UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Silica Diagenesis and lithostratigraphy of the Miocene Monterey Formation of the northwestern Ventura basin, California, including biostratigraphy, pyrolysis results, chemical analyses, and a preliminary temperature zonation of the opal-CT zone

By

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ABSTRACT

Lithostratigraphy and diagenesis of the Miocene Monterey Formation were studied at seven surface localities parallel to the axial trend of the Miocene Santa Barbara basin between Goleta and the North Sulphur Mountain area of the Ojai oil field in the northwestern Ventura Basin, California.

The lithostratigraphy of the Monterey Formation in this area of the Ventura Basin is generally similar to the Santa Barbara coastal area where Isaacs (1981b) has described five informal members of the Monterey. In the study area, the basal and upper members are characterized mainly by high content of biogenic (or diagenetic) silica and are highly resistant to erosion where diagenetic silica has formed. Overlying the basal member is a sparsely siliceous member which is generally poorly exposed; this member consists mainly of organic matter-rich marls containing abundant carbonate, organic matter, detrital minerals, and commonly phosphate in blebby or disseminated layers. Overlying the carbonaceous marl member is the transitional marl-siliceous member which consists of marls interbedded with siliceous rocks characteristic of upper Monterey strata.

The Monterey sequence exposed at Goleta closely resembles Isaacs' three upper members of the Monterey Formation, however, about 50 km east of Goleta at Sulphur Mountain, upper Monterey strata differ from strata west of Goleta in the following characteristics: 1) carbonate bearing and carbonate-free siliceous strata are interbedded in rocks overlying the transitional member, 2) strata above the transitional member are neither commonly finely laminated nor commonly in alternating massive and laminated cycles, and 3) discrete sand layers up to $1/2$ m thick are present in the transitional member on the north side of Sulphur Mountain.

At Goleta the Monterey Formation is diatomaceous, but at all other sites opal-CT is the main silica phase that has formed in rocks of the transitional member. Silica diagenetic grade, as determined from silica phases and opal-CT d-spacings together with rock composition, generally increases eastward between Goleta and Sulphur Mountain. Eastward increasing silica diagenesis correlates with eastward increasing kerogen maturity, as determined by T_{max}.

A temperature scale for silica diagenesis has been constructed from a reevaluation of silica diagenesis in cuttings from the Point Conception COST well (OCS Cal 78-164 No. 1) together with empirical data on silica phases, opal-CT d-spacings, and rock composition from the Santa Barbara coastal area and northwestern Ventura basin. Temperatures estimated for the northern Ventura basin from this scale range from approximately <43°C at Goleta to 68°C at Sulphur Mountain. Because many variables, including overburden thickness, affected paleotemperatures, only general conclusions can be drawn about the burial depth of Monterey rocks from silica diagenetic grade. Estimates of overburden thickness (burial depth) based on a bottom water temperature of 4°C and a geothermal gradient of 24°C/km (the Pliocene to present-day gradient in the Ventura Basin and a probable minimum value) range from 1630 m at Goleta to 2670 m at Sulphur Mountain Road, whereas estimates based on a gradient of 48°C/km (a value probably not exceeded) range from 810 m at Goleta to 1330 m at Sulphur Mountain Road. Overburden estimates based on a graduated geothermal gradient (decreasing with increasing burial depth due to compaction and silica phase changes) range from 650 m at Goleta to 1265 m at Sulphur Mountain Road.

Major trends in silica diagenesis reflect general overburden history. Specifically, uplift of the Santa Ynez and Topa Topa Mountains which commenced during deposition of the Sisquoc Formation exerted strong control over post-Monterey depositional patterns and thicknesses in the northwestern Ventura basin. The Red Mountain fault, a major structure south and east of Rincon Point, was not a significant control because it was not active until after most post-Monterey burial and diagenesis had already occurred.

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INTRODUCTION

This report presents the results of a study of the lithostratigraphy and maturity of silica diagenesis of the Monterey Formation at seven surface sites in the northern Ventura basin near Ojai, California. Emphasis in the report is on interpretation of the results of the evaluation of silica diagenesis.

The Monterey Formation, because of its unusual characteristics, is an extremely important economic resource in California. In addition to containing the world's largest diatomite quarries (Oakshott, 1957; Durham, 1973), the Monterey has long been regarded to be the primary petroleum source rock in California (Bramlette, 1946; Taylor, 1976) and is also an important reservoir rock in several parts of California (U.S. Geological Survey, 1974; Williams, 1982). The potential of the Monterey as a petroleum reservoir is illustrated by the recently discovered Point Arguello oil field off the coast near Point Conception, a giant field estimated to have as much as 500 million barrels of recoverable oil (Williams, 1982). This is the largest oil field discovered in North America since Prudhoe Bay in Alaska. The "pay zone" of the Point Arguello field is more than 1000 feet of Monterey strata.

Bramlette (1946) recognized that the abundant and varied siliceous rocks of the Monterey Formation had originated from marine diatomaceous deposits by diagenetic alteration. Diagenesis is a process which appears to enhance the reservoir quality of these originally high-porosity, low-permeability rocks by increasing their brittleness and thus their permeability by subsequent fracturing. In recent years, many studies have focused on silica diagenesis of siliceous rocks in California (Murata and Nakata, 1974; Murata and Larson, 1975; Murata and Randall, 1975; Murata and others, 1977; Pisciotto, 1978, 1981; Isaacs 1980, 1981c, 1982; and Surdam and Stanley, 1981) and in other locations around the margin of the Pacific Ocean basin (Mitsui and Taguchi, 1977; Hein and others, 1978; Iijima and Tada, 1981) where diatomaceous siliceous deposits are present.

During increasing diagenesis of diatomaceous rocks, silica phases and phase transformations occur in the established sequence: opal-A (in diatom frustules), which is metastable, transforms to opal-CT, an intermediate metastable phase, from which the stable phase, quartz, finally forms. Because several of the recent studies of silica diagenesis have focused on the temperatures of silica transformations, in particular on the "opal-CT zone" boundary temperatures, and because six of the seven study sites are opal-CT bearing, a preliminary temperature scale for opal-CT and silica diagenesis was developed during the course of this study in conjunction with a re-evaluation of silica diagenesis in the Point Conception COST well (OCS Cal 78-164 No. 1) (Isaacs and Keller, 1983; Isaacs and others, 1983a; Keller and Isaacs, in preparation). This temperature scale was used to determine the burial/diagenesis temperatures attained by the transitional marl-siliceous member of the Monterey Formation in the study area. Because these relatively low-temperature transformations in diatomaceous siliceous rocks apparently are not affected by retrograde processes, the temperatures determined by this scale approximate the maximum _in situ_ temperatures prior to uplift and erosion.

In the area of this study along the northern margin of the Ventura basin, between Goleta and Sulphur Mountain (Fig. 1), the amount of post-Monterey overburden and the maximum burial depth and temperature of the Monterey Formation are not known precisely. Throughout most of the Neogene, deposition in the area was accompanied by large scale deformation and tectonism, including the growth of anticlines, reverse faulting, and major uplifts (Yeats, 1976). Because the thickness of late Miocene through Pleistocene deposits varies tremendously in the study area, maximum burial depth or thickness of overburden for the uplifted and eroded Monterey Formation can not be accurately estimated from nearby outcrops. However, in this area of recent great uplift and complex deformation, the temperature scale of silica diagenesis might be used to estimate the maximum burial/diagenesis temperatures of moderately buried siliceous rocks of the Monterey Formation.

The regional tectonic and sedimentation history in the area of this study have been synthesized by Yeats (1968, 1976), Vedder and others (1974), Fischer (1976), Blake and others (1978), and Ingle (1980, 1981). Geologic maps based on extensive earlier, as well as more recent, mapping of the area by Dibblee (1982a, b, c, d) are now available. The lithostratigraphy and diagenesis of the Monterey Formation in the Santa Barbara coastal area (Fig. 1), adjacent to this study, have recently been described in detail by Isaacs (1980, 1981b, 1981c, 1982). The results of that work provided the main data base for the temperature scale of silica diagenesis developed during this study.

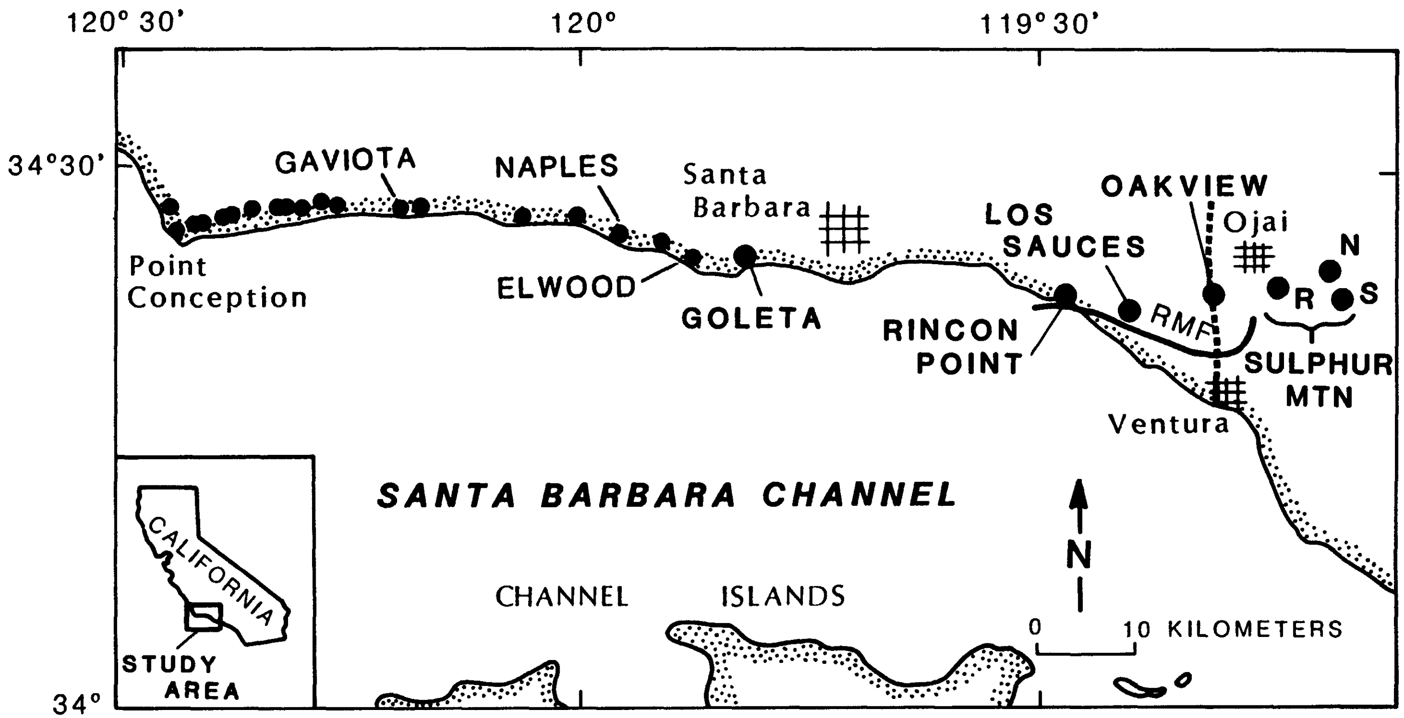


Figure 1. Index map of the study area. Large dots are sites of this study, and smaller dots are study sites of Isaacs (1980, 1981, 1982). RMF=Red Mountain fault, and for Sulphur Mountain localities R=road, N=north, and S=south. The Ventura River is shown by the dashed line through the town of Ventura.

GEOLOGIC AND STRUCTURAL SETTING

Introduction

The area of this study is the northern margin of the onshore Ventura basin located in the western Transverse Ranges Province, a problematic tectonic block which has anomalous east-west structural grain in contrast to the predominantly northwest trend of Cenozoic structures in most of coastal California. In this area is a thick sequence of mainly marine Cretaceous to Holocene rocks composed predominantly of terrigenous clastics.

The Miocene Monterey Formation, in contrast, is composed mostly of bioclastic strata or their diagenetic equivalents. West of the Ventura basin along the Santa Barbara coast, the Monterey Formation crops out in a continuous, well exposed homoclinal sequence of mostly marine deposits of Upper Cretaceous to Holocene age (Dibblee, 1950, 1966). In the Ventura basin the geology is complicated by structures that were active during major Neogene deformation and tectonism; but in the area of this study no large lateral displacements of Monterey facies have occurred. The Monterey Formation east of Rincon Point is exposed on the hanging wall of the north-dipping and seismically active Red Mountain fault and, east of the Ventura River, in a set of tightly overturned folds (Fig. 2, Fig. 1) (Yeats, 1976).

Cretaceous to Pleistocene Depositional History

Cretaceous to Eocene sedimentation in the study area, both marine and non-marine, was centered in an east-west structural trough (Vedder and others, 1974) commonly referred to as the Santa Barbara embayment. Neogene sedimentation in the area presumably was strongly influenced by a change in the relative motion between the Pacific and North American Plates (Blake and others, 1978), which had initially collided about 29 Ma (Atwater, 1970).

Plate adjustments resulted in rapid subsidence and formation of borderland basins in latest Oligocene time (c. 25 Ma) (Ingle, 1980, 1981). Nonmarine red beds of the Oligocene Sespe Formation were capped by latest Oligocene and early Miocene shallow marine sands of the Vaqueros Formation. Overlying deeper marine early Miocene shales of the Rincon Shale have been interpreted as slope deposits (Ingle, 1980, 1981). By late early Miocene time (c. 18 Ma), the basin sea floor was at depths of about 1500 m, and sea level was relatively high and rising. Beginning in late early Miocene time the Monterey Formation was deposited in a series of "empty basins, momentarily deficient in terrigenous debris due to rapid tectonic adjustment of basin margins, formation of intervening banktops and sills, eastward transgression of the Miocene strandline and associated spigots of terrigenous sediment, and continued trapping of coarse terrigenous materials along the eustatically drowned margin" (Ingle, 1981).

These basins were characteristically rather narrow steep-sided basins in which pelagic sedimentation was predominant. In the Miocene Santa Barbara basin, the Monterey sediment was mostly rich in calcareous and siliceous microfossils. The overall abundance and ratio of these components depended on the strength of upwelling (Berger, 1974); upwelling was caused by eastern boundary currents (Soutar and others, 1981). Low-oxygen conditions were presumably important for preservation of the abundant carbonaceous organic matter that

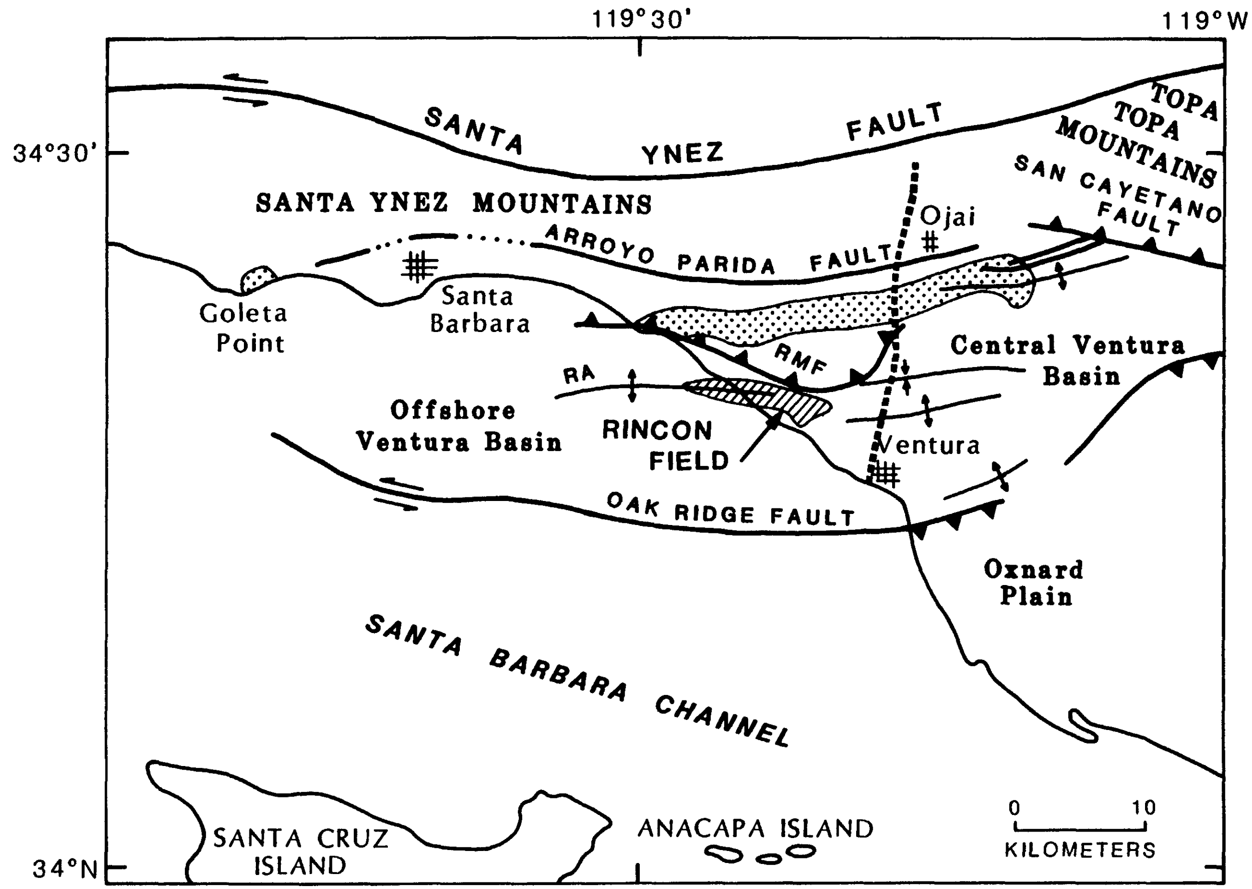


Figure 2. Sketch map of the major structural features in the northern Ventura basin and vicinity modified from Yeats (1976) and Jackson and Yeats (1982). RMF=Red Mountain fault, RA=Rincon anticline. Dot pattern shows the area of this study. Hatch pattern delineates the Rincon oil field. The Ventura River is shown as a dashed line through Ventura.

rained down and the varve-like laminations in Monterey sediment that resulted from a low abundance of burrowing organisms (Govean and Garrison, 1981; Soutar and others, 1981; Isaacs, 1983). Fine-grained terrigenous debris, also an important component of Monterey sediment, is much more abundant in the underlying Rincon Shale and the overlying Sisquoc Formation.

In latest Miocene and early Pliocene time increased influx of fine terrigenous debris and biogenic silica (Isaacs, 1983) produced a terrigenous-rich diatomaceous deposit, the Sisquoc Formation or "Santa Margarita" Formation in the Ventura basin. The contact between the Monterey and Sisquoc Formations is apparently conformable and gradational in many parts of the Santa Barbara and Ventura basins; however, in some parts of these basins angular unconformities are present at this boundary (Dibblee, 1950; 1966).

The Pliocene and early Pleistocene Pico Formation, including "Repetto" strata, overlies the Sisquoc Formation with angular discordance in the Ventura basin. The Pico is composed predominantly of terrigenous clastics deposited in the Ventura basin during continued subsidence, or alternatively, subsidence coincident with uplift of the Santa Ynez-Topa Topa Mountains. The thickness of the Pico Formation or time equivalent Plio-Pleistocene strata is quite variable in the Ventura basin and in the area of the Santa Barbara embayment (California Oil and Gas Division, 1974). Near Ventura the Pliocene sedimentation rate was as high as 1.4 mm/yr (Yeats, 1976). In the central Ventura basin, the Pico consists of approximately 4,000 m of interbedded mudstone, sandstone, and conglomerate as a series of deep water turbidite flows (Kew, 1924; Jackson and Yeats, 1982). However, drastic northward thinning of the Pico Formation is documented by a thickness of about 3,350 m in the Rincon field (Fig. 2) compared to about 975 m close to Rincon Point (Fig. 1) near the Pico "hinge zone" (Jackson and Yeats, 1982). Furthermore, evidence of facies changes in Pico strata with Wheelerian stage (Upper Pliocene) microfauna are interpreted (Jackson and Yeats, 1982) to indicate that the area north of the Red Mountain fault was more positive than areas to the east and south during deposition of upper Pico strata. Tremendous uplift in the Sulphur Mountain area has exposed Monterey strata in the crest of a major anticline, whereas deep-water Plio-Pleistocene deposits crop out both to the north and south (Yeats, 1976). The original extent of the Pico to the west of Rincon Point is not known; however, Dibblee (1966) maps approximately 100 m of possible Pico strata as far west as Goleta.

Overlying the Pico Formation with angular discordance, the Pleistocene Santa Barbara Formation is a shallow marine sandstone north of the Red Mountain fault in the western part of the study area, but consists of mudstone, siltstone, and shale in the central Ventura basin south of the Red Mountain fault. The non-marine Casitas Formation was deposited in the Pleistocene Carpinteria Basin north of Rincon Point. The Casitas Formation grades downward and laterally into the Santa Barbara Formation, was deposited where the Carpinteria basin shoaled (Jackson and Yeats, 1982), and probably is equivalent to the Saugus Formation further east in the Ventura basin.

Summary of Post-Monterey Structure and Tectonics

Active structures related to continuing tectonic adjustments along the San Andreas fault system probably controlled Plio-Pleistocene deposition and paleogeography in the Ventura basin (Yeats, 1976; Blake and others, 1978). Before the Pliocene, tectonism mainly controlled the position of the basins but subsequent deposits were influenced by many active local structures, such as the growth of anticlines, reverse faulting, and great uplifts. Major Pliocene and Pleistocene structural features--the uplifted Santa Ynez Mountains, the Santa Ynez fault, and the Red Mountain and San Cayetano faults--are expressions of major crustal shortening, or compressional tectonics, in the Ventura basin (Yeats, 1976).

According to Dibblee (1966), uplift of the Santa Ynez Range, presumably associated with vertical displacement along the Santa Ynez fault, began in early to middle Pliocene time. Drastic thinning of the Sisquoc Formation from 640 m in the Rincon field to 300 m in the area of the Pleistocene Summerland Offshore anticline along the northern margin of the Ventura basin is probably evidence for uplift of the Santa Ynez Mountains as early as latest Miocene or early Pliocene, during deposition of the Sisquoc Formation (Jackson and Yeats, 1982). By the end of deposition of the Sisquoc Formation, the Santa Ynez Mountains and the Ventura basin were identifiable geomorphic and tectonic units (Yeats, 1976).

Open folds were the primary structures that formed prior to deposition of the Pleistocene Santa Barbara and Casitas Formations, and strata referred to the Saugus Formation near Ojai (Schlueter, 1976). Examples in the western part of the study area are the Los Sauces Creek anticline, Rincon Mountain syncline, and the Snowball anticline which is a major east-west fold with its south limb dying out near Rincon Point. In the east near Sulphur Mountain the Reeves syncline and Lion Mountain anticline were folded and also offset by the Big Canyon fault prior to deposition of the non-marine deposits referred to the Pleistocene Saugus Formation.

A major fold occurring after deposition of the Santa Barbara Formation, in the main part of the Ventura basin, is the Summerland Offshore anticline, from which the Summerland offshore oil field produces from the (Vaqueros) sands underlying "incompetent" Monterey strata (Jackson and Yeats, 1982). Because the Summerland anticline was not formed until after deposition of the Santa Barbara Formation, Jackson and Yeats (1982) infer that the time of oil migration into this field, and by analogy perhaps other fields in the northern Santa Barbara Channel, was the middle to late Pleistocene. Major folding in the main part of the Ventura basin is, thus, inferred to have occurred after deposition of the Santa Barbara Formation in contrast to folding on the south flank of the Santa Ynez Range, which occurred primarily prior to deposition of the Santa Barbara Formation.

The major Pleistocene to Recent structures in the study area are large displacement, north- and south-dipping reverse faults that produce scarps and cut late Pleistocene marine terraces. South-dipping faults are related to bedding slip in pre-Pleistocene strata and the north- dipping faults truncate bedding and are seismogenic (Jackson and Yeats, 1982). The San Cayetano and Red Mountain faults are the main north-dipping faults in the study area and are presumed to be active (Fig. 2) (Schlueter, 1976; Jackson and Yeats, 1982). Vertical separation along the Red Mountain fault decreases westward from approximately 4.5 km north of the Rincon field to 350 m at Rincon Point. Offset along the San Cayetano fault, a major reverse fault with an approximate length of 40 m, ranges up to as much as 9 km of apparent stratigraphic throw just west of Sespe Creek and north of the study area (Fine, 1954). At Sespe Creek the Eocene is thrust over Pleistocene (Schlueter, 1976).

TERMS

Terms for siliceous rocks and calcareous or dolomitic siliceous rocks have become increasingly confused with terms for silica and carbonate minerals. To avoid this confusion, this report follows the usage of Murata and Nakata (1974) and Keene (1975). The following definitions and descriptions are slightly modified from Isaacs (1980), with the addition of the terms "marl" and "silica diagenetic grade".

Rock Names

Chert: an aphanitic rock with a smooth or sometimes vitreous surface, considerable hardness (>5), toughness, and brittleness. When fractured, cherts always break into angular fragments, usually across bedding planes, and may fracture conchoidally.

Porcelanite: an aphanitic rock with a rough or somewhat grainy, matte surface. Compared to a nonsiliceous mudstone or shale, it is tough, brittle, and hard--but less so than a chert. Porcelanites have hardnesses of 3 or less and, even where laminated or well bedded, fracture irregularly with a rough splintery surface.

Siliceous mudstone (or siliceous shale): less distinctly siliceous rocks which are massive (or finely layered) and free of carbonate. Siliceous mudstones and siliceous shales have grainy surfaces, are not brittle, and dent when impacted. They are, however, usually harder and tougher than nonsiliceous mudstones and shales.

Marl: an earthy impure rock containing abundant carbonate. Marls generally contain 30-70% carbonate and are quite friable where weathered.

Terms for carbonate-bearing rocks: A large proportion of the rocks in this study contain some carbonate. Many of the rocks, whose bulk compositions fall near the center of a carbonate-clay-silica diagram, have no well-accepted nomenclature, and some suggested compositional names are misleading. "Cherty limestone", for example, does not accurately describe an opal-CT-bearing coccolith-rich rock with 45 percent porosity. For this reason, and because most of the calcareous (or dolomitic) rocks are macroscopically indistinguishable from one another, they are usually described as calcareous (or dolomitic) siliceous rocks. The exceptions are limestones, dolostones, marls, calcareous (or dolomitic) cherts, and in some cases, calcareous (or dolomitic) porcelanites; these terms are used for calcite-bearing (or dolomite-bearing) rocks whenever applicable.

Minerals and Materials in Rocks

Silica, or silica component: all minerals (and mineraloids) composed of silica or hydrated silica which is either biogenic or derived from biogenic silica. The term includes amorphous opal, opal-CT, and diagenetic quartz, but excludes detrital quartz.

Opal-A: The hydrated silica mineraloid, as defined by Jones and Segnit (1971); siliceous microfossil tests and frustules are composed of this mineraloid.

Opal-CT: a disordered, diagenetic silica mineral, as defined by Jones and Segnit (1971), presumed to be composed of both α-cristobalite and α-tridymite. Opal-CT is often called cristobalite and has many other names in the literature, as summarized by Wise and Weaver (1974).

Opal-CT d-spacing: the spacing of the principal XRD peak of opal-CT at 21.5° to 22.0° (Cu Kα 2θ). This term has the same meaning as "d-101 spacing of cristobalite", as used by some authors (e.g., Murata and Larson, 1975).

Detrital minerals: detrital grains that are not biogenic. The term excludes detrital biogenic debris (siliceous tests, calcareous shells, and organic matter), closely related diagenetic minerals (opal-CT, diagenetic quartz, and dolomite), as well as pyrite. Silt and clay grains derived from arenaceous foraminiferal tests are, however, included in detrital minerals.

Aluminosilicates: all detrital minerals except detrital quartz.

Organic matter: materials which are organic in the geochemical sense--including all carbon compounds except oxides and carbonates (Krauskopf, 1967, p. 283). The term excludes biogenic carbonate and silica minerals.

Rock Comparisons

Component composition: the composition of a rock as expressed by specific groups of minerals and materials (components)--namely, carbonate minerals, detrital minerals, organic matter, apatite, and silica.

Relative detritus content: the percentage of detrital minerals in the sum of detrital minerals + silica. Thus the relative detritus content is the detritus content normalized to a basis free of carbonate, apatite, organic matter, etc.

Relative silica content: the percentage of silica in the sum of detrital minerals + silica.

Lithology: "physical character of a rock, generally as determined megascopically or with the aid of a low-power magnifier" (American Geological Institute, 1982). As used here, diatomites are different in lithology from porcelanites or cherts.

Laminated: characterized by very thin layering. "Regularly" laminated rocks are marked by distinct, continuous laminations, usually 0.05 to 0.2 mm in thickness. While having prominent planar fabric, "irregularly" laminated rocks have comparatively few continuous laminations, usually 3 to 10 mm apart.

Diagenesis

Silica diagenetic grade: the maturity or rank of silica in diatomaceous siliceous rocks. The term is used in the same sense as "metamorphic" grade.

For example, diatomaceous rocks have low diagenetic grade, opal-CT rocks intermediate diagenetic grade, and quartz rocks high diagenetic grade (see also Pisciotto, 1981).

STRATIGRAPHY

Introduction

The major objective of this study was to determine the regional pattern of silica diagenesis in the Monterey Formation of the northern Ventura basin by evaluating silica diagenetic grade of the same time-stratigraphic horizon at as many localities as practical. Recognition of the lithostratigraphy within the fine-grained Monterey Formation, often difficult in well exposed sections, was therefore the primary limiting factor in choosing sampling sites for this study. In this chapter, lithostratigraphy and partial age correlation of the Monterey Formation of the northern Ventura basin are described and compared to the adjacent Santa Barbara Coastal area (Fig. 1) where Isaacs (1981b, 1983) has informally divided the Monterey into five members (Fig. 3).

Lateral lithologic correlations are based on field examination of lithology and primary sedimentary features (see also Isaacs, 1981a). Microfossil biostratigraphy was valuable in structurally complex areas for constructing the lithologic sequence and also for lateral correlation of the horizon sampled for evaluation of silica diagenesis.

Geologic Setting

In the northern Ventura basin, the Monterey Formation is underlain by marine mudstone of the uppermost Oligocene and lower Miocene Rincon Shale and is overlain by marine shale of the latest Miocene and early Pliocene Sisquoc Formation (Dibblee, 1966, 1982) which was originally reported in the Ventura basin as the Santa Margarita Formation (Hudson and Craig, 1929). Overlying these rocks are more coarsely clastic Pliocene and Pleistocene strata (Kew, 1924; Schlueter, 1976; Yeats, 1976; Jackson and Yeats, 1982 and references therein) including the Pico, Santa Barbara, and Casitas Formations, and farther east, the Saugus Formation (see Ch. 2). Most outcrops of the Monterey in the study area are structurally deformed and not exposed with all subsequent overburden intact; the "entire stratigraphic thickness is neither exposed at the surface nor penetrated by any one well" (Schlueter, 1976, p.17).

Although upper Monterey strata have been eroded there, the most complete accessible section of the Monterey Formation in the northern Ventura basin occurs just south of the town of Oakview (Fig. 4). The Monterey rocks of the northern Ventura basin, mainly at the composite Oakview section, are compared to the lithologic members which Isaacs (1980, 1981b, 1983) informally defined at San Augustine Canyon for the Monterey Formation of the Santa Barbara coastal area. Detailed locality descriptions and biostratigraphy are presented in Appendix A.

Monterey Formation

The lithostratigraphy of the Monterey Formation along the trend examined in this study is generally similar to that in the area west of Goleta (Fig. 5, see also Fig. 1). The two areas (Fig. 6) lie approximately along an east-west line parallel to and north of the axis of the Miocene basin trough in

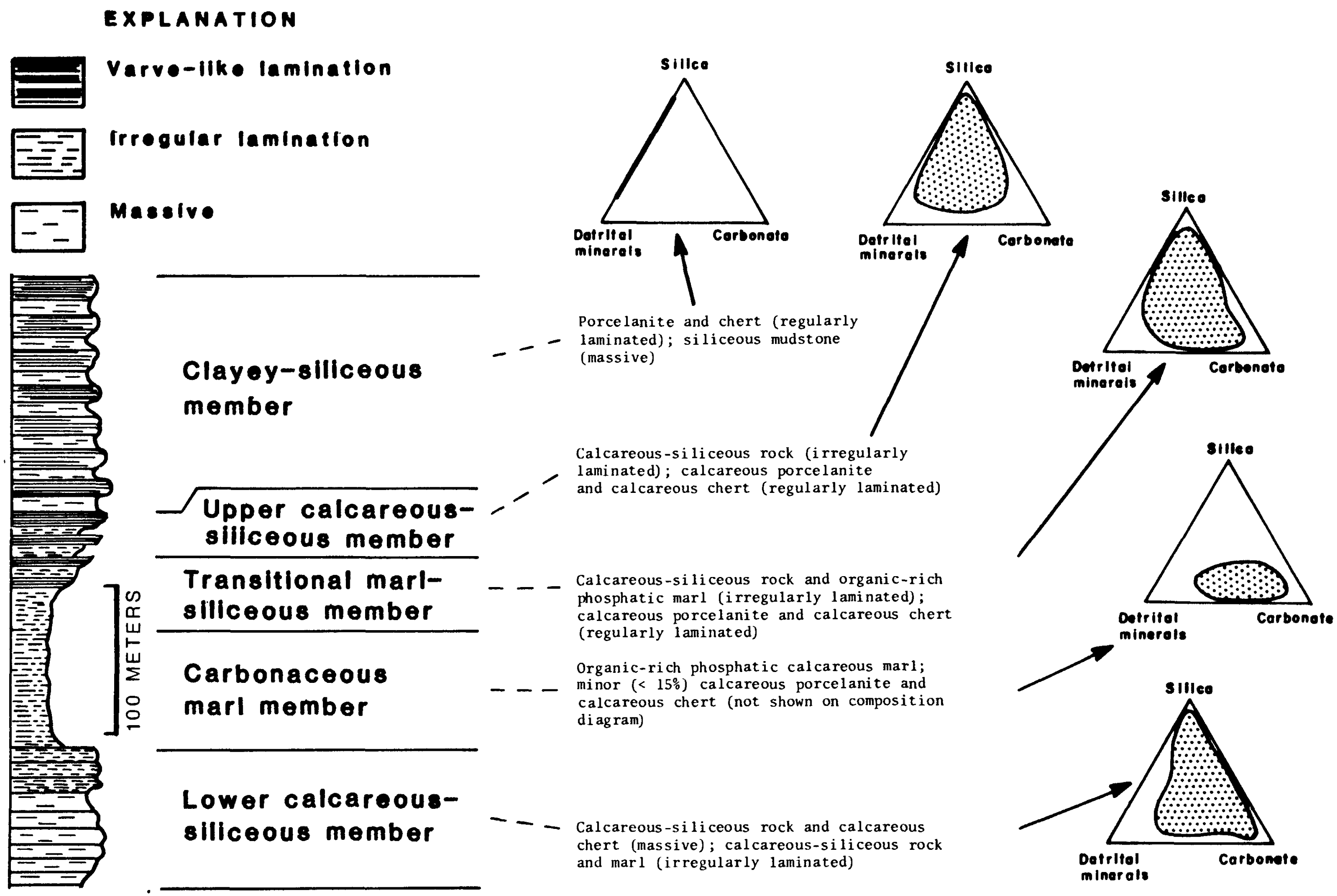


Figure 3. Generalized lithostratigraphic sequence of the Monterey Formation in the Santa Barbara coastal area from Isaacs (1981b, 1983).

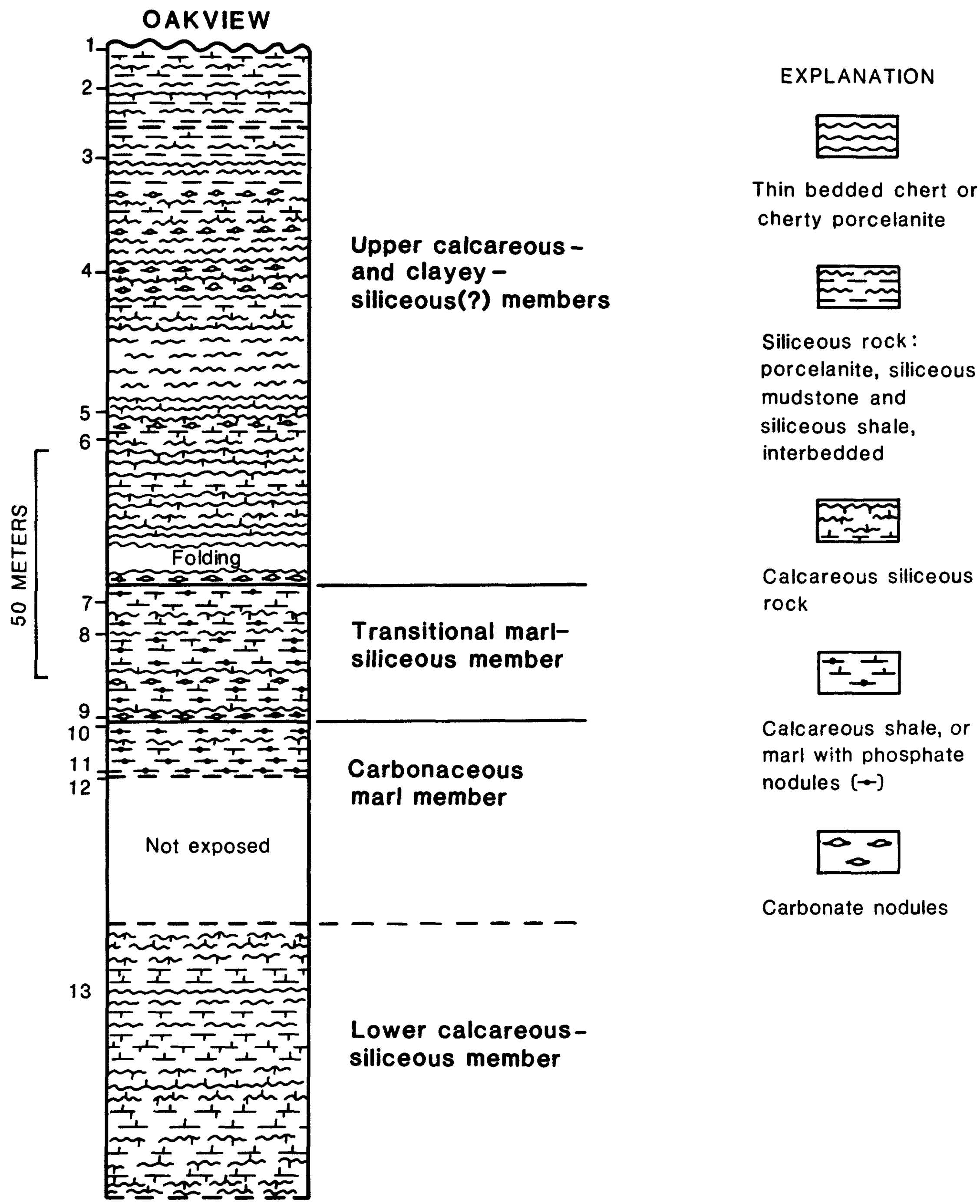


Figure 4. Composite lithostratigraphic sequence of the Monterey Formation in the northwestern Ventura basin compiled from sections on Highway 33 near Oakview, California. Numbers at left margin are the locations of microfossil age-dates, see Appendix A.

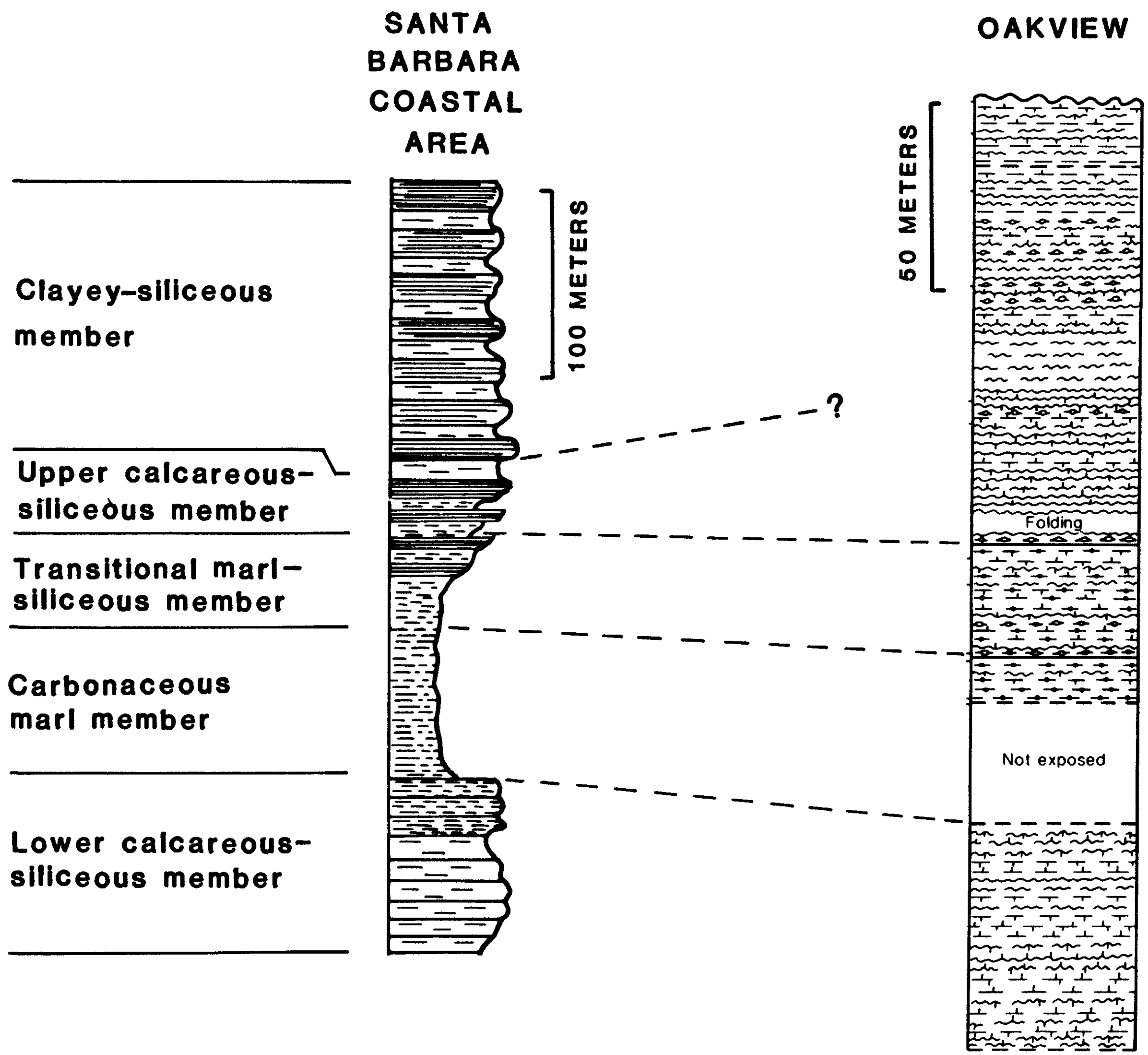


Figure 5. Lithostratigraphic sequence of the Monterey Formation at Oakview correlated to the lithologic sequence in the Santa Barbara coastal area. Note that the Oakview section is about half as thick as the Santa Barbara coastal section. (See Figs. 4 and 5 for explanation of lithologic symbols.)

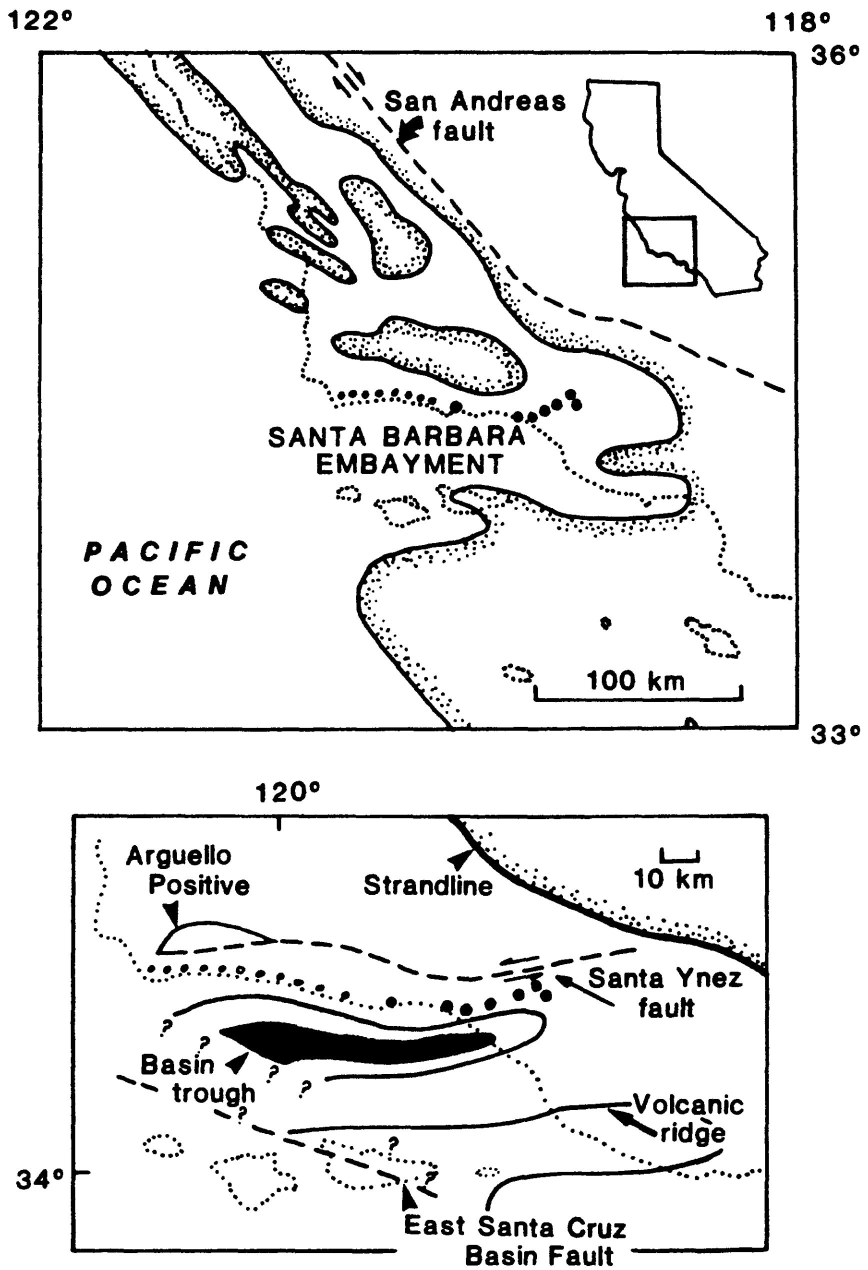


Figure 6. Non-palinspastic reconstructions of Miocene paleogeography of the Santa Barbara area from Isaacs (1983). Above: relief of Central California west of the San Andreas fault at the beginning of the transgression during latest Oligocene, early Miocene time (Ca. 25 Ma). Below: position of the basin axis in early Miocene time and the middle Miocene strandline. Small circles to the left are sites of Isaacs (1980,1981), larger circles at right are sites of this study. Miocene reconstruction was adapted from Loel and Corey (1932), Corey (1965), Edwards (1971), Fischer (1976), and Clifton (1981).

which the Monterey was deposited (Edwards, 1971; Fischer, 1976). Despite general similarities, the lithostratigraphy of the Monterey in the two areas differs in minor ways as described below. The following description of the lithologic members in the Ventura basin utilizes Isaacs' (1983) revised member names (Fig. 3).

Lower calcareous-siliceous member

The Monterey exposed near Oakview exhibits an abrupt conformable contact with the underlying Rincon Shale. The bentonite or tuff-breccia which defines this contact in parts of the Santa Barbara coastal area does not occur here. However, the massive, spheroidally weathering clay shales of the poorly-resistant Rincon Shale contrast sharply with the overlying well bedded, resistant calcareous-siliceous rocks of the lower Monterey (Fig. 7). Rocks equivalent to Isaacs' (1983) lower calcareous-siliceous member (Fig. 4) are well exposed, although deformed, at Rincon Point and Oakview (Fig. 8). This member is lithologically correlative with the siltstone and shell zone, locally called the Point Sal Formation, plus the oil sand zone and part of the dark brown zone of Canfield's (1939) zonation of the Monterey Formation in the Santa Maria basin (Isaacs, 1981b; Pisciotto, 1981). Age of this member (App. A) is latest Saucesian near the base (determined at Rincon Point) and Luisian-Relizian near the top (determined at Oakview). Lithologically the member consists of distinctively thick-bedded, massive to irregularly laminated, calcareous or dolomitic, siliceous rocks (Fig. 4). At Oakview the member, although folded, is probably thicker than 60 m.

Carbonaceous marl member

The best outcrops of the carbonaceous marl member (Isaacs, 1983) in the northern Ventura basin are exposed during low tide along the beach northwest of Rincon Point, at Carpinteria State Beach (Fig. 9 top) and in stream cuts on Sulphur Mountain (Fig. 9 bottom). Lithologically this member consists mainly of carbonaceous marls, i.e. sparsely siliceous rocks which contain abundant calcite and organic matter and commonly phosphate in blebby or disseminated layers (Fig. 3). The member, for the most part, has a Luisian fauna and is correlative with the lowest part of the buff and brown zone, the bentonitic-brown zone, and the uppermost part of the dark brown zones of Canfield's (1939) zonation of the Monterey Formation in the Santa Maria Valley (Isaacs, 1981b; Pisciotto, 1981). Because of its sparse silica (biogenic and diagenetic), exposures are good only in very actively eroding areas. At Oakview only the upper part of this member is exposed, but its total thickness is estimated to be 40 ± 5 m.

Transitional marl-siliceous member

As suggested by its name, this member is a transitional unit in which the lithologies dominant in the members directly above and below are intimately interbedded. Where diagenetic silica has formed, the distinctive interbedding (Fig. 10) allows for confident field recognition of this member, even in structurally disturbed areas, provided enough of the overlying or underlying lithologic sequence is exposed. In addition to the ease of field recognition, three other characteristics of this member make it ideal as a lithostratigraphic horizon for evaluating silica diagenesis: (1) it is usually thin,

Figure 7. Contact between resistant, siliceous shales of the Monterey Formation (at right) and clay shales of the Rincon Shale. Exposure is located on Santa Ana Road several kilometers north of Foster County Park, Ventura County, California.

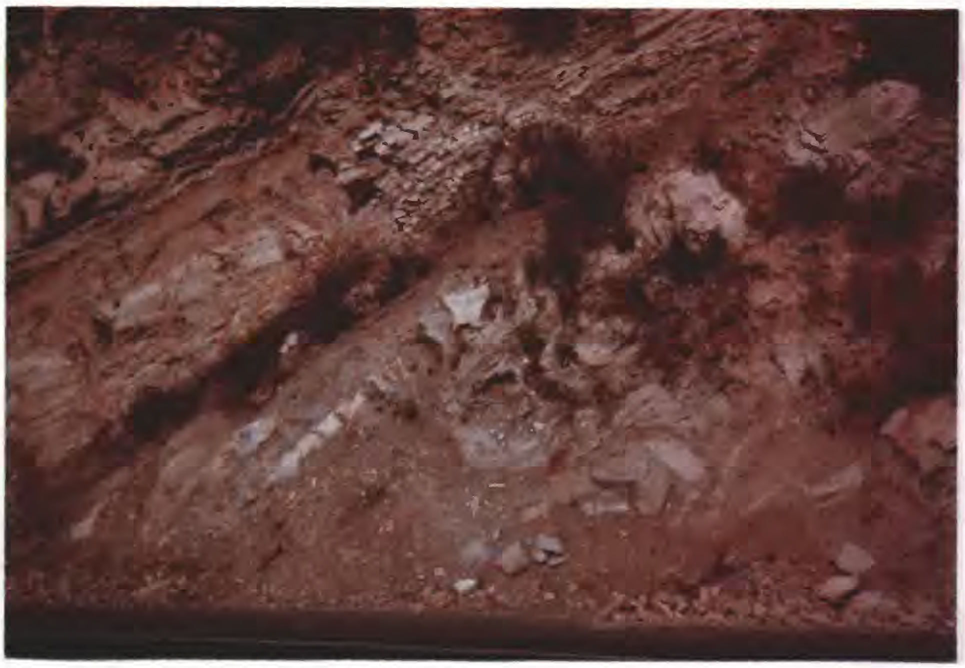


Figure 8. Exposures of the lower calcareous-siliceous member of the Monterey Formation at Rincon Point (above) and south of Oakview on Highway 33 (below), showing typical thick bedding and massive to irregularly laminated character.

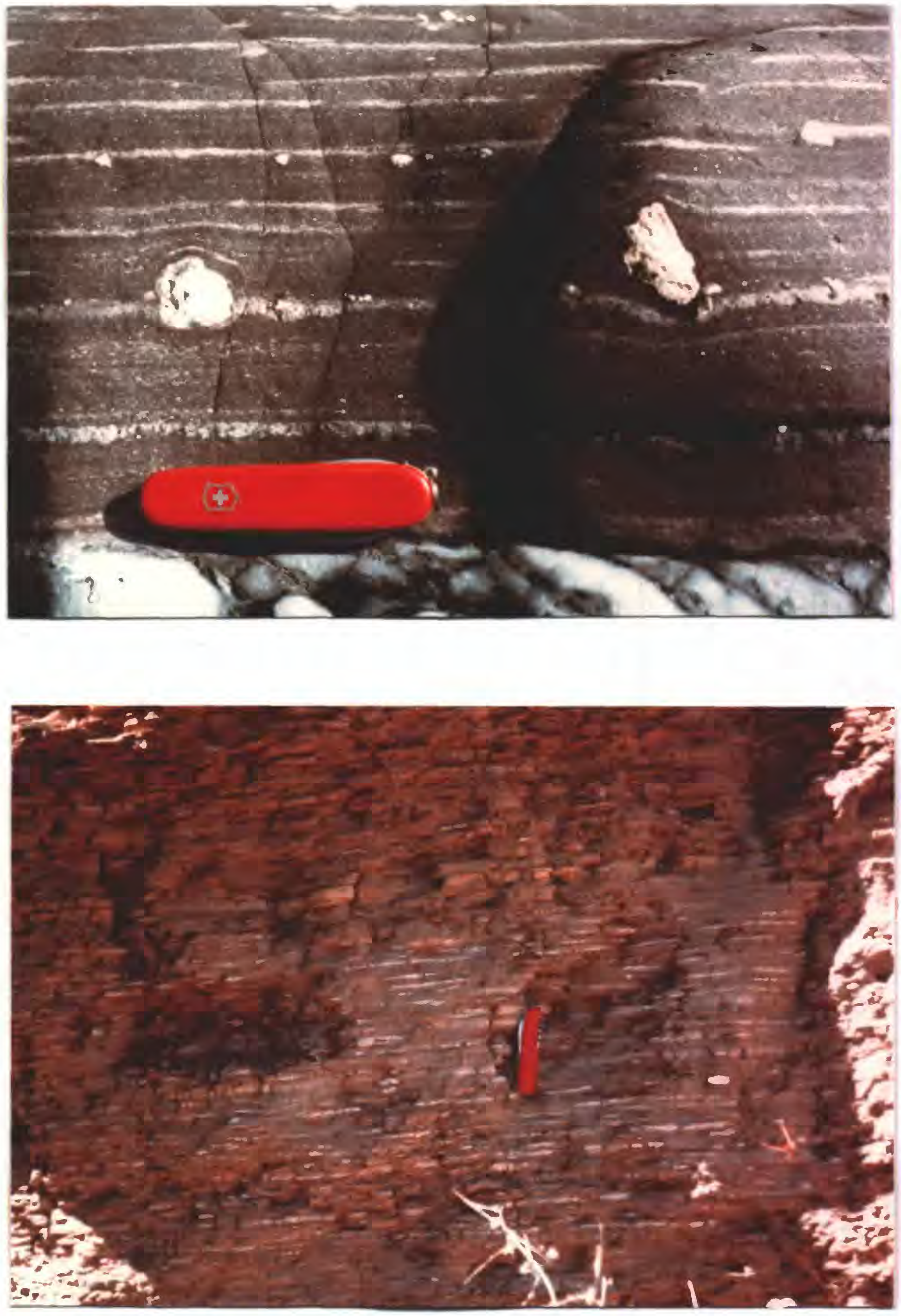


Figure 9. Exposures of the carbonaceous marl member of the Monterey Formation at Carpinteria State Beach (top) and on Sulphur Mountain Road (bottom) about 13.5 km east of Highway 33. Note the phosphate nodules, common in this member.

Figure 10. Outcrops of the transitional marl-siliceous member of the Monterey Formation on the beach at Rincon Point (above) and in a stream cut on Sulphur Mountain Road (below) about 13.5 km east of Highway 33. Note distinctive interbedded calcareous-siliceous rocks (more resistant and light colored) and calcite-rich detritus-rich rocks (less resistant and dark colored). At Rincon, silica is opal-CT in the light beds and opal-A in the dark beds. At Sulphur Mountain, silica is entirely opal-CT in the light beds but a mixture of opal-CT and diagenetic quartz in the darker beds.

less than 50 m thick; (2) its age is usually within the early Mohnian (App. A), which is characterized by distinctive, restricted benthonic foraminifera and calcareous nannofossils; and (3) its lithologic diversity aids in precise evaluation of silica diagenesis (see the following chapter).

In the northern Ventura basin, the transitional member is, for the most part, early Mohnian (App. A) with its base near the boundary between the Luisian and Mohnian stages. The transitional member correlates lithologically with the lower part of the cherty zone and possibly with the upper part of the bentonitic-brown zone of Canfield's (1939) zonation of the Monterey Formation in the Santa Maria Valley (Isaacs, 1981b). The member consists of poorly exposed, silica-poor marls interbedded with calcareous-siliceous rocks that are well exposed (Fig. 10) except at Goleta (Fig. 11) where no diagenetic silica has formed. Silica-poor marls decrease, whereas silica-rich calcareous rocks increase upsection. At Oakview, as at most sections in the Ventura basin, both upper and lower contacts of the transitional member are gradational, with the lower contact more so. The thickness of this member at Oakview is about 30 m $\pm$ 5 m.

On the north slope of Sulphur Mountain the transitional member contains friable sands (Fig. 12) up to 1/2 meter thick interbedded with calcareous siliceous shale, porcelanite, and chert. These sands, which increase to about 150 m thick in the Silverthread oil field 2 km farther north, have been interpreted as deep-water turbidites (Schlueter, 1976) which interfinger, or "shale out", to the south.

Upper calcareous-siliceous member and the clayey-siliceous member

Isaacs' (1983) upper two members of the Monterey Formation differ in characteristics of bedding and lamination and--of particular importance--in mineral composition. Carbonate is absent, except for rare nodules, in the uppermost, or clayey-siliceous member (Fig. 3). In the Santa Barbara coastal area west of Goleta rock types change gradationally upsection at the upper contact of the transitional member: sparsely siliceous, organic-matter-rich marls disappear and calcareous-siliceous rocks are dominant in the upper calcareous-siliceous member. Upsection in this member, within a distance of about 5 m, carbonate disappears except in rare nodules and all overlying strata (called the clayey-siliceous member) are finely laminated silica-rich rocks alternating with siliceous mudstones (Fig. 3). The upper calcareous-siliceous member probably correlates with the upper part of the cherty zone, and the clayey-siliceous member correlates with the arenaceous zone in the Santa Maria Valley (Isaacs, 1981b).

In the Ventura basin rocks above the transitional member are only partly exposed at Rincon Point, structurally disturbed in Los Sauces Canyon, partly eroded at Oakview, and partly faulted out at some locations on Sulphur Mountain (Schlueter, 1976). These partial sections together indicate that the Monterey Formation above the transitional member is mainly interbedded porcelanite, siliceous shale, mudstone, and chert. Rocks have high, but varying, silica (biogenic and diagenetic) content.

Composition and bedding of rocks overlying the transitional member in the northern Ventura basin contrast in several respects with correlative rocks in

Figure 11. Exposure of the transitional marl-siliceous member at Goleta Slough, Goleta State Beach. No diagenetic silica has formed here, but the clay rich beds can be differentiated from the more siliceous beds by their dark color and massive character. The diatomites are light colored and slightly blocky. All beds are calcareous.

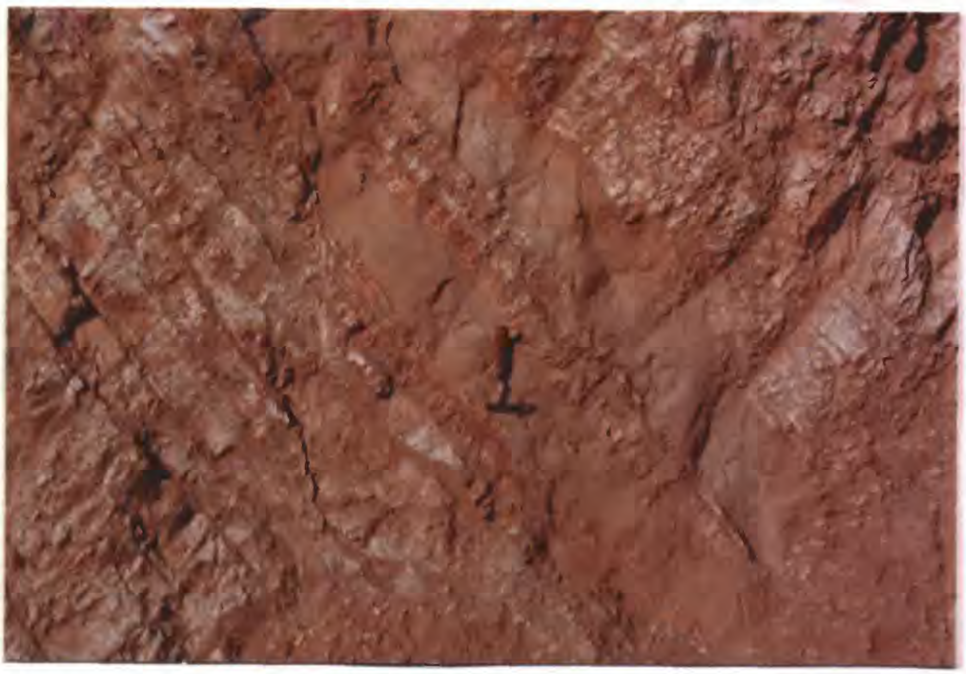


Figure 12. Exposure of the transitional marl-siliceous member of the Monterey Formation on the north slope of Sulphur Mountain (SMN) showing sands interbedded with porcelanites, cherts, and siliceous shales.

the Santa Barbara coastal area. For example, in contrast to the Santa Barbara coastal area, carbonate in the rocks above the transitional member is not restricted to a carbonate-bearing member overlain by a carbonate-free member in the northern Ventura basin. Instead, at sample localities on Sulphur Mountain (App. A) a calcareous-siliceous unit occurs at the top of the Monterey; and at Oakview, from about 40 m above the top of the transitional member, both calcareous and carbonate-free rocks are interbedded (Fig. 13 top) throughout overlying Monterey strata (Fig. 4). In the northern Ventura basin, carbonate thus occurs in strata directly above the transitional member and is also present sporadically in overlying strata except for the uppermost part of the Monterey exposed on the north side of Sulphur Mountain where it is again abundant. Monterey strata above the transitional member are not clearly divided into a carbonate-bearing and a carbonate free member in the northern Ventura basin east of Oakview.

Another contrast between the northern Ventura basin and the Santa Barbara coastal area is that prominent lamination is rare in the silica-rich beds of the upper Monterey near Sulphur Mountain. Also, the distinctive cycles of silica-rich rock alternating with detritus-rich rock of Isaacs (1981a) upper two members are present (Fig. 13 bottom) but more rare in the rocks of the northern Ventura basin.

Tuff is another distinctive, although not abundant, rock type in upper Monterey strata at Rincon, Oakview, and Sulphur Mountain. Tuff beds are glassy, gray to brown, and range from one cm to about 1/2 m in thickness. In this part of the Ventura basin, tuffs are generally present throughout the Monterey but are quite abundant in a 20 m thick section of Mohnian age at the top of the exposed Monterey at Oakview.

Upper Monterey strata (above the transitional member) are mostly Mohnian in age, but at Goleta and Sulphur Mountain the topmost rocks could be as young as "Delmontian" (App. A). At Oakview, where the top is eroded, only 121 m of upper Monterey strata are exposed above the transitional member; the youngest Monterey strata here have a diatom flora that occurs elsewhere in rocks of latest early Mohnian to earliest late Mohnian age (App. A).

Age Correlation

Microfossil sample sets were collected primarily to establish the time equivalence of the stratigraphic horizon sampled to evaluate diagenesis and secondarily to assist in unraveling the stratigraphy of the Monterey rocks which occur in the incomplete and broken exposures at Rincon, Los Sauces, and parts of Sulphur Mountain. Samples were not, in general, collected at regular intervals. Instead, they were collected within the transitional member (the diagenetic sampling horizon), near member boundaries, and near distinct stratigraphic markers. At the Oakview section, which is the most complete section, more detailed sampling was done so that the lithostratigraphy and age of the Monterey in the northern Ventura basin could be compared to the Santa Barbara coastal area (Fig. 5).

Results from dating the diagenetic sampling horizon are shown in Figure 14. The age of this horizon in the northern Ventura basin is approximately the same as, or slightly older than, the age of the transitional member

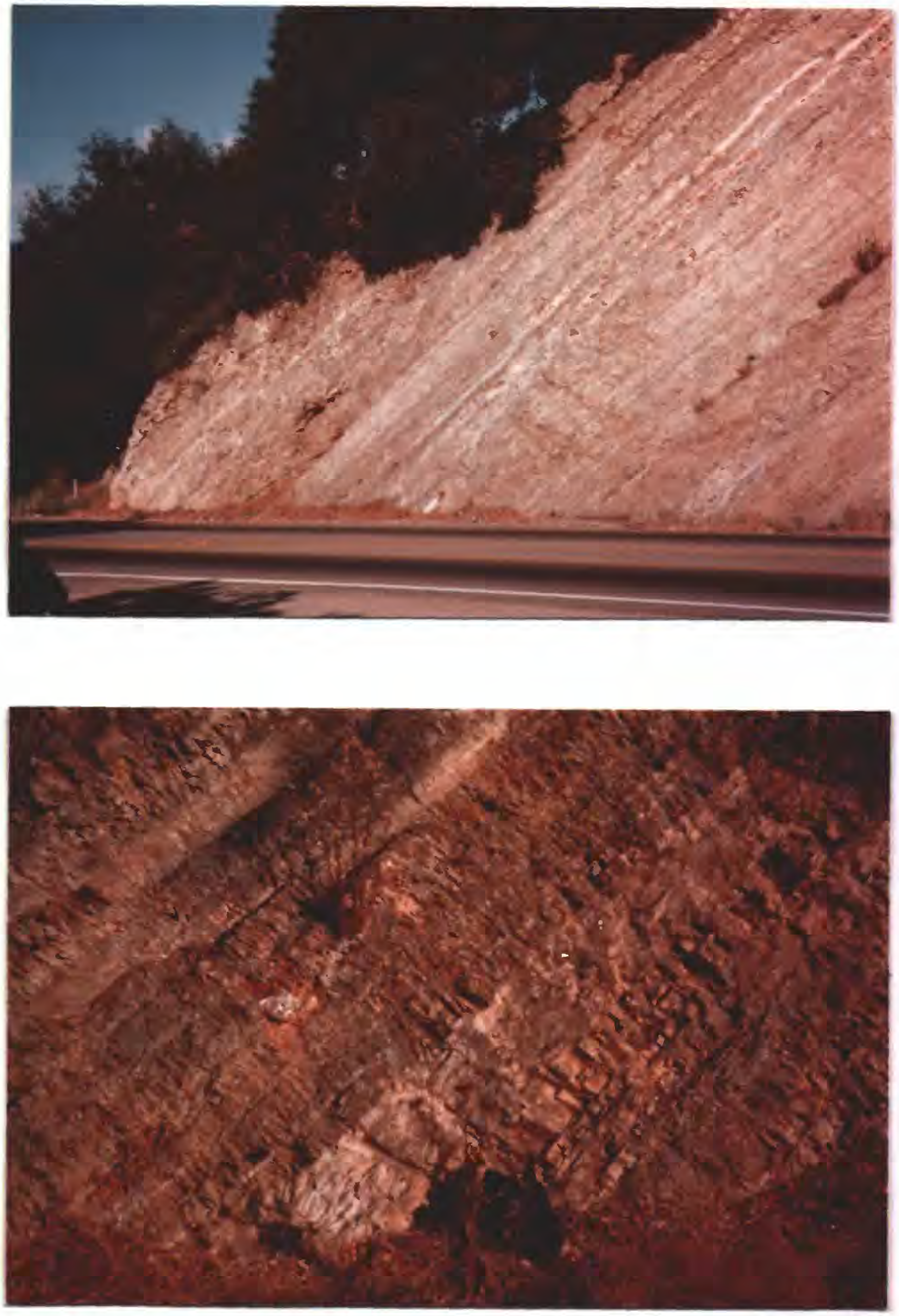


Figure 13. Exposures of upper Monterey strata above the transitional marl-siliceous member on Highway 33 just south of Oakview. The top view shows the uppermost Monterey strata on the north limb of the syncline and the bottom view shows slightly younger Monterey strata (App. A) in alternating cycles of siliceous and detritus-rich beds on the south limb of the syncline.

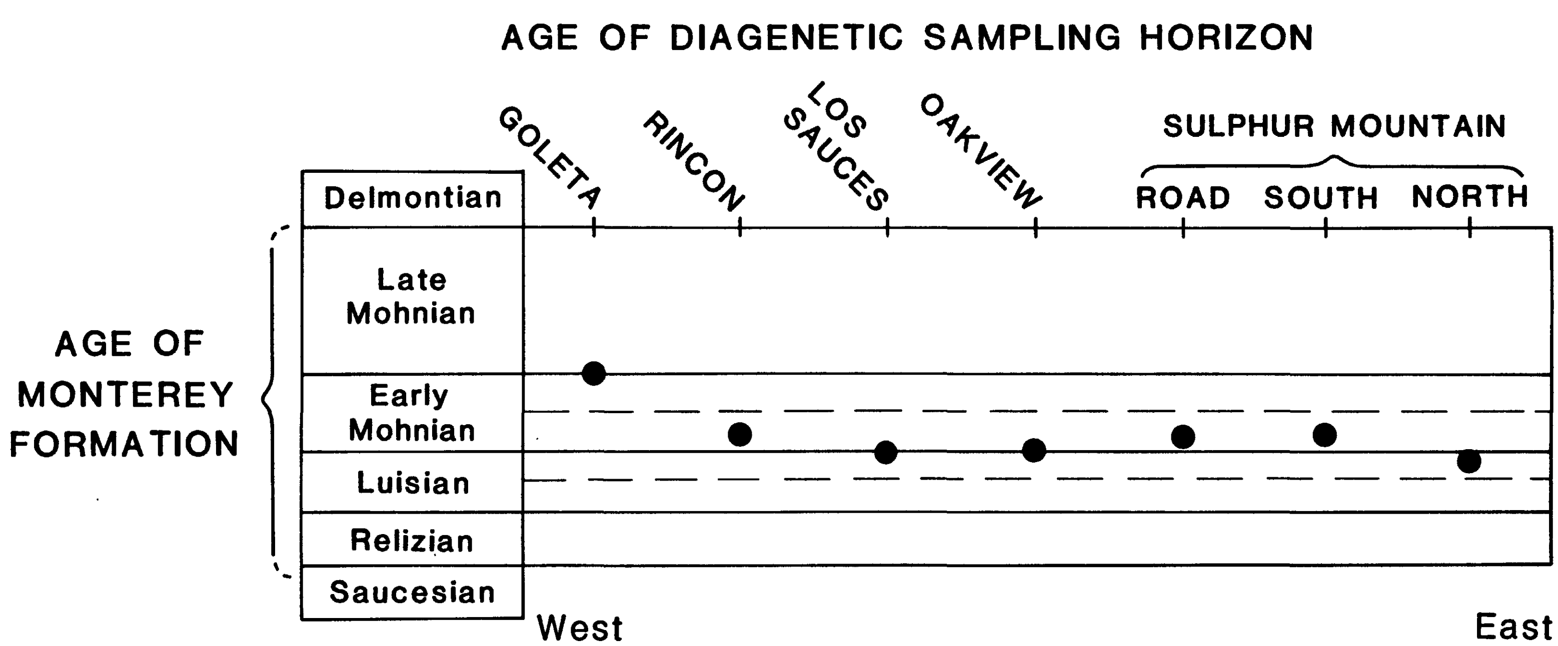


Figure 14. Age of the diagenetic horizon in the transitional marl-siliceous member of the Monterey Formation between Goleta and Sulphur Mountain, based on microfossil biostratigraphy by G. H. Blake, J. A. Barron, and R. E. Arnal (App. A).

between Elwood Beach and Point Conception (Isaacs, 1981b). At Goleta, which is east of Elwood, only the top strata of the transitional member of the Monterey are exposed, and these strata are close in age to the boundary between early and late Mohnian. At Oakview, however, strata of similar age occur about 120 m above the transitional member which ranges in age from early Mohnian to latest Luisian (App. A).

Microfossil age-dates of the Monterey Formation at Oakview, Rincon, and Sulphur Mountain (App. A) indicate that the Monterey was deposited over the same total time span (latest Saucesian to early "Delmontian") in both the northern Ventura basin and the Santa Barbara coastal area. However, the ages of the upper members of the Monterey Formation in these two areas may not be exactly equivalent. In particular, the transitional member appears to be slightly older in the Ventura basin, and the strata above the transitional member are different enough in the two areas (Fig. 5) to preclude precise lithologic correlation.

Summary

Although thicknesses vary, the lithostratigraphy and age of the Monterey Formation in the northern Ventura basin are similar to the Monterey of the Santa Barbara coastal area (Fig. 5).

At Oakview and Sulphur Mountain the lithostratigraphy of upper Monterey strata (above the base of the transitional member) differs in several minor respects from Isaacs' (1983) three upper members: (1) carbonate is abundant directly above the transitional member in a 40 m thick unit similar to the upper calcareous-siliceous member; however, overlying strata, presumably correlative with the clayey-siliceous member contain both calcareous and carbonate-free strata; (2) finely laminated siliceous rocks are not as common; (3) alternating silica-rich and detritus-rich cycles are more rare, or less apparent; and (4) on the north slope of Sulphur Mountain, the Monterey contains friable sands up to $1/2$ m thick interbedded with calcareous-siliceous rocks in the lower Mohnian rocks of the transitional member. To the east of Oakview, on Sulphur Mountain, the Monterey is reported to be about twice as thick (780 m, Schlueter, 1976) as the Monterey of the Santa Barbara Coastal area (400 m, Isaacs, 1981a). However, this greater thickness was not observed at the surface sections examined for this study; indeed, the measured section at Oakview, although incompletely exposed, is estimated to be only about half as thick as the average Santa Barbara coastal section (see Fig. 5).

EVALUATION OF SILICA DIAGENESIS

Introduction

Silica diagenetic grade of the transitional marl-siliceous member of the Monterey Formation was studied at seven surface localities on the northern margin of the onshore Ventura basin (Fig. 1). This chapter includes a brief background of relevant studies, the methods used to evaluate silica grade, and results and interpretation. The findings of this study have implications relating to: 1) maximum burial temperatures of the Monterey Formation, 2) late Miocene and Plio-Pleistocene depositional trends in the study area, and 3) the timing of major structural events, uplift of the Santa Ynez and Topa Topa Mountains and offset along the Red Mountain fault.

Background

The Monterey Formation is primarily composed of siliceous and calcareous biogenic material with moderate amounts of terrigenous clays. As originally deposited, the opaline silica of diatomaceous sediment is metastable. The typical sequence of silica phases, from opal-A (in diatom frustules) to opal-CT to quartz, has been widely recognized with increasing diagenesis in the Monterey Formation (Murata and Nakata, 1974; Murata and Larson, 1975; Pisciotto, 1978, 1981; Isaacs, 1980, 1981c, 1982; Surdam and Stanley, 1981) and in other diatomaceous deposits bordering the Pacific Basin (e.g. Mitsui and Taguchi, 1977; Hein and others, 1978; Iijima and Tada, 1981).

The X-ray diffraction characteristics of diagenetic silica in rocks of the Monterey Formation change consistently with increasing diagenesis (Murata and Larson, 1975; Isaacs, 1981c; Pisciotto, 1981). The principal X-ray diffraction characteristics of silica phases in the diagenetic sequence are as follows: (1) opal-A has a low broad hump near 4.0 Å; (2) opal-CT has a principal broad peak near 4.1 Å; and (3) diagenetic quartz has the typical quartz pattern with a principal quartz peak at about 3.3 Å. Within the opal-CT-bearing zone of the Monterey Formation at Chico Martinez Creek in the Temblor Range and at several other places in California, the principal d-spacing of opal-CT has been shown to decrease from about 4.12 Å, where first formed, to about 4.04 Å, at the base of this zone (Murata and Nakata, 1974; Murata and Larson, 1975; Pisciotto, 1981). Therefore, in a sequence of siliceous rocks that have been buried deeply enough for opal-CT to form, the principal d-spacing of opal-CT generally decreases with increasing burial depth and temperature.

This pattern of decreasing d-spacing is used in this study to develop a temperature zonation for the "opal-CT zone". The term "opal-CT zone" is used to describe strata between the first and last occurrences of opal-CT in a sequence of diatomaceous/siliceous rocks, approximately equivalent to a temperature range of 50° to 80°C (Murata and Larson, 1975; Murata and others, 1977). Murata and Randall (1975) regarded opal-CT d-spacings as temperature indicators and contoured d-spacing values as isothermal surfaces in order to delineate the details of folds in the Monterey Formation of the Temblor Range. Their method was refined by Mizutani (1977) who concluded on the basis of experimental work that for the purpose of zonation of diagenesis, the principal d-spacing of opal-CT is the best measure [of diagenetic grade] for siliceous sediments in the early stages of diagenesis.

The main factor that controls rates of silica transformations in the Monterey Formation is generally regarded to be temperature (Murata and Larson, 1975; Murata and others, 1977; Pisciotto, 1981). Murata and co-workers (1977) suggest that pressure as an independent variable could theoretically affect transformation rates but that in the Monterey Formation fluid pressures were probably always close to hydrostatic and not overpressured. Another factor that may be important in controlling rates of silica diagenesis is time as indicated by experimental results of Kastner and coworkers (1977) and Mizutani (1977). For the Monterey Formation of the Temblor Range, Murata and others (1977) dismissed factors other than temperature, in particular geochemical factors and pressure, as having only minor influence on silica diagenesis. Time is probably not nearly as important as temperature to silica diagenesis in the Monterey because diatomaceous deposits as old as Cretaceous are well known and time differences within the Monterey are comparatively small.

The temperatures of silica phase transformations and opal-CT d-spacings are apparently affected by bed composition, probably as a result of the chemistry of pore waters during diagenesis (Kastner and others, 1977). The formation of opal-CT was shown to be retarded by greater clay content in detritus-rich diatomaceous rocks from the Bering Sea (Hein and others, 1978) and by small amounts of montmorillonite added to diatom frustules in low-temperature experiments (Kastner and others, 1977). In the Monterey Formation, the relative detritus content, a reflection of clay mineral content (mostly mixed-layer illite-smectite), strongly influences silica diagenesis in several ways: (1) opal-CT forms at lower temperatures in rocks with smaller relative detritus content; (2) newly formed opal-CT has d-spacings which are significantly smaller (4.08 Å) in rocks with greater relative detritus content than in rocks with lesser detritus content (4.12 Å); and (3) diagenetic quartz forms at lower temperatures in rocks with a greater relative detritus content (Isaacs, 1981c; 1982) (see also Murata and others, 1979). Judging from the thicknesses of the phase transition zones in single sections of the Santa Barbara coastal area (about 200 m for opal-A to opal-CT and >300 m for opal-CT to quartz [Isaacs, 1980]), differences in the relative detritus content may produce a difference of as much as 10° to 15° C in the silica phase transformation temperature, assuming a geothermal gradient of about 20°C/km. The presence of calcite, on the other hand, seems to have only two minor influences on silica diagenesis in the Monterey Formation. In calcareous rocks, (1) minor amounts of quartz forms in sparsely detrital rocks at about the same temperature as opal-CT forms and (2) quartz cherts form locally by replacement (Isaacs, 1982). Although replacement-type cherts are not common and are not present in the samples of this study, some diagenetic quartz is present in most carbonate-bearing opal-CT rocks having sparse clays. The early formation of diagenetic quartz in such rocks is important to note as its presence can be easily misinterpreted as a sign of close proximity to the opal-CT/quartz transformation.

Temperatures of the two silica phase transformations have been estimated by several recent studies. These temperature estimates are based on several different approaches: 1) measurements of the depth of the opal-A to opal-CT boundary forming in the subsurface of the Bering Sea combined with *in situ* measurements of temperature (Hein and others, 1978); 2) estimates of maximum overburden together with estimates of thermal gradients based on modeling of heat flow and other parameters in uplifted sections (Murata and Larson, 1975; Murata and others, 1977; Pisciotto, 1978, 1981); and 3) determination of oxygen isotope ratios (Murata and others, 1977; Pisciotto, 1978, 1981).

Temperatures for the two phase transformations determined by the second and third approaches are approximations, at best, because several critical assumptions are required by each approach. For example, the values for pore water isotope composition and an appropriate expression for silica-water fractionation that are required in order to calculate isotope temperatures are not precisely known, and reasonable assumptions produce a broad range of phase transformation temperatures (Pisciotto, 1981; see also Isaacs and others, 1983b). Also, because of the difficulty of physically removing contaminating clay minerals, isotopic ratios must be determined on rocks with extremely sparse clays and the temperature of silica crystallization in such rocks may differ significantly from values in the majority of Monterey rocks. In particular, both empirical evidence (Isaacs, 1980) and isotope evidence (Haimson and Knauth, in preparation) indicate that many quartz cherts, which are particularly attractive for isotope studies because of their purity, form in carbonate-bearing sequences at about the same time that opal-CT forms; i.e., their formation temperatures are much lower than formation temperatures of diagenetic quartz in the majority of Monterey rocks.

Temperature estimates in uplifted sections are based on values of maximum overburden and paleogeothermal gradient which are imprecisely known because of erosion and probable changes in temperature distribution related to uplift. Moreover, the temperature values for the two silica phase changes in the uplifted Santa Maria area (38° to 54° C for opal-A to opal-CT, 55° to 110° C for opal-CT to quartz), that were derived from estimated maximum overburden and present geothermal gradients by Pisciotto (1978, 1981), were based mostly on uncorrected non-equilibrium borehole temperatures which do not yield actual thermal gradients but merely lower limits. Even values based on equilibrium borehole temperatures (50 to 54° C for opal-A to opal-CT, 77 to 110° C for opal-CT to quartz) are questionable in the Santa Maria area because of the difficulty of precisely determining maximum overburden and the underlying assumption that the present gradient equals or exceeds the past gradient (Pisciotto, 1981).

The most promising approach for estimating silica phase transformation temperatures, so far, has been to use in situ measurements in sections which are presently at maximum burial, such as in the Bering Sea. Data from the Bering Sea, however, have provided somewhat ambiguous results. For example, Hein and others (1978) indicate a 35° to 51° C temperature range for the zone of the opal-A to opal-CT transformation in "silty diatomaceous rocks" at DSDP Site 184 in the Bering Sea. This temperature range is based on a thermal gradient of 48° C/km, which apparently is an average gradient determined from the two temperature measurements at site 184 (Erickson, 1973, p. 647). Erickson (1973) states, however, that the best estimate of the thermal gradient for site 184 is 82° C/km, based on the better of the two temperatures (the one at a subseafloor depth of 174 m) measured at that site. In any case, as stated by Erickson (1973), "values [of heat flow at sites 183, 184, and 185] are based on geothermal gradients established using only one or two downhole temperatures; therefore, the possible error is large." Thus, limitations of the Bering Sea temperature data have so far prevented establishing an adequate baseline there for the opal-A to opal-CT transformation.

Temperature Zonation For Silica Diagenesis

What is needed to determine accurate temperatures of silica phase transformations are studies in non-uplifted basins which are presently at maximum burial and temperature and where good temperature data can be obtained. From these baseline observations of silica diagenesis, a temperature scale for the opal-CT zone and for silica diagenesis could be determined. After the relatively simple determination of silica diagenetic grade, this zonation would indicate the temperature of maximum diagenesis that had been attained in uplifted, opal-CT-bearing Monterey sequences.

A well which closely fits the requirements of a baseline for silica phase transformations is the Point Conception deep stratigraphic test well, OCS-Cal 78-164 No. 1. Neogene strata in this well appear to have been neither uplifted (McCulloch and Vedder, 1979) nor subjected to temperatures greater than present values (McCulloh, 1979). Moreover, although temperatures in the well were not measured at equilibrium, values were empirically adjusted yielding an average geothermal gradient of 48° C/km (McCulloh and Beyer, 1979).

Evaluation of silica diagenesis in individual cuttings from this well indicates that opal-CT formed at approximately 48° C in rocks with 65% relative detritus content and that quartz formed at 85° C in rocks with 20% relative detritus content (App. B; see also Isaacs and Keller, 1983; and Isaacs and others, 1983a). In addition to the data from individual cuttings, composite cuttings analyzed from the depth intervals near the opal-CT to quartz transformation indicate that opal-CT and diagenetic quartz occur in approximately equal abundance at a drilled depth of about 5700 ft (corresponding to a temperature of about 68°C) in a composite sample composition of 58% relative detritus content. Temperatures for the opal-CT to quartz transformation derived from the two sampling methods are in close agreement. These temperatures for the two silica phase transformations (opal-A to opal-CT based on individual cuttings and opal-CT to quartz based on composite cuttings) were used to calibrate a preliminary temperature zonation for the opal-CT zone based on empirical relationships between silica phases, rock composition, and opal-CT d-spacings in the Monterey Formation of the Santa Barbara coastal area and the northern onshore Ventura basin (App. B).

The baseline temperatures for the two silica phase transformations from the OCS-Cal 78-164 No. 1 well are quite similar to the phase-transformation temperatures derived from oxygen isotopes reported by Murata and coworkers (Murata and Larson, 1975; Murata and others, 1977), 48° ± 8°C for the opal-A to opal-CT transformation and 79° ± 2°C for the opal-CT to quartz transformation. They are also within the same range, but more precise than, the equilibrium values for the phase transformation temperatures reported by Pisciotto (1978, 1981).

Methods

Silica diagenetic grade in the rocks of this study was evaluated primarily from the opal-CT-bearing rocks in each group of samples. The abundance of silica phases in each sample group, however, was also determined because this indicates general trends in diagenesis. Because samples from the same location were collected within about 10 stratigraphic meters and thus experienced the same temperature conditions, differences in the silica phase or opal-CT d-spacing of samples from the same location are attributed mainly to differences in sample composition and, in particular, to the ratio of silica to detritus (Isaacs 1980, 1981c, 1982). As used in this report, the collective diagenetic characteristics of samples within a single horizon at a particular locality define a diagenetic assemblage. The temperatures represented by the diagenetic assemblages were determined from the temperature zonation described in the previous section and in Appendix B.

As an independent measure of maturity in the study area, powdered whole rock samples were pyrolyzed using the Rock-Eval method (Espitalie and others, 1977; Peters and others, 1981) to investigate the pyrolytic characteristics of the organic matter. Four samples from each of four localities were analyzed using the same splits that were used for X-ray diffraction study of silica phases. Rock-Eval II pyrolysis measurements (App. C) were made by K.E. Peters at Chevron Oil Field Research Company in La Habra, California.

Silica phases were identified by X-ray diffraction supplemented, where samples are diatomaceous, by strew-mount slides and identification of diatoms in hand specimen. Where applicable, the proportion of silica phases in a sample was determined by X-ray diffraction using constants developed for the Santa Barbara coastal area (see Isaacs, 1980, Appendix B, p. 207), and d-spacings of opal-CT were measured against a silicon standard. Mineral abundances were determined using the methods of Isaacs (1980, Appendix B, p. 207) and constants developed for the Santa Barbara coastal area (see also Isaacs and others, 1983a).

The abundance of silica phases and values of the principal d-spacing of opal-CT are reported in Appendix D, partial chemical analyses and the ratio of silica to detritus in Appendix E, and pyrolysis results in Appendix C.

Results

The distribution of silica phases in the transitional member of the Monterey Formation in the study area (Fig. 15) indicates a general trend of eastward increasing diagenesis. Rocks at Goleta, in the west, are diatomaceous whereas rocks at the six study sites between Rincon Point and Sulphur Mountain are opal-CT-bearing. Diagenetic quartz is only abundant in the east at Sulphur Mountain Road. Importantly, at all locations except Goleta, which is the least mature, opal-CT is the main silica phase in rocks of the transitional member, a relation indicating that only moderate temperatures (between approximately 50° and 80° C) were reached during burial and diagenesis.

A more detailed evaluation of the diagenetic assemblages, including comparison of opal-CT d-spacings to relative detritus content (Figs. 16 and 17), shows a more complex diagenetic pattern. Figure 16 also shows clearly that

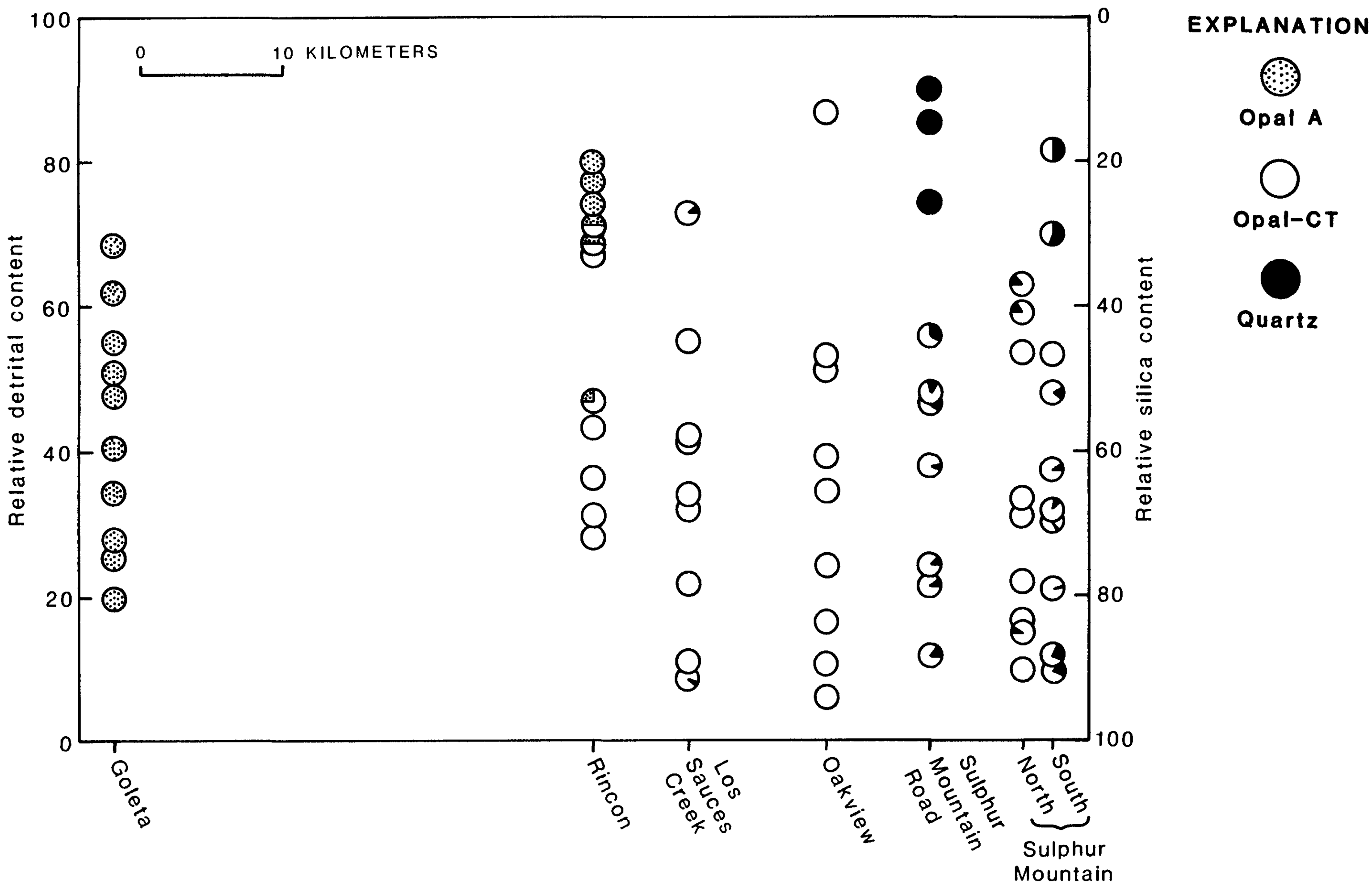
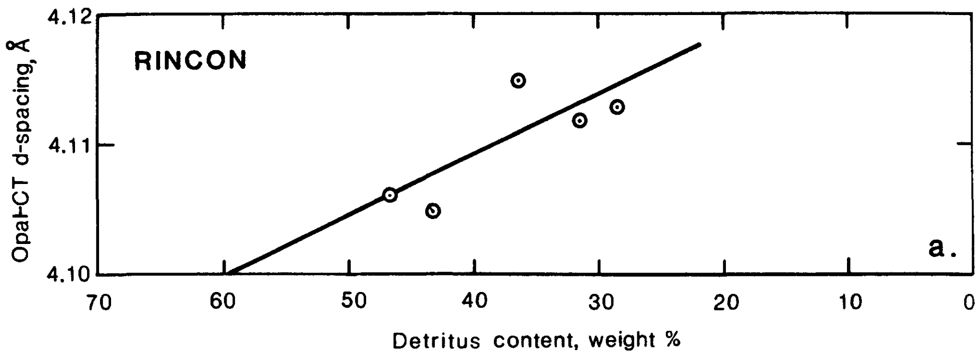


Figure 15. Lateral distribution of silica phases in the transitional marl-siliceous member of the Monterey Formation between Goleta and Sulphur Mountain. Note the presence of early formed diagenetic quartz in rocks with a low detritus content at eastern localities. Silica and detritus contents are expressed as a weight % of the sum of silica plus detritus (carbonate and organic-matter-free basis).



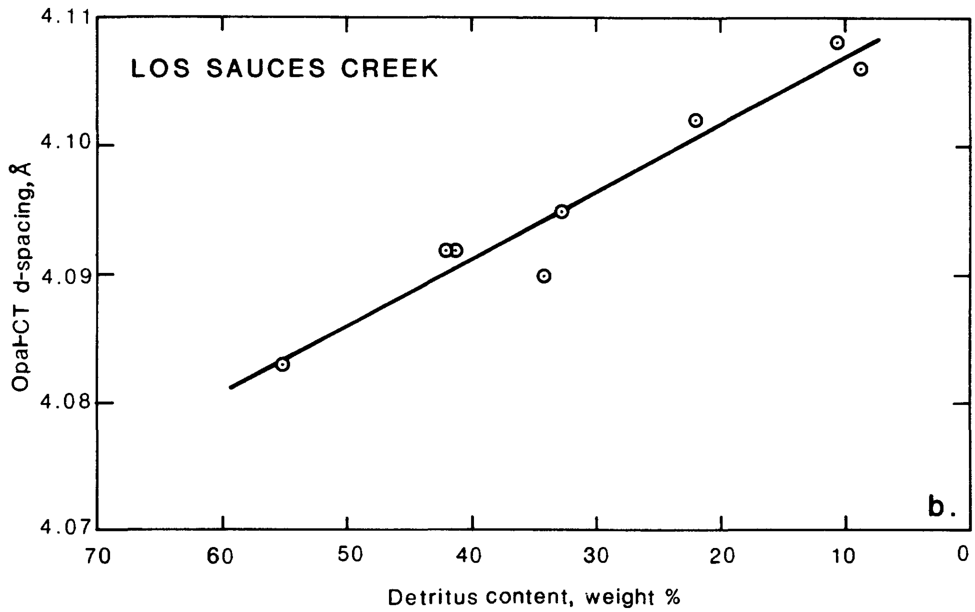
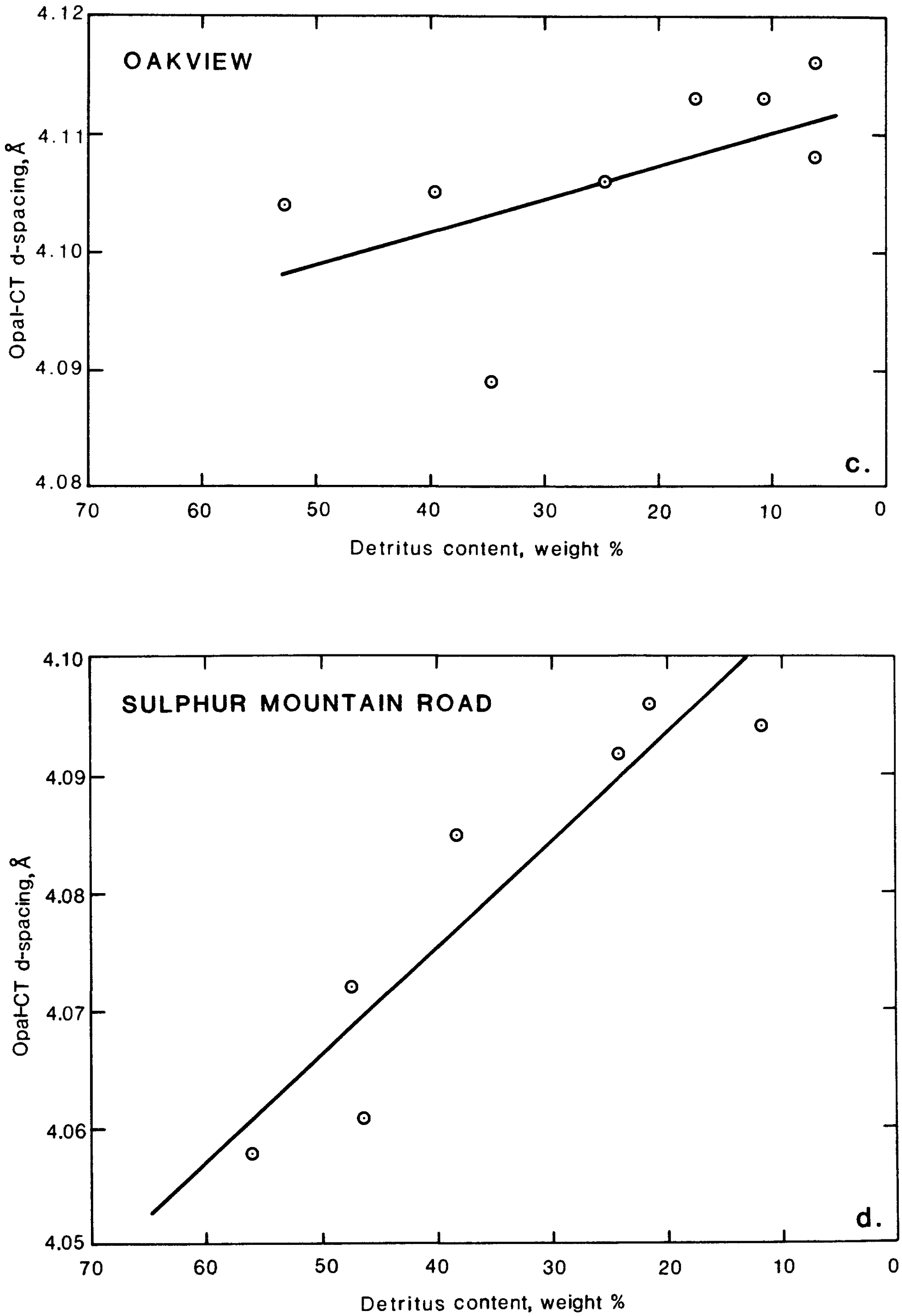


Figure 16. Relation between opal-CT d-spacings and detritus content for the transitional member of the Monterey Formation between Rincon Point and Sulphur Mountain (graphs a to f). Detritus content in weight %, carbonate and organic matter-free basis.



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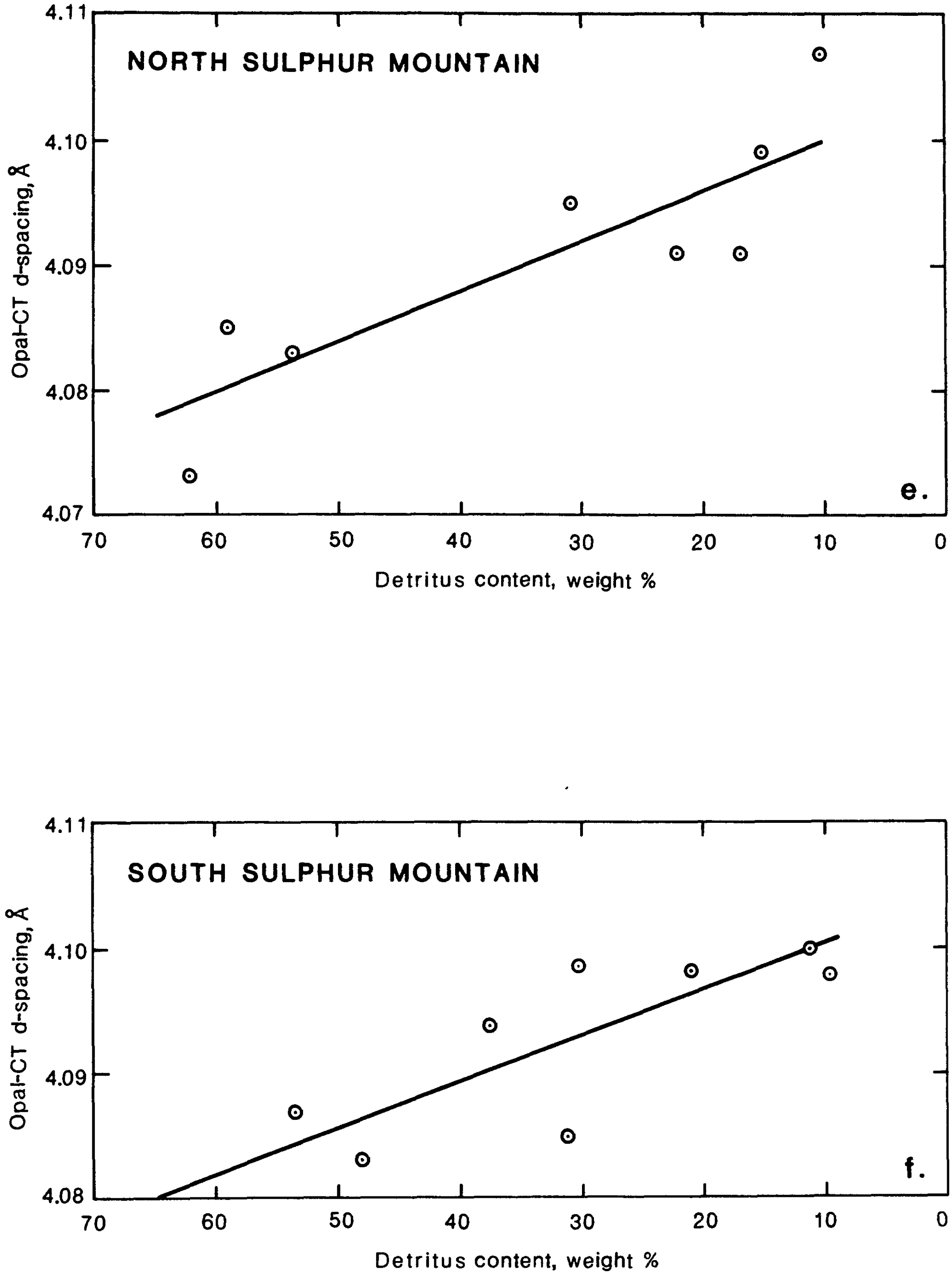

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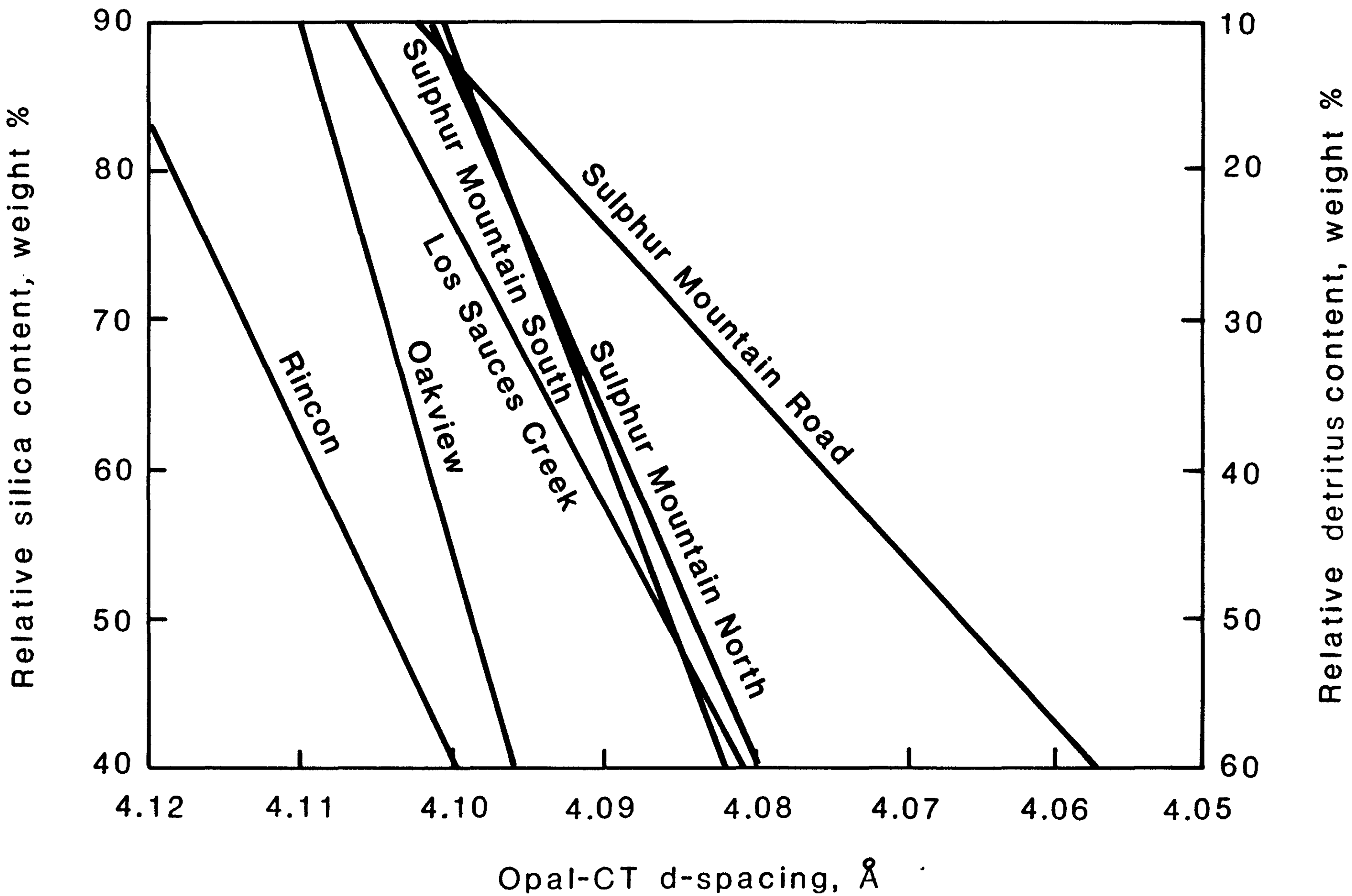

Figure 17. Summary of the relation between opal-CT d-spacings and detritus content between Rincon Point and Sulphur Mountain showing a general eastward decrease in d-spacings.

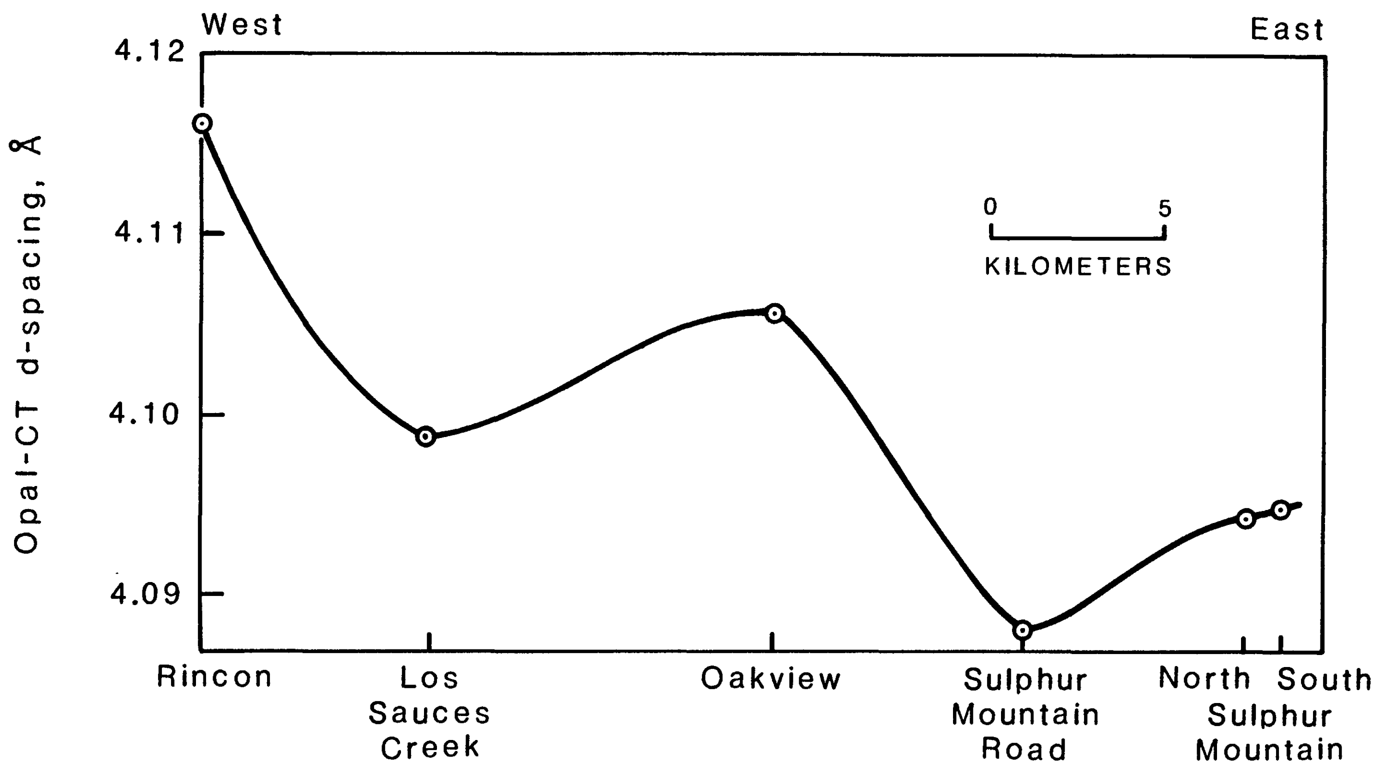

Figure 18. Comparison of the diagenetic grade of the transitional marl-siliceous member of the Monterey between Rincon Point and Sulphur Mountain, expressed as the opal-CT d-spacing for a rock with 25% relative detritus content. Note that lower points indicate greater maturity.

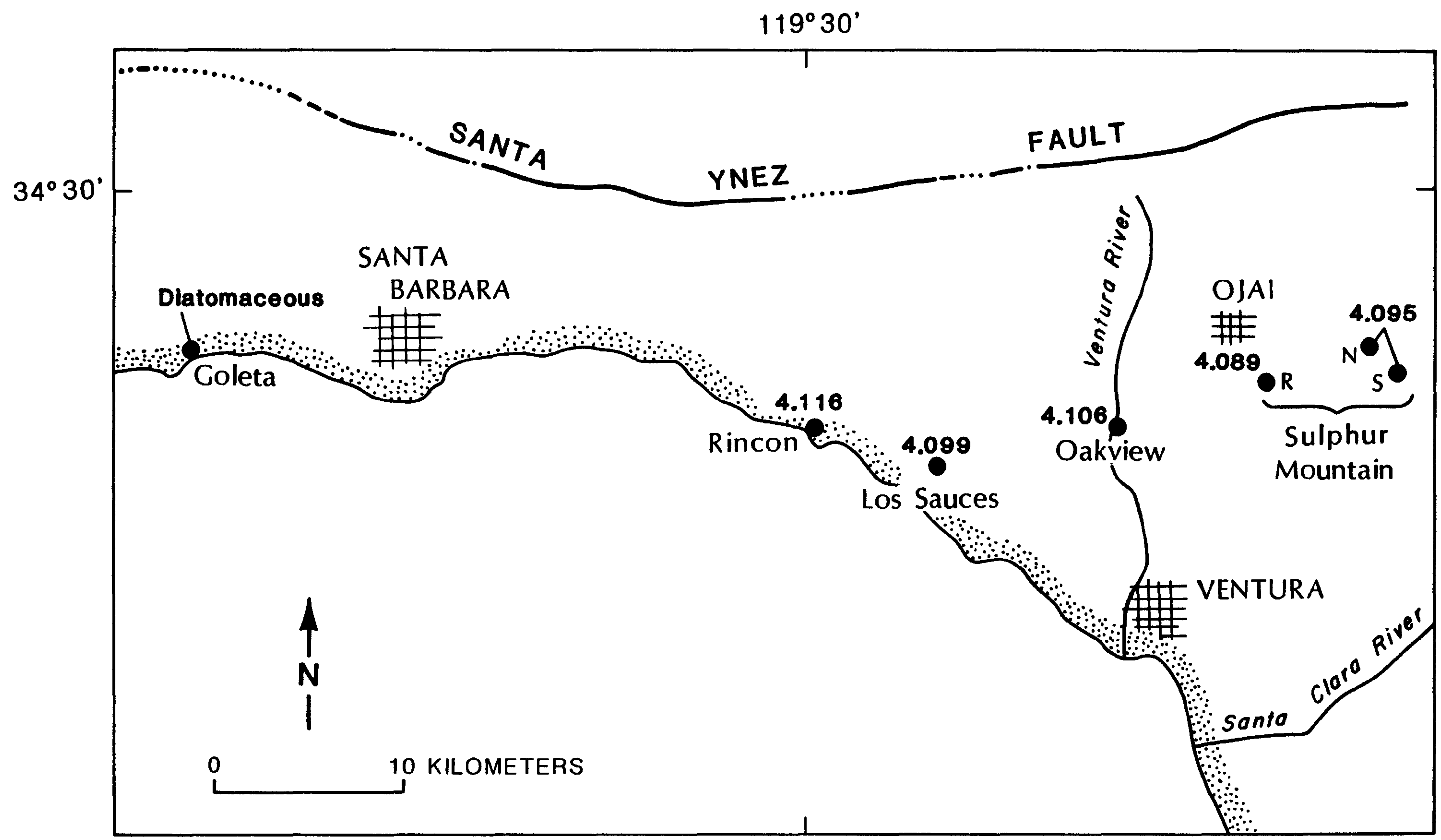

Figure 19. Geographic pattern of the opal-CT d-spacings shown in Figure 19 for sites between Rincon and Sulphur Mountain. For Sulphur Mountain sites R=road, N=north, S=south.

silica grade could easily be misrepresented by measurements of opal-CT d-spacings on only one or two samples from a site without concomitant knowledge of rock composition (relative detritus content). The east-west pattern of diagenetic assemblages between Rincon Point and Sulphur Mountain are summarized in Figures 18 and 19, where the opal-CT d-spacings of samples with the same composition (25% relative detritus content) from each location are compared (Figs. 18, 19). These figures show that the general eastward increasing trend in diagenesis is not linear.

Figure 20 shows the maximum temperature of diagenesis for each location, estimated by comparison of the silica diagenetic assemblages with the preliminary temperature zonation for the opal-CT zone. This comparison indicates that while the Monterey Formation was not heated to a constant temperature throughout the study area, that the maximum temperature difference between sites is no more than about 25° C. The temperature varied from less than 43° C at Goleta to about 68° C at Sulphur Mountain Road. Significantly, at none of the sites was the temperature high enough to transform the silica of the transitional member to predominantly quartz.

The results from pyrolysis (see App. C) agree in general with the results from silica diagenesis (Fig. 21). A puzzling relation, however, is that Goleta, the westernmost locality in the least mature stage of silica diagenesis, apparently has more mature kerogen than do Rincon and Los Sauces Creek, as indicated by a slightly higher average temperature of maximum pyrolysis yield (T_{max}). The average T_{max} increases from about 400° C at Rincon and Los Sauces to 408° C at Goleta. This relation may reflect differences in weathering of the samples inasmuch as exposed diatomaceous rocks are more rapidly leached of organic matter than opal-CT rocks, and some data suggests that weathering mimics the process of thermal alteration (G. E. Claypool, personal communication, 1983).

According to Claypool (1979), T_{max} provides an estimate of kerogen maturity wherein the transition from immature to mature is indicated by a temperature of 425°C. K.E. Peters (written communication, 1982) estimates that the oil "birthline" occurs at a T_{max} of about 435° C for the measurements of this study which were made at his lab. By either criterion, the kerogen of Monterey strata at all sites is immature. However, kerogen in the west (Goleta, Rincon, and Los Sauces) is less mature than in the east (Sulphur Mountain Road) (Fig. 21). Thus, kerogen maturity in the study area, as determined by T_{max}, generally confirms the eastward increasing maturity pattern shown by silica diagenesis.

Interpretation of Silica Diagenetic Grade

The main factors that influence silica diagenetic grade are the conditions of the environment that directly affect the temperature in a layer of sediment, including the thickness of overburden (burial depth), heat flow, and thermal conductivity. Overburden thickness and thermal conductivity are certain to have varied through time and space in the study area. As for heat flow, no evidence suggests that it has varied during post-Monterey time in the study area. The following interpretation of diagenetic grade of the Monterey Formation emphasizes the processes controlling the deposition and thickness of post-Monterey strata interpreted in the framework of overburden estimates

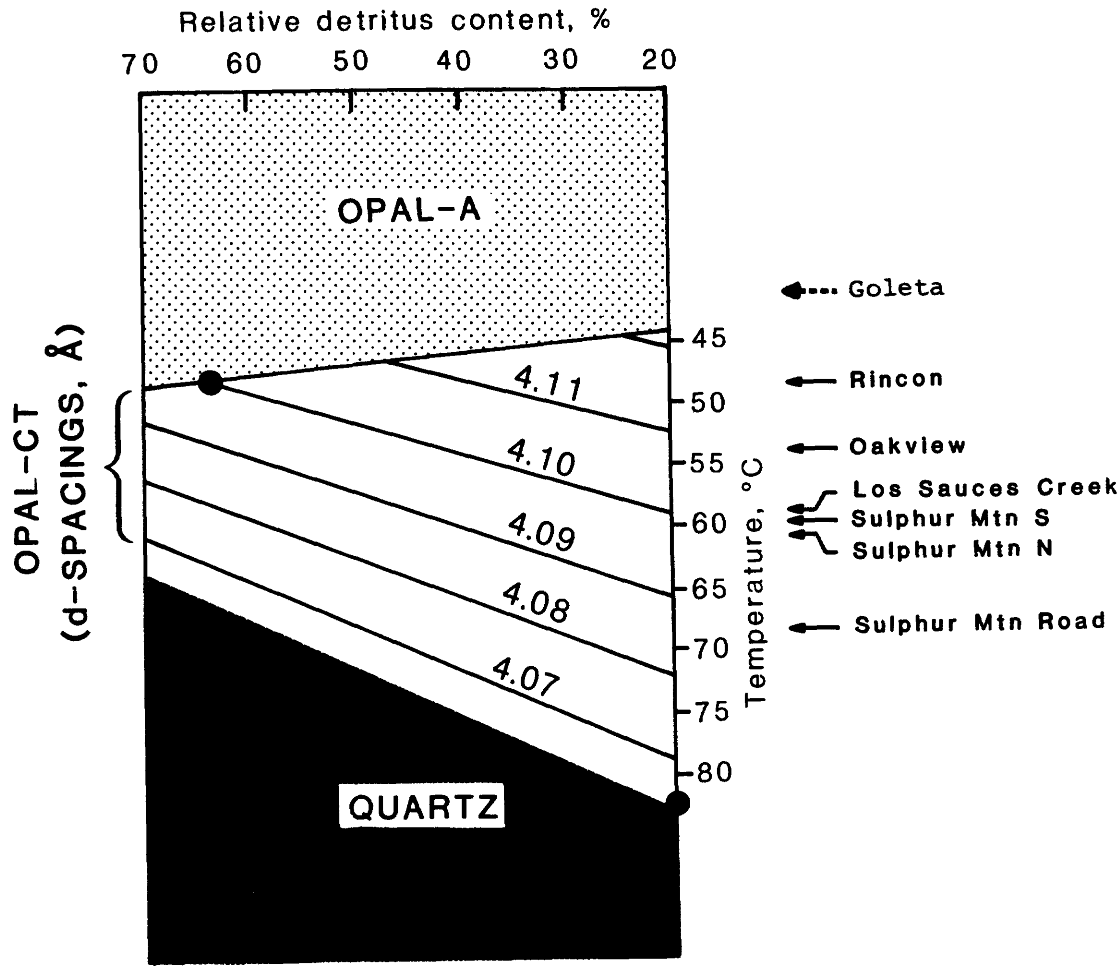

Figure 20. Temperature zonation for opal-CT, showing the diagenetic grade and approximate temperature of sites between Goleta and Sulphur Mountain based on opal-CT d-spacings and rock composition. Large dots indicate the phase transformation points in the Point Conception COST well. Note that the diagenetic grade of Goleta is approximate because it is diatomaceous. The zonation is adapted from Isaacs (1981b, Fig. 19) (see also Appendix B).

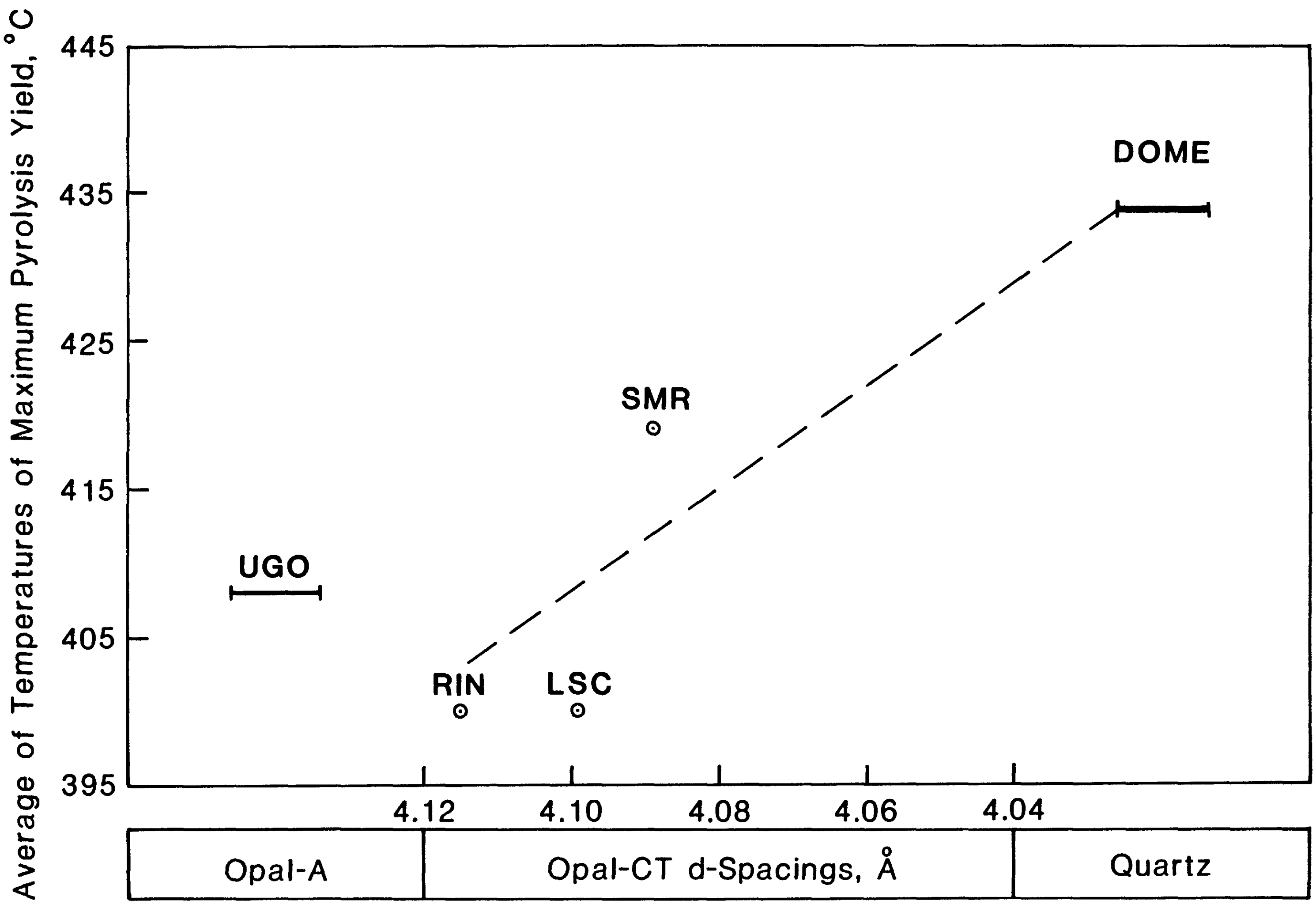

Figure 21. Relation between kerogen maturity (as determined from the average of the temperatures of maximum pyrolysis yield) and diagenetic silica grade at selected sites. Pyrolysis data represent averages of 4 samples at each site except the Union Dome 18 well (Orcutt oil field, Santa Maria basin) which represents an average of 2 samples. Silica diagenetic grade is taken from Fig. 19, except for Dome samples in which silica is diagenetic quartz.

based on three different thermal histories for the Monterey, including a history which takes into account the abrupt changes in thermal conductivity that occur during burial and diagenesis of the Monterey and other diatomaceous deposits.

Of major influence on overburden thickness is tectonism. Interruption of the burial/heating process during uplift causes an interruption of diagenesis in the uplifted block (Mizutani, 1977; Pisciotto, 1981). In an adjacent block which might be in a position to receive more sedimentation, continued burial to a higher temperature would result in a higher silica grade. An alternativebut temporary (and possibly insignificant) result of uplift is that the ambient temperature in the uplifted block would be raised slightly upon uplift from a deep marine environment, where the surface temperature is about 2° to 6° C, to a warmer subaerial environment where surface temperatures range from about 13° to 20°C (Pisciotto, 1981). A slight rise in temperature during uplift might produce a change in silica phase of strata at certain ambient temperatures (Isaacs, personal communication, 1982) and might increase slightly the diagenetic grade of all strata before overburden could be eroded. However, the possible increase in diagenetic grade due to uplift would be slight and is due to temporary heating. Moreover, some evidence suggests that isotherms may not re-equilibrate very quickly during rapid denudation after uplift (Benfield, 1949).

Estimates of maximum overburden thickness based on diagenetic temperature are approximations, at best, because thermal and burial histories of the Monterey Formation, where uplifted, are poorly understood. In particular, variables related to the thermal history and important to the determination of maximum overburden thickness (burial depth), such as the heat flow, thermal conductivity, and possible post-Monterey variations in these thermal characteristics, are difficult to reconstruct. Also, the burial and uplift history of the Monterey are complex (see Ch. 2). In the study area, the original thickness and extent of post-Monterey strata can only be estimated.

Limits can, however, be placed on the maximum overburden thickness (burial depth) of the transitional member at each site based on temperatures determined by silica diagenetic grade and some simplifying assumptions (Table 1). Values of overburden thickness in all columns of Table 1 are based on a bottom water temperature of 4° C (Natland, 1957). In column three, thickness values are based on a uniform geothermal gradient, linear with depth, of 24° C/km, which corresponds to the Pliocene to present-day gradient in the deeper part of the Ventura basin (Bostick and others, 1978). This gradient represents a minimum likely paleovalue, as it is approximately the lowest reported in the region today, and may result from an apparently low heat flow due to the rapid accumulation of very thick post-Miocene deposits and subsequent downward displacement of isotherms (Bostick and others, 1978). Values in the third column, based on the minimum gradient, are probable maximum estimates of overburden thickness. Values in the fourth column are based on a linear geothermal gradient of 48° C/km, which corresponds to the present-day, and probably the post-Monterey maximum, geothermal gradient in the Point Conception COST well (OCS Cal 78-164 No. 1) (McCulloh and Beyer, 1979). Although higher gradients are reported in the onshore Santa Maria and parts of the Los Angeles basins (French, 1940), reported gradients near the Santa Barbara coastal area and Ventura basin are less than 48° C/km. Finally, values of overburden

Table 1. Estimates of the maximum thickness of overburden for the transitional marl-siliceous member of the Monterey Formation at sites along the northern margin of the Ventura basin, based on temperatures derived from silica diagenetic grade (Fig. 20) and a bottom-water temperature of 4°C for three different geothermal gradients (see text). Location of sites is shown in Figures 1 and 19.

Location	Diagenetic Temp., °C	Overburden Thickness, m: Linear Geothermal Gradient 24°C/km	Linear Geothermal Gradient 48°C/km	Graduated Geothermal Gradient
Goleta	<43	<1630	<810	<650
Rincon	48	1830	920	747
Los Sauces	58	2250	1130	997
Oakview	53	2040	1020	872
Sulphur Mtn. Rd.	68	2670	1330	1265
Sulphur Mtn. North	60	2330	1170	1047
Sulphur Mtn. South	59	2290	1150	1022

Table 2. Graduated thermal gradient model used in Table 1. Variations in the geothermal gradient are calculated from a constant heat flow (1.2 x 10^{-6} cal/cm^2-sec) and varying values of thermal conductivity related to silica phase (Benfield, 1947; Erickson, 1973; Murata and others, 1977; Isaacs, in preparation, 1983).

Temp.,°C	Silica phase	Thermal Conductivity, mcal/cm-sec-°C	Thermal Gradient, °C/km	Depth, m
0-44	Opal-A	2.0	60	0-667
44-50	Opal-A + Opal-CT	2.4	50	667-747
50-64	Opal-CT	3.0	40	747-1147
64-83	Opal-CT + quartz	3.5	34	1147-1706

thickness for each site based on a non-linear geothermal gradient (Table 2) are shown in Column 5 of Table 1. The non-linear geothermal gradient is based on the abrupt changes in physical properties, including thermal conductivity, which occur during diagenesis in diatomaceous deposits and in the Monterey Formation (Benfield, 1947; Erickson, 1973; Murata and others, 1977; Isaacs, in preparation, 1983).

The range of overburden values for each site in Table 1 indicates that temperature estimates from silica diagenetic grade permit only general conclusions about overburden because of the many uncertainties in the thermal and burial history of the rocks. Based on Pliocene-to-present-day low and high geothermal gradients near the study area Monterey strata at the site with the greatest diagenetic grade are unlikely to have been buried more than about 2,700 m or less than 1,300 m.

Of regional significance, therefore, is that the intermediate silica grades, indicating moderate temperatures between about 48° and 68° C, at study sites between Rincon Point and Sulphur Mountain did not result from burial by overlying strata as thick as 6 to 7 km. Such thicknesses of strata overlie the Monterey in the deepest part of the central Ventura basin and at Wheeler Canyon, just 10 km south of the Sulphur Mountain south site (Natland, 1957; Bostick and others, 1978). These great thicknesses of post-Monterey strata represent deposition in a relatively stable tectonic block, the central Ventura basin, where silica diagenetic grade of Monterey-equivalent rocks is inferred to be high (diagenetic quartz). On the northern flank of the basin, and just 10 km north of Wheeler Canyon, however, intermediate silica diagenetic grades indicate that the northern block has received less than half the overburden of the central block. This variation in post-Monterey overburden, <2.7 km to 6 or 7 km, over a distance of about 10 km is quite abrupt, but variations of this magnitude are also present in the Santa Barbara area; the Monterey of the onshore Elwood area is diatomaceous whereas 3 km offshore the Monterey is opal-CT and diagenetic quartz. In a general way, therefore, silica grade reflects the contrasting post-Monterey tectonic histories of different parts of the Ventura and Santa Barbara basins, and indicates the presence of tectonic boundaries.

What is the tectonic explanation of the intermediate silica grades of the northwestern Ventura basin? Because all study sites, except Goleta, are located on the north, upthrown side of the Red Mountain fault and related structures to the east of the Ventura River (Yeats, 1976; Jackson and Yeats, 1982), and because the Monterey is not exposed in the area between the fault and the central Ventura basin, a major question is whether diagenesis was interrupted by offset along this fault. The Red Mountain fault, however, did not exist prior to about the middle of the Pleistocene (Yeats, 1976)--too recently to have had much effect on the silica diagenetic grade of the Monterey in the uplifted northern block, inasmuch as the diagenetic grade of that block can be accounted for by pre-mid-Pleistocene deposits. Post-middle-Pleistocene faulting, therefore, probably did not significantly influence the diagenetic grade that developed in the block north of the Red Mountain fault.

Uplift of the Santa Ynez and Topa Topa Mountains is more likely to have been the main factor contributing to the moderate silica diagenetic grades in the study area, inasmuch as all study sites are located on the south flank of

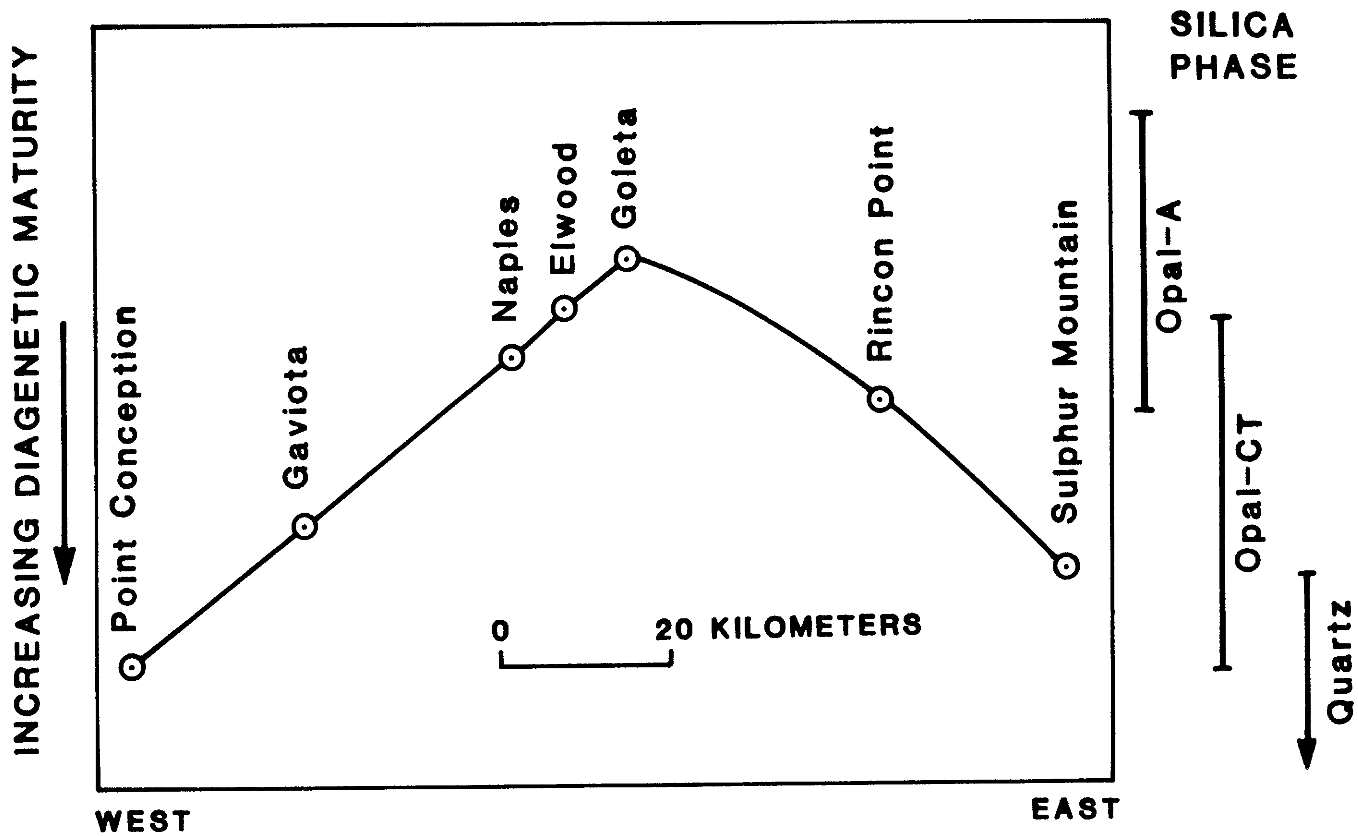

Figure 22. Comparison of silica diagenetic grade of the transitional marl siliceous member of the Monterey Formation between Point Conception and Sulphur Mountain. Data between Point Conception and Elwood are from Isaacs (1980), and between Goleta and Sulphur Mountain from this report (Apps. D and E).

the Santa Ynez and Topa Topa Mountains, where uplift probably commenced as early as early Pliocene during deposition of the Sisquoc Formation (Jackson and Yeats, 1982). Furthermore, unconformities between the Miocene and Pliocene and in mid-Pleistocene rocks in the Ventura basin, and many faulting and folding events, indicate that the time between 3.5 Ma and the present has been very active tectonically. Tectonism and deformation were thus probably important influences over diagenesis in that they exerted control over depositional patterns and thicknesses. Submarine topographic control over depositional patterns and southward migration of the shoreline presumably were also important during the Pliocene (Fischer, 1976; Yeats, 1976; Hsu, 1977). Variation in the thickness of Post-Monterey deposition due to all these factors can account for the general eastward trend of increasing silica diagenesis and the fluctuations about this trend.

Summary

Regional comparisons of silica diagenetic grade and, therefore, of approximate maximum temperatures attained at particular horizons of the Monterey Formation can be made without knowledge of past or present geothermal gradients, thermal and burial history, and rock thermal conductivities. Because many variables affect paleotemperatures other than overburden thickness, only general conclusions can be drawn about the burial depth of Monterey rocks from silica diagenetic grade. Major trends in silica diagenesis do reflect general overburden history, as concluded from the silica diagenesis trend between Point Conception and Elwood (Isaacs, 1981c). In the northern Ventura basin as well the silica diagenesis trend reflects the post-Monterey depositional history which was controlled by tectonism and deformation.

A general comparison of silica diagenetic grade in the transitional member of the Monterey Formation extending east from Point Conception, including the Santa Barbara coastal area (Isaacs, 1981c), and then east into the Sulphur Mountain area of the northern onshore Ventura basin is shown in Figure 22. The most pronounced feature of this regional comparison is a general trend of increasing diagenesis both east and west from Goleta where the lowest diagenetic grade is found. Significant east-west fluctuations in general trend of diagenetic grade due to the Santa Ynez fault (near Gaviota) and between Rincon Point and Sulphur Mountain (Fig. 18) are not shown in Figure 22. Also significant north-south variations in diagenetic grade occur between Sulphur Mountain and the central Ventura basin and between Elwood onshore versus offshore. Therefore, because tectonism and deformation produce very abrupt variations in depositional patterns and thicknesses and thus in silica diagenetic grade of the Monterey Formation, care must be exercised in projecting the results of this study and others into nearby areas in the structurally disturbed Transverse Ranges.

Conclusions

1) Evaluation of silica diagenetic grade in rock assemblages of the transitional-marl siliceous member of the Monterey Formation at sites between Goleta and Sulphur Mountain indicates that A) diagenetic grade is primarily moderate and all rock assemblages are primarily opal-CT-bearing except for Goleta which is diatomaceous, and B) diagenetic grade generally increases eastward between Goleta and Sulphur Mountain.

2) Organic matter maturity generally confirms the trend indicated by silica diagenetic grade.

3) Temperatures represented by silica diagenetic grade were determined for each study site and ranged from <43°C at Goleta to approximately 68°C at Sulphur Mountain Road. These temperatures were determined from a temperature zonation of the "opal-CT zone" that was developed from the temperatures of silica phase transformations in the Point Conception COST well together with empirical data on rock composition, silica phases, and opal-CT d-spacings from the Santa Barbara and Ventura basins.

4) Estimates of overburden thicknesses based on these diagenetic temperatures range from a low at Goleta (between 650 and 1630 m) to a high at Sulphur Mountain Road (between 1270 and 2670 m).

5) The difference between thick post-Monterey overburden (6 to 7 km) in the central Ventura basin and the moderate overburden (<2.7 km maximum) estimates for the northern margin of the basin is attributed mainly to the control over depositional thicknessess exerted by uplift of the Santa Ynez and Topa Topa Ranges (beginning during deposition of the Sisquoc Formation) rather than to offset along the Red Mountain fault which did not begin until after most deposition and diagenesis had already occurred.

6) In the structurally disturbed Transverse Ranges abrupt north-south and east-west changes in silica diagenetic grade occur, probably for the most part as a reflection of the control of tectonism over post-Monterey depositional patterns and thicknesses. The ability to project trends in silica diagenesis and estimate prior maximum temperature and burial depths of the Monterey Formation is thus greatly enhanced by access to Monterey samples.

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APPENDIX A

BIOSTRATIGRAPHY AND SITE DESCRIPTIONS

This appendix includes detailed locality descriptions, microfossil biostratigraphy, and a measured section at Oakview. Localities are listed in order from west to east.

GOLETA SLOUGH (UGO)
34°22.4' North, 119°49.5' West

Location: Bluffs adjacent to Goleta Slough at Goleta State Beach Park, Santa Barbara County, California. From the easternmost parking lot, outcrops of the transitional member of the Monterey Formation can be seen in cliffs adjacent to the slough and are easily accessible although wading is usually required in winter months.

Geology: East of the slough along the beach are outcrops of the upper two members of the Monterey Formation and the conformably overlying Sisquoc Formation. The two lower members of the Monterey Formation are not exposed.

Microfossil Biostratigraphy: All microfossil age-dates from diatoms and correlations with benthic foraminiferal stages are by J. A. Barron.

Stratigraphic position and sample number	Microfossil Identifications and Age of sample
SISQUOC FORMATION	
UGO 10-1	Thalassiosira antiqua (common) T. hyalinopsis T. nativa Nitzschia reinholdii Actinoptychus undulatus f. maxima Flora usually found in lower Sisquoc Formation. Upper Nitzschia reinholdii Zone approximately equivalent to lower "Delmontian" Stage

MONTEREY FORMATION	
Clayey-siliceous member (from outcrops just west of Goleta State Beach Park) UGO 1-1	Coscinodiscus nodulifer Synedra jouseana Thalassiosira antiqua Absence of Rouxia californica and Hemiaulus polymorphus Flora of the upper Nitzschia reinholdii Zone equivalent to early "Delmontian" and same age as SMN 100
Clayey-siliceous member UGO 9-1	Thalassiosira antiqua Hemiaulus polymorphus Rhaphoneis amphiceros var. elongata (common) Synedra jouseana absence of Rouxia californica Upper Nitzschia reinholdii Zone equivalent to early "Delmontian", probably only slightly older than UGO 1-1
Upper calcareous-siliceous member UGO 4-9	Rouxia californica (common) Nitzschia fossilis Hemiaulus polymorphus Coscinodiscus nodulifer Silicoflagellate: Distephanus pseudofibula upper Denticulopsis hustedtii Zone equal to North Pacific Diatom Zone XII and equivalent to late Mohnian
Transitional marl siliceous member UGO 2A-1	Denticulopsis lauta D. dimorpha D. katayamae Rouxia californica R. fusiformis Thalassiosira sp. 1 of Barron Subzone d of Denticulopsis hustedtii-D. lauta Zone Probably correlative with late Mohnian but near late Mohnian/early Mohnian boundary

RINCON POINT (RIN)
34°22.8' North, 119°29' West

Location: Rincon Beach County Park, Santa Barbara and Ventura Counties, California. Outcrops of the transitional member were sampled from the northern face of the road cut next to the railroad tracks at the point where the freeway crosses over the tracks.

Geology: Parts of the Monterey Formation are well exposed at Rincon Point along the beach and in roadcuts adjacent to and leading to the Southern Pacific railroad tracks. During low tide, outcrops of the Monterey Formation can be seen along the beach between the County Park and the Chevron-Casitas pier which is about 2 1/2 km west of the park. From west to east, the beach outcrops expose the lower calcareous-siliceous member (Fig. 8a) overlain by the carbonaceous marl member in turn overlain by the transitional marl-siliceous member (Fig. 10a). In the railroad cuts, the transitional member is overlain by about 175 m of lower Mohnian and upper Mohnian rocks to the east. The Monterey ranges in age from Saucesian in the west to late Mohnian in the east, described in the following as "upper part of Monterey".

Rincon Point is between the north branch of the Red Mountain fault and the Carpinteria fault (Jackson and Yeats, 1982); and the exposures here are generally folded and faulted. Strike is roughly parallel to the coast.

Microfossil Biostratigraphy:

Stratigraphic position and sample number	Microfossil Identifications and Age of Sample		
	G. H. Blake	R. E. Arnal	J. A. Barron
Uppermost outcrops RIN 4-1 and 4-2	4-1: late Mohnian 4-2: Mohnian-Luisian (probably reworked)		4-2: Uppermost Denticulopsis hustedtii Zone; equivalent to late Mohnian
Upper part of Monterey RIN 101	Discorbinella valmonteensis(?), Pullenia bulloides, Bolvina; seminuda; late Mohnian	Discorbinella valmonteensis, Bolivina sinuata alisoensis(?); Mohnian	
RIN 102	Discorbinella valmonteensis(?), Pullenia bulloides, Cassidulina crassa; late Mohnian	Discorbinella valmonteensis, Cassidulina crassa, possibly C. barbarana; probably late Mohnian or late-early Mohnian	
RIN 104 to 107	Bulimina uvigerinaformis; early Mohnian	Bulimina uvigerinaformis Zone; late early Mohnian	
Transitional member, RIN 110 & 111	Epistominella gyroidinaformis; early, early Mohnian	Cibicides illingi; Mohnian, probably early	Younger than subzone a of Denticulopsis lauta Zone
Carbonaceous marl member, RIN 6-1	Baggina robusta, Siphogenerina hughesi, S. branneri; early Relizian		
Lower calcareous siliceous member RIN 7-1	Bulimina inflata alligata, Baggina cancriformis, Siphogenerina transversa; Saucesian		

LOS SAUCES CREEK (LSC)
34°21.8' North, 119°24.7' West

Location: Los Sauces Creek, type locality for the Saucesian Stage (Kleinpell, 1938), Ventura County, California. Samples for diagenesis were collected on private land approximately 2 km north of the coastal outlet of Los Sauces Creek.

Geology: This site is located between two splays of the Red Mountain fault and on the south flank of the Los Sauces Creek anticline (Jackson and Yeats, 1982). Downstream from the diagenesis site are upper Monterey strata of early Mohnian age, and the contact between the Monterey and Sisquoc Formations is well exposed. At Los Sauces Creek continuity between outcrops is not good in many places due to structural deformation.

Microfossil Biostratigraphy:

Stratigraphic position and sample number	Microfossil Identifications and Age of Sample	
	G. H. Blake	R. E. Arnal
Calcareous siliceous shales (upper Monterey) LSC 101-105	*Bulimina Uvigerinaformis*; early Mohnian	*Bulimina uvigerinaformis* Zone; late early Mohnian
Transitional marl siliceous member LSC 109	*Eponides multicameratus*, *Eponides rosaformis*; early Mohnian	*Eponides rosaformis*; early Mohnian or Luisian
Transitional marl siliceous member LSC 110	*Eponides rosaformis*, *Valvulineria californica*, *Cassidulina williami*, Luisian	*Eponides rosaformis*, no *Valvulineria californica*; early Mohnian or Luisian

OAKVIEW (OAK)
34°23.2'North, 119°18.2' West

Location: The Oakview section is located about 1 km south of the town of Oakview on Highway 33, about 15 km north of the city of Ventura, 10 km southwest of Ojai, and just east of the Ventura River. The Monterey Formation is exposed in the center of a syncline, so that the section is repeated on the north and south limbs of this fold within a distance of about 1.5 km. The section is more complete on the north limb so the transitional member was sampled and most of the section was measured on the north limb. On the south limb of the fold outcrops are present both north and south of the westernmost entrance to Sulphur Mountain Road.

Geology: The most important structural features in the study area are two major reverse faults, the Red Mountain fault to the southwest of Oakview and the San Cayetano fault to the northeast. The Oakview section is located in the zone between these two faults where major crustal shortening is thought to be taken up in a series of tight overturned folds and faults east of the Ventura River (Yeats, 1976).

On both limbs of the syncline uppermost Monterey strata are eroded; however, 18 m more of younger strata crops out on the south limb. On the north limb of the syncline the top of the Monterey section begins opposite the Rancho Arnaz Cider Stand, and north from the cider stand is in the direction of older rocks. 62 m of upper Monterey strata equivalent in part to the clayey-siliceous member (?) and the upper calcarous-siliceous member (see Ch. 4, and microfossil dates following this discussion) overlie 30 m of the transitional member. Below the transitional member, 12 m of the carbonaceous marl member crop out and about 32 m are not exposed. The basal Monterey or lower calcareous-siliceous member is structurally disturbed on both north and south limbs but is estimated to be greater than 60 m thick. In this area the underlying Rincon Formation is exposed on the south limb of the syncline near Oakview but is much better exposed directly west of the Ventura River, along Santa Ana Road several km north of Foster County Park (see Dibblee, 1982d).

Microfossil Biostratigraphy:

Stratigraphic position and sample number	Microfossil Identifications and Age of Sample		
	G. H. Blake	R. E. Arnal	J. A. Barron
Upper Monterey OAK 1*			*Actinocyclus ingens* *Denticulopsis hustedtii* *D. katayamae* *D. hyalina* *D. dimorpha* (very rare) upper subzone d of *Denticulopsis hustedtii-D. lauta* Zone
8 m to OAK 2*			Non-diagnostic fragments of *Coscinodiscus* and sponge spicules
14 m to OAK 3**			Lower subzone d of *Denticulopsis hustedtii-D. lauta* Zone. Could be as young as *Denticulopsis hustedtii* Zone if *Denticulopsis dimorpha* (rare) is reworked

* Samples from the uppermost Monterey, south limb of syncline.

** Sample number. The location of all samples is shown on Figure 4 in Chapter 4, p. 21.

Microfossil biostratigraphy: - continued

	G. H. Blake	R. E. Arnal
25 m to OAK 4	Hopkinsina magnifica, Bolivina malagaensis, Virgulina californica; early Mohnian	Virgulina californica grandis or ticeensis, Epistominella capitan-ensis; Mohnian undifferentiated
30 m to OAK 5	Eponides rosaformis, Cibicides illingi, Epistominella capita-nensis, Bolivina tumida; early Mohnian	Cibicides illingi, C. altamiraensis, Bolivina parna; definitely Mohnian, probably early Mohnian
6 m to OAK 6	Early Mohnian	Same as OAK 5 sample
Transitional marl siliceous member 36 m to OAK 7	Valvulineria miocenica, Bolivina pseudospissa, Siphogenerina collomi; possibly early Mohnian with reworked Luisian	Rotalia garveyensis(?), Cibicides illingi(?), C. altamiraensis; Mohnian, probably early Mohnian
7 m to Oak 8	Cibicides illingi, Valvulineria miocenica, Uvigerina subperigrina, U. hootsi; early Mohnian	Good early Mohnian fauna
18 m to Oak 9	Baggina californica, Bolivina californica, Bolivina seminuda, Uvigerina modeloensis, early Mohnian	

Microfossil biostratigraphy: - continued

	G. H. Blake	R.E. Arnal
Carbonaceous marl member 2 m to Oak 10	_Valvulineria miocenica_, _Pullenia bulloides_, _Valvulineria californica_ ss, _Bolivina advena striatella_; Luisian	_Pullenia miocenica_, _Valvulineria californica_, and _V. californica obesa_ Luisian
10 m to Oak 11	_Valvulineria miocenica_ _Bolivina advena striatella_, _B. imbricata inflata_, _Pullenia bulloides_, _P. miocenica globosa_, _Valvulineria californica_ ss; Luisian	
2 m to Oak 12	_Siphogenerina reedi_, _S. branneri_, _Baggina robusta_, _Pullenia miocenica globosa_; late Relizian, early Luisian	Luisian
Lower calcareous siliceous member Oak 13	_Cassidulina margareta_, _Valvulineria depressa_ _Bolivina brevior_; Relizian-Luisian	

SULPHUR MOUNTAIN ROAD (SMR)
34°24.4' North, 119°14' West

Location: This locality is a stream cut on the south side of Sulphur Mountain approximately 13.5 km east of the junction of Highway 33 and Sulphur Mountain Road. The stream intersects Sulphur Mountain Road at the 8.4 mile road sign. A path along the east side of the stream intersects the stream bed at good outcrops of phosphatic, carbonaceous marls (Fig. 9b, Ch. 4). The transitional member crops out about 15 m upstream where the gradient steepens. Diagenesis was evaluated from samples collected at this break in slope.

Geology: This locality is situated on the south limb of the overturned Sulphur Mountain anticline. Strata in the stream bed dip south and are probably overturned (see microfossil age-dates). The transitional member crops out in prominent dip slopes of calcareous cherts and porcelanites alternating with recessive ledges of phosphatic carbonaceous marls (Fig. 10b). Downstream (downsection?) from the diagenetic locality, phosphatic carbonaceous marls predominate and are slightly older.

Microfossil Biostratigraphy: All identifications by Gregg H. Blake

Stratigraphic position and sample number	Microfossil Identification and Age of Sample
Transitional marl siliceous member (diagenetic) (horizon)	Bulimina uvigerinaformis, Hopkinsina magnifica, Bolivina pseudospissa; early Mohnian
Carbonaceous marl member (?)	Uvigerina joaquineensis, Bolivina hughesi, Planulina ornata, Uvigerinella californica, Uvigerina segundoensis, Bolivina californica, Baggina subinaequalis; early early Mohnian

SULPHUR MOUNTAIN NORTH (SMN)
34°25.7' North, 119° 9.5' West

Location: In the upper Ojai Valley, the northernmost locality on Sulphur Mountain is a deeply weathered roadcut located on Sulphur Mountain Road between 1 1/2 and 3 1/2 km south of the junction of Highway 150 and the northern entrance to Sulphur Mountain Road. The top of the Monterey section crops out just north of the entrance to Sarabond Ranch, about 3 1/2 km from Highway 150. Proceeding north (downsection) from the ranch entrance along the road, the sands in the transitional marl-siliceous member crop out approximately 1/2 km downhill and the diagenesis sampling site is about 1/4 km farther downhill.

Geology: Youngest Monterey strata at Sulphur Mountain North are calcareous diatomaceous shales with a flora from the middle of the *Nitzschia reinholdii* Zone correlated elsewhere to the latest Mohnian (see age-dates by J. A. Barron below) in fault contact with the Pico Formation (Schlueter, 1976). Monterey strata of Luisian to latest Mohnian age and equivalent to at least parts of the upper 4 members crop out between the Big Canyon and Sisar faults at this location. Monterey strata strike approximately parallel to the Big Canyon fault with southward dips that steepen and then are overturned to the south, approaching the fault.

Microfossil Biostratigraphy:

Stratigraphic position and sample number	Microfossil Identifications and Age of Sample		
	G. H. Blake	R. E. Arnal	J. A. Barron
Upper Monterey, top of exposure SMN-100	*Uvigerina hootsi*, *Uvigerina modeloensis*; Mohnian	*Uvigerina hootsi*; Mohnian undifferentiated	Middle of *Nitzschia reinholdii* Zone; latest Mohnian
Transitional marl siliceous member (with interbedded sands) SMN 106	*Epistominella gyroidinaformis*, *Bolivina sinuata alisoensis*; early, early Mohnian	*Bolivina modeloensis*; Mohnian, probably *Bolivina modeloensis* Zone, early Mohnian	
Top of Carbonaceous marl member (?) (diagenetic horizon) SMN 107A	*Siphogenerina collomi*, *Valvulineria californica* ss; Luisian	*Siphogenerina collomi*, *Valvulineria californica* ss; Luisian	
Carbonaceous marl member SMN 108	*Siphogenerina collomi*, *Valvulineria californica* ss; Luisian		

SULPHUR MOUNTAIN SOUTH (SML)
34° 24.7' North, 119° 8.8' West

Location: The Sulphur Mountain south locality is a roadcut on the south facing slope of Sulphur Mountain located on private land about 2 km south of the locality at Sulphur Mountain north. Access after obtaining permission from Union Oil Company is through locked gates either from the north via Sulphur Mountain Road or from the south via a side road west of Wheeler Canyon Road. A large landslide in the early Mohnian section of the Monterey has made this side road impassable. North of this slide, which has taken out part of the road, are the outcrops of the transitional member sampled for diagenesis.

Geology: The Monterey section here is located on the south limb of the overturned Sulphur Mountain anticline. A complete nearly vertical upper Monterey section outcrops south of the landslide with good outcrops of the overlying Sisquoc Formation and younger formations. North of the landslide, carbonaceous marls are interbedded with siliceous rocks in the transitional member and farther north phosphatic carbonaceous marls crop out and are the dominant lithology.

Microfossil Biostratigraphy:

Stratigraphic position and sample number	Microfossil Identifications and Age of Sample	
	G. H. Blake	R. E. Arnal
Transitional marl-siliceous member SML-108	*Bolivina tumida*, *Virgulina californica*, *Baggina subinaequalis*, with abundant reworked Luisian: *Valvulineria californica obesa*, and *V. californica* ss, *Bolivina advena striatella*; early Mohnian	*Bulimina uvigerinaformis* Zone; early Mohnian
SML-109	*Baggina californica*, *Bolivina sinuata alisoensis*, *Eponides rosaformis*; early Mohnian	*Bolivina modeloensis* Zone (?); early Mohnian

APPENDIX B

DIAGENETIC BASELINES FOR SILICA DIAGENESIS

Estimates that have been made of the temperature of silica phase transformations in the Monterey Formation (Murata and Larson, 1975; Murata and others, 1977; Pisciotto, 1978, 1981) are complicated by uncertainties in the oxygen isotopic composition of pore waters during diagenesis, geothermal gradients, and the amount of uplift and erosion subsequent to maximum burial. To be widely applicable, models for reconstructing paleotemperatures from diagenetic characteristics require careful baseline observations at subsurface sites where present temperatures and burial depths are maximum (McCulloh and others, 1978). Because no evidence suggests that the Miocene to Recent strata in the Point Conception COST well (OCS Cal 78-164 No. 1) have been uplifted and because measured temperatures in the well have been empirically adjusted to yield approximate equilibrium values (McCulloh and Beyer, 1979), this well was used for estimating actual temperatures of silica phase transformations.

In modeling temperatures of the two silica phase transformations, temperature is assumed to be the primary influence on silica diagenesis with rock composition (relative detritus content) a significant secondary influence. Relations between rock composition and silica diagenesis which have been established empirically in outcrop sections (Isaacs, 1982; Keller, this report) form the basis of a general model of silica diagenesis as a function of temperature and rock composition. Temperatures based on depths of the two silica phase transformations in rocks of specific compositions from the Point Conception COST well are then used in combination with the reported thermal gradient to calibrate the general model of silica diagenesis (Fig. 21). A major assumption is that the present-day empirically adjusted gradient in this well is representative of conditions during diagenesis.

The stratigraphic position of the opal-A to opal-CT transformation in the Point Conception COST well is estimated from data reported by McDougall and others (1979). Barron (in McDougall and others, 1979) reports the presence of diatom frustules in most samples above 4300 feet (measured well depth) and only very poorly preserved fragments of frustules in underlying strata. Because all X-ray diffraction analyses reported for the interval 4300-5300 feet include minor opal-CT (Hein and others, 1979), 4300 feet thus approximates the opal-A to opal-CT transformation. Because the interval 3700-4700 feet is interpreted to represent the Foxen Mudstone (McCulloch and others, 1979) which is compositionally homogenous compared to the Monterey Formation, the kinetics of the opal-A to opal-CT transformation are not expected to vary much among beds (Isaacs and others, 1983a). This zone of silica phase transformation is thus comparatively narrow in the Point Conception COST well.

Chemical analyses of composite cuttings (Piper and Fowler, 1979), when converted to approximate mineral abundances, indicate a silica/detritus ratio of about 0.5 (a relative detritus content of 65%). The opal-A to opal-CT transformation in rocks having a relative detritus content of 65% was therefore placed at 4300 feet or a subseafloor depth of 2835 feet (865 m). Based on a sea floor temperature of 6°C and a thermal gradient of 48°C/km (McCulloh and Beyer, 1979), the temperature at 4300 feet is 47.5° C.

The stratigraphic position of the opal-CT to quartz transformation in the Point Conception COST well falls within the Monterey Formation (Isaacs and others, 1983a). Because of the diverse composition of beds in the Monterey Formation, the kinetics of the opal-CT to quartz transformation undoubtedly vary considerably among individual beds. This silica phase transformation thus probably occurs over a broad depth interval, as observed in adjacent sections of the Monterey on land (Isaacs, 1982).

Two approaches, using individual cuttings and also composite cuttings, were used to determine the depth interval of the opal-CT to quartz transformation in the Point Conception COST well. Individual cuttings above 5400 feet contain all diagenetic silica as opal-CT. No information is available on individual cuttings between 5400 and 6565 feet, but some individual cuttings as shallow as 6565 feet contain all diagenetic silica as quartz. The deepest interval in which abundant opal-CT is commom in individual cuttings is from a measured well depth of 6935 feet (subseafloor depth of 1665 m). Because many cuttings from the overlying samples at 6835 feet contain some opal-CT, a position of 6900 feet is estimated for the opal-CT to quartz transformation in rocks averaging 58% silica and 16% detritus (or relative detritus content of 20%). Based on a sea floor temperature of 6°C and a thermal gradient of 48°C/km (McCulloh and Beyer, 1979), the temperature at 6900 feet is about 85°C.

X-ray diffraction of powders of composite cuttings at depth intervals between 5575 and 5845 feet indicate that opal-CT and quartz would occur in approximately equal abundance at a measured well depth of 5700 feet, corresponding to a temperature of 68°C. The composite sample at this depth has a composition of 58% relative detritus. Temperatures derived from calibration of the silica diagenesis model (based on both individual and composite cuttings) agree very closely; for a rock of the same composition the difference in temperature indicated by these two approaches is no more than 2°C. The temperature for the opal-CT to quartz transformation from composite cuttings was used in the final calibration of Figure 21, however, because this method is believed to incur less sampling bias.

The two composition-temperature points for silica phase transformations in the Point Conception COST well were used to calibrate the empirical model of silica diagenesis for the Monterey Formation (Fig. 21). Interpolation between these two temperatures approximates the maximum temperature reached during diagenesis in all horizons having opal-CT-bearing rocks. Note that a rock with 25% relative detritus content will, according to Figure 21, form opal-CT at about 45°C and quartz at about 81°C. These values compare favorably with temperature estimates for the two phase transformations (48±8°C and 79±2°C, respectively) made by Murata and others (1977) for Monterey rocks with approximately the same detritus content from the Temblor Range, California.

APPENDIX C

PYROLYSIS DATA

Pyrolysis measurements were made at Chevron Oil Field Research Company by Kenneth E. Peters using the method of Espitalie and others (1977). In this method, the pyrolytic characteristics of organic matter are investigated with a "Rock-Eval II Pyroanalyzer" which is designed for the rapid determination of hydrocarbon potential and generative history using whole-rock samples. For this study, homogenized whole-rock samples were pyrolyzed isothermally under helium at 300°C for 3 minutes followed by temperature programming at 25°C/min from 300°-550°C (Peters and others, 1981).

Four samples each from four of the study sites were pyrolyzed. These samples were splits of the powders used for X-ray diffraction. Replicate determinations made on two samples on different days showed that measured values varied by as much as 0.14 for S_1, 0.25 for S_2, and 1°C for T_{max}. There is no error estimate for S_3 because the result from one of the runs was suspect. In diagenetic grade, these samples range from diatomaceous rocks (Goleta) to mixed opal-CT and quartz rocks (Sulphur Mountain Road). In order to determine the relationship between kerogen maturity, as determined by T_{max}, and silica diagenetic grade in more "mature" rocks, two Monterey samples that have only quartz as diagenetic silica were also pyrolyzed with the Ventura basin sample set. These two samples (UD 18-1 and 2) are from 10,317 and 10,593 ft (respectively) in the Union Dome 18 oil well in the onshore Santa Maria basin.

Explanation:

S_1 = Free hydrocarbons (mg HC/g of rock sample)

S_2 = Second hydrocarbon peak from kerogen cracking (mg HC/g of rock sample)

S_3 = Measure of the organic CO_2 (mg CO_2/g of rock sample)

T_{max} = Temperature (° C) at which the kerogen breaks down in a sample. A measure of kerogen maturity.

TABLE C-1 PYROLYSIS DATA

Sample No.	S_1 (mg HC/g rock)	S_2 (mg HC/g rock)	S_3 (mg CO_2/g rock)	T_{max} (°C)
UGO 2-1	1.77	21.5	3.35	408
UGO 2-5C	1.32	16.7	3.02	411
UGO 2-10	1.85	13.9	1.31	406
UGO 2B-11	1.64	15.0	2.08	408
RIN K-1	2.01	33.9	2.34	401
RIN K-3	7.81	56.2	2.97	398
RIN 5-1	9.14	60.3	2.78	404
RIN 5-10	8.49	67.3	3.60	398
LSC 6-8	0.48	6.16	0.35	403
LSC 6-10	1.62	31.2	2.50	403
LSC 6-11A	2.80	53.0	3.89	398
LSC 6-12A	4.22	55.7	3.94	397
SMR-B	0.50	19.3	0.95	415
SMR-D	0.43	18.9	1.77	414
SMR-E	0.02	4.87	3.40	423
SMR-G	0.02	4.58	3.49	425
UD 18-1	0.84	5.69	0.49	431
UD 18-2	1.14	7.05	0.15	436

APPENDIX D

SAMPLE DATA TABLE

This appendix presents the results of mineral abundance calculations based on X-ray diffraction (using constants developed for the Santa Barbara coastal area by Isaacs, 1980) and chemical analyses (reported in Appendix C). Note that the sum of silica plus detrital minerals plus other minerals is normalized to 100% and calculated on an organic-matter-free basis. In the two right hand columns, organic matter and opal-CT d-spacings are reported. Also note that "-" indicates "none present" for the eight columns on the left, and "not measured" for the two columns on the right.

Explanation of data columns (from left to right):

Sample number: All samples at the same locality were collected within 10 stratigraphic meters. Localities are presented in order from west to east. Abbreviations of the localities are as follows: UGO = Goleta Slough, RIN = Rincon Point, LSC = Los Sauces Creek, OAK = Oakview, SMR = Sulphur Mountain Road, SMN = Sulphur Mountain north, and SML = Sulphur Mountain south.

Silica components: Defined in Chapter 3.

Op-A : opal-A
Op-CT : opal-CT
Qtz : diagenetic quartz

Detritus components: Defined in Chapter 3

Alum : aluminosilicate minerals
Qtz : detrital quartz

Other minerals:

Cal : calcite
Dol : dolomite
Ap: apatite

Organic Matter: organic matter content in weight percent, calculated from measurements of organic carbon content (in Appendix C) multiplied by 1.5 (see Isaacs, 1980).

O-CT d-sp: Opal-CT d-spacing, in Å. Measured as described by Isaacs (1980); however, in this report a silicon standard was used. D-spacings of Isaacs (1980), which were measured against a quartz standard, require an increase of 0.004 Å in order to be comparable to the measurements in this study.

TABLE D-1 SAMPLE DATA

Sample No.	Silica			Detritus		Other			Organic Matter	O-CT d-sp.
	Op-A	Op-CT	Qtz	Alum	Qtz	Cal	Dol	Ap		
UGO										
2-1	30	-	-	37	12	18	-	3	9.7	-
2-2	41	-	-	19	9	30	-	1	6.9	-
2-4	46	-	-	15	3	35	-	1	5.8	-
2-5	33	-	-	32	9	23	-	2	8.0	-
2-6	51	-	-	14	6	30	-	-	5.1	-
2-7	31	-	-	25	7	31	-	6	8.0	-
2-8	36	-	-	21	12	29	-	1	7.7	-
2-9	28	-	-	26	7	35	-	4	8.2	-
2-10	73	-	-	14	4	8	-	1	5.2	-
2B-11	64	-	-	17	5	13	-	1	-	-
RIN										
5-1	-	51	-	31	8	10	-	-	19.9	4.105
5-2	9	8	-	30	12	40	-	-	30.9	-
5-3	-	62	-	21	7	8	-	2	13.9	4.112
5-4	11	12	-	41	11	24	-	1	30.7	-
5-5	-	27	-	43	13	16	-	1	27.4	-
5-6B	-	66	-	21	5	7	-	1	17.9	4.113
5-7	20	-	-	60	20	-	-	-	26.3	-
5-9	26	-	-	55	19	-	-	-	33.8	-
5-10	16	-	-	42	13	22	-	7	20.3	-
5-11	-	47	-	21	6	25	-	1	12.3	4.115
5-12	5	19	-	17	4	54	-	1	-	4.106
LSC										
6-1	-	35	-	27	9	18	-	1	13.0	4.083
6-2	-	56	-	20	6	13	1	1	7.0	4.090
6-3	-	27	-	13	5	46	3	2	-	4.092
6-4	-	50	-	25	9	11	1	1	8.0	4.092
6-5	-	39	-	7	2	38	1	-	-	4.102
6-6	-	58	-	19	7	13	1	-	7.0	4.095
6-7	-	75	-	7	2	13	-	1	3.0	4.108
6-8	-	70	3	4	5	19	-	-	3.0	4.106
6-10	-	17	2	32	10	25	-	1	12.0	4.074
OAK										
8-3	-	72	-	19	4	5	-	-	-	4.106
8-4	-	92	-	4	2	2	-	-	-	4.116
8-6	-	58	-	30	8	4	-	-	-	4.105
8-8B	-	93	-	5	1	1	-	-	-	4.108
9-0B	-	13	-	65	22	-	-	-	-	-
9-3A	-	42	-	35	9	14	-	-	16.4	-

TABLE D-1 SAMPLE DATA - Continued

Sample No.	Silica Op-A	Silica Op-CT	Silica Qtz	Detritus Alum	Detritus Qtz	Other Cal	Other Dol	Other Ap	Organic Matter	O-CT d-sp.
OAK cont'd.										
9-3B1	-	83	-	8	2	7	-	-	-	4.113
9-3B2	-	75	-	12	3	10	-	-	-	4.113
105R2A	-	26	-	22	7	43	-	2	-	4.104
106R	-	30	-	12	4	11	43	-	-	4.089
SMR										
10A	-	18	4	14	5	58	-	1	4.2	4.061
10B	-	25	3	19	6	47	-	-	4.7	4.072
10C	-	33	1	16	5	45	-	-	5.0	4.085
10D	-	16	7	22	7	48	-	-	6.3	4.058
10E	-	-	13	28	9	34	-	16	3.5	-
10F	-	-	9	40	13	38	-	-	3.5	-
10G	-	-	7	48	16	23	-	6	3.6	-
10H	-	60	3	13	4	20	-	-	2.8	4.096
10I	-	60	9	7	2	22	-	-	2.4	4.094
10J	-	60	3	15	5	17	-	-	3.5	4.092
SMN										
107-A	-	29	3	34	12	22	-	-	-	4.085
107-1	-	31	6	46	15	-	-	2	-	4.073
107-2B	-	85	-	11	4	-	-	-	-	4.099
107-2C	-	82	3	11	4	-	-	-	-	-
108-1	-	67	-	24	6	2	-	1	-	4.095
108-2	-	80	-	13	3	4	-	-	-	4.091
108-3	-	32	-	27	10	31	-	-	-	4.083
108-4	-	62	-	25	6	6	-	1	-	-
108-7	-	78	-	18	4	-	-	-	-	4.091
108-8	-	90	-	7	3	-	-	-	-	4.107
SML										
2-1	-	77	8	7	2	6	-	-	-	4.098
2-2	-	59	1	20	6	10	-	4	10.2	4.099
2-3	-	63	1	13	4	19	-	-	5.8	4.010
2-6	-	45	-	40	12	-	-	3	4.6	4.087
2-7B1	-	50	3	18	6	23	-	-	8.8	4.085
2-7B2	-	56	14	7	2	17	3	-	2.7	4.010
2-8Z1	-	9	10	33	11	37	-	-	16.6	-
2-8Z2	-	36	3	27	9	25	-	-	11.9	4.083
2-9	-	40	2	19	6	30	3	-	-	4.094
2-10	-	9	9	61	18	-	-	3	-	-

APPENDIX E

CHEMICAL ANALYSES

Major oxide analysis or partial chemical analysis of all samples for which silica grade was evaluated are presented in this appendix. Sample preparation and chemical methods are first described, and then data are presented in the tables that follow.

Sample Preparation

Each rock sample was cut on either a dry or free-flowing water saw into an approximately 8 to 12 gm piece. Pieces were ground first with a plattner mortar, subsequently with a mullite mortar, and sieved with a brass sieve to 100 mesh. Magnetic fragments from the plattner mortar were carefully removed with a magnet. Powders were then split with a riffle splitter into portions for oxide analyses, X-ray diffraction, and analysis of organic carbon content. For four samples each from four sites, the X-ray portion was again split to make a sample for pyrolysis. Samples were stored in glass vials with plastic caps.

Methods of Chemical Analysis

Quantitative major oxide analyses were performed on forty samples from four localities by J. E. Taggart Jr., A. Bartel, J. S. Wahlberg, and J. Baker at the U.S. Geological Survey, using a Phillips PW 1600 wavelength dispersive simultaneous X-ray spectrometer by methods described in Taggart and others (1981). Results are presented for SiO_2, Al_2O_3, CaO, MgO, Fe_2O_3 (Note: all iron is expressed as Fe_2O_3), P_2O_5, Na_2O, K_2O, TiO_2, and MnO.

For thirty samples from three sites only SiO_2 and Al_2O_3 were determined. These samples were analyzed by atomic absorption spectrometry at Skyline Labs., Inc., Wheat Ridge, Colorado. These analyses follow the U.S. Geological Survey results.

For samples from Rincon Point, organic carbon was measured using a Leco apparatus by G. Mason at the U.S. Geological Survey. All other organic carbon determinations were made by the direct carbon wet oxidation method at Rinehart Labs., Inc., Arvada, Colorado.

Explanation of column headings:

Sample: site abbreviations follow the usage in Appendices A and B.

Major oxides: as explained above.

LOI: Loss on ignition to 925°C. This was measured only on the samples analyzed for major oxides at the U.S. Geological Survey.

Org. C: organic carbon content, n=not measured.

S/D: Ratio of silica to detritus as defined in Chapter 3.

Table E-1 CHEMICAL ANALYSES

Sample	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	P_2O_5	Na_2O	K_2O	TiO_2	MnO	LOI	Org.C	S/D
LSC													
6-1	52.5	6.31	10.4	0.70	2.40	0.57	1.0	1.37	0.34	<0.02	21.4	8.73	0.81
6-2	65.2	4.85	7.95	0.58	1.63	0.46	0.69	0.99	0.21	<0.02	15.7	4.40	1.93
6-3	39.6	3.08	26.2	0.86	1.13	0.34	0.47	0.65	0.13	0.02	26.1	n	1.42
6-4	63.0	5.88	7.44	0.86	2.23	0.52	0.92	1.25	0.28	<0.02	15.5	5.19	1.39
6-5	52.3	1.71	21.6	0.53	0.49	0.26	0.30	0.36	0.07	<0.02	21.4	n	3.55
6-6	65.4	4.61	7.96	0.73	1.59	0.39	0.72	0.91	0.21	<0.02	15.1	4.40	2.07
6-7	72.1	1.70	7.72	0.17	0.81	0.21	0.47	0.36	0.06	<0.02	13.1	2.00	8.33
6-8	72.8	1.01	10.4	0.17	0.29	0.08	0.22	0.19	0.02	<0.02	13.3	1.65	10.43
6-10	44.4	7.50	14.2	0.76	3.29	0.52	0.88	1.52	0.39	<0.02	24.0	7.95	0.37
RIN													
5-1	55.7	5.58	5.03	0.74	2.05	0.27	0.66	1.06	0.29	<0.02	26.4	12.48	1.31
5-2	28.8	4.8	15.8	1.05	1.89	0.56	0.62	0.83	0.25	<0.02	40.8	19.50	0.41
5-3	64.0	4.03	5.20	0.48	1.32	0.91	0.61	0.77	0.21	<0.02	20.3	9.09	2.21
5-4	36.2	6.58	10.1	0.94	2.49	0.47	0.80	1.12	0.34	<0.02	37.0	19.82	0.44
5-5	42.9	7.21	7.11	0.92	2.77	0.37	0.87	1.21	0.38	<0.02	33.1	17.74	0.48
5-6B	62.1	4.18	3.73	0.47	1.50	0.34	0.59	0.79	0.21	<0.02	24.0	11.27	2.54
5-7	41.5	10.3	1.89	1.20	3.99	0.53	1.26	1.80	0.54	<0.02	35.6	16.41	0.25
5-9	42.2	8.42	1.06	0.94	2.50	0.12	1.01	1.46	0.46	<0.02	40.5	20.93	0.35
5-10	34.0	7.84	13.3	1.11	2.80	2.63	1.01	1.37	0.40	<0.02	31.1	13.52	0.29
5-11	56.1	4.00	11.4	0.57	1.29	0.29	0.57	0.74	0.19	<0.02	22.2	8.05	1.74
5-12	24.2	3.22	24.4	0.78	1.05	0.41	0.39	0.55	0.15	<0.02	41.7	n	1.14

TABLE E-1 CHEMICAL ANALYSES - continued

Sample	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	P_2O_5	Na_2O	K_2O	TiO_2	MnO	LOI	Org.C	S/D
UGO													
2-1	43.1	7.75	11.3	1.33	2.77	1.55	3.33	1.34	0.42	<0.02	24.9	6.49	0.61
2-2	43.2	4.17	16.0	1.33	1.69	0.41	2.58	0.82	0.30	<0.02	28.3	4.58	1.46
2-4	39.0	3.26	19.0	1.50	1.28	0.49	2.31	0.56	0.18	<0.02	30.6	3.85	2.56
2-5	42.3	6.97	13.5	1.59	2.54	1.14	3.01	1.20	0.40	<0.02	25.8	5.30	0.81
2-6	47.4	3.03	16.2	1.01	1.28	0.24	2.16	0.64	0.18	<0.02	26.7	3.43	2.55
2-7	35.0	5.45	19.2	1.57	2.03	2.43	2.22	0.85	0.31	<0.02	28.6	5.34	0.97
2-8	44.0	4.59	15.6	1.09	2.00	0.42	2.09	0.89	0.25	<0.02	27.3	5.14	1.09
2-9	35.1	5.58	19.9	1.28	2.15	1.47	2.09	0.86	0.32	<0.02	28.9	5.47	0.46
2-10	67.6	3.11	4.67	0.74	1.25	0.29	2.18	0.60	0.21	<0.02	18.1	3.48	4.06
2-11	58.8	4.09	7.82	0.80	1.65	0.49	2.48	0.77	0.24	<0.02	21.0	n	2.91
SMR													
10A	31.2	3.10	31.0	0.92	1.60	0.69	0.53	0.65	0.18	0.03	29.0	2.83	1.16
10B	42.7	3.93	23.2	0.77	1.74	0.23	0.61	0.82	0.23	<0.02	23.6	3.16	1.12
10C	47.5	3.29	21.8	0.50	1.12	0.35	0.53	0.74	0.17	<0.02	22.4	3.32	1.62
10D	39.5	4.52	24.2	0.73	1.77	0.26	0.72	0.97	0.25	<0.02	25.5	4.17	0.79
10E	34.2	6.30	26.5	0.68	2.23	6.69	0.79	1.22	0.33	<0.02	19.7	2.34	0.35
10F	41.2	8.66	19.9	0.85	2.78	0.27	0.95	1.61	0.44	<0.02	22.3	2.36	0.17
10G	45.4	10.5	15.3	1.03	3.40	2.42	1.27	1.88	0.56	<0.02	17.2	2.39	0.11
10H	67.0	3.02	11.1	0.57	1.18	0.14	0.89	0.58	0.23	<0.02	13.5	1.85	3.71
10I	68.3	1.82	12.7	0.30	0.61	0.13	0.72	0.31	0.17	<0.02	13.6	1.63	7.67
10J	66.4	3.10	11.6	0.53	1.13	0.14	0.61	0.60	0.18	<0.02	14.1	2.33	3.15

TABLE E-2 PARTIAL CHEMICAL ANALYSES

Sample Number	SiO_2	Al_2O_3	Org.C	S/D
OAK 8-3	69.7	3.80	n	3.06
OAK 8-4	99.0	1.00	n	15.33
OAK 8-6	65.5	5.80	n	1.52
OAK 8-8B	93.0	1.10	n	15.50
OAK 9-0B	61.3	14.10	n	0.15
OAK 9-3A	51.3	6.20	10.91	0.75
OAK 9-3B1	84.2	1.80	n	8.30
OAK 9-3B2	76.8	2.50	n	5.00
OAK 1052A	41.5	4.80	n	0.90
OAK 106R	35.2	2.60	n	1.88
SML 2-1	86.2	1.60	n	9.44
SML 2-2	66.2	4.20	6.82	2.31
SML 2-3	71.2	2.90	3.86	3.77
SML 2-6	71.5	8.90	3.09	0.87
SML 2-7B1	61.5	3.90	5.86	2.21
SML 2-7B2	72.1	1.60	1.81	7.78
SML 2-8ZI	39.6	6.70	11.04	0.43
SML 2-8ZII	54.0	5.60	7.94	1.08
SML 2-9	58.4	4.50	n	1.68
SML 2-10	59.7	13.10	n	0.23
SMN 107A	65.1	8.70	n	0.71
SMN 107-1	68.4	10.10	n	0.61
SMN 107-2B	92.4	2.60	n	5.67
SMN 107-2C	92.5	2.70	n	5.67
SMN 108-1	80.8	5.40	n	2.23
SMN 108-2	89.9	3.00	n	5.00
SMN 108-3	54.8	6.50	n	0.87
SMN 108-4	75.9	5.60	n	2.00
SMN 108-7	86.2	4.00	n	3.55
SMN 108-8	93.6	1.60	n	9.00