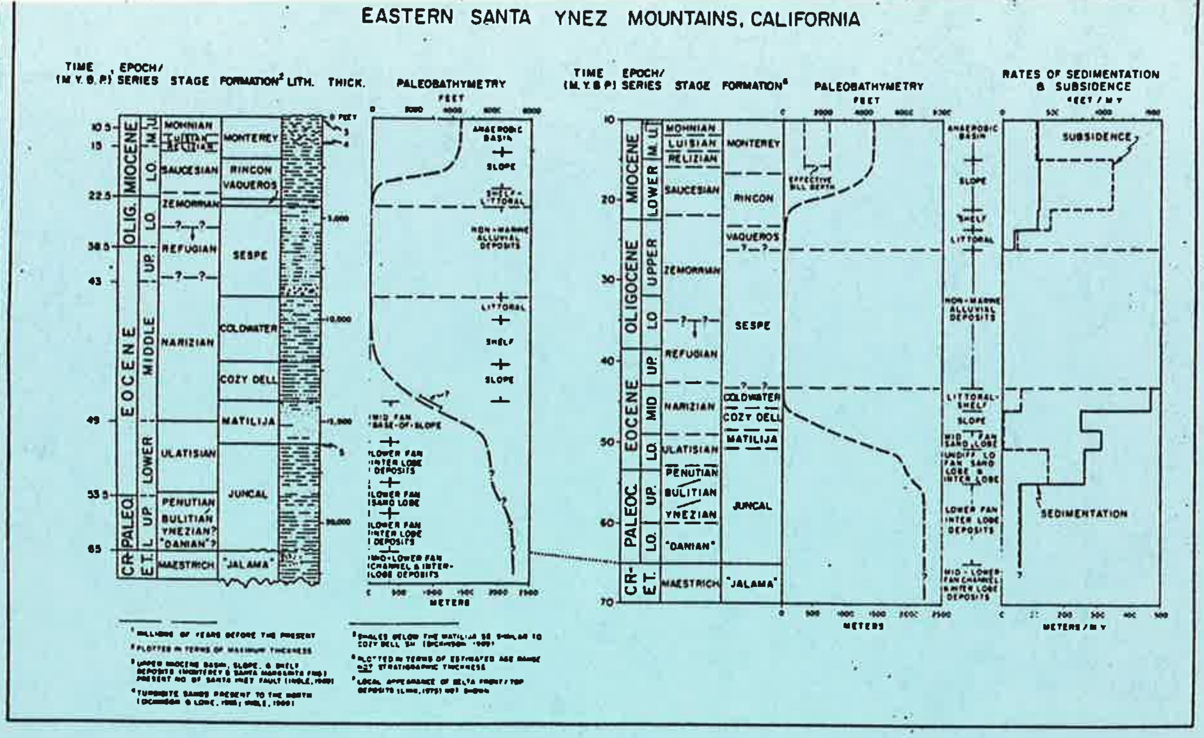
Department of Geology, School of Earth Sciences, Stanford University, Stanford, California 94305

ABSTRACT

Analyses of foraminiferal biofacies and lithofacies within thick Cenozoic sequences exposed in the Santa Ynez Mountains, Ventura Basin, Santa Rosa and San Miguel Islands, Palos Verdes Hills, and the Santa Ana Mountains-San Joaquin Hills area of southern California clearly delineate major Paleogene and Neogene depositional cycles characterizing the tectonically complex portion of the Pacific rim assigned to the Southern California Continental Borderland. Emphasis is placed on estimated upper depth limits of selected species of benthonic foraminifera in reconstructing paleobathymetry of each of six sequences analyzed, with integrated assessment of modern microfaunal and sedimentologic patterns allowing identification of up to 40 lower bathyal through littoral paleoenvironmental boundaries. Each sedimentary column and associated paleobathymetric-paleoenvironmental curve is plotted both in relation to maximum unit thickness and to an updated Cenozoic time scale utilizing available planktonic zonal criteria, radiometric ages, and magnetostratigraphy. The lithostratigraphic-chronostratigraphic plots yield estimated rates of uplift, subsidence, and sediment accumulation for each paleoenvironmental segment identified (basin plain, slope, shelf, etc.), reflecting interplay between tectonic and depositional events during Paleogene and Neogene basin-filling episodes in the northern and eastern portions of the borderland. Paleogene deep marine sedimentation in this region was focused in an east-west trough (Santa Barbara Embayment) in the area of the present Santa Ynez Mountains and northern Channel Islands. Filling of this depocenter was slow during Late Cretaceous through early Eocene time when lower bathyal (≥2,000 m) basin plain and distal fan deposits accumulated at rates of 20–50 m/m.y. balanced by equally slow subsidence. Subsequently, great wedges of outer, middle, and supra fan sediments filled the trough from the north and east at rates of 200–300 m/m.y. during the middle Eocene. This accelerated to 500 m/m.y. during the late Eocene as subsidence waned to less than 100 m/m.y. and slope, shelf, and littoral facies transgressed westward over proximal fan and base-of-slope deposits. A tectonic pause accompanied by widespread nonmarine deposition and erosion occurred over the southern California margin during the Oligocene aided by a global eustatic event. Nonmarine deposition was terminated by abrupt and widespread subsidence (150–500 m/m.y.) during the latest Oligocene-early Miocene coincident with initiation of equally dramatic tectonic events elsewhere around the Pacific rim. Rapid subsidence produced a series of effectively silled middle bathyal Miocene basins momentarily deficient in terrigenous debris allowing relatively undiluted deposition of prolific numbers of diatom frustules from highly productive surface waters. Most middle to late Miocene basin sills hovered at depths within the oxygen minimum zone creating oxygen deficient (0.1–0.5 ml/l.) subsill water, effectively excluding well-developed megainvertebrate faunas capable of destroying bedding and thus facilitating accumulation and preservation of diatomaceous muds and laminated diatomites (Monterey Formation). Tectonic reorganization of the Miocene borderland basins began in late Miocene-early Pliocene time with further subsidence to lower bathyal depths in some synclinal areas. In addition, an increasing influx of terrigenous material in the form of local fan lobes and fine-grained detritus diluted diatom frustules and capped underlying diatomites with early Pliocene mudstones and distal sands. Major flexing of the borderland occurred about 3 m.y. ago (middle Pliocene) marked by rapid uplift (400–1,000 m/m.y.) of anticlinal interbasin ridges and borderland margins as illustrated in the Palos Verdes Hills and Santa Ana Mountains-San Joaquin Hills sequences. This same event was accompanied by dramatic increases in rates of sedimentation (>2,000 m/m.y.) and subsidence (> 1,000 m/m.y.) in synclinal nearshore depocenters such as the Los Angeles and Ventura basins. Both of these basins were filled to capacity by the late Pleistocene as signaled by rapid reductions in rates of sediment accumulation and subsidence (<1,000 m/m.y.). A major late Pleistocene tectonic episode then deformed borderland margins, basin sills, and interbasin ridges to their present configuration initiating modern depositional patterns.



Paleobathymetry, marine paleoenvironments, and estimated rates of sedimentation and subsidence within Cenozoic sediments exposed in the eastern Santa Ynez Mountains, California. Note that paleobathymetry is plotted both in terms of maximum stratigraphic thickness of each formation and alternately in terms of estimated duration of each unit in time following the time scale and correlations presented on Figure 2. The stratigraphic column was compiled from Dibblee (1966), Stauffer (1967a), and Dickinson (1969). Estimated paleobathymetry is based on biofacies analysis of benthonic foraminifera reported from these strata by authors noted on Figure 10 together with data in Blaisdell (1953) and Ingle (1969); stage assignments follow these same authors.

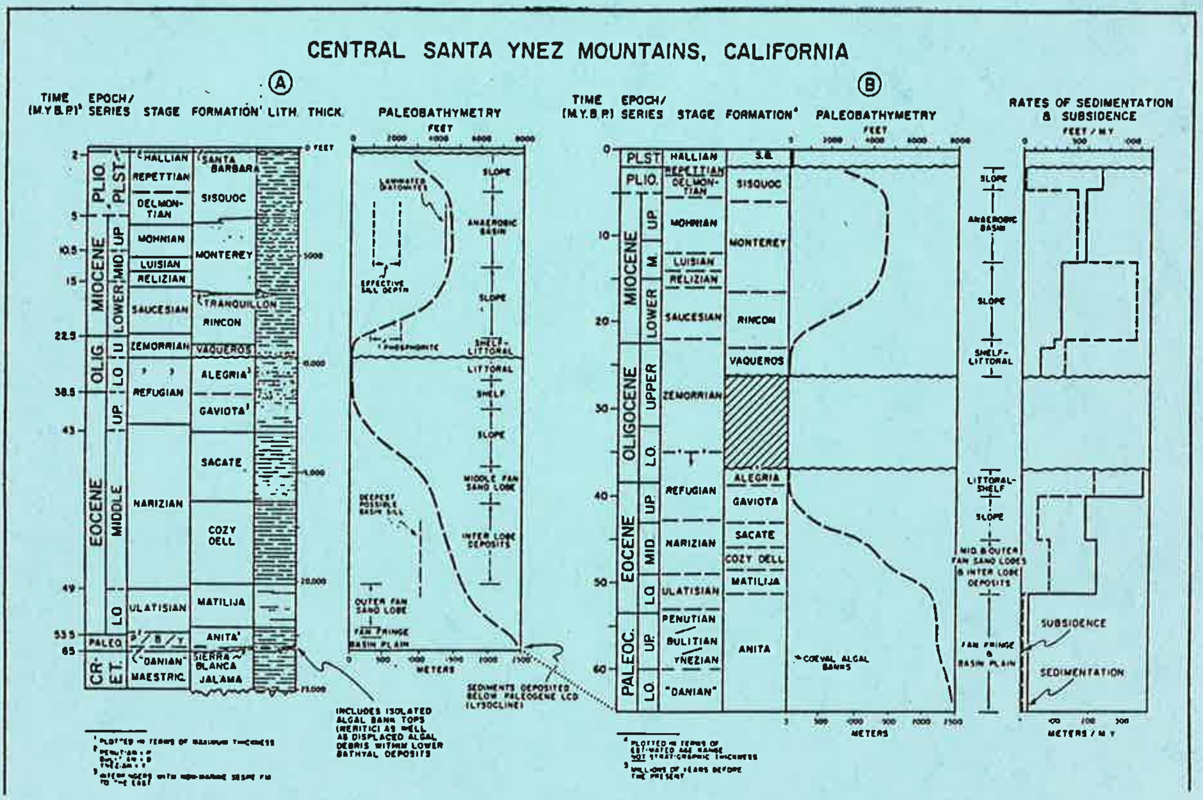
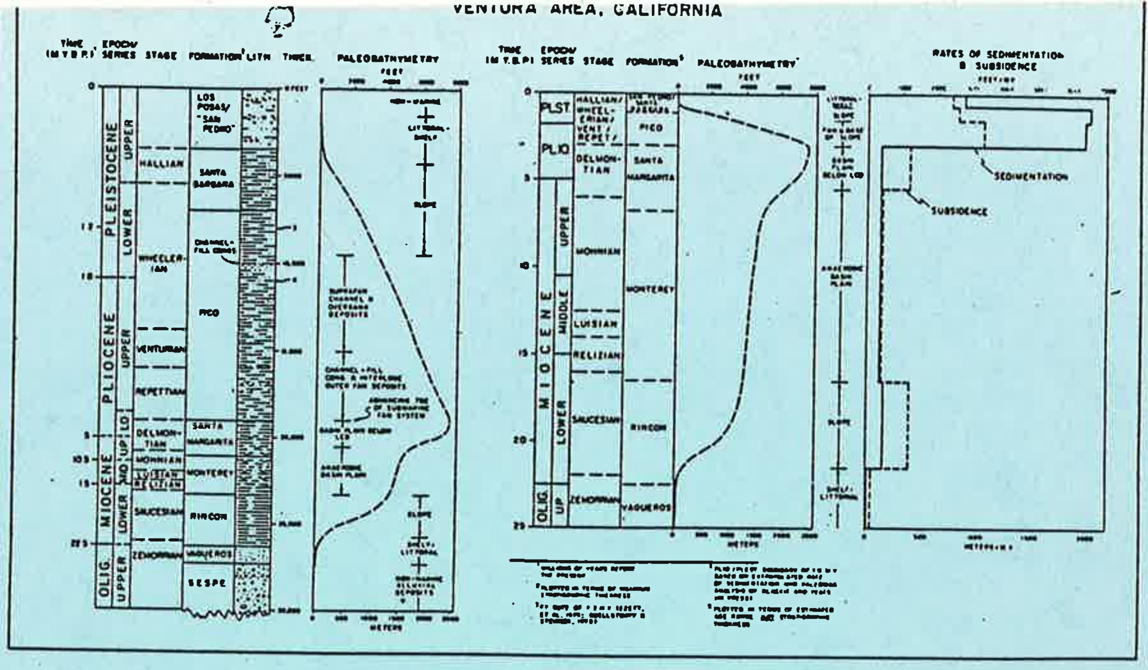


Figure 5

Paleobathymetry, marine paleoenvironments, and estimated rates of sedimentation and subsidence within Cenozoic deposits exposed in the central Santa Ynez Mountains, California. Note that paleobathymetry is plotted in terms of maximum stratigraphic thickness of each formation (A) and alternately in terms of estimated duration of each unit in time (B) based on correlations of provincial stages with the radiometric time scale presented on Figure 2. The stratigraphic column is adapted from Dibblee (1950, 1966) and Kleinpell and Weaver (1963). Estimated paleobathymetry is based on an analysis of benthonic foraminifera reported in these units by Woodring and Bramlette (1950), Wilson (1954), Mallory (1959), Hornaday (1961), Weaver and Weaver (1962), Kleinpell and Weaver (1963), Bandy and Kolpack (1963), Weaver and Molander (1964), Edwards (1972), and Gibson (1973), utilizing methods discussed in text and biofacies detailed in Tables 1 and 2; stage assignments follow these same authors. However, it is important to note that Gibson (1973) documents early as well as early middle Eocene ages for portions of the upper Anita Formation based on planktonic criteria implying facies control of Ulatisian benthonic foraminiferal faunas within these beds; these discrepancies, as well as similar facies problems in older and younger strata, are not fully documented in this generalized column but are noted in text and Figure 2. Interpretation of sediment character and structures is based on descriptions in these same reports. Rates of subsidence and sedimentation were computed for each depositional-paleoenvironmental unit (shelf, slope, etc.) following the method outlined by Bandy and Arnal (1960).



Paleobathymetry and marine paleoenvironments within Neogene deposits of the western Ventura Basin, California. Note that paleobathymetry is plotted in terms of maximum stratigraphic thickness of each formation and alternately in terms of the estimated duration of each unit in time following the time scale presented on Figure 2. Chronostratigraphy incorporates fission-track dates reported by Izett, Naeser, and Obradovich (1974) and Boellstorff and Steineck (1975) and the paleomagnetic data of Blackie and Yeats (1976). Estimated paleobathymetry is based on biofacies analysis of benthonic foraminifera reported from these units by Natland (1933, 1952, 1957), Natland and Kuenen (1951), and Ingle (1967a).

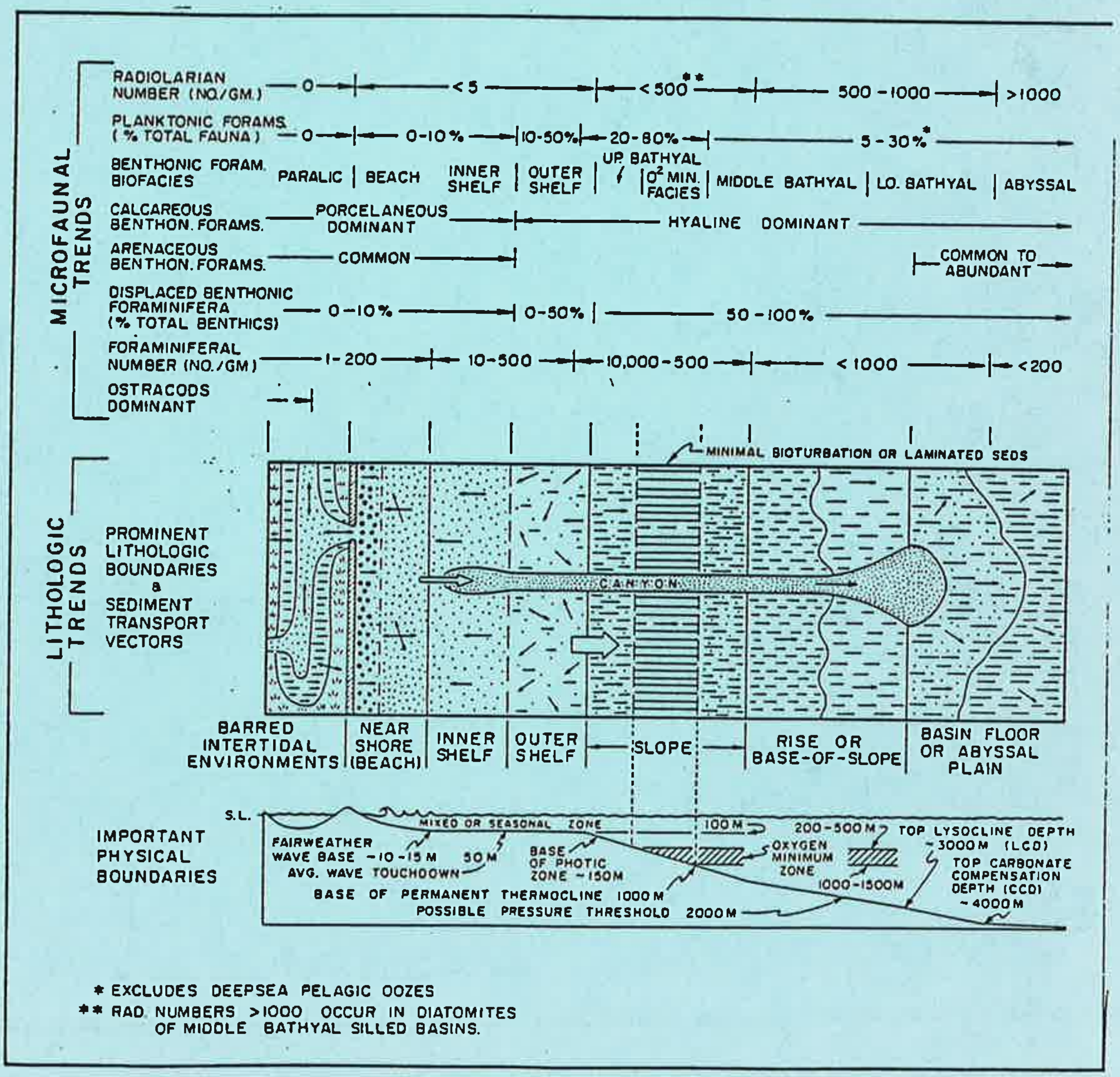
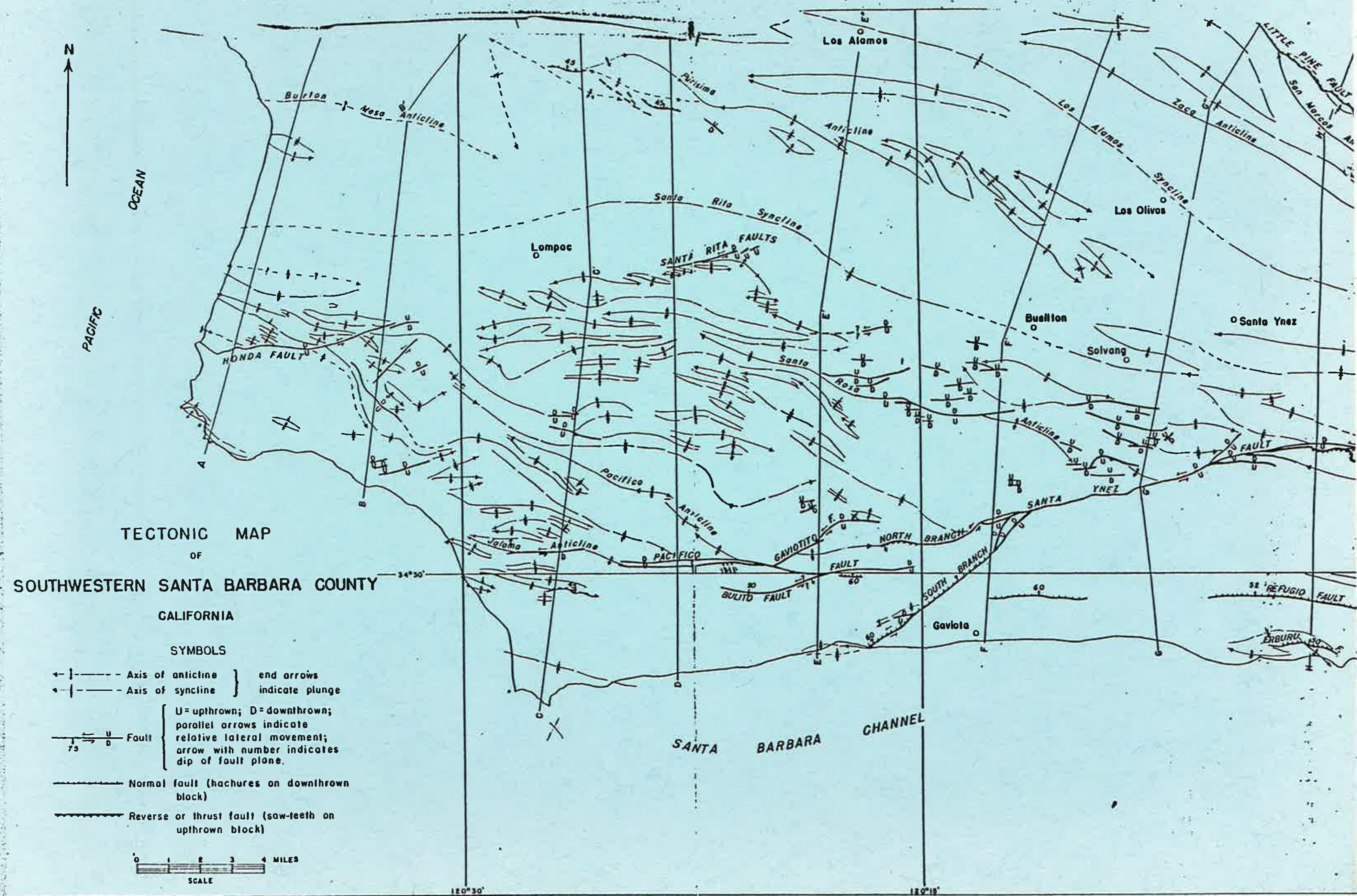


Figure 6

Mode of significant microfaunal and sedimentologic trends across a schematic littoral to abyssal bathymetric gradient along with associated major physical oceanographic boundaries. Arrows indicate general direction of sediment transport with large open arrows indicating transport of suspensates. Foraminiferal trends are based on late Neogene and Recent distributional patterns and abundances. Lithologic patterns modified from Emery (1969): figure from Ingle (1975b).



TECTONIC MAP
OF
SOUTHWESTERN SANTA BARBARA COUNTY
CALIFORNIA

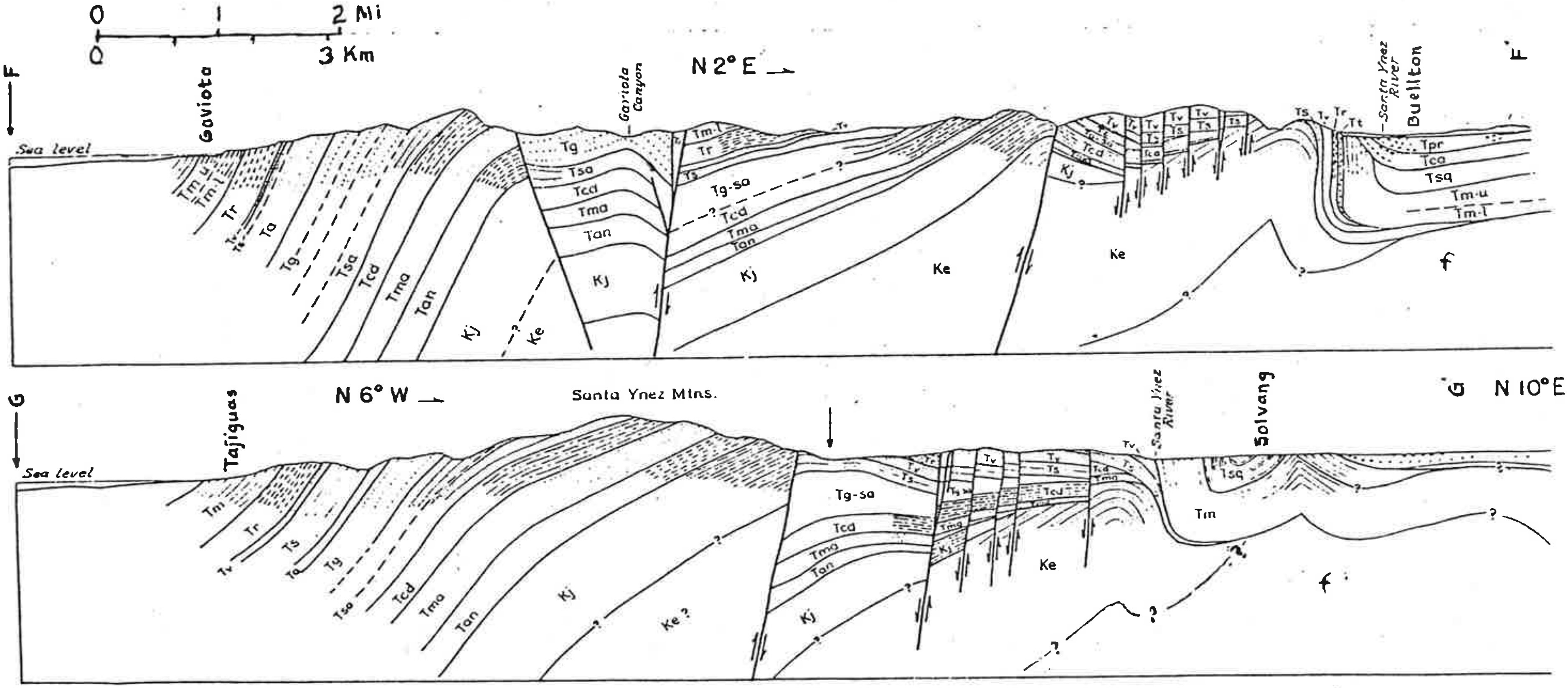
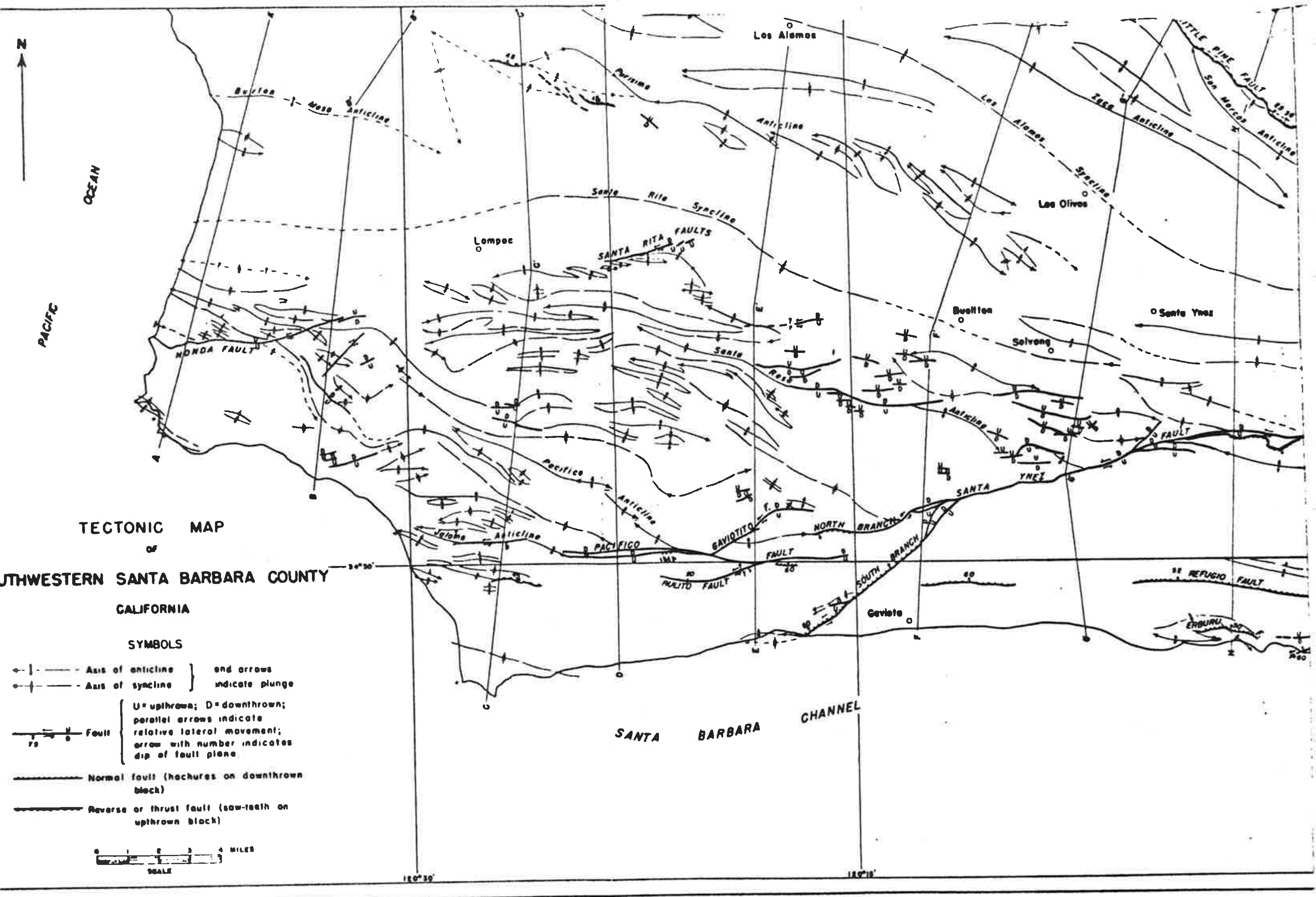


Figure 8. Cross-section of west-central Santa Ynez Mountains from Gaviota and Tajiguas to Buellton and Solvang, showing northward thinning and overlapping of Tertiary and Upper Cretaceous formations. From Dibblee 1950.



TECTONIC MAP
OF
UTHWESTERN SANTA BARBARA COUNTY
CALIFORNIA

SYMBOLS

Axis of anticline } end arrows indicate plunge
Axis of syncline }

Fault { U = upthrown; D = downthrown; parallel arrows indicate relative lateral movement; arrow with number indicates dip of fault plane.

Normal fault (hachures on downthrown block)

Reverse or thrust fault (saw-teeth on upthrown block)

0 1 2 3 4 MILES
SCALE

SOUTHWESTERN SANTA BARBARA COUNTY [Bull. 150

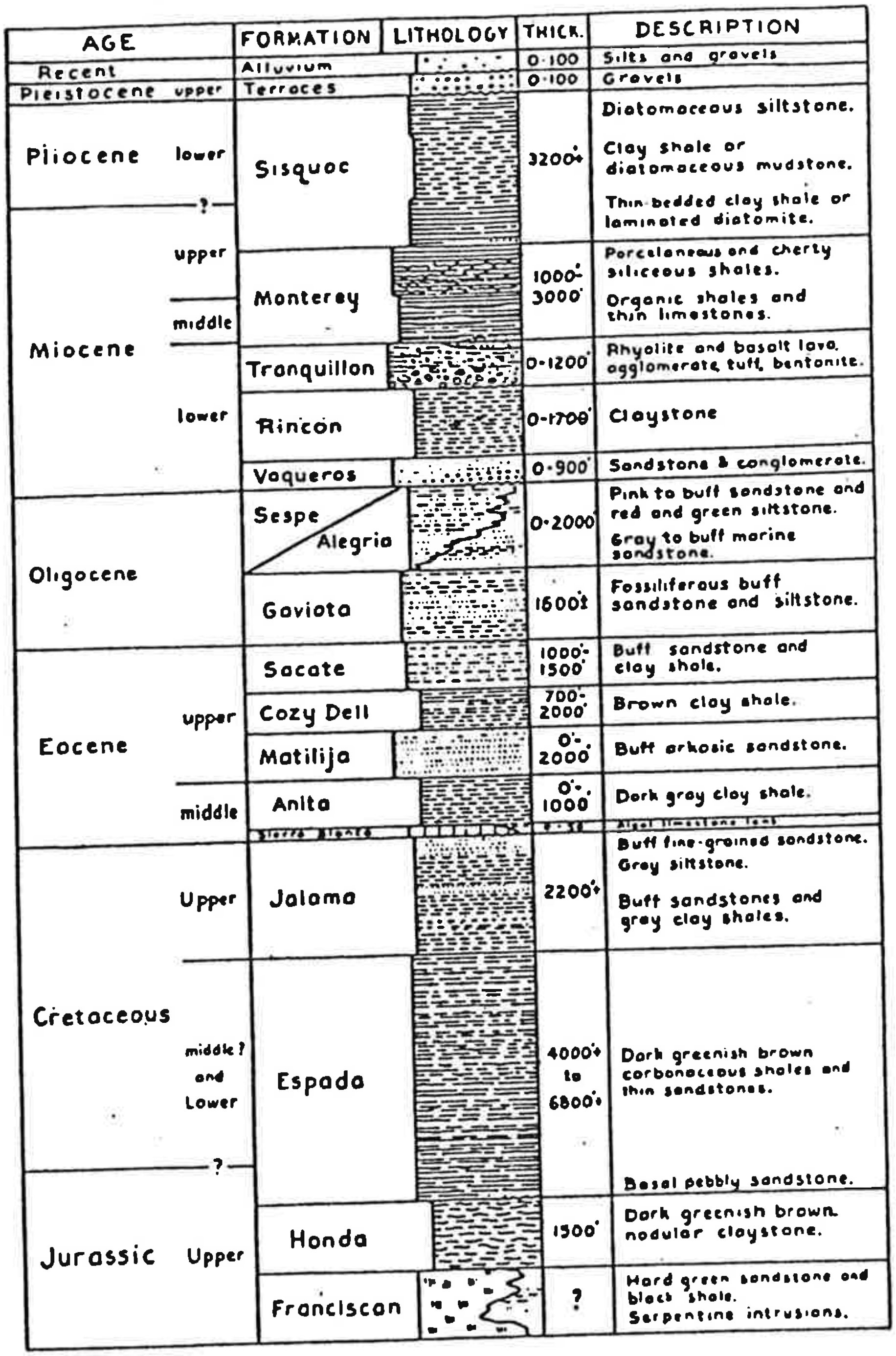
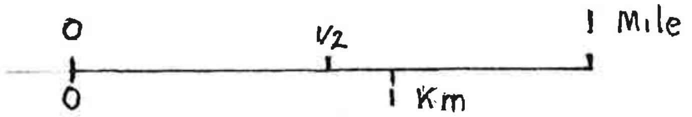


Figure 2. Stratigraphic column, western Santa Ynez Mountains.

WESTERN SANTA YNEZ MOUNTAINS

LEGEND OF STRATIGRAPHIC UNITS OF GEOLOGIC MAPS

Qmf	Man-made fill	HOLOCENE	QUATERNARY
Qg	River sand-gravel		
Qa	Alluvium		
Qls	Landslide	?	
Qoa	Older alluvium	PLEISTOCENE	
	unconformity		
QTp	Paso Robles Formation (nonmarine)	? PLIOCENE	?
Tca	Careaga Sand (marine)		TERTIARY
	unconformity in northern areas		
Tsqd	Sisquoc diatomite (marine)	MIOCENE	
Tmd	Monterey diatomite (marine)		
Tm	Monterey siliceous or cherty shale (marine)		
Tml	Lower Monterey shale (marine)		
Tls	Dolomitic limestone (marine)		
Ttb	Tranquillon basaltic tuff-breccia		
	unconformity in northern areas		
Tr	Rincon clay shale (marine)		
Tvq	Vaqueros sandstone (marine)	?	
Tvqc	Vaqueros conglomerate (marine	OLIGOCENE	
Tsp	Sespe red beds (nonmarine)		
Tsg	Sespe conglomerate (nonmarine)		
	unconformity in northern areas		
Ta	Alegria formation (marine)	? EOCENE	
Tg	Gaviota formation (marine)		
Tsa	Sacate formation (marine)		
Tcd	Cozy Dell shale (marine)		
Tma	Matilija sandstone (marine)		
Tan	Anita shale (marine)		
Tsb	Sierra Blanca limestone (marine)		
	unconformity in northern areas		
Kj	Jalama formation (marine)	UP. CRETACEOUS	
Ke	Espada shale (marine)	LO. CRETACEOUS	



SCALE OF MAPS 1:24000

GEOLOGY OF HOLLISTER RANCH AREA WEST OF GAVIOTA

T.W.Dibblee Jr. 1958

GEOLOGY OF RANCHO SAN JULIAN AREA SOUTHEAST OF LOMPOC

T.W.Dibblee Jr. 1958

GEOLOGY OF NOJOQUI VALLEY AREA SOUTH OF BUELLTON

T.W.Dibblee Jr. 1958

GEOLOGY OF LOWER NOJOQUI CREEK AREA SOUTH OF BUELLTON

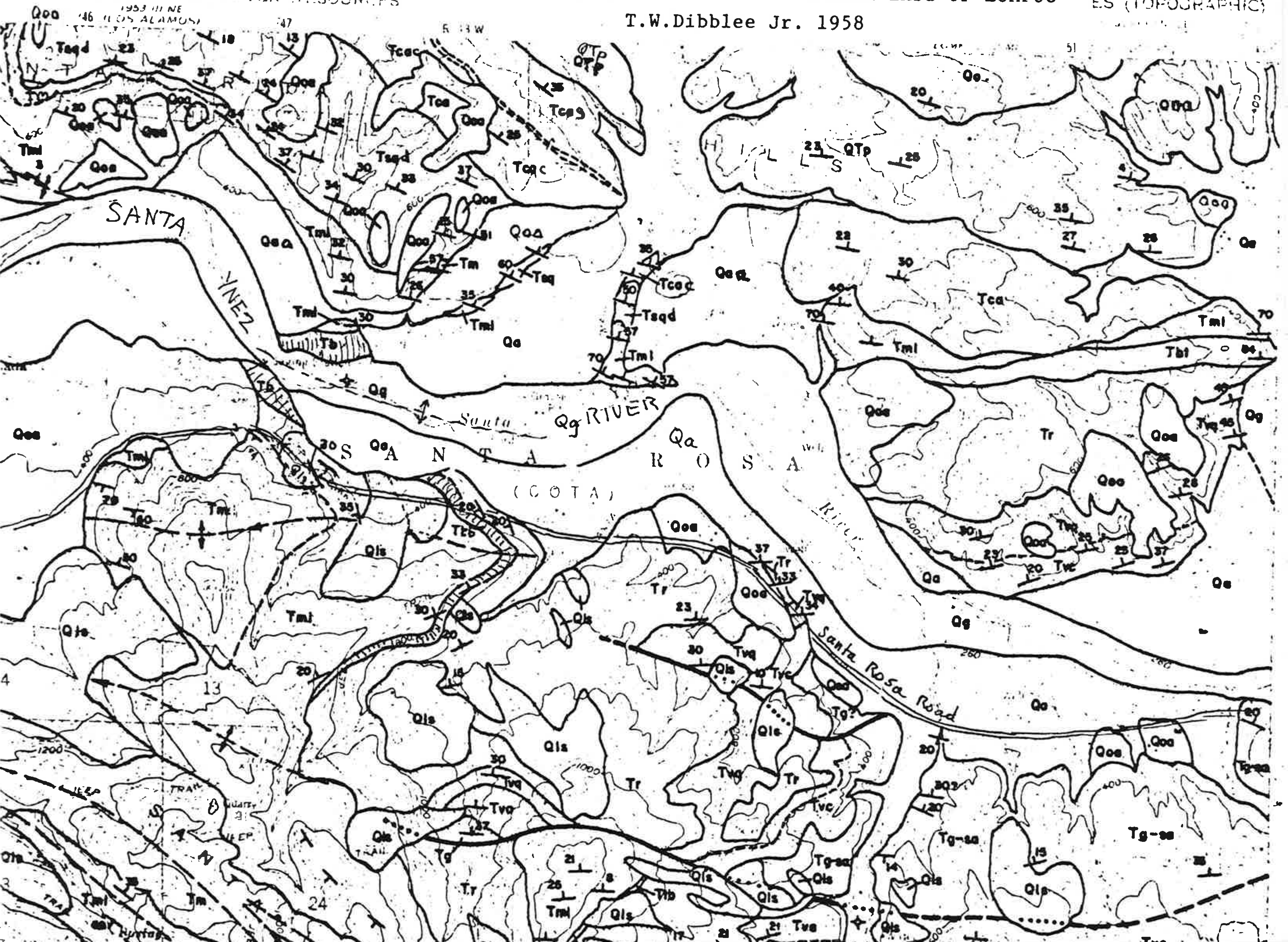
T.W?Dibblee Jr. 1958

EDMUND G. BROWN, GOVERNOR
BANKS, DIRECTOR OF WATER RESOURCES

SANTA ROSA HILLS QUADRANGLE
NTA BARBARA CO.
ES (TOPOGRAPHIC)

GEOLOGY OF SANTA ROSA PARK AREA EAST OF LOMPOC

T.W.Dibblee Jr. 1958



GEOLOGY OF GREFCO DIATOMITE QUARRIES SOUTHEAST OF LOMPOC

T.W.Dibblee Jr. 1958

Understanding California's Geology - Our Resources - Our Hazards

CALIFORNIA GEOLOGY

SEPTEMBER 1981

CALIFORNIA DIVISION OF MINES & GEOLOGY

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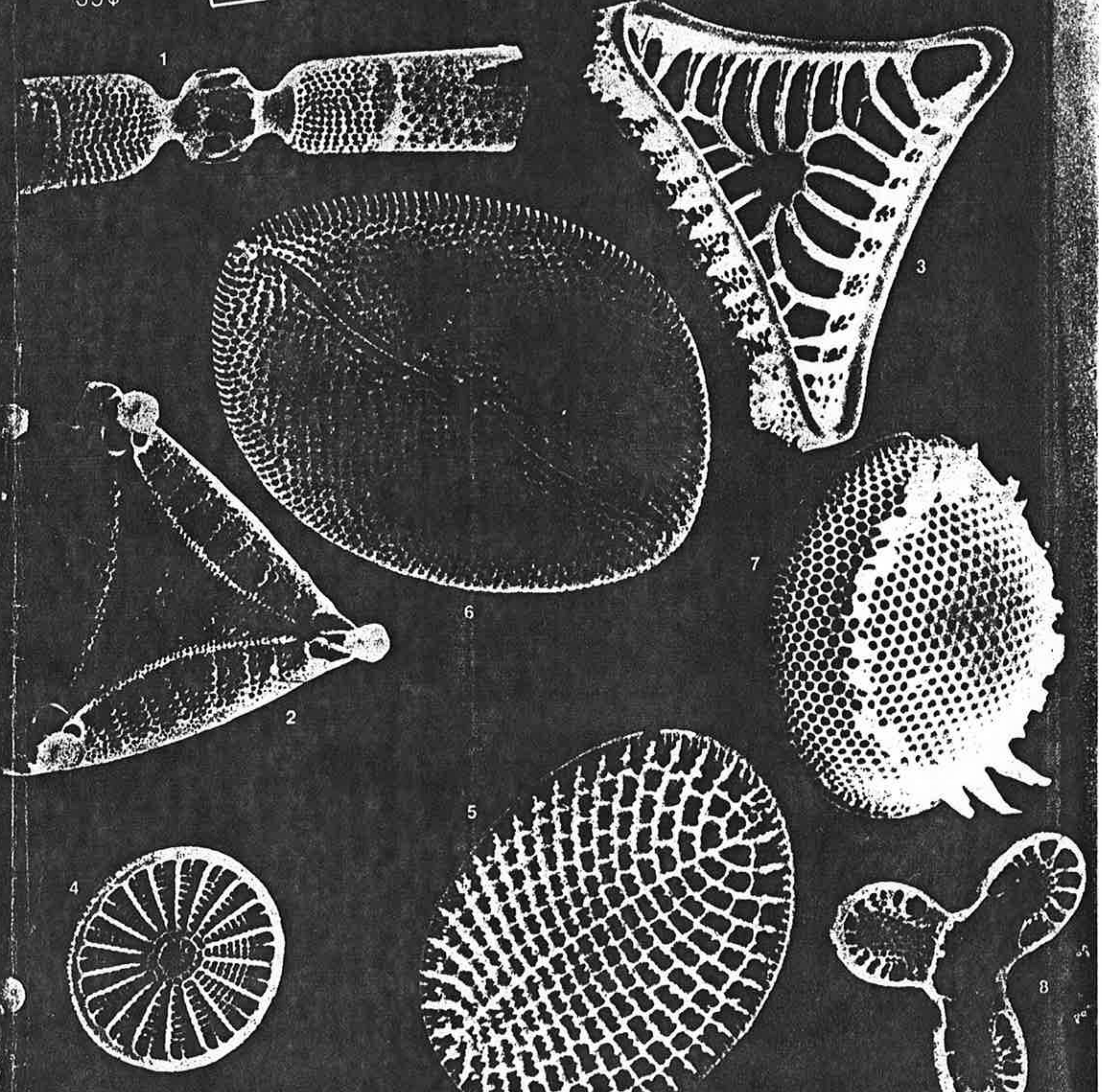

Cover: Photomicrographs showing the intricate and diverse shapes of some diatoms: 1. Strangulonema barbadenis, Eocene, South Atlantic, x 2000 approx., 2. Entogonia sp., same locality, x

Photomicrographs furnished by H. S. Culver. The accumulation of these microscopic skeletal remains in marine and fresh water environments during Tertiary and Quaternary epochs has resulted in the formation of diatomaceous earth. Diatomaceous earth, its

CALIFORNIA'S DIATOMITE INDUSTRY

By

GARY C. TAYLOR, Geologist
California Division of Mines and Geology

This article is compiled in part from *Diatomite industry in California* by William B. Clark, CALIFORNIA GEOLOGY, v. 31, no. 1, p. 3-9, 1978 (out of print) and *Diatomite* in *Mineral resources of California* by George B. Cleveland, CDMG Bulletin 191, p. 151-158, 1966. Up dated information on the status of the diatomite industry through 1980 is included...*editor*

INTRODUCTION

The United States is the world's largest producer and consumer of diatomite. California produces in excess of 60 per cent of the approximately 700,000 short tons mined annually in the United States.

The Lompoc District in western Santa Barbara County contains the most extensive known deposits of high-quality diatomite of marine origin in the world. A recently completed exploration drilling and testing program by Grefco, Incorporated, within the Lake Britton area of Shasta County, has defined a large Pliocene embayment that possibly contains the largest commercial grade freshwater deposit of diatomite in the world. Exploitation of this massive deposit could assure both California's and the nation's continued preeminence in the mining, processing, and exportation of diatomite.

In 1979, diatomite production in the United States totaled 717,000 short tons valued at $90.3 million. California's share of this production amounted to 59 per cent or 422,000 short tons valued at $60.9 million. Since 1974, California has been the source of 58 per cent or more of the United State's annual production of diatomite (figure 1). The diatomite industry contributed approximately 4 per cent of the $1.8 billion total of nonfuel mineral production recorded in California for the year 1979 (U.S. Bureau of Mines).

Studies made by the diatomite producers and data collected by the U.S. Bureau of Mines and the California Division of Mines and Geology indicate that the known reserves of diatomite in the Lom-

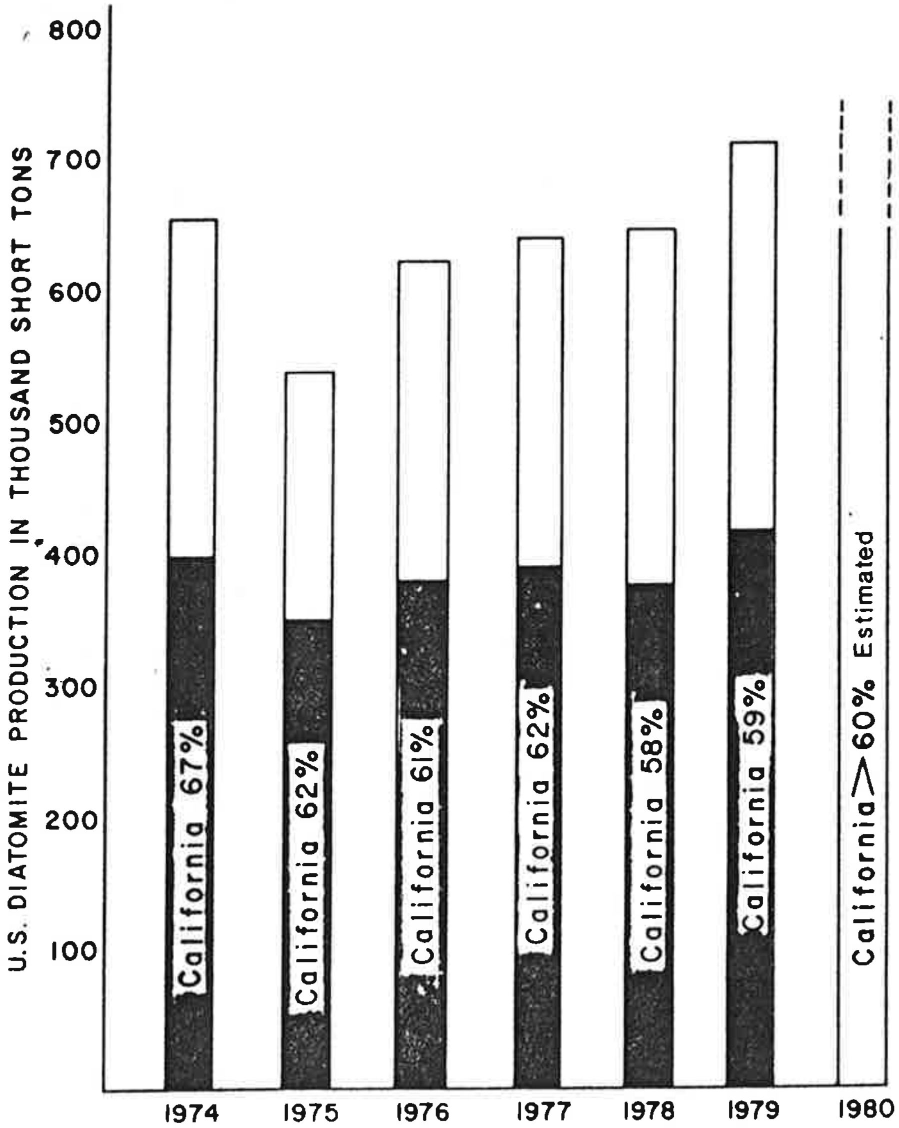

Figure 1. Bar graph showing California's percentage of the total United States diatomite production.

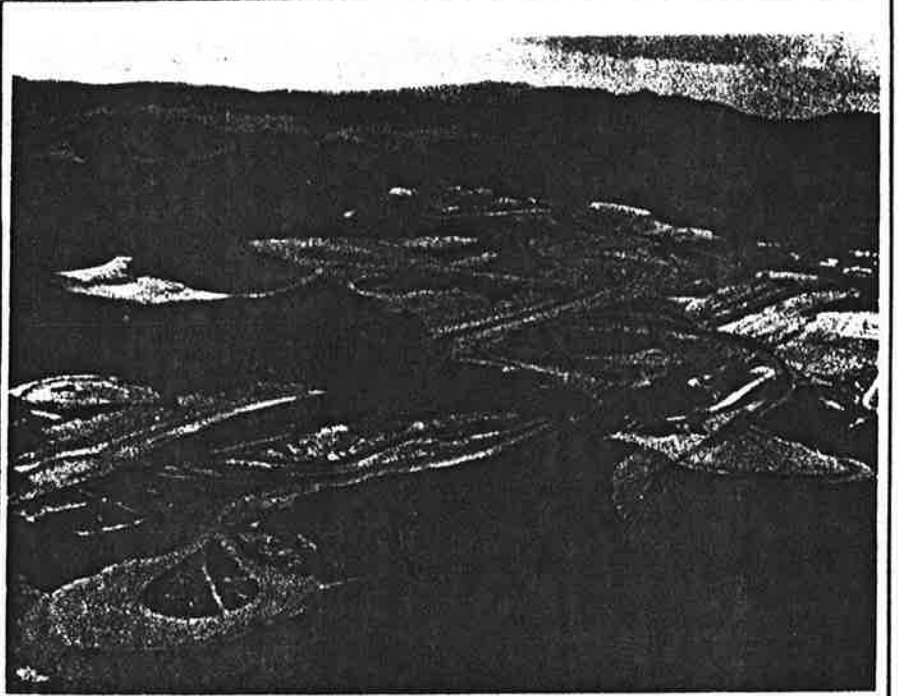

Photo 1. Oblique aerial view of the diatomite quarries, Lompoc, Santa Barbara County; view west. *Photo courtesy Johns-Manville Corporation.*

poc District range from between a 50-year to a 100-year supply at the present rate of production. Total resources for the extensive deposits of diatomite of freshwater origin in the Lake Britton region have not yet been determined, but reserves delineated to date could supply a plant for over 50 years of production (Smith, 1980). Total diatomite resources in the western United States have been estimated to be 600 million tons (Schroeder, 1970).

HISTORY OF DEVELOPMENT

The commercial value of diatomite was not recognized until the late 1880s, when a small amount was mined from the deposits at Lompoc for building stone. In 1889, production records show that 39 tons of diatomite were mined from deposits near Calistoga in Napa County. During the early 1900s, only a few hundred tons were mined annually in California, but the material was being tested for use in insulation, filtering, and in refining of beet sugar. The latter use became the foundation of the modern diatomite industry. Suitability for filter application has been a prime consideration in the evaluation of any diatomaceous earth deposit planned for large scale exploitation.

The Lompoc deposits were being actively developed at the turn of the century, and, beginning in 1904, the deposits in Monterey County were developed. At the time of World War I, California's annual production had reached about 13,000 tons.

The diatomite industry developed rapidly after World War I from an important statewide industry, to one of national and even international significance. The Johns-Manville Corporation acquired a large part of the Lompoc deposits in 1928, and in 1930 the Dicalite Company opened the extensive deposits in the Palos Verdes Hills in Los Angeles County. The industry was consolidated by a few large corporations during the 1940s, and with the stimulus of World War II and industrial expansion since then, a steady rise in both tonnage and average price has been recorded. The Dicalite Company acquired deposits near Lompoc in 1942, and in 1944 the company was purchased by the Great Lakes Carbon Corporation. Mining of diatomite near Bradley, in Monterey County, ceased in 1942 after nearly $500,000 worth of material had been produced by the Pacatome Company. The Palos Verdes Hills deposits near Walteria were abandoned in 1958 due to encroaching urbanization and depletion of ore reserves.

Although some effort was made toward the commercial production of diatomite in other counties during the period 1947-1955 (Oakeshott, 1957), by 1955 only the major deposits at Lompoc were being operated by Johns-Manville Corporation and Dicalite Division of Great Lakes Carbon Corporation. In the period from 1955-1980, diatomite production increased appreciably in the Lompoc area and minor production was contributed by operators in Napa, Kern, and Lassen Counties.

In 1980, production of diatomite was recorded in four districts within California by the following listed producers (figure 2):
(1) The Lompoc Mining District in western Santa Barbara County (photo 1), by Johns-Manville Corporation and Grefco, Incorporated;
(2) The Casmalia Mining District in western Santa Barbara County, by Airox Earth Resources;
(3) The McKittrick District in western Kern County, by Excel Minerals Company (photo 2); and

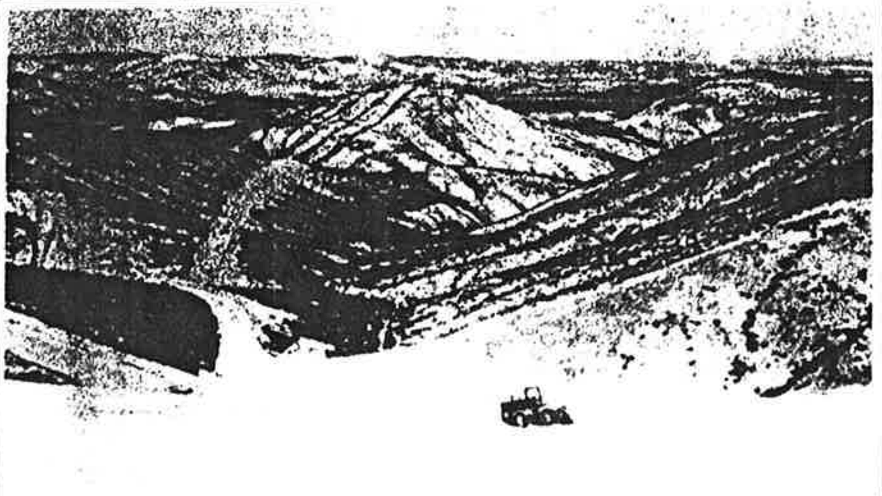

Photo 2. Diatomaceous shale pit on the Hudson Ranch near Maricopa, Kern County; view northwest. *Photo by W. B. Clark.*

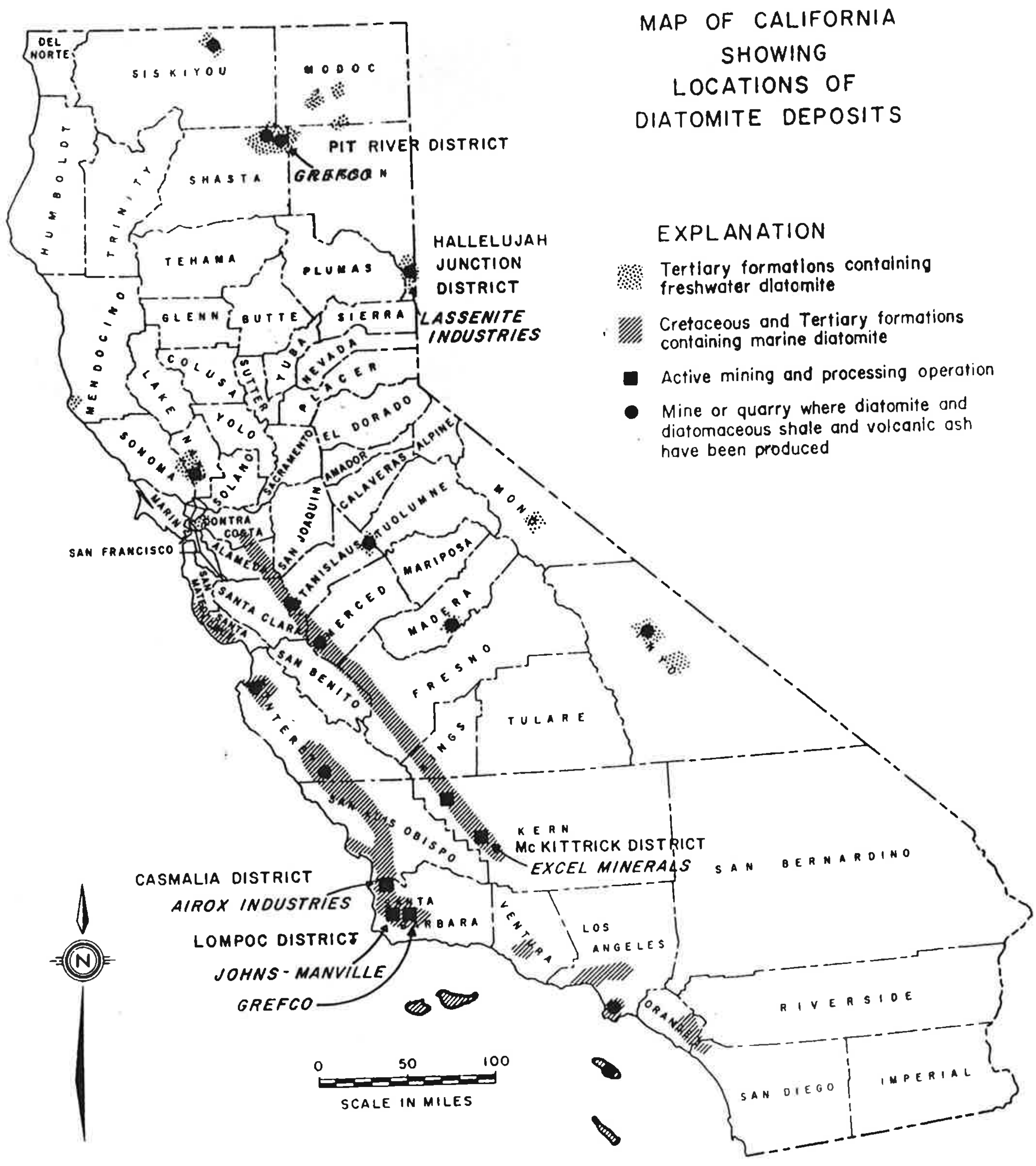

Figure 2. Locations of diatomite deposits and producers in California.

(4) The Hallelujah Junction Mining District in southeastern Lassen County, by Lassenite Industries.

GEOLOGY

Diatomaceous earth (kieselguhr) is an accumulation of fossils. The fossils are mainly diatoms, a class of minute plants that live in water. They are simple, one-celled forms of largely floating (plankton) organisms that have a siliceous skeleton. Upon death, these relatively inert skeletal remains sink. Enormous numbers of these remains accumulate as a diatomaceous ooze on the bottom of lakes, estuaries, and oceans. Removal of organic material and compaction through geologic time changes the ooze to a soft sedimentary rock called diatomite.

The shape and ornamentation of the diatom shell (frustule), which is the most diverse imaginable (figure 3 and photo 3), is the main basis for separating the many thousands of known species. The

Photo 3. Photomicrograph of Lake Britton diatoms (1000x). *Photo by Craig Smith.*

shells and shell particles range in size from a few microns to a few hundred microns; each particle is essentially flat, commonly perforated and relatively inert. All the particles are loosely packed to yield a highly porous and permeable material. This combination of properties makes diatomite an efficient medium for commercial application in filtration, fillers, insulation, and a myriad of other uses.

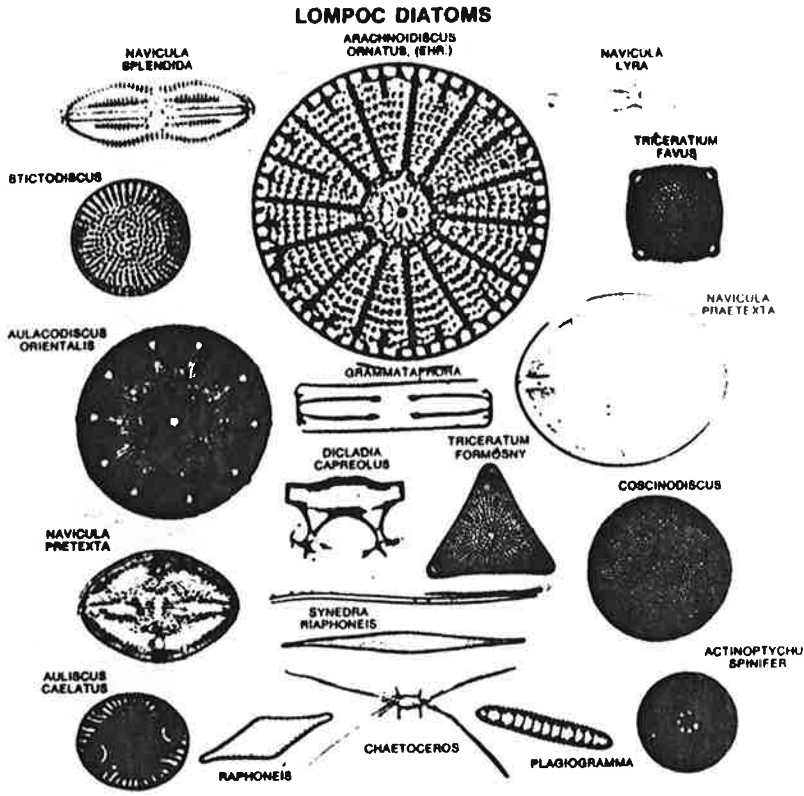

Figure 3. Lompoc diatoms. *Courtesy Johns-Manville Corporation.*

...Cool, clear, well-lighted water promotes the growth of diatoms, but more important is a constant source of chemical nutrients to replenish those taken out of solution during the growth of the diatom community. The principal lacustrine deposits of [California] all lie in volcanic terranes, and the common association of volcanic ash with diatomaceous earth in both marine and lacustrine strata is well established. Volcanic processes appear to play a significant part in the formation of diatomaceous earth, and this relationship can best be demonstrated for deposits of lacustrine origin and near-shore deposits of marine origin. During volcanic episodes, established drainage systems commonly are dammed by lava flows, and new basins may be created atop the flows themselves; these may ultimately fill with water and form lakes. Lakes, being infinitely smaller systems than oceans, are much more sensitive to slight chemical and physical changes. Chemical nutrients essential to diatom growth are not readily supplied to streams feeding lake waters during normal weathering and erosion. However, solutions and emanations accompanying volcanism, and ranging widely in chemical composition and concentration, may be introduced into lake waters, enriching them in those elements necessary for diatom growth. Chief among these elements is silica which the diatom uses in building its shell. Silica is presumed to be supplied both by silica-rich hydrothermal solutions and by the chemical breakdown of volcanic ash. Ash deposited directly into a lake breaks down chemically and provides a ready source of silica, while a long-term supply is derived from subaerially deposited ash, which is carried by streams into the lake basin during subsequent erosion of adjacent highlands. Among the several other elements required by diatoms, the concentration of nitrogen and phosphorus is considered a limiting factor in diatom growth because of the relative paucity of these elements in lake and ocean water.

Recent work has shown that the volcanic environment is not a requisite for the formation of thick marine diatomaceous sediments. Studies indicate that in the Gulf of California, the concentration of silica, and presumably other nutrients, is replenished periodically and diatoms flourish. The subsequently formed sediments are of purity comparable to those of California's principal commercial diatomite deposits. The nature of diatomaceous earth formed in a marine environment differs somewhat from that formed in a lacustrine environment. Generally, each habitat supports a diatom flora indigenous to it, and relatively few diatoms flourish in both marine and lacustrine waters. Moreover, marine deposits generally comprise a wider variety of species. An individual deposit of either marine or lacustrine origin may have an advantage over the other type in certain commercial applications, but suitable material from both kinds of deposits has been successfully processed for all the principal uses. Generally, the marine deposits have proven to be a more abundant and versatile source of material for a wider range of applications than have those of lacustrine origin.... (Cleveland, 1966).

Diatomaceous bearing strata are massive, laminated to lenticular, and range from a few inches to hundreds of feet in thickness (photo 4). In the Lompoc Area, total stratigraphic thickness of the diatomite-bearing zone may exceed 1000 feet. However, most of this section contains too much clay, chert, and other impurities for industrial use, and only selected strata from a few feet to a few tens of feet thick are quarried for commercial applications. In the Lake Britton area the diatomite beds are massive, tens of feet thick, and with almost insignificant sand and silt zones, although considerable variability is shown in density, whiteness, compactness, and purity (Smith, 1980).

PHYSICAL PROPERTIES OF DIATOMITE

...Diatomaceous earth is light colored, generally gray to white, but commonly ivory, pale pink, pale green, yellowish-brown, or dark brown. Diatomaceous earth, being composed principally of opaline-like silica ($SiO_2 \cdot nH_2O$), is a relatively inert rock [that is] soluble only in strong acids or alkalies. Commonly, clay and volcanic ash are the main impurities, with some silica sand, calcium or magnesium carbonates, and iron oxides or iron carbonates present. The pH ranges from about 4.5 to 8. The natural moisture content is generally high, ranging commonly above 50 per cent in commercial deposits. The specific gravity of opal ranges from 1.8 to .25. However, because of the porosity of the individual diatom shell and the degree of compaction, the apparent specific gravity of dry unconsolidated diatomaceous earth ranges from .12 to .25, and dry consolidated material has a specific gravity of about 0.4. The porosity of commercial diatomaceous earth ranges from 75 to 85 per cent. The combined water (about 6 per cent) is driven off between 500° and 800°C and the melting point is reached between 1,400° and 1,600°C; however, earths containing certain impurities may melt well below 1,400°C. Specifications for commercial diatomite (largely filter use) emphasize particle-size distribution and species of diatoms (shapes and sizes), as well as density and physical state, with chemical purity generally a secondary consideration.:. (Cleveland, 1966).

GEOGRAPHIC DISTRIBUTION

Although diatomaceous oozes are accumulating in both the freshwater and marine basins in existence today, all commercial production of diatomite is from deposits ranging in age from Cretaceous to Pliocene and localized in five major geographic regions—the Transverse Ranges, Modoc Plateau, Coast Ranges, Basin and Ranges, and the Peninsular Ranges. Minor deposits are located elsewhere in the state (figure 2).

Transverse Ranges

...The most extensive deposits of diatomite of marine origin occur in the Lompoc district in the northern foothills of the Santa Ynez Mountains in western Santa Barbara County (figure 4). The thick beds of gently-folded diatomite are in the Sisquoc Formation (Mio-Pliocene) and the Monterey Formation (Miocene) (photo 4).

The two largest diatomite mining and processing operations in the State are located at Lompoc. Diatomite and bituminous diatomaceous shale are mined in the Casmalia Hills north of Lompoc, in Santa Barbara County. Diatomite of marine origin is found in several other areas in the Transverse Ranges, including sizeable deposits at South Mountain, southeast of Santa Paula in Ventura County, and in the Santa Monica Mountains in Ventura and Los Angeles Counties.

Modoc Plateau

Extensive deposits of diatomite of freshwater origin are in the Modoc Plateau region of northeastern California. These deposits were accumulating during the same time that volcanic activity occurred in Miocene, Pliocene, and Pleistocene times.

The largest known diatomite deposits in the Modoc Plateau occur in eastern Shasta County. The most extensive deposit is northeast of Burney in the vicinity of Lake Britton (figure 5). In this deposit, flat-laying beds of diatomite up to several hundred feet thick crop out along the shore of Lake Britton for a distance of at least 10 miles. Diatomite has been mined intermittently here since the 1920s. Two other large deposits are at nearby Hat Creek and near the Pit River powerhouse west of Fall River Mills.

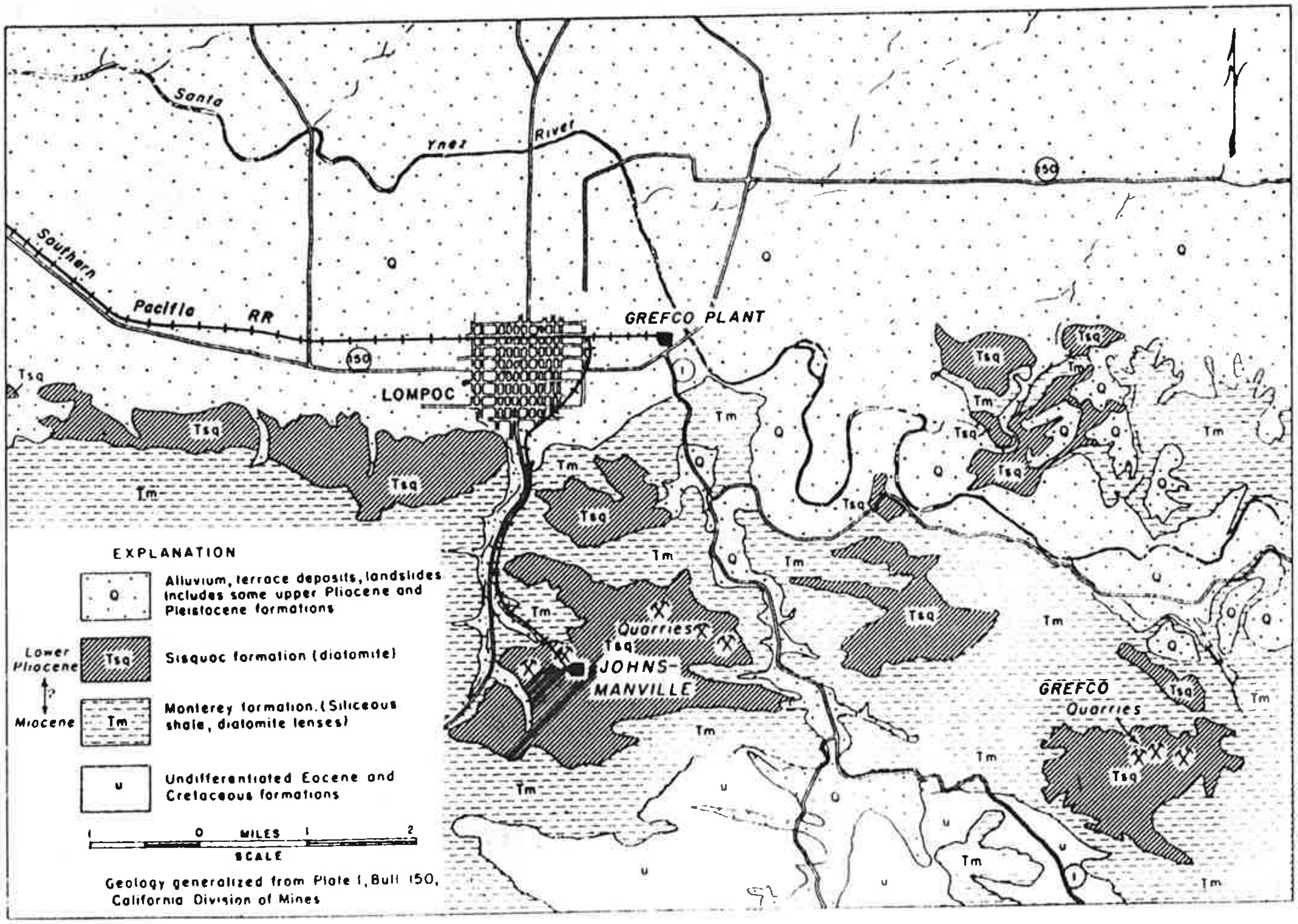

Figure 4. Geology of the Lompoc area, Santa Barbara County, showing distribution of the diatomite-bearing Sisquoc Formation. *After Dibblee, 1950.*

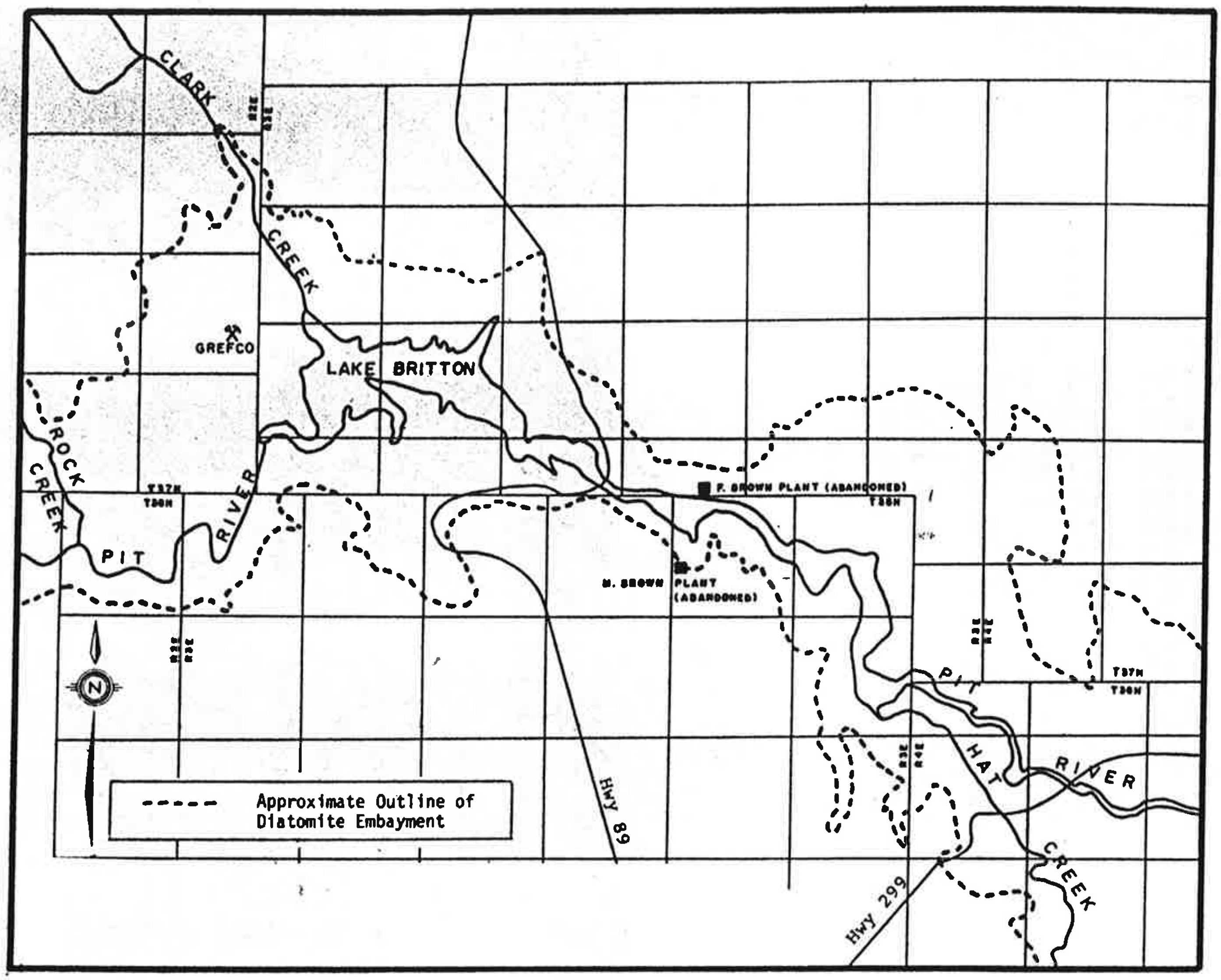

Figure 5. Pit River diatomite province. *After Smith, 1980.*

Another sizeable deposit of diatomite is in the Willow Creek-Tableland-Mount Dome area about 15 miles southeast of Dorris in northeastern Siskiyou County. Here, diatomite of freshwater origin occurs in horizontal beds up to 200 feet in thickness. In places it is capped by volcanic rocks. Other deposits of unknown size in the Modoc Plateau region occur south of Alturas in Modoc County.

Coast Ranges

Thick sequences of diatomite and diatomaceous shale and chert are found along the eastern foothills of both the Diablo Range and Temblor Range. These beds are near the west margin of the San Joaquin Valley and extend north and northwest from Kern County to the Mount Diablo area, Contra Costa County. The principal diatomite deposits occur in portions of the Moreno Formation (Late Cretaceous and Paleocene), the Kreyenhagen Formation (Eocene and Oligocene), and the Monterey and Reef Ridge Formations (Miocene). At the present time diatomite is produced in western Kern County near McKittrick and diatomaceous shale is mined near Maricopa. Diatomite has been produced also near Crows Landing in western Stanislaus County. Extensive undeveloped diatomite deposits occur northwest of Coalinga in the Cantua Creek area of western Fresno County.

In the Santa Lucia Mountains, diatomite and diatomaceous sedimentary rocks occur in a number of places west of Bradley in southern Monterey County. The diatomite in the Monterey Formation (Miocene) is marine in origin. Moderate amounts of diatomite were produced commercially at Hames Valley in this area from 1906 to 1942. Other diatomaceous beds are in the Santa Lucia Range area near King City and 4 miles southeast of Monterey. The deposit near Monterey was worked during the 1920s and 1930s. Diatomite deposits also occur south of Morro Bay in San Luis Obispo County.

In the northern part of the Coast Ranges, diatomite beds associated with Pliocene volcanic activity were deposited in freshwater lakes. These deposits occur chiefly in Sonoma and Napa Counties. Diatomite has been mined intermittently in Napa County for many years and is also found in the Pinole area of Contra Costa County.

Peninsular Ranges

Probably the most extensive deposit, and also at one time very significant commercially, was on the Palos Verdes peninsula in western Los Angeles County. Until the area was covered with housing developments in the late 1950s, large amounts of diatomite from the Valmonte Member (upper Miocene) of the Monterey Formation were mined and processed. Diatomite also occurs in the Puente Hills in Los Angeles County and in the western foothills of the Santa Ana Mountains near Santa Ana and San Juan Capistrano, Orange County.

The eight channel islands—the northernmost four located in the Peninsular Ranges and the southern four in the Transverse Ranges—contain deposits of

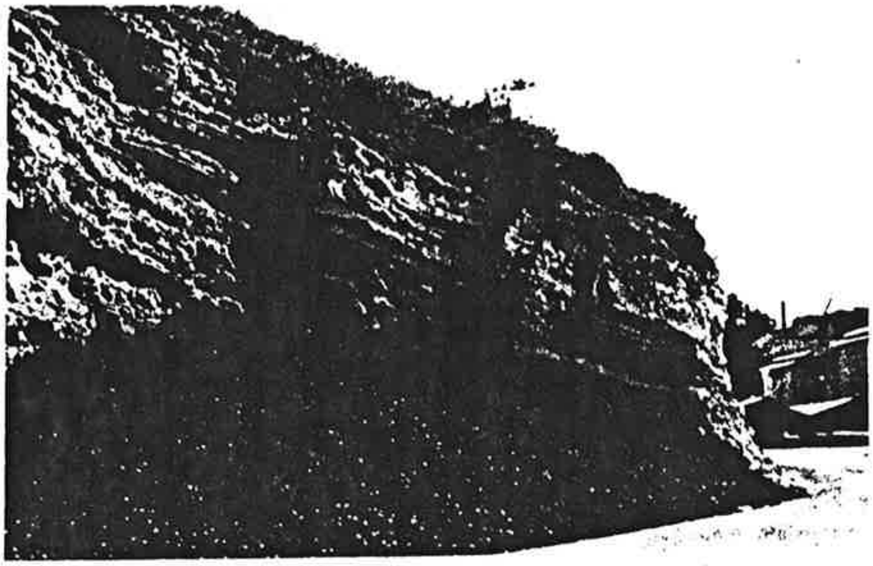

Photo 4. Interbedded diatomite and chert near Lompoc, Santa Barbara County. *Photo by William B. Clark.*

diatomite and diatomaceous shale. These rocks are Miocene in age, some of which are part of the Monterey Formation. The largest deposits are on Santa Catalina, San Clemente, Santa Cruz, and Santa Rosa Islands. Minor amounts of diatomite were produced from the deposit on Santa Catalina Island.

Basin and Ranges

Diatomaceous sedimentary and volcanic rocks in the Basin and Ranges of eastern and southeastern California usually contain volcanic ash and are associated with the volcanic activity that occurred during Pliocene and Pleistocene times. The diatomite was deposited in a series of lakes that existed in those times. At the present time significant amounts of diatomaceous volcanic ash are being mined and marketed as a pozzolan* additive near Hallelujah Junction in southeastern Lassen County. Diatomite is found in Long Valley (Mono County) and in the Owens Valley (Inyo County) where there has been minor production.

Other Deposits

Several thousand tons of diatomite were mined in the early 1900s and early 1960s from a deposit of Plio-Pleistocene age near Knight's Ferry in the lower western Sierra Nevada foothills in western Tuolumne County and eastern Stanislaus County. This deposit is of lacustrine (lake) origin, at least 15 feet thick, and is associated with volcanic rocks.

USES

Recent studies by the U.S. Bureau of Mines, the U.S. Geological Survey (Schroeder, 1970; Durham, 1973), and the California Division of Mines and Geology have indicated that there are at least 300 different uses for diatomite, and possibly there could be as many as 500. The uses of diatomite fall into 10 main categories: (1) filters, (2) mineral filler, (3) insulating material, (4) fine abrasives, (5) absorbents, (6) catalysts, (7) reactive-silica source, (8) structural materials, mainly lightweight aggregate, (9) pozzolans, and (10) conditioners or anticaking agents.

The most important use of diatomite is in filtration (table 1). In 1979 the U.S. Bureau of Mines estimated that approximately 65 per cent of diatomite produced is used for filtering agents (Meisinger, 1979).

Probably the largest use of diatomite as a filtering media is for the filtration of impurities in the brewing process. Sugar refineries, food processers, wineries, and soft-drink manufacturers also use large amounts of diatomite. Commercial dry cleaning establishments, which use large amounts of cleaning fluid over and over again, use substantial amounts of diatomite to purify the fluid. More and more diatomite is being used in water filtration in domestic water works, sewage treatment plants, and swimming pools.

In mineral filler, which accounted for 21 per cent of consumption in 1979 (table 1), the chief use of diatomite is as a paint flattening agent. Diatomite also is used to provide bulk and reinforcement in paper, fertilizers, plastics, asphalt products, and insecticides. Diatomite sometimes is used in the manufacture of silica beads which are utilized as catalyst supports in the manufacture of high-octane gasoline in oil refineries. Diatomite is a source of silica for several other uses such as in the manufacture of sodium, calcium, and magnesium silicates for the chemical industry.

The absorptive qualities of diatomite make it useful in cleansing agents such as floor-sweep compounds and in litter boxes for pets. For many years significant amounts of diatomite have been used in light-weight aggregates and as pozzolan for certain types of concretes....(Clark, 1978).

MINING AND PROCESSING

The suitability of a diatomite deposit as a source of filter media as well as other uses depends upon a number of factors. These include species of diatoms present, size and shape of the diatoms, distribution and relative abundance of the individual diatoms within the deposit, and impurities. Size, location, and accessibility of the deposit are important also. In evaluating an undeveloped deposit, a detailed microscopic examination of collected samples is made. Laboratory testing of the physical properties of the diatomite and small scale pilot-plant studies of processing steps are made. Systematic sampling is necessary, because there may be a considerable amount of both lateral and vertical variation within depositional facies and properties of the diatomite within a single deposit.

Mining

Although open-pit mining methods are presently employed in California and most other places, there were at one time several underground mines located in Lompoc, Hames Valley, Lake Britton, and the Palos Verdes peninsula. Modified room-and-pillar methods generally were employed as diatomite, especially the massive variety, stands well without support.

Diatomite and most diatomaceous shales are quite soft and are usually mined by a combination of ripping and scraping with bulldozers. In these operations tractor-mounted rippers and scrapers are employed for the stripping of overburden, waste removal, and mining of commercial-grade rock. Seldom, if ever, is it necessary to use explosives. Sometimes power shovels are used, usually near the quarry walls.

Excavated rock is loaded with front-end, belt-conveyor, or wheel loaders into end-

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*Pozzolan: Siliceous material such as diatomaceous earth, opaline chert, and certain tuffs, which can be finely ground and combined with Portland cement (in a proportion of 15 to 40 per cent by weight). The pozzolan reacts with calcium hydroxide that is liberated as concrete hardens, forming compounds with cementitious properties, which can counteract the adverse effects of certain undesirable aggregates. Portland-pozzolan cements are highly resistant to penetration and corrosion by salt water (American Geological Institute, 1980).

TABLE 1 - DOMESTIC CONSUMPTION OF DIATOMITE
BY PRINCIPAL USE 1954-1980
(U.S. BUREAU OF MINES MINERAL YEARBOOKS)
Percent of Total Consumption

USE	1954	1965	1970	1975	1976	1977	1978	1979	1980
Filtration	51	50	58	60	60	59	63	65	W*
Fillers	29	25	19	W*	W*	W*	23	21	W*
Insulation	8	5	4	4	5	5	3	3	W*
Other (includes abrasives, absorbents, additives, carriers and coatings) . . .	12	20	19	36	35	36	11	11	W*

W* - withheld to avoid disclosing individual company confidential data, included with "other"

dump or bottom-dump trucks for delivery to the mill. Some of the trucks or ore carriers used in the quarries have capacities of as much as 60 bank cubic yards (or 99 loose cubic yards) (photo 5). From the quarries the diatomite is trucked to the mill. At Lompoc, the Johns-Manville Corporation utilizes a tunnel mined in diatomite for hauling rock from quarries to the processing plant.

Processing

...At the two large Lompoc plants where there are many final products, processing is complex (figure 6). Selective mining in the quarries and blending in the ore bins usually are necessary so that plant feed meets the quality requirements for the various processes. The crude diatomite is crushed in rolls or hammer mills, dried and milled by heated air in milling blowers, and air classified. Following collection in cyclones, the sized diatomite is sent either to storage silos and sacked or bulk loaded for shipment to market, or it is further processed by calcining.

Calcining is done in gas or oil-fired rotary kilns at temperatures of 1800° to 2200°F (980° to 1200°C) (photo 6). Part of the diatomite is calcined without fluxing and the rest with flux of soda ash. The product from the latter operation is called "flux calcined" grade. The particles from this operation have reduced surface areas, are white, and most impurities have been rendered insoluble. After cooling, the calcined diatomite is further air classified and then sent to storage for packaging and bulk loading.

At Casmalia, bituminous diatomite, which contains up to 35 gallons of oil per ton, is crushed to minus 3/4 inch and belt conveyed to a vertical fluid reactor. The rock is burned in the reactor at a temperature of 1800°F (980°C) by the oil contained in the rock. The calcined rock from the reactor then goes to a ball mill for fine grinding (390-mesh), classification with cyclones, and then to storage silos for bulk shipment. At the new cat-litter plant in Casmalia, white diatomite is processed by crushing, calcining, and air classification. At McKittrick, where cat litter and absorbent floor sweeps are produced, the diatomite is sent through hammer mills, screens, kiln drying, classifiers; it is then packaged.

At Hallelujah Junction, diatomaceous volcanic ash is screened and then put through rotary kilns. The clinker is cooled and finely ground in ball mills. It is then air classified and the final product, pozzolan, is shipped out in bulk by truck or rail... (Clark, 1978).

MARKETING

Finished diatomite is marketed in various amounts, in many types of packages, and is transported to market in various ways. The prices received for diatomite vary widely depending upon its usage, size and nature of packaging, and transportation costs. The average values per ton of diatomite (by uses) from 1969 to 1980 are shown in table 2.

Like most other segments of the mineral industry, diatomite mining and processing is faced with many varied problems, all of which contribute to increased costs and prices. Continuing cost increases in fuel, transportation, labor and packaging materials increased the average 1979 unit price of $125.91 per ton 13 per cent over the $111.23 per ton in 1978 and almost 60 per cent over the price of $80.01 per ton received in 1975 (table 2, U.S. Bureau of Mines, 1979).

Finished diatomite from California is shipped all over the United States and exported to all continents. U.S. diatomite exports totaled 170,000 tons in 1979 and a large percentage of this diatomite was produced in California. Much of the material that is exported goes to Japan and western Europe, particularly West Germany, Belgium, and Holland. Most diatomite used in California is shipped to the Los Angeles and San Francisco areas and to various food and wine-processing centers and sugar refineries in the central and coastal valleys.

ENVIRONMENTAL IMPACTS

...Diatomite mining encompasses the removal of large amounts of fine-grained and often dusty rock from open pits. Since processing of diatomite is done in the dry state, the potential effects on the environment could be significant. However, all diatomite mining and processing operations in California are under strict regulation and control of the various State and County boards. Particle emission standards and liquid waste discharge requirements have been set by those agencies for all diatomite mining and processing operations. The producers, recognizing the importance of protecting the environment, have spent significant amounts of money for new equipment and modification of their mining and processing operations to meet the regulations.

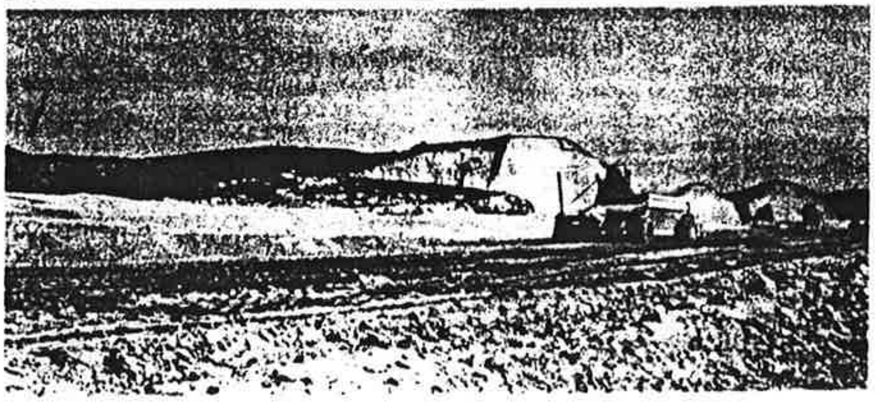


Photo 5. Large ore carrier and loader in one of the quarries at Lompoc, Santa Barbara County. *Photo courtesy Johns-Manville Corporation.*

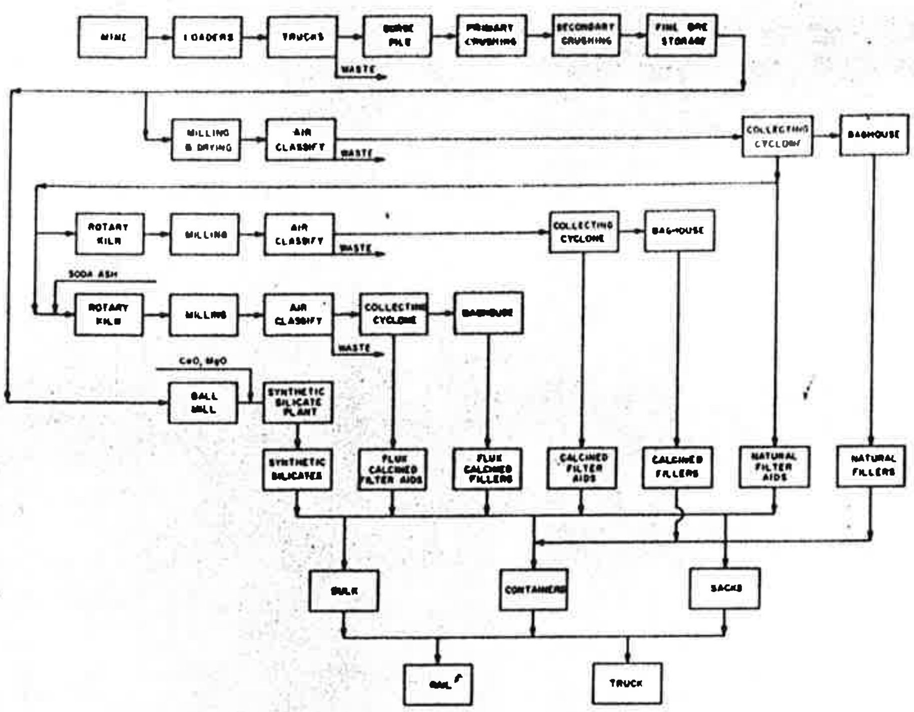
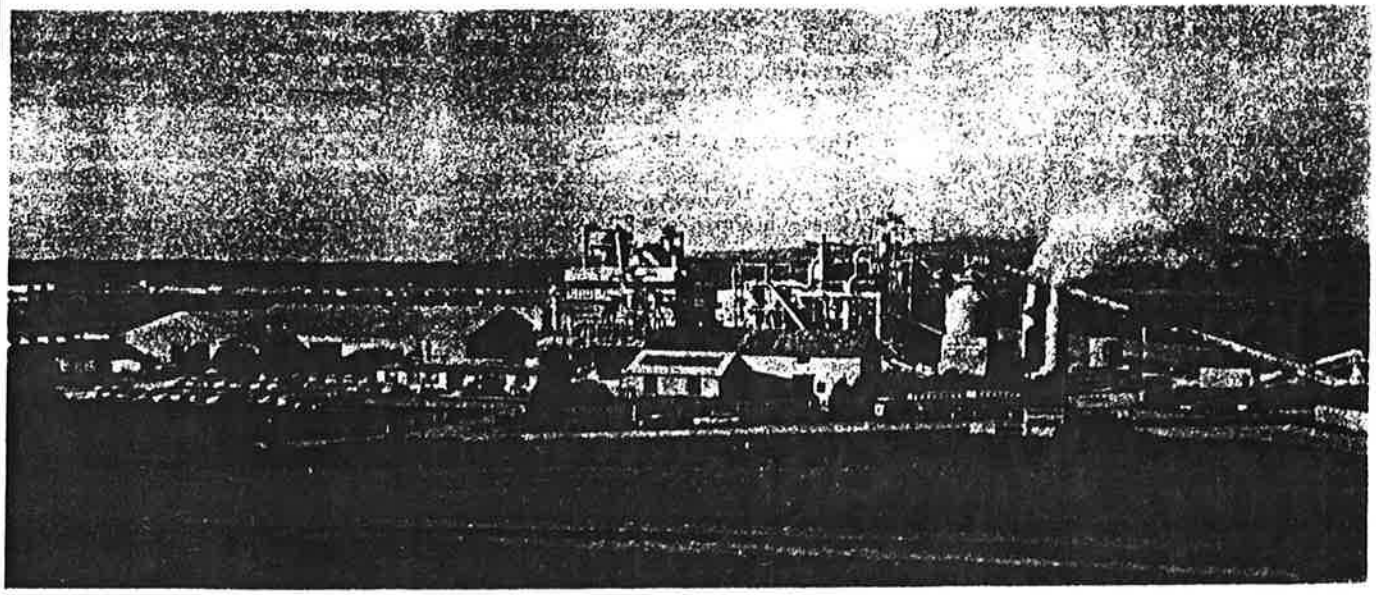


Figure 6. Generalized flowchart of diatomite-processing plant at Lompoc. *Courtesy Johns-Manville Corporation.*

At Lompoc, which is in a region of changing land uses and development, the two major producers have made diligent efforts to minimize the effects of diatomite mining and processing on the environment. Whenever possible, mining operations are conducted out of sight of homes and heavily traveled roads. The roads in mine areas are watered frequently to keep down the dust. Vegetative cover is planted on spoil banks.

There are numerous dust collectors in the processing plants which not only prevent the spreading of dust, but help to prevent pneumoconiosis, a form of silicosis, in the workers. In addition, the plants are largely automated with television surveillance of the various processing equipment. No liquid wastes are discharged from these plants and stack emissions are kept at a minimum (photo 6).

Photo 6. Grefco, Incorporated, diatomite processing plant at Lompoc; view north. Steam vapor on right is from the drying units. *Photo courtesy Grefco, Incorporated, Dicalite Division.*



PROBLEMS AND OUTLOOK

Like virtually all industries in California, including the mineral industry, the diatomite mining and processing industry faces a myriad of problems. All of these problems are contributing to increased costs in all phases of their operations. The most significant problems faced by diatomite producers are: (1) conflicting land uses which include zoning laws and taxation, (2) plant and mine pollution control costs, (3) increasing labor costs, and (4) rising fuel costs and availability of fuel.

Other significant problems include occasional shortages of soda ash (the chief fluxing agent), increased transportation costs and the availability of rail cars and trucks, packaging costs and availability of packaging material, increased equipment costs, prevention of pneumoconiosis among the workers, and occasional weather conditions such as heavy windstorms or rainstorms. [The current ongoing development of overseas diatomaceous earth deposits by European and other consuming nations with the resultant development of national self-sufficiency carries the potential for development of an exportable surplus and could have an economic impact on future domestic diatomite production.] Despite these various problems, it is believed that California will continue to be a major domestic and international source of diatomite for many years to come.

ACKNOWLEDGMENTS

We wish to acknowledge the assistance of the technical staff of the Johns-Manville Corporation, Grefco Incorporated, and the Airox Corporation who supplied some of the illustrations used with this article. Mr. A. C. Meisinger, Commodity Specialist, U.S. Bureau of Mines, Washington, D.C., also provided data.

TABLE 2 AVERAGE VALUE PER TON OF DIATOMITE, BY USES 1969-1980
(U.S. BUREAU OF MINES MINERALS YEARBOOKS)

USE	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
Filtration	$ 70.14	$ 61.67	$ 72.64	$ 73.08	$ 65.18	$ 87.40	$ 91.73	$ 99.34	$109.79	$122.18	$136.52	NA
Insulation	46.12	47.84	45.34	47.02	50.39	55.59	62.61	62.36	70.08	81.86	94.67	NA
Abrasives	134.19	119.19	139.04	125.27	125.46	129.51	145.56	146.04	156.07	172.26	174.09	NA
Fillers	61.26	53.26	65.92	69.37	62.01	77.12	79.66	92.44	106.62	102.51	118.22	NA
Lightweight aggregate .	NA	42.08	42.97	43.07	45.02	47.31	52.69	55.87	NA	NA	NA	NA
Miscellaneous	35.05	33.58	37.91	39.01	36.99	46.25	45.63	48.10	63.65	76.07	87.81	NA
Weighted average . . .	60.96	54.63	64.25	65.90	59.26	76.31	80.01	87.08	98.56	111.23	125.91	NA

NA - not available to avoid disclosing company proprietary data

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DIATOMITE

By Gordon B. Oakeshott

The use of diatomite (diatomaceous earth), especially for filtration and in fillers, has been increasing rapidly in the past few years. Production in California has more than doubled in the last 15 years; production for 1953-55 increased 20 percent over that of 1950-52. California is the principal diatomite-producing state and contains the world's largest diatomite quarries near Lompoc in Santa Barbara County.

GEOLOGIC OCCURRENCE

Diatomite is a light-colored, light-weight sedimentary rock composed largely of the microscopic tests of diatoms. Diatoms are silica-secreting single-celled plants, of which more than 25,000 species are known (Hanna, 1951); 200 to 300 species have been identified in the deposits at Lompoc in Santa Barbara County. These vary widely in form, but disc-shaped and needle-shaped forms are most common. Radiolaria, silico-flagellates, and sponge spicules are other common siliceous organisms found in some diatomite.

Diatomite can be tentatively identified in the field or in hand specimen by its light color and extreme lightness of weight. It is most easily confused with some types of volcanic ash, but microscopic examination permits a ready distinction between the glass particles in volcanic ash and the diatom tests of diatomite. Some diatoms are too small to be recognized as such by the use of the ordinary hand lens (magnification 14X), but diatoms can be seen by this means in most California diatomite.

In California the marine diatomaceous shales, of the upper Miocene and lower Pliocene epochs, are notable also for perfectly preserved fossil fishes; in some places shark teeth, whale bones, and fossil birds have been found. Impure varieties of diatomite contain clay, silt, fine sand, limestone, thin beds of volcanic ash, and hard silica rock, including opal and opaline and porcelaneous chert materials. Commercial grades of diatomite contain less than 15 percent of such impurities. Every gradation is found, from nearly pure diatomite through diatomaceous shale into clay shales and siltstones. Some varieties of diatomite are partly calcareous in that they contain foraminifera.

Lenses, nodules, and layers of porcelaneous silica rocks, and opaline and chalcedonic cherts are common in even the purer forms. Numerous phosphatic nodules or pellets and thin beds of silvery volcanic ash may also occur in certain stratigraphic positions. Many diatomaceous beds grade laterally into chert beds and also grade into coarse clastic sediments.

Diatomaceous rocks, such as those of the upper Miocene and lower Pliocene formations in California, are now known to be of shallow-water origin. These rocks formed with clastic sediments under conditions that allowed diatom tests to accumulate in greater volume than the clastic material. Bramlette (1946) has recently discussed the origin of diatomite and other siliceous rocks of the Monterey formation. He believes that the silica needed to form the large quantities of diatoms originated in the finely divided particles of volcanic ash so commonly associated with beds of both marine and fresh-water diatomite.

In general, geologists mapping diatomite in California find it useful to recognize three types of diatomite—pure, thinly stratified; impure, coarsely stratified; and impure, massive. The apparently pure, thinly stratified beds are of greatest commercial interest, but the suitability of each stratum exposed in an operating quarry must be determined only by actual testing of the product.

In California, the diatomite of actual or potential commercial importance is found in sedimentary rock formations of two different modes of origin: (1) the marine upper Miocene Monterey formation including its equivalents by other names, and the lower Pliocene Sisquoc formation, and (2) fresh-water lake beds of Tertiary and Quaternary age. The first group, by far the more important, has yielded nearly all of the diatomite produced in the state. The Monterey formation is widely exposed throughout the Coast Ranges from Point Arena in Mendocino County southward to San Onofre in San Diego County, and extends eastward into the San Joaquin Valley. Diatomite is a common rock type in this formation. Thicknesses of diatomite of as much as 1,000 feet occur in the Sisquoc formation of the Santa Maria Basin and Santa Ynez Mountains in Santa Barbara County. In eastern and northern California numerous fresh-water deposits of diatomite have been found in lake beds of Tertiary and Quaternary age. These are associated with volcanic rocks. Diatomite also occurs in some marine Eocene and Cretaceous formations in the Diablo Range.

There is no significant difference in the commercial value and application of marine and freshwater diatomite. The diatomite mined in California is obtained almost wholly from Tertiary marine strata, but Nevada's large production comes from fresh-water Tertiary strata.

Upper Miocene and Lower Pliocene Deposits. The foothills of the Santa Ynez Mountains south of Lompoc Valley and the Santa Rita Hills, both in Santa Barbara County, comprise an area that contains what are often regarded as the most extensive deposits of commercial diatomite in the world. Johns-Manville Products Corporation, which in 1953 celebrated the 60th anniversary of the first shipment of commercial diatomite in California, operates huge quarries 3 miles south of Lompoc. The other major diatomite operator in California, Dicalite Division of Great Lakes Carbon Corporation, works a similar deposit 7 miles southeast of Lompoc. Both of these deposits, which are probably correlative, are of marine origin and belong to the Sisquoc formation of uppermost Miocene (?) to lower Pliocene age. Their geologic occurrence (fig. 2) has been mapped and described by Dibblee (1950). The best grade of commercial diatomite is in the lower part of the Sisquoc formation. A report of the U. S. Geological Survey by Woodring and Bramlette (1950) describes and shows the location of diatomite beds in the Sisquoc formation in the Santa Maria district north of the area mapped by Dibblee. These two papers constitute the best guide to the location of the diatomite deposits of commercial grade in the coastal regions of central and southern California.

GREFCO, INC. DIATOMACEOUS EARTH OPERATION, LOMPOC, CALIFORNIA

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Grefco, Inc. operates two diatomaceous earth mines in the western Santa Ynez mountains. The larger of the two mines, the Palos Colorados Mine, is located approximately 7 miles southeast of Lompoc. The Miguelito Mine is located about two miles south of Lompoc on the west side of Miguelito Canyon. Diatomite from the Palos Colorados and Miguelito mines is trucked to the Grefco plant at Lompoc for processing. (See Figure #1-Index Map).

HISTORY

Grefco, Inc. had its beginning as the Dicalite Comapny in 1929. In that year the company began operations at the Walteria plant in the Palos Verdes Hills south of Los Angeles. In 1942 Dicalite leased the Palos Colorados Mine, which was their beginning at Lompoc. In 1944 the Dicalite Company was purchased by Great Lakes Carbon Corporation.

Ore from Lompoc was shipped to the Walteria plant for processing until 1952; in that year the Lompoc plant was built. Meanwhile in 1951 the rights to the Miguelitc Mine had been acquired assuring adequate reserves for the future. In 1953 the Walteria plant was shut down, the plant was dismantled and re-erected at Lompoc. The re-erected Walteria plant established a second processing unit and virtually doubled Lompoc's production.

In 1966 Great Lakes Carbon Corporation sold controlling interest in the company to General Refractories Corporation. Grefco, wholly owned subsidiary of General Refractories currently operates the Lompoc operations along with several other deposits in the western United States.

GEOLOGY

At the Palos Colorados Mine about 2,000 feet of stratigraphic section is exposed or inferred. In this mine the lower portion of the section is represented by the "upper" Monterey Formation (late Miocene) which is characterized by alternatin beds of diatomite, siltstone, argillaceous diatomite, silty diatomite, volcanic ash, and an abundance of cherts. For the purpose of simplification the term chert includes any hard dense siliceous rock regardless of its origin.

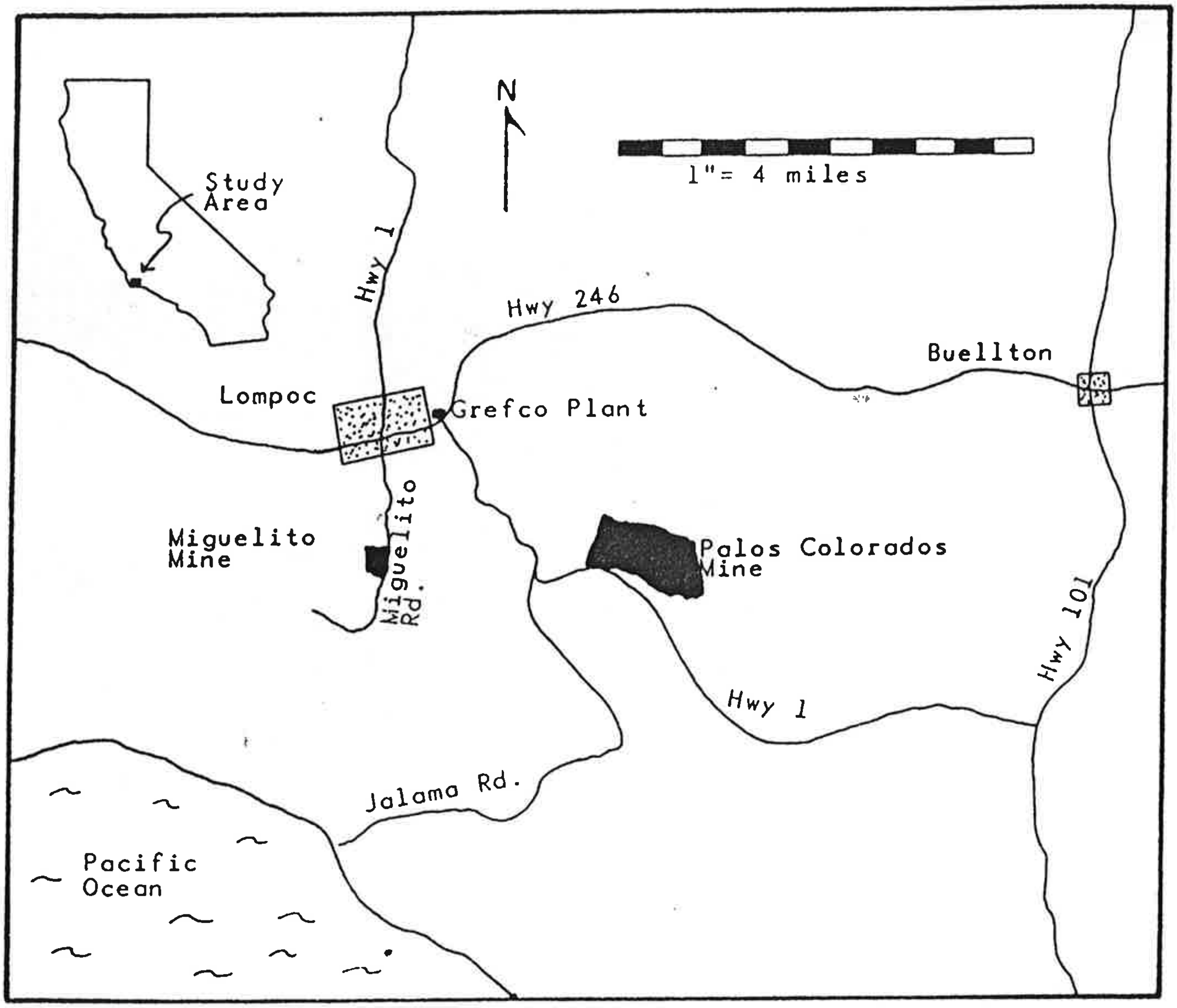


FIGURE 1 LOCATION MAP

Lying conformably on top of the Monterey formation is the Sisquoc formation. The Sisquoc is distinguished from the Monterey by the absence of interbedded opaline and cherty shales (Dibblee, 1950). Except for the lack of cherts the Sisquoc is not significantly different from the Monterey. Figure #2 presents a condensed stratigraphic column of the Palos Colorados Mine. Representative columns of the Sisquoc (Column #1) and Monterey (Column #2) are also illustrated at an enlarged scale.

The diatomite of the Palos Colorados Mine is located in a large east-west basin which is folded into several anticlines and synclines (Figure #3). The anticlines and synclines plunge to the west, consequently the younger Sisquoc beds are found in the western portion of the mine. Sections A & B are both N-S sections with section A being east of section B.

FIGURE #2
STRATIGRAPHY OF THE
PALOS COLORADOS MINE

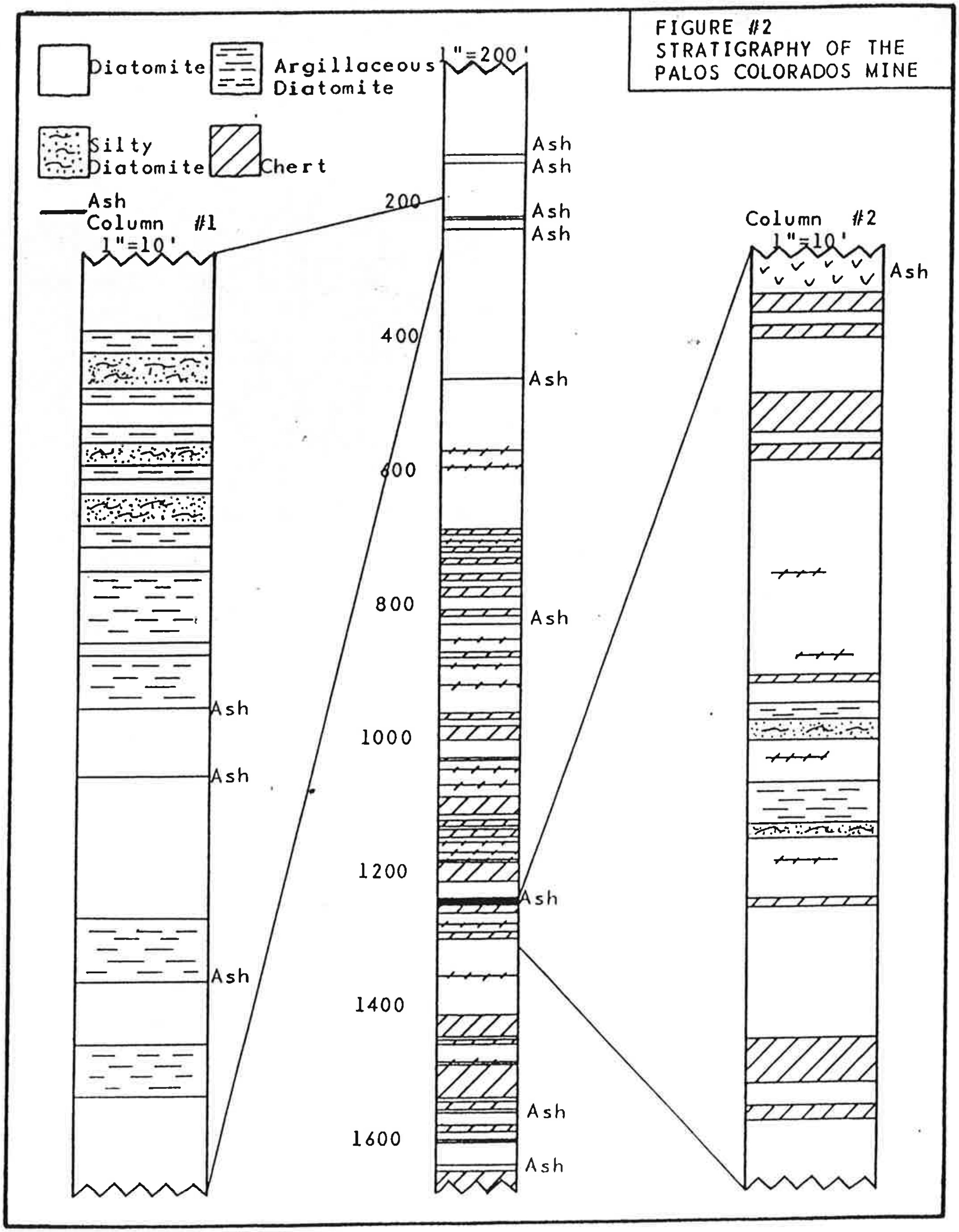


FIGURE 3
North-South Cross Sections of the Palos Colorados Mine

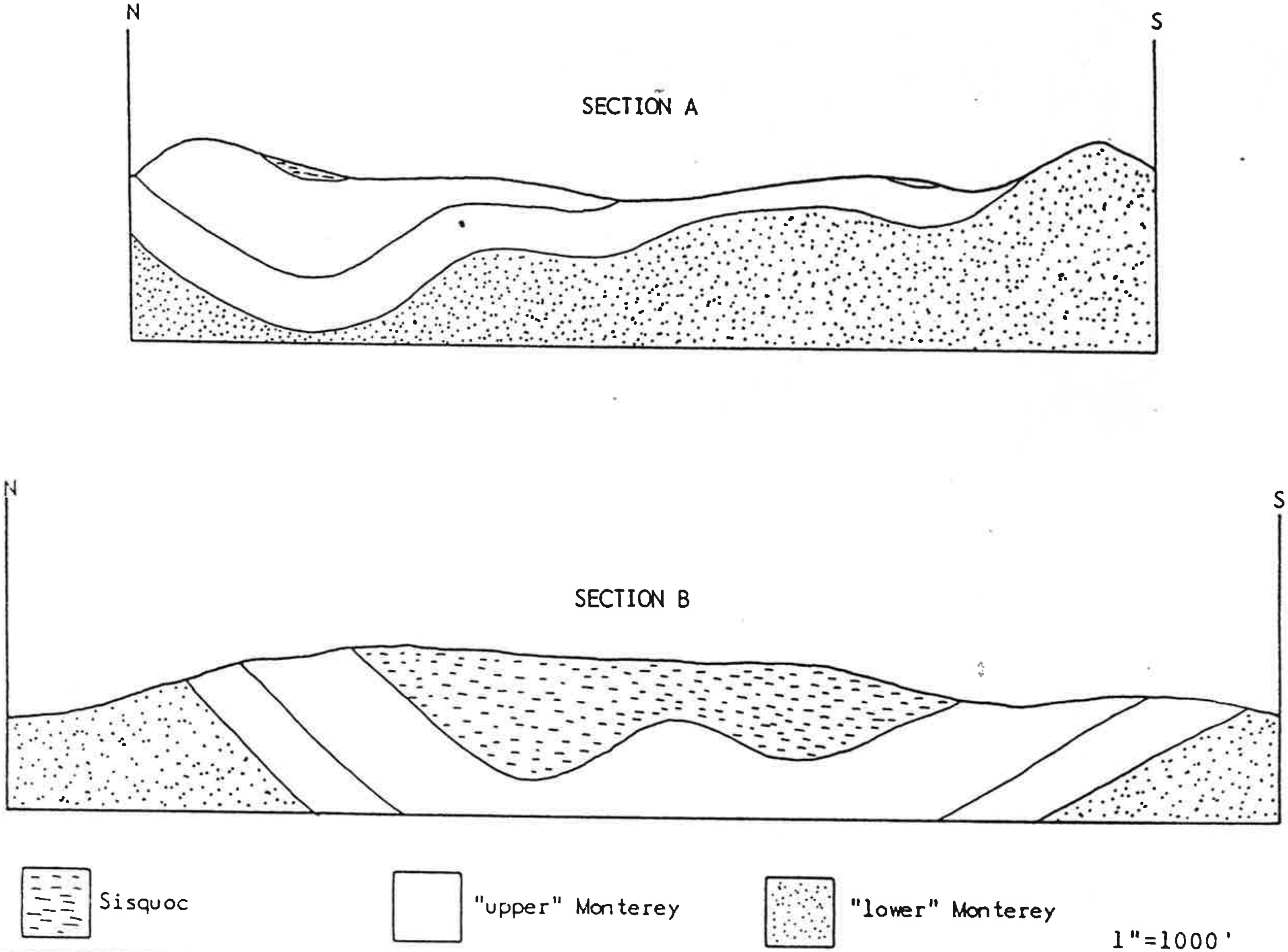
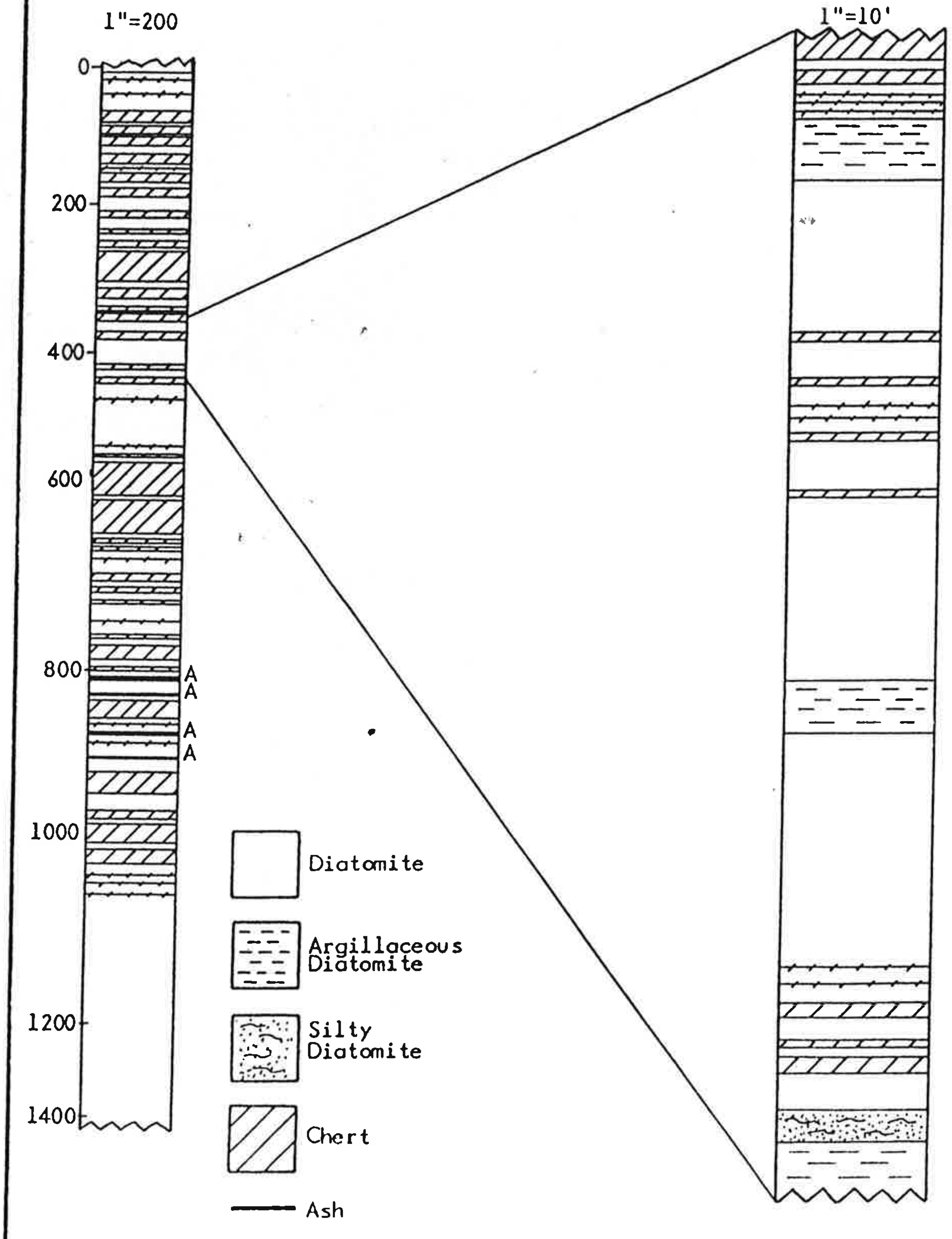


FIGURE #4
STRATIGRAPHY OF THE MIGUELITO MINE



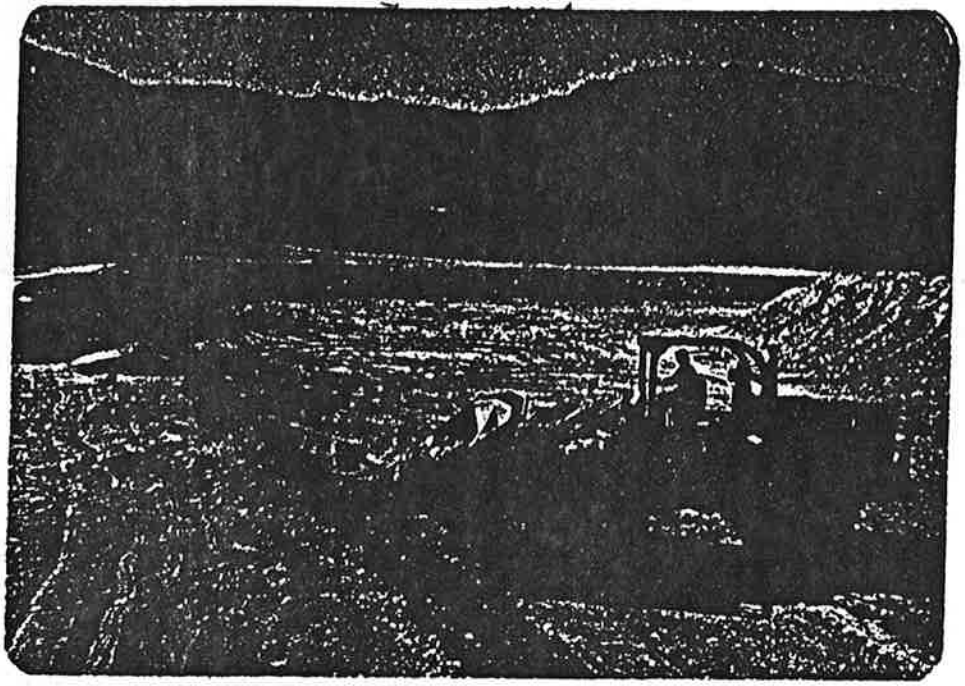


PHOTO #1
Front end loader working bench face, stockpile can be seen in right middle ground.

At the Miguelito Mine only "upper" Monterey beds are present. Figure #4 illustrates a typical stratigraphic column from this mine. The beds at this mine formed in a similar basin and at about the same time as the Monterey beds at the Palos Colorados Mine. For the most part the beds at this quarry are folded into east-west anticlines and synclines. At the western end of the quarry the beds rise sharply terminating the deposit.

Economic beds of diatomite vary in thickness from a few feet to tens of feet thick. These beds may be laminated or massive. The color of the diatomite varies from white to cream and occasionally light brown. The color is greatly influenced by moisture, diatomite that is white when dry may become light brown when wet.

MINING

Mining at the Grefco quarries is done by open pit methods as is all diatomite mining in the United States. Grefco, Inc. uses two mining systems at the Lompoc quarries. The system selected is determined by strata configuration 1)Ripping by dozer and lifting and hauling by scraper on wide or flat lying beds. Waste disposal areas are adjacent to the quarry area and crude is stockpiled on level surfaces for later hauling to the plant. 2)Front end loaders are used on thin and/or steeply dipping strata (Photo #1). Crude is stockpiled adjacent to the working face and the waste is removed to the edge of the working area for subsequent scraper removal.

Crude is transported from the mines to the plant by bottom dump trucks. The haul distances vary from seven to ten miles.

PROCESSING

The crude trucked from the quarries is separated by quality into ten to fifteen stockpiles. Desired crudes are blended from the various stockpiles and fed into a crude storage bin. Blending of crudes make it possible to produce many different products specifically suited to customer needs.

Processing consists of two phases, the wet end and the finish end. The wet end phase includes flash drying, addition of a fluxing agent for white products, trapping impurities and classifying. The material then enters the finish end where additional trapping and classifying is done. Finally the product passes into one of several bins for packing in bags or for bulk loading.

QUALITY CONTROL

Due to specialized uses of diatomite many qualities need to be controlled to meet rigid product specifications. Prior to any mining areas are drilled and sampled. Once waste rock is removed strata to be mined are sampled. They are sampled again after they are put into stockpiles. At this point the stockpiles are coded as to their quality and are later hauled to the plant as required. Stockpiles at the plant are continuously sampled and tested to monitor plant feed. Samples are frequently obtained at various stages in the processing and also at the final product stage. A final quality assurance check is made on all material prior to bagging or bulk loading.

USES

At the Lompoc plant two basic types of products are made, calcined and flux-calcined. Calcined and flux-calcined products are commonly referred to as pink and white products due to their color. Flux-calcined products account for about 70% of the plant's production. The majority of the diatomaceous earth produced by Grefco at Lompoc is used for filtration. Calcined products have slower flow rates than flux-calcined products. The beer, wine, sugar, oil, and water are some of the many items filtered by diatomaceous earth. When making some white products the smallest premium particles are separated out, these fines are collected by the baghouse. White baghouse fines are used as fillers. The paint, paper and plastics industries are major users of diatomaceous earth fillers.

Acknowledgements

I wish to express my appreciation to all those people at Grefco who made this paper possible. Special thanks is due to Joe Horton for his advice and comments.

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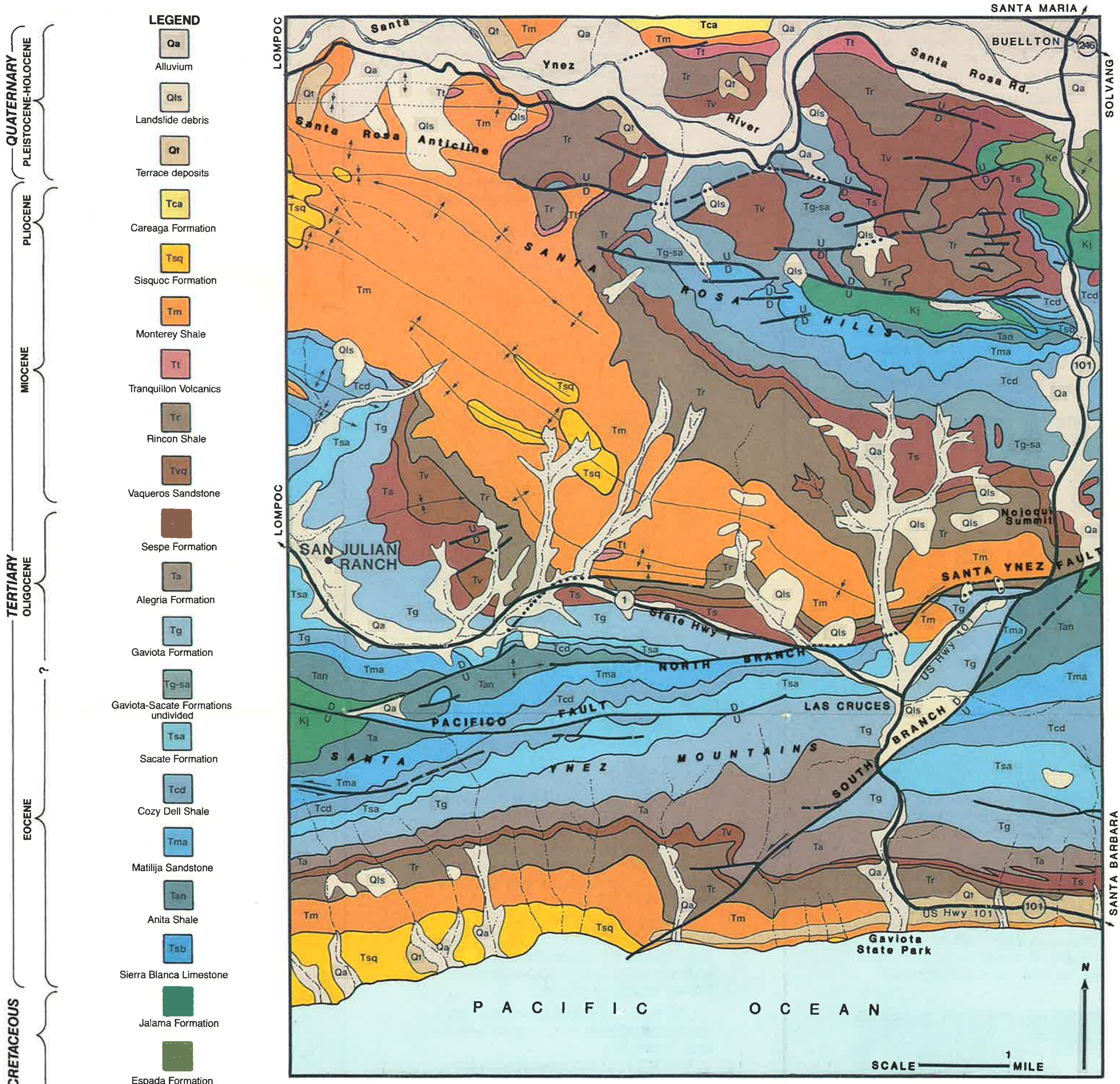
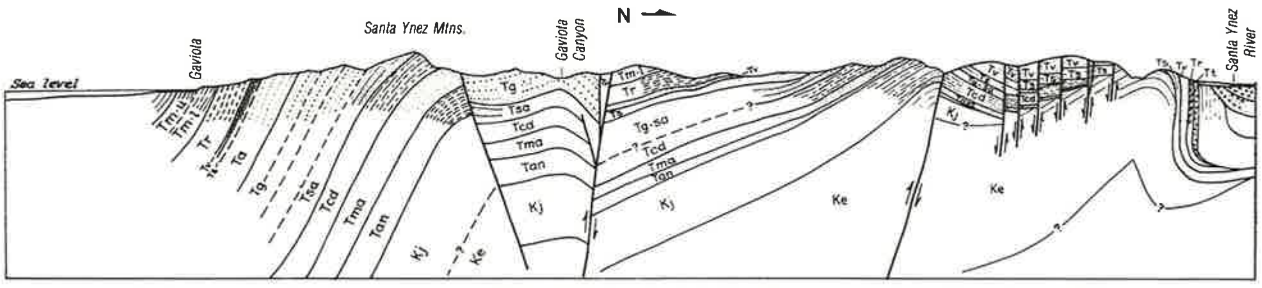


GEOLOGIC MAP OF THE SAN JULIAN RANCH AREA, SANTA BARBARA COUNTY, CALIFORNIA



Geologic cross-section of the region from Gaviota Beach north to the Santa Ynez River, as interpreted and drawn by Tom Dibblee.

COVER ILLUSTRATION

A simplified, full-color geologic map of the San Julian Ranch area, where Thomas Dibblee, Jr. grew up and learned the basics of geologic mapping in diverse and extremely complex terrain.

Map design, drafting and color process by Helmut E. Ehrenspeck.

Map adapted from Cal. Div. of Mines, *Bull. 150: Geology of Southwestern Santa Barbara County*, by Thomas W. Dibblee, Jr., 1950.