U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

GEOLOGY HANDBOOK FOR THE COOPERATIVE MONTEREY ORGANIC GEOCHEMISTRY STUDY, SANTA MARIA AND SANTA BARBARA-VENTURA BASINS, CALIFORNIA

by

Caroline M. Isaacs[1]

Open-File Report 92-539-E

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards or with the North American Stratigraphic Code. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

[1]U.S. Geological Survey
345 Middlefield Road, MS 999
Menlo Park, California 94025

1992

CONTENTS

INTRODUCTION

This chapter defines and describes geologic terms used in the preliminary geologic background for the Cooperative Monterey Organic Geochemistry Study (CMOGS). CMOGS, its purposes and participants, are more generally described in the *Preface* (Chapter A, this report).

To organic geochemists, the Monterey Formation of California is widely known as an excellent petroleum source rock, and has received much attention for its unusual petroleum generating characteristics. To geologists, the Monterey Formation is unusual in a wide variety of characteristics - in composition, sedimentology, porosity, permeability, inorganic diagenesis, fracturing, well-log response, seismic characteristics, etc. In the Santa Barbara-Ventura and Santa Maria areas, the Monterey Formation is particularly complex due to its specially marked heterogeneity and spatial variability.

Because of the unusual geologic characteristics and natural complexity of the Monterey Formation in these areas, this chapter of the report is intended to clarify the basic terms and concepts used in the geologic framework. These range from the definition of formation itself through various rock constituents to interpreted sedimentologic, oceanographic, and diagenetic conditions. Most definitions are taken from standard references, with commentary focused mainly on the Monterey Formation of the Santa Barbara-Ventura and Santa Maria areas. **Bold-faced words** indicate separately defined terms.

STRATIGRAPHIC TERMS

stratum = "A tabular or sheetlike body...of sedimentary rock, visually separable from other layers above and below; a *bed...*" (AGI, 1980).

stratigraphy = "(a) The science of rock **strata**...concerned not only with the original succession and age relations of rock strata but also with their form, distribution, lithologic composition, fossil content, geophysical and geochemical properties - indeed, with all characters and attributes of rocks *as strata*; and their interpretation in terms of environment or mode of origin, and geologic history....(b) The arrangement of strata, esp. as to geographic position and chronologic order of sequence...." (AGI, 1980). Major types of stratigraphy include **lithostratigraphy, biostratigraphy,** and **chronostratigraphy**. Other types of stratigraphy are **paleomagnetic stratigraphy, oxygen isotope stratigraphy,** and **strontium isotope stratigraphy.**

biostratigraphy = "**Stratigraphy** based on the paleontologic aspects of rocks, or stratigraphy with paleontologic methods; specif. the separation and differentiation of rock units on the basis of the description and study of the fossils they contain" (AGI, 1980).

Examples of biostratigraphic units are the North Pacific diatom zone *Denticulopsis hustedtii* and the calcareous nannofossil zone CN4 (see Figure 1, Chapter E, this report).

chronostratigraphy = time-stratigraphy = "The branch of **stratigraphy** that deals with the age of strata and their time relations" (AGI, 1980). A chronostratigraphic unit (= time-stratigraphic unit) is a "body of rock strata that is unified by having been formed during a specific interval of geologic time. It represents all the rocks formed during a certain time span of Earth history, and only the rocks formed during that time span" (AGI, 1980), for example the Cretaceous system. The time represented by chronostratigraphic units are geologic-time units, such as the Cretaceous period; geologic-time units are arranged in the **geologic time-scale**.

paleomagnetic stratigraphy = "The use of natural remanent magnetization to identify stratigraphic units. It depends on the temporal variation of the ambient magnetic field, which is due to geomagnetic secular variation and reversals" (AGI, 1980).

In contrast to **biostratigraphy** which involves unique evolutionary changes and events, paleomagnetic stratigraphy is mainly based on the alternation of only two states (normal and reverse magnetic fields) in sequence, and thus (1) must be broadly placed in the **geologic time-scale** by some other stratigraphic technique, and (2) must involve a time span that is long enough, with samples sufficiently closely spaced, to establish pattern recognition. In the Monterey Formation, paleomagnetic stratigraphy has proven very useful for establishing detailed time-correlation where there are only sparse or poorly preserved fossils (e.g. Khan and others, 1989). Work with this technique is also currently in progress at Lions Head (Khan, unpublished data). Unfortunately, the technique is hard to apply to the subsurface because of the critical importance of the orientation of the samples.

strontium isotope stratigraphy = the use of $^{87}Sr/^{86}Sr$ ratios in minerals to identify stratigraphic units. It is based on empirically determined values assumed to represent paleo-seawater variations through time. Values are not all unique, and some periods when values changed more rapidly can be more precisely resolved than others.

This technique has recently been applied to the Naples section on the Santa Barbara coast in conjunction with biostratigraphy (DePaolo and Finger, 1991; see also Chapter D, this report). Strontium isotopes are usually determined on the strontium in calcite, and post-depositional recrystallization of calcite may create problems. The technique is currently being developed for use on barite which has much less post-depositional alteration (Paytan and others, 1991).

geologic time-scale = the chronologic arrangement of geologic-time units.

Biostratigraphy, paleomagnetic stratigraphy, etc. identify relative time frameworks that must be correlated with the standard geologic time-scale and with absolute time. For

example, biostratigraphy is a complex discipline based on appearances and disappearances of particular species, and assemblages of fossils through relative time. Generally speaking, each group of fossils (such as **diatom** frustules) are studied by different specialists, and the zonation of each fossil group is correlated with zonations based on other fossil groups (sometimes via a more global stratigraphic technique such as paleomagnetic stratigraphy) to create a biostratigraphic framework. Biostratigraphic zones are not global, and some are only applicable very locally due to the limited geographic distribution of a given fossil.

Absolute time (i.e., time measured in years) is determined for the geologic time-scale by the direct and indirect use of the radioactive decay of elements (e.g., K-Ar radiometric dating of volcanic strata interbedded with fossiliferous strata). Because of the greater imprecision of K-Ar dating before 6 Ma, time-scales for older strata (back to late Jurassic) are mainly based on correlation of sea-floor magnetic anomaly patterns with the radiometric time scale by assuming constant rates of seafloor spreading (Kennett, 1982).

The most widely applied biostratigraphic framework and geologic time-scale for the Monterey Formation in California (Figure 1, Chapter D, this report) is by Barron (1986).

lithostratigraphy = "The element of **stratigraphy** that deals with the lithology of strata and with their organization into units based on lithologic character" (AGI, 1980). **Formations** are lithostratigraphic units.

formation = a mappable unit of rocks. "A body of rock strata...which is unified with respect to adjacent strata by consisting dominantly of a certain lithologic type or combination of types or by possessing other unifying lithologic features. Thickness may range from less than a meter to several thousand meters, depending on the size of units locally required to best express the lithologic development of a region....Most formations have a prevailingly tabular shape, and are mappable at the Earth's surface at scales on the order of 1:25,000 or are traceable in the subsurface. A formation...may contain rock of one lithologic type, repetitions of two or more types, or extreme heterogeneity that in itself may constitute a form of unity compared to the adjacent strata. Also, it may represent a long or short time interval, be composed of materials from one or several sources, and include breaks in the chronostratigraphic sequence; its age or time value may not necessarily be the same wherever it is recognized. Formations may be combined into *groups* or subdivided into *members*....In Germany, the term 'Formation' is equivalent to the time-stratigraphic term 'system'." (AGI, 1980).

Of principal importance is that a formation is *not* a homogeneous unit of uniform composition and origin. Also, although the term "formation" is often used to designate strata inferred to have originally been a continuous body of rocks, this is not the case for most formations in California, certainly not for the term "Monterey Formation" which is used to designate strata deposited in at least 8 separate basins.

The concept of formation has to be viewed in the context of the enormous scale that geologists address in both time and space. In the Santa Maria Basin alone (which includes the Lion's Head section) are over 3000 cubic kilometers of sedimentary rock mainly

deposited during the last 20 million years (Crawford, 1971). Unfortunately, nature did not package these strata into homogeneous units with clear and distinct age-constant boundaries. Rocks are spatially variable, in tectonically active margins like California perhaps extremely so. Formations merely group the diversity of rocks into a modest level of coherence.

In the 19th and early 20th centuries, ages in a formation at one place were often assumed to apply to the formation hundreds of miles distant. Later, many formations were found to be time-transgressive (i.e., not everywhere deposited during the same time span) so that in the 1940s the distinction was made between rock-stratigraphic (lithostratigraphic) and time-stratigraphic (chronostratigraphic) units. In order to achieve some uniformity, standards of nomenclature were developed. The North American Stratigraphic Code, for example, runs to many pages, and new names have to meet clear standards. The rigor introduced by this system does not always correspond with logical geologic practice and is much hampered by prior usage.

The name "Monterey Formation" was originally applied to diatomaceous rocks in the vicinity of Monterey California (its "type locality"), and soon the term was used to designate other diatomaceous or siliceous deposits of about the same age throughout the state. Many of these early formation names were applied rather broadly. For example, numerous sandstone units in coastal California were given the name "Vaqueros", presumably on the assumption that they were originally a continuous body of sandstone of the same age. But this turned out not to be the case. Some bodies of rock designated "Vaqueros" are lower bathyal (>2000 m deep) turbidite deposits of early Miocene age (c23 Ma) (e.g., Graham, 1976), some are shoreline deposits (paleodepths <150 m) (Edwards, 1971, 1972; Ingle, 1980, 1981; cf. Figure 4, Chapter A, this report) perhaps as young as 16 Ma, and some include thick shale sequences that may be major source rocks as in the Cuyama basin (Lagoe, 1987). These differences cause ongoing confusion to those not closely familiar with the history of these terms.

The classic geologic paper on the Monterey Formation was researched mainly in the 1930s and published in 1946 by Milton Bramlette. Here is his introductory statement: "The Monterey formation of California includes the Miocene strata characterized by an unusually high proportion of silica. The formation is widely distributed in and near the Coast Ranges from a latitude north of San Francisco to one south of Los Angeles, and in many areas it is several thousand feet thick. The siliceous rocks are more than a mile thick over some areas many square miles in extent, and about half a mile thick in much greater areas; and their volume thus amounts to thousands of cubic miles. *It shows remarkably rapid variations in thickness and lithologic character that permit few generalizations on the formation as a whole....*Although the formation is characterized by...highly siliceous rocks, it includes, in many areas, large amounts of interbedded rocks of other types, particularly of normal clastic shale, mudstone, and sandstone. The more siliceous rocks also grade laterally into strata that are made up dominantly of normal clastic rocks, and where these clastic rocks predominate the name Monterey formation does not seem appropriate" (Bramlette, 1946, p. 2). Heterogeneity and spatial variability are thus hallmarks of the Monterey Formation.

What can be said about the significance of Monterey formation boundaries? The oldest strata generally designated "Monterey" are in the southern Salinas basin and the Santa Barbara-Ventura basin; the base of the formation at Naples is 17.85 ± 0.10 Ma (Arends and Blake, 1986; Barron, 1986; DePaolo and Finger, 1991). Does this mean that sedimentation of biogenic silica abruptly started at 17.85 Ma? Actually, there are "unusually siliceous" strata widespread in the underlying Rincon Shale and age-equivalent units throughout the state (Isaacs and Lagoe, 1987), but Rincon strata *as a whole* are not "unusually siliceous". Even if they had the exact same biogenic silica influx as the average Monterey, they would not be unusually siliceous because of the very rapid influx of terrigenous **detrital** debris which diluted the **biogenic** debris; only determination of biogenic silica accumulation or **sedimentation rates** can clarify whether the formation boundary marks a change in biogenic accumulation (cf. Figure 7 in *Preliminary Geologic Background*, Chapter A, this report). Similarly, strata deposited between 17.8 and 16 Ma near Naples in the South Elwood and Hondo fields include abundant sandstones and thus have been designated by some (e.g., Hornafius, 1991) as part of the Rincon Shale. This usage doesn't necessarily mean that pelagic sedimentation during this interval was any different in the areas of those fields, just that coarse clastics are abundant. In the onshore Santa Maria basin, strata partly of the same age (17.0-16.0 Ma) containing common sandstone beds are termed Point Sal Formation, so the base of the Monterey there is about 16 Ma.

The upper boundary of the Monterey Formation is even more varying; in age, it ranges from at least as old as 13 Ma (where clastics are common as in parts of the Salinas basin) to at least as young as 6 Ma (as at Naples) (Barron, 1986). Actually, Bramlette (1946) originally included within the Monterey Formation the fine-grained rocks now termed "Sisquoc Formation", but later designated these as a fine-grained facies of a formation which had been originally defined as a shallow-water sandstone (Woodring and Bramlette, 1950). A complication in the offshore Santa Maria area is that the Sisquoc-Monterey boundary as defined in the surface onshore does not have very distinctive log-characteristics. Thus in much of the offshore area the upper part of the Monterey as defined in the surface onshore is actually included in the Sisquoc Formation (e.g. Crain and others, 1985; but compare MacKinnon, 1989). Since the typical Monterey in offshore Santa Maria is about 1000 ft (300 m) thick and the upper part alone may be 1200 ft (360 m) thick, isopach maps of the "Monterey" in various areas may not be even lithologically comparable (Ogle and others, 1987). How similar in age are these various formation boundaries? That question is hard to answer since the upper part of the Monterey usually has no calcareous microfossils and diatoms are destroyed by silica diagenesis; the basic answer is that no one knows.

For comments on lithologic boundaries *within* the Monterey Formation, see below.

member = "A lithostratigraphic unit...comprising some specially developed part of a *formation*. It may be formally defined and named, informally named, or unnamed. It is not necessarily mappable, and a named member may extend from one formation into another" (AGI, 1980).

facies. "'The general term facies has been greatly overworked....If the term is used, it is desirable to make clear the specific kind of facies to which reference is made...' (a) The aspect, appearance, and characteristics of a rock unit, usually reflecting the conditions of its origin; esp. as differentiating the unit from adjacent or associated units. Cf: *stratigraphic facies; lithofacies; igneous facies.* (b) a mappable, areally restricted part of a lithostratigraphic body, differing in lithology or fossil content from other beds deposited at the same time and in lithologic continuity. Cf: *sedimentary facies.* (c) A distinctive rock type, broadly corresponding to a certain environment or mode of origin, e.g. 'red-bed facies', 'black-shale facies'. Cf: *petrographic facies.* (d) A body of rock distinguished on the basis of its fossil content. Cf: *biofacies....* (e) A local assemblage or association of living or fossil organisms, esp. one characteristic of some type of marine conditions. Cf: *biofacies....* (f) The environment or area in which a rock was formed, e.g. "sandy-bottom facies"....Cf: *environmental facies.* (g) Rocks of any origin formed within certain pressure-temperature conditions. Cf: *mineral facies; metamorphic facies*....Etymol: Latin (and French), 'face, form, aspect, condition'." (AGI, 1980).

With regard to members and facies, none of the subdivisions of the Monterey Formation were defined or intended to represent a facies in the sense of distinguishing the environment of deposition. The subdivisions are merely descriptive groups of rocks, members or lithofacies. The following discussion describes most subdivisions in the area and what they mean.

To start with the coastal region near Santa Barbara, Dibblee (1950, 1966) mapped the area which includes the Monterey Formation exposed between Santa Barbara and Point Conception and extending as far north as the diatomite quarry near Lompoc (see Plate 1, Chapter F). In Dibblee's mapping, the Monterey was divided into two parts - an upper part and a lower part. Only along the coast west of Gaviota was the Monterey further subdivided into 5 informal members designated B, C, D, E, and F. He described the rocks in these members but did not designate a specific "type locality" that could be re-examined in detail.

When Isaacs worked in the Santa Barbara coastal area, she grouped the rocks into mappable informal members mainly for the purpose of identifying laterally equivalent units of originally similar composition and age to examine in the context of progressive east-west silica diagenesis. The "type locality" is located at San Augustine Canyon midway between Gaviota Beach and Point Conception. These units went through a series of names (published and unpublished) because the connotations of various names seemed to be misleading. The current member names (as of Isaacs, 1984) attempt to characterize the composition of the members without too much misleading connotation. Keller (1984) extended these members in the coastal area as far east as Oakview near Ventura.

Other major subdivisions of the Monterey Formation in the Santa Barbara area include Arco's subdivisions of the South Elwood well in the Santa Barbara Channel (to date unpublished and proprietary), and Exxon's subdivision of the Hondo field in the Santa Barbara Channel (published in U.S. Geological Survey, 1974 and reprinted in 1983). Both of these subdivisions are principally based on log characteristics, and little is known about

their age even within the operating companies. Some further information on this topic is forthcoming in the USGS Santa Maria volume.

Subdivisions of the Monterey Formation specifically designed for the Santa Maria basin include Canfield's (1939) subsurface zones and Woodring and Bramlette's (1950) members. Canfield's zones have historically been widely used in the subsurface but are a mixture of paleontologic, lithologic, and well-log characteristics considered by most researchers to be too confusing to sort out. Unocal now has a new (but proprietary) scheme in the area. Canfield's lowermost zone was later re-defined as a separate formation (the Point Sal Formation), and current actual usage includes several of Canfield's original zones in that formation. Woodring and Bramlette (1950) mapped much of the area covering the Santa Maria basin north of Lompoc, adopted and described the Point Sal Formation, and divided the remaining Monterey strata into mappable members termed lower member, middle member, and upper member. In the southern part of the Santa Maria district (near Lompoc), Dibblee (1950) divided the Monterey into a differently defined lower part and upper part. However, he tended to draw formation contacts in this area at the opal-A/opal-CT silica phase boundary (see **silica diagenesis**), so most of his formation boundaries have been significantly revised by later workers (Barron, 1975, 1981; Dumont, 1986).

A subdivision developed in the Salinas basin but widely used in the Santa Maria basin, and sometimes in the Santa Barbara area, is the calcareous facies-phosphatic facies-siliceous facies scheme. This scheme was originally used by Pisciotto and Garrison (1981) to designate lithofacies, but the terms are now used variously and ambiguously, in some cases corresponding to none of the definitions of facies cited above. For example, some researchers use the term "siliceous facies" to designate an upper stratigraphic member of the Monterey Formation, some to designate any group of rocks that are silica-rich (esp. cherty) even though it may occur in the middle or base of the formation (e.g. White, 1989; Dunham and Cotton-Thornton, 1990), some to designate the presence of a significant siliceous component in a sequence (e.g. MacKinnon, 1989), etc. One of the problems with the terms where used as quasi-members is that they lead to confusion in many areas where, for example, the so-called phosphatic facies is more calcareous than the so-called calcareous facies or where the so-called calcareous facies is more siliceous than the so-called siliceous facies.

In the southern part of the offshore Santa Maria basin and adjacent coast, a modification of Isaacs' terms for the Santa Barbara coastal area is used by Chevron (Crain and others, 1985; MacKinnon, 1989), a somewhat different modification is used by Exxon (Bohacs, 1990), and a modification of Exxon's terms for the Hondo field is used by (at least some at) Mobil (Hornafius, 1991).

Why is this nomenclature so confusing and why doesn't everyone use the same scheme uniformly? The answer is probably threefold: differences in nomenclature schemes reflect (1) the use of different methods that can distinguish different lithologic characteristics (e.g. log vs. field differentiation), (2) different perspectives, levels of experience, and purposes among researchers and subsurface exploration geologists, and (3) true lithostratigraphic variations. A clear comprehensive picture is unlikely anytime soon.

ROCKS AND ROCK CLASSIFICATIONS

Rock = "An aggregate of one of more minerals, e.g. granite, shale, marble; or a body of undifferentiated mineral matter, e.g. obsidian, or of solid organic material, e.g. coal..." (AGI, 1980).

Rocks are not like plants and animals, divided into clearcut "species". Rocks are aggregates, and sedimentary rocks in particular commonly have highly gradational compositions due to varying sources and **sedimentation** processes.

There are many different ways of seeing and distinguishing rocks depending on the purpose. For rock classification, some geologists like detailed systems based on precisely defined (and usually arbitary) ranges of chemistry or mineralogy; this is often not very useful to the person examining the rocks in the field or trying to synthesize large areas and distinguish spatial and vertical trends. For example, a term as common as "marl" generally means an impure limestone or earthy calcareous rock, but even in a broad classification such as Dean and others' (1984) "marl" means a rock having 17-67% detrital mud, 17-67% biogenic calcite, and less than 17% biogenic silica. When used as a field term, without an XRD machine and SEM handy to identify coccoliths (generally $< 10\mu$) and estimate their abundance, "marl" probably means an impure rock that fizzes a lot when hydrochloric acid is applied.

Another problem with many descriptive rock names is what could be called the ham soup problem. How much ham is there? 1%? 0.01%? For example, many "phosphatic shales" have less than 1% apatite (0.4% phosphate), such as the lower 400 feet or so at Lion's Head; should these really be called phosphatic? Conversely, other "phosphatic shales" have as much as 5-10% apatite (2-4% phosphate), but also contain as much as 25%-65% calcite not included in the name. Shouldn't they be called calcareous?

In many rock classification schemes, in addition to the problem of figuring out what's in the rock and what's relevant to include in the name is the problem of figuring out where the components came from inasmuch as nearly all rock classification systems combine genetic and descriptive features. For example, in ODP's classification (Mazzullo and others, 1988), it is not enough to guess how much calcite is there, a geologist also has to decide whether the calcite is "pelagic" (deep-marine) or "neritic" (near-shore) before even starting. Many specific rock names also have embedded in their definition genetic aspects that cannot possibly be determined most of the time when naming rocks.

Rock names used in the Monterey Formation are based mainly on Bramlette (1946). In the Santa Maria and Santa Barbara areas, Isaacs (1981a) was also influential in recognizing and distinguishing among the large gradational classes of mixed calcareous-siliceous and dolomitic-siliceous rocks having diagenetic silica. Dunham and Blake (1987) modified Isaacs' (1981a) names to provide a clear-cut field classification system whose main purpose was to identify reservoir rocks, particularly highly siliceous glassy cherts. Dunham's system has been further simplified by Bohacs (1990) for use by seismic stratigraphers.

None of these schemes has any particular significance; in many ways they resemble schemes for identifying and classifying visual kerogen types. If we added to visual kerogen classifications some classification schemes based on color in the outcrop, weathering attributes, log type, and maybe satellite qualities, we would have the many varieties of rock classification in a nutshell.

In any case, names commonly used in the Monterey are: *porcelanite* (siliceous rock with a matte texture resembling unglazed porcelain; usually with diagenetic silica/detritus in the range 0.7-6 and carbonate <60%), *chert* (semi-glassy or very glassy flint-like siliceous rock; usually with diagenetic silica/detritus >6), *limestone* (hard highly calcareous rock), *marl* (impure calcareous or dolomitic rock), *dolomite* or *dolostone* (hard highly dolomitic rock), *siliceous shale* (laminated or platy impure siliceous rock), *siliceous mudstone* (massive impure siliceous rock), *calcareous shale* (laminated or platy impure calcareous rock; as generally used, not necessarily clay-rich), *diatomite* (highly diatomaceous rock), *diatomaceous shale* and *diatomaceous mudstone*, etc. Rocks that are complex mixtures of calcite/dolomite, detritus, and diagenetic silica have been variously identified depending on the geologist as limestone, dolomite, chert, porcelanite, calcareous shale, mudstone, shale, calcareous-siliceous rock, etc.; there is little uniformity. Also, it is well known that some well-loggers call everything that is hard dolomite, and others call everything that is hard chert. So lithologic descriptions have to be carefully evaluated before they can be interpreted.

Why are the rock names in the Monterey so imprecise and confusing? Because the **grain size** is small, it is hard to tell what the grains are, **diagenesis** destroys many of the components (such as **diatom** frustules), alters others, much of the **calcite** is invisible even with a petrographic microscope, and much diagenetic silica is unidentifiable even with a high-powered scanning electron microscope (SEM). For the most part, geologists classify rocks in the Monterey by interpreting their physical characteristics (hardness, taste, etc.); lots of times these interpretations are incorrect. Fine-grained rocks are just difficult to work with.

MINERALS & MINERAL SOURCES

mineral = "A naturally occurring inorganic element or compound having an orderly internal structure and characteristic chemical composition, crystal form, and physical properties. Those who include the requirement of crystalline form in the definition would consider an amorphous compound such as opal to be a *mineraloid*" (AGI, 1980). There are also *mineral groups* containing minerals of related but varying chemical compositions (and associated crystal form and physical properties); e.g., feldspars which have the general formula $M(Al,Si)_4O_8$ where Si:Al ranges from 3:1 to 1:1 and M = K, Na, Ca, Ba, Rb, Sr, and Fe (AGI, 1980).

Examples of minerals encountered in the Monterey Formation are quartz, pyrite, **calcite**, and **dolomite** (just to be confusing, the term "dolomite" is also used as a rock name with a

different meaning). Mineral *groups* include feldspar, **apatite**, and **clay minerals**. The term "opal-A" refers to amorphous opal, which may be considered a mineraloid. The term "opal-CT" refers to crystalline opal which may consist of two intimately interlayered minerals, α-cristobalite and α-tridymite (see **silica diagenesis**).

detrital = pertaining to detritus, a "collective term for loose rock and mineral material that is worn off or removed by mechanical means...esp. fragmental material, such as sand, silt, and clay, derived from older rocks and moved from its place of origin" (AGI, 1980).

biogenic = produced directly by the physiological activities of organisms, either plant or animal. Reference: AGI (1980).

authigenic = "Formed or generated in place; specif. said of rock constituents and minerals that have not been transported or that crystallized locally at the spot where they are now found, and of minerals that came into existence at the same time as, or subsequently to, the formation of the rock of which they constitute the part" (AGI, 1980).

diagenetic = pertaining to or caused by diagenesis (AGI, 1980). As used here, "diagenetic" refers to silica, **calcite**, and **clay minerals** that are inferred to have been formed from pre-existing minerals by nearly *in-situ* isochemical reactions such as recrystallization, whereas "authigenic" refers to the formation of new minerals that are significantly different chemically from pre-existing minerals.

calcite = a mineral, one of the three forms of calcium carbonate, $CaCO_3$.

Most calcite in the Monterey Formation is **biogenic** and in the form of **microfossils**, mainly calcareous nannofossils (see **calcareous nannoplankton**), and also **foraminifera** tests. Naturally occurring calcite often has subsititution of other elements in the structure, particularly Mg, Fe, and Mn (Berry and Mason, 1959). High-magnesium calcite is particularly common in many megafossils and in **benthic foraminifera**, and is less stable than low-magnesian calcite (Scholle, 1977; see **calcite diagenesis**).

dolomite [mineral] = the mineral calcium magnesium carbonate, ideal formula $CaMg(CO_3)_2$, though ferrous iron or manganese can substitute for part of the magnesium. Reference: AGI (1980). Where Fe exceeds Mg in the structure, the mineral is called ankerite.

Dolomite is **authigenic** (see **dolomite authigenesis**). In the Monterey Formation, nearly all dolomite has excess calcium (up to 58 mol %), and some dolomite has substitution of iron (up to 16 mol %) and/or manganese (up to 0.5 mol %). References: Murata and others (1969, 1972); Pisciotto (1981); Garrison and others (1984).

apatite = a group of calcium phosphate minerals having the general formula $Ca_5(PO_4,CO_3)_3(F,OH,Cl)$, including fluorapatite, chlorapatite, hydroxylapatite, carbonate-apatite, and **francolite.**

Apatite in the Monterey Formation is mainly carbonate-fluorapatite and is in part **detrital** (derived from pre-existing rock), in part **biogenic**, and in part **authigenic** (Pisciotto and Garrison, 1981; Garrison and others, 1987). Most of the apatite is authigenic, though it may be formed almost at the seafloor (see **apatite authigenesis**). Minor (<1%) biogenic apatite includes **fish debris** (scales and bones). Minor detrital apatite is generally concentrated in sandstone beds, and can be used by fission-track methods for dating or estimating thermal exposure (Naeser and others, 1989).

aluminosilicate minerals = aluminum-bearing silicate minerals, including **clay minerals**, feldspars, and zeolites. Feldspars are almost entirely of **detrital** origin (though in some beds most feldspar may be in arenaceous **foraminifera** tests and thus arguably **biogenic**). Zeolites are mainly **authigenic.**

clay minerals [mineral] = a complex and loosely defined group of finely crystalline, metacolloidal, or amorphous hydrous silicates essentially containing aluminum (or sometimes magnesium and iron) and with a crystal structure of two- or three-layer type. The structure may also include iron, magnesium, chromium, lithium, manganese, and other ions, and exchangeable cations include calcium, sodium, potassium, magnesium, hydrogen, and aluminum. Clay minerals are formed chiefly by alteration or weathering of other silicate minerals such as feldspars. The most common clay minerals belong to the kaolin, smectite, and illite groups. Reference: AGI (1980).

In the Monterey Formation, mixed-layer illite/smectite is the most common clay mineral, but illite, kaolinite, chlorite, and others are also present (see Chapter B, this report). Most of the clay minerals are **detrital**, though some fraction may be **authigenic**. Mixed-layer illite/smectite undergoes important changes with burial (see **clay diagenesis**).

detrital quartz = (a term used by Isaacs for) quartz inferred to be **detrital** rather than **diagenetic.** The abundance value is determined as a proportion of **aluminosilicate minerals** based on average amounts in opal-A and opal-CT rocks. In some beds most such quartz may be in arenaceous **foraminifera** tests and thus arguably **biogenic.**

biogenic and diagenetic silica = (a term used by Isaacs for) for various silica (SiO_2) minerals which are either clearly **biogenic** (as in **diatom** frustules) or almost certainly derived from biogenic materials. The term includes all opal-A, opal-CT, and diagenetic quartz (for definitions, see **silica diagenesis**).

MICROFOSSILS

microfossil = "A fossil too small to be studied without the aid of a microscope....It may be the remains of a microscopic organism" (such as a diatom frustule) "or a part of a larger organism" (such as a fish bone) (AGI, 1980). Nannofossils are "mostly near the limit of resolution of the light microscope and hence best studied with electron microscopy" (AGI, 1980).

Of the microfossils found in the Monterey Formation, the most abundant are siliceous **diatom** frustules and calcareous coccoliths (see **calcareous nannoplankton**). In addition to diatom frustules, other siliceous microfossils present (probably representing 2-10% of the total) include the shells or skeletal parts of **radiolarians**, **silicoflagellates**, ebridians, and sponges (see **sponge spicules**). Coccoliths are estimated to represent generally over 90% of calcareous microfossils in the Monterey Formation of the Santa Barbara coastal area, though **foraminifera** are much more obvious both in the field and under the microscope (Isaacs, 1981a).

algae = photosynthetic, almost exclusively aquatic plants of a large and diverse division of nonvascular plants, including seaweeds and their fresh-water allies. Algae range in size from simple unicellular forms to giant kelps several meters long, and display extremely varied life-cycles and physiological processes. Algae range from the Precambrian. As photosynthetic organisms, algae live in the near-surface photic zone where light is present. Except for blue-green algae (cyanobacteria), algae are classed as protists. References: AGI (1980), Stanley (1986).

Microfossil remains of algae in the Monterey Formation are predominantly frustules of **diatoms** and coccoliths (see **calcareous nannoplankton**).

protist = a single-celled (or simple multicellular) organism of the Kingdom Protista, including dinoflagellates, diatoms, red algae, green algae, foraminifera, coccolithophores, etc. Protists can be divided more or less into autotrophic (plant-like) organisms (that nourish themselves by utilizing inorganic material to synthesize their living matter) and heterotrophic (animal-like) organisms (that nourish themselves by utilizing organic material to synthesize their living matter). References: AGI (1980), Stanley (1986), Buzas and others (1987).

The most important group of heterotrophic (animal-like) protists having microfossil remains in the Monterey Formation are **foraminifera**, though **radiolarian** tests are also present. The most important groups of autotrophic (plant-like) protists having microfossils remains in the Monterey Formation are **diatoms** and coccolithophores (see **calcareous nannoplankton**), but **dinoflagellates** and **silicoflagellates** are also widespread.

flagellate = a **protist** organism that bears a flagella (a long whiplike protoplasmic process that projects from a cell or microorganism and is the primary organ for controlling movement through water). Reference: AGI (1980).

Flagellated protists with important microfossil remains in the Monterey Formation include **silicoflagellates** and **dinoflagellates**.

plankton = aquatic organisms that drift or swim weakly (AGI, 1980). Divided into phytoplankton (plants) and zooplankton (animals).

Plankton with important microfossil remains in the Monterey Formation include **diatoms**, **calcareous nannoplankton**, and **planktonic foraminifera**; also present are remains of **silicoflagellates**, **dinoflagellates**, and **radiolarians**.

nekton = aquatic organisms that are actively free-swimming such as fish.

Microfossil remains of nekton in the Monterey Formation are mainly bones and scales of fish (see **fish debris**) but may also rarely include otoliths (fish ear bones).

benthos = those forms of marine life that are bottom-dwelling. Certain fish that are closely associated with the benthos may be included. Reference: AGI (1980).

Microfossil remains of benthos in the Monterey Formation principally include tests of **benthic foraminifera** and **sponge spicules**.

diatom = a microscopic, single-celled plant or **protist** (generally heterotrophic) including solitary and colonial **algae**, which grow in both marine and fresh water. Diatoms are mainly planktonic, but some are benthic in shallow coastal regions. Diatoms secrete walls of opaline silica, called *frustules*, in a great variety of forms. Marine diatom frustules range from 2 μm to 2 mm, most commonly in the range 10-100 μm. About 20,000 living and fossil species have been described, of which about 10,000 species are living species. Diatoms probably evolved in the Jurassic and were widespread by the middle Cretaceous.

Diatoms are estimated to contribute between 20 and 25% of the global net primary production of plants on earth. As algae, diatoms live in the **photic zone** but species have varying light requirements leading to some depth zonation, and a number of species have such low light requirements that they can actively grow on the underside of sea ice. Diatoms are particularly well-adapted to highly fertile marine surface waters and are often dominant in those locations, but may be virtually absent in low-**productivity** oceanic areas. Diatom growth can be very rapid, with populations able to double in about a day. Phosphate and nitrate are the main critical nutrients; silica is probably not a limiting factor. Diatoms produce resting spores when conditions become adverse, and sink into deeper waters; apparently resting spores can absorb nutrients.

Diatom assemblages are related to water masses, with different assemblages having various geographic distribution in the modern ocean. The assemblages preserved in deep-sea sediments **are** significantly changed by **dissolution**; only a fraction (< 10%) of deposited frustules are estimated to be buried in sediment.

References: Werner (1977), AGI (1980), Kennett (1982).

calcareous nannoplankton = coccolithophorids and related organisms with minute calcareous plates such as discoasters. Coccolithophorids are a group of biflagellate, unicellular, golden brown **algae** which form calcareous surface scales known as coccoliths. The entire shell, known as a coccosphere, is usually spherical with a diameter 2-25μm, while the scales are 2-10 μm in diameter. Coccolithophorids are primary producers in the oceans and mainly are found in the **photic zone.** They are more tolerant of lower nutrient levels than other plankton, so are *relatively* more abundant in less fertile waters. Because they are composed of low-magnesium **calcite**, coccoliths are relatively stable diagenetically. Calcareous nannoplankton range from early Jurassic. References: Scholle (1977), Raymont (1980), Kennett (1982).

foraminifera = a diverse group of heterotrophic (animal-like) **protists** belonging to the phylum Foraminifera which are shell-bearing, the tests being one to many chambers composed of secreted **calcite** (rarely silica or aragonite) or of aggultinated particles. Most foraminifera are marine and can also live in brackish and saline lakes. The range is Cambrian to the present. About 38,000 types of forams have been named, and about 10,000 other types are still present in the seas (AGI, 1980; Kennett, 1982, and references therein). Foraminifera are divided into **planktonic foraminifera** and **benthic foraminifera.**

planktonic foraminifera = free-floating or drifting **foraminifera.** Planktonic foraminifera first appeared in Jurassic sediments, about 400 species are altogether known, and about 30 species live in the presentday ocean. According to Kennett (1982), much more is known about their stratigraphic distribution than about their modern biology. Planktonic foraminifera live mainly in the **photic zone**, and the few deeper water species probably spend their earlier life in near-surface waters; they live in marine waters of normal salinity and are very rare in brackish waters. They are also uncommon in most nearshore shallow waters. Surface waters with high nutrients generally support the largest populations, and "concentrations seem to be at least ten times greater in fertile high-latitude coastal and equatorial regions of upwelling than in the more sluggish central and mid-latitude regions" (Kennett, 1982). Planktonic foraminifera are also very sensitive markers of water masses.

benthic foraminifera = bottom-dwelling **foraminifera.** Most benthic foraminifera are mobile, though some forms may be attached to the bottom either temporarily or permanently. Benthic foraminifera occur in brackish to normal marine water and live at all depths. They are also found at all latitudes, though highest diversities are found in tropical areas. Large benthic foraminifera (300 μm-16 mm) occur in shallow tropical seas, but smaller benthic foraminifera (20-300 μm) are geographically more widespread and are

mainly used for **biostratigraphy**. The shell or test is usually composed of **calcite**, though some are made of aragonite (a calcium carbonate mineral) or opaline silica, and many species form test walls of cemented sedimentary particles (known as arenaceous or agglutinated foraminifera) which may include sand, silt, **sponge spicules**, even coccoliths. Membranous material is also used, though not preserved in the geologic record.

The bathymetric distribution of benthic foraminifera is widely used to provide estimates on the paleodepth in which sediments were deposited (see **paleodepth**). Different water masses tend to have different assemblages. Controls on the distribution of arenaceous or agglutinated forams are not well-known, though it is generally thought that the saturation level of calcite is a major controlling factor. Reference: Kennett (1982).

silicoflagellate = a single-celled **flagellated** marine **planktonic** organism with an internal skeleton of opaline silica. Silicoflagellates are tubular-shaped and in the size range 20-50 μm. They are regarded both as **protozoa** (animals) and **algae** (plants); as **algae**, they are photosynthetic and confined to the **photic zone**. A generation span is about 2 days. About 58 living species are known, but they are seldom abundant in sediment and of only moderate use for **biostratigraphy** since the average zone is 5 million years in length. Silicoflagellates appeared in the middle Cretaceous. According to Kennett (1982), silicoflagellate skeletons are less resistant to **dissolution** than **diatom frustules**. Reference: Kennett (1982).

sponge spicule = a needlelike rod or a fused cluster of rods in the skeleton of a sponge, composed of opaline silica. Sponges are aquatic invertebrates that live in virtually all water depths (littoral through abyssal). References: AGI (1980), Bohacs (1990).

radiolarian = a diverse group of **planktonic** heterotrophic **protists** of the subclass Radiolaria with protoplasmic extensions radiating from the spherical main body. Radiolarian skeletons are composed of silica or strontium sulfate and are in the size range 50-400μ. Radiolaria do not commonly live in nearshore waters. Most radiolaria live in near-surface waters, but some live in water depths of several thousand meters. Their siliceous skeletons are highly resistant to **dissolution**. References: AGI (1980), Anderson (1983), Kennett (1982).

dinoflagellate = a single-celled microscopic flagellated organism, chiefly marine and usually solitary, with an organic cell wall. Dinoflagellates have resemblances to both plants and animals; most are autotrophic but some are heterotrophic. They inhabit all water types and are capable of extensive diurnal vertical migrations in response to light. Dinoflagellates appear to thrive best in low or moderate **upwelling** and mixing conditions (Estrada and Blasco, 1979; Vork, 1984). Fossil dinoflagellates are thought to represent cysts and range in size from 25μ to 250μ. Reference: Williams (1978), AGI (1980).

fish debris = fossil remains of fish, including scales (a thin flat overlapping horny plate forming the outer protective covering of many fish) and bones. Fish scales and bones are composed of **apatite**.

OCEANOGRAPHIC AND ENVIRONMENTAL TERMS

mixed layer = the surface zone of the ocean which is well mixed by winds, waves, seasonal cooling, and salinity increase due to evaporation; the mixed layer is generally less than 250 m thick. Reference: Kennett (1982).

photic zone = that part of the ocean in which there is sufficient penetration of light to support photosynthesis. The depth varies, averages about 80 m, but can exceed 150 m in central ocean areas. Reference: AGI (1980).

thermocline (permanent) = a zone of rapidly changing temperature below the surface or mixed layer of the ocean; the thermocline generally ranges from about 150 m to depths of about 1000 m. References: AGI (1980), Raymont (1980), Kennett (1982).

oxygen-minimum zone = a zone at intermediate water depths (in the range 150-1000 m) in which dissolved oxygen is relatively low compared to the surface or mixed layer, and also lower than in deeper water. Values of oxygen in the oxygen-minimum zone vary considerably in the ocean today from as high as 4 ml/L in the Antarctic Convergence to very low values (<0.1 ml/L) in the eastern tropical Pacific. Reference: Raymont (1980). Although low oxygen values are often regarded by geologists as solely reflecting local respiration of zooplankton due to high **productivity**, they may also be a water mass characteristic not specifically reflecting local productivity, as in the eastern tropical Pacific including the Gulf of California (Wyrtki, 1966; Soutar and others, 1981).

anoxic = free of oxygen. The term is widely used by geologists in practice to mean "very low in oxygen", generally < 0.15 ml/L.

anaerobic = (a) "Said of an organism (esp. a bacterium) that can live in the absence of free oxygen; also, said of its activities....(b) Said of conditions that exist only in the absence of free oxygen" (AGI, 1980). The term is widely used by geologists in practice to mean "very low in animal life."

anaerobic sediment = "A highly organic sediment characteristic of some fjords and basins where restricted circulation of the water results in the absence or near absence of oxygen at the sediment surface, and bottom water is rich in hydrogen sulfide" (AGI, 1980).

euxinic = "(a) Pertaining to an environment of restricted circulation and stagnant or anaerobic conditions, such as a fjord or a nearly isolated or silled basin with toxic bottom waters. Also, pertaining to the material (such as black organic sediments and hydrogen-sulfide muds) deposited in such an environment or basin, and to the process of deposition of such material (as in the Black Sea). (b) Pertaining to a rock facies that includes black shales and graphitic sediments of various kinds" (AGI, 1980).

dysaerobic = low in oxygen, generally meaning oxygen levels in the range 0.15-1.0 ml/L.

aerobic = "(a) Said of an organism...that can live only in the presence of free oxygen; also, said of its activities....(b) Said of conditions that can exist only in the presence of free oxygen" (AGI, 1980).

Because a practical limit of oxygen detection in much oceanographic work has been 0.15 ml/L, the term "anoxic" has often been used in practice to describe a condition of <0.15 ml/L (e.g. Ingle, 1981). Chemically speaking, of course, there is a significant difference between true anoxia and oxygen in the range 0.01-0.15 ml/L.

What do geologists actually mean when they say a deposit was anoxic or anaerobic? In some cases, they may mean no more than that the deposit is organic-rich, in other cases they may mean that the deposit contains pyrite, in others that there are minor remnants of preserved bedding features, in others that there are vague laminae, in others that there are varve-like (continuous and even) laminae. In the Monterey Formation, the conclusion is usually drawn from the presence of pyrite, or from the presence of lamination. (Note however that there are thick Monterey sequences with almost no traces of lamination, such as the upper Monterey of the Salinas Basin.) Another criteria is a benthic foraminifera assemblage specially adapted to low-oxygen conditions; of course, if the assemblage was living *in situ*, the bottom water contained some oxygen as foraminifera are aerobic organisms.

Actually, evidence of preserved layering, even lamination closely resembling modern varves, is not evidence of anoxia (*sensu strictu*) in bottom water. For example, the bottom water directly overlying the famous varves in the present-day Santa Barbara Basin contains measurable oxygen (0.1 ml/L), and an abundant standing crop of specially adapted **benthic foraminifera** is present at the sediment-water interface; calculations of oxygen flux suggest that this abundant fauna is not limited by the available oxygen (Phleger and Soutar, 1973). The truly anoxic zone with free sulfide does not generally begin until 12 cm below the sediment surface (Sholkovitz, 1973) and overlying surface sediment has a completely different color. Interestingly, a low-diversity benthic foraminifera fauna is presently living *in situ* to depths of 12 cm below the sediment-water interface in the San Pedro basin (Silva and Corliss, 1991; and personal communication). Recent work on surficial sediments and oxygen in the bottom water of the modern Santa Barbara Basin suggests that a seasonal bottom-water cycle involving bacterial growth may actually cause varve formation (Reimers and others, 1990).

Although not necessarily indicating true anoxia, the presence of varves and thinly laminated sediment does correspond to bottom-water with exceedingly low oxygen (<0.1-0.2 ml/L) which generally excludes large scavenging organisms that might disrupt layering. But although studies of modern sediments have shown that lamination is well-preserved only where oxygen is very low, the converse is not necessarily true. For example, in his study of the distribution of laminated diatomaceous sediment in the Gulf of California, Calvert (1964) showed that all completely laminated sediments were between 300 and 1400 m water depth (within the oxygen-minimum zone), but about half of the sediments within that zone were either homogeneous, mottled, or only partially laminated. Soutar and others (1981) similarly showed that the relation between sediment layering and bottom-water oxygen is complicated by many other influential factors; they cite evidence, for example, that an invasion once every 3-4 years of the pelagic red crab *Pleuroncodes* would completely disrupt sediment layering. Savrda and others (1984), from study of sediments in the modern California Continental Borderland, concluded that an "anaerobic biofacies" (<0.1-0.2 ml/L) could be distinguished from an "aerobic biofacies" (>0.1-0.2 ml/L), but that there were no criteria that could be confidently used to distinguish an intermediate "dysaerobic biofacies".

Detailed study has shown that many parts of the Monterey Formation were deposited in oxygenated water, or with oxygen fluctuating from "anoxic" (<0.1-0.2 ml/L) to "more oxygenated" (Savrda and Bottjer, 1986; cf. Govean and Garrison, 1981). Among features of more oxygenated biofacies are preserved thin-shelled 'paper pectens' identified as probably *Delectopecten* and/or *Cyclopecten* (as are common in sample KG-22) (Savrda and Bottjer, 1987).

nutrient = "In oceanography, any inorganic or organic compound used to sustain plant life..." AGI (1980).

There are many nutrients required for marine **plankton** growth, and some of them (such as CO_2) are generally available in excess. The major nutrients usually considered limiting to growth are nitrogen and phosphorus, which are essential to all **algae**. (Although sometimes regarded as a limiting nutrient, silicon is mainly used by algae forming siliceous skeletons such as diatoms; opinions vary on whether silicon is limiting.) Because phosphate and nitrate is rapidly consumed by organisms in the **photic zone**, concentrations of these nutrients are generally low in surface waters but much higher in deeper water. In the Pacific Ocean, both phosphate and nitrate increase with depth to about 1000 m, and are nearly constant below that depth. Nutrients increase most rapidly with depth where there is a strong **thermocline**. Any mechanism that transports deeper water that is nutrient-rich to the photic zone thus has the potential for increasing **primary productivity**, for example divergence in water circulation as in equatorial current systems or in **upwelling** areas associated with eastern boundary currents. If the transported water is from very shallow depths or is not nutrient-rich, productivity may not be much affected. Reference: Raymont (1980).

upwelling = the rising of cold, heavy subsurface water toward the surface, especially along the western coasts of continents (as along the coast of Southern California), due to displacement of surface water transported away from the coast by the action of winds parallel to it or by diverging currents. Upwelling may also occur in the open ocean where cyclonic circulation is relatively permanent, or where southern trade winds cross the equator. Upwelled water generally derives from about 100-300 m and upwells at a rate of about 1-5 m/day. References: AGI (1980), Raymont (1980).

The terms "upwelling", "upwelling deposit", and "upwelling system" are used loosely by most geologists when referring to ancient sediments and rocks. The main intention is probably to designate something interpreted as a "high-**productivity**" deposit, as evidenced for example by high abundance of preserved diatom tests, based on the general idea that upwelled subsurface water necessarily causes high productivity because it is more nutrient-rich. However, upwelling is not synonymous with productivity. In fact, upwelled water may not induce high productivity if the upwelled water is not also high in nutrients, or if the rate and duration of upwelling is inappropriate to the biotic system (Raymont, 1980; Soutar and others, 1981). Nor is upwelling necessarily required for high productivity; for example, large-scale horizontal advection of nutrient-rich water has been proposed as a major factor in promoting the productivity in the presentday California Current (cf. Bernal and McGowan, 1981).

productivity = "(a) A general term for the organic fertility of a body of water", or **primary productivity** (AGI, 1980).

production = "A time-rate unit of total amount of organisms grown" (AGI, 1980).

primary productivity = "In a body of water, the rate of photosynthetic carbon fixation by plants and bacteria forming the base of the food chain" (AGI, 1980).

Although diatom-rich sediments are generally recognized as an indication of high productivity in overlying waters, the converse is not necessarily true: areas of high productivity may not have abundant diatom frustules either due to dilution (as in the modern Santa Barbara Basin where **diatom** frustules represent only about 5% of both downward sediment flux and sediment), dissolution, or resedimentation. How can we judge productivity? Measures of productivity that have been utilized include: (1) the ratio of silica/carbonate based on the general observation that **diatoms** are proportionately much more abundant than **calcareous nannoplankton** in highly productive waters (after Berger, 1974; and others). This criteria is affected by differential **dissolution** and also by other sources of calcite in the Monterey Formation, such as **benthic foraminifera**; (2) the relative abundance of the "**upwelling**" diatom species *Thalassionema nitzschioides* (Barron and Keller, 1983); and (3) the rate of silica accumulation. Based on these criteria, the organic-rich carbonaceous marl member of the Monterey Formation at Naples represents a period of relatively low productivity, underlying and overlying strata show much higher

productivity, and the Sisquoc Formation overall the highest productivity (Isaacs, 1984, 1985).

oxygen isotope stratigraphy = the use of oxygen isotope ratios (O^{18}/O^{16}) to identify stratigraphic units, usually by determination on calcareous marine microfossils. Although originally expected to reflect mainly temperature, the dominant signal (about two-thirds) from oxygen isotopes is now accepted to be seawater composition, principally influenced by glaciation and continental ice buildup. For middle Miocene and younger sediments, oxygen isotope stratigraphy is thus mainly used as a correlation tool, or for comparing (near-)surface temperatures with bottom temperatures. However, varying depths of foraminiferal habitats and fractionation by various species ("vital effect") also complicate that picture. Reference: Kennett (1982).

surface temperature = temperature of water at the sea surface. In today's ocean, surface temperatures range from -2° C to 30° C, with a mean annual value of 17° C. The annual range is about 2° C in polar and equatorial regions, 5-8° C in temperate regions, and as high as 20° C in coastal areas. References: Raymont (1980), Kennett (1982).

bottom temperature = temperature of water at the sea bottom. Temperature at depths (>1000 m) are comparatively stable and vary globally by only about 2° C. Reference: Kennett (1982).

Determining surface paleotemperatures (or quasi-paleotemperatures) from ancient sediments is complicated by the annual range in temperature usual in temperate regions and coastal areas compared to the lifespan of many plankton (hours or days), by the varying (and often unknown) depths at which particular species lived, the character of the **thermocline**, and by varying fractionation in different species. Oxygen isotopes are usually determined on the calcareous shells of **planktonic foraminifera**, and surface "temperatures" can be approached by parallel analyses on species thought to inhabit shallow (20-50 m), intermediate (100-200 m), and deep (200-400 m) water (Kennett, 1982). There is much literature on this subject.

The abundance of **diatom** frustules in the Monterey Formation is sometimes attributed to cold surface temperatures, but actually the temperature itself does not cause diatom abundance. As shown by Tont (1981), diatom abundance in modern coastal waters is correlated with surface temperature *anomalies*; both the temperature anomaly and the diatom abundance are produced by coastal **upwelling**. Greater thermal stratification or more intense ocean circulation are considered possible influences in promoting upwelling.

Because of Antarctic glaciation, major changes occurred in the thermal and water mass structure of the Pacific Ocean during the Miocene, and these changes have been widely cited as the "event" that caused the lithologic change marked by the base of the Monterey Formation *or* the "event" that caused various members or lithofacies (usually highly siliceous strata). Oddly enough, however, no **oxygen isotope stratigraphy** was done on the Monterey itself until the very recent work of Ben Flower at the Naples Beach section

(Flower and Kennett, 1991). His results are based on shells of **benthic foraminifera** (thus reflecting bottom water composition), and show that the mid-Miocene oxygen isotope shift occurred in the carbonaceous marl member, during deposition generally interpreted as low-**productivity** and just before a long period of very slow deposition or non-deposition.

paleodepth = "The depth at which an ancient organism or group of organisms lived" (AGI, 1980).

The principal means used to determine paleodepth are distinctive assemblages of **benthic foraminifera**, which have a preference for certain water depths. Some of the limitations of this approach include that (1) depth preferences may differ in various regions; (2) shallow and nearshore differences are more distinct than deep-water differences; (3) fossil paleodepths are commonly determined by analogy with modern foraminiferal distributions, but species have evolved through geologic time; (4) the water-mass structure of the oceans has been relatively stable since the mid-Miocene but earlier is thought to have been different, thus limiting the reliability for strata older than 15 Ma of paleodepths based on analogy with modern distributions patterns; (5) the biologic and ecologic factors responsible for the depth distribution are poorly understood; (6) downslope transport of shallower assemblages often obscures the *in situ* assemblage; and (7) the foraminiferal assemblage in deep silled basins more likely represents the overlying water mass above the sill depth rather than the paleodepth *per se* (Ingle, 1980; Kennett, 1982; Lagoe, 1984).

The standard classification for paleodepths in the Miocene of California is Ingle (1980). The biofacies (see **facies**) and inferred paleodepths are: inner neritic zone ("inner shelf") 0-50 m; outer neritic zone ("outer shelf") 50-150 m; upper bathyal ("slope") zone 150-500 m; upper middle bathyal ("slope") zone 500-1500 m; lower middle bathyal 1500-2000 m; lower bathyal ("basin floor") zone >2000 m. The geomorphic terms ("slope" and "basin") that are frequently equated with these biofacies are either schematic or based on sedimentologic interpretations. For example, the maximum depth of the modern Santa Barbara Basin floor is 590 m, thus falling in the upper middle bathyal or "slope" zone.

SEDIMENTATION PROCESSES AND RATES

sedimentation = "The act or process of forming or accumulating sediment in layers, including such processes as the separation of rock particles from the material from which the sediment is derived, the transportation of these particles to the site of deposition, the actual deposition or settling of the particles..." (AGI, 1980). Deep marine sedimentation processes include **pelagic sedimentation** and **resedimentation** (Stow and Piper, 1984; Garrison, 1990).

pelagic sedimentation = processes that move material from the sea surface to the seafloor, including **fecal pellet** sedimentation, **marine snow**, and individual particle settling (Stow and Piper, 1984; Garrison, 1990).

fecal pellet = "An organic excrement, mainly of invertebrates, occurring esp. in modern marine deposits but also fossilized in some sedimentary rocks..." (AGI, 1980). Fecal pellets mainly derive from the smaller zooplankton. Although generally small (50-250μ), fecal pellets sink much more rapidly than individual particles (about 40-400 m/day) and have an organic coating which protects the enclosed material from dissolution. A single pellet may contain 10^5 coccoliths. Reference: Kennett (1982).

By analogy with modern marine sediments (Berger and Soutar, 1967; Schrader, 1971; Honjo and Roman, 1978), a major mechanism of sediment delivery in the Monterey Formation has been thought to be fecal pellets (e.g., Garrison, 1990). With the development of highly sophisticated sediment traps in recent decades, there have been many studies of fecal pellets in modern oceans and coastal areas. In the presentday Santa Barbara Basin, Dunbar and Berger (1981) have shown that at least 60% and possibly as much as 90% of trapped material was fecal pellet aggregate. Fecal pellets do not contain just microfossils and organic materials. Over 85% of the material in the Santa Barbara Basin fecal pellets is clay minerals and silt-sized quartz (Dunbar and Berger, 1981). Other debris includes coccoliths and coccospheres, diatom frustules (0-6%), and organic matter (av TOC 3.3% estimated to represent 6% organic matter, C/N = 7.1). No foraminiferal tests were observed in the pellets, although they are present in the sediment; foraminifera (and also some diatoms) settle as individual particles.

Pellet flux was estimated to represent about one-half of total sediment flux; total pellet flux was estimated at 660 g m^{-2} yr^{-1}, of which 22 g m^{-2} yr^{-1} was carbon flux (Dunbar and Berger, 1981). For comparison, a carbon flux of 22 g m^{-2} yr^{-1} (2.2 mg/cm^2/yr) is an order of magnitude higher than average values estimated for the organic-rich carbonaceous marl member (KG-1, KG-2, KG-4) of the Monterey Formation in the Santa Barbara coastal area (0.2-0.3 mg/cm^2/yr) but comparable to values for the Sisquoc Formation which are estimated to exceed 1.1 mg/cm^2/yr (Isaacs, 1984, 1985).

marine snow = aggregations of organic detritus, micro-organisms and clay minerals in clusters from 0.5 mm to a few meters across, formed by mucus-producing organisms or by biologically enhanced physical aggregation of small particles as in diatom blooms. Chemical and microbial alteration of organic matter within marine snow clusters can be substantial (Alldredge and Silver, 1988, as summarized by Garrison, 1990).

resedimentation = resuspension, lateral transport, and redeposition of sediment. Mechanisms of resedimentation for deep-water sediments include deep-water currents, nepheloid layer transport, turbidity currents, and other mass flow deposits (Stow and Piper, 1984; Garrison, 1990). Bottom currents are especially important in winnowing sediments.

winnowing = "The selective sorting, or removal, of fine particles by wind action, leaving the coarser grains behind. The term is often applied to removal by or sorting in water..." (AGI, 1980). Sorting by bottom currents depends on grain size.

grain size = "The general dimensions (such as average diameter or volume) of the particles in a sediment or rock...based on the premise that the particles are spheres or that the meaurements can be expressed as diameters of equivalent spheres. It is commonly measured by sieving, by calculating settling velocities, or by determining areas of microscopic images" (AGI, 1980). As generally defined, smallest particles are mud (including clay <3.9μ and silt 3.9-63μ), intermediate particles are sand (63μ-2 mm), and large particles are gravel (>2 mm).

Among major sedimented materials in the Monterey Formation, **clay minerals** are generally clay size (<2 μ), the coccoliths of **calcareous nannofossils** are generally clay to fine silt size (2-10 μ), non-clay grains of **detrital minerals** are probably fine silt to very fine sand size, diatom frustules are generally silt to very-fine-sand size (10-100 μ), benthic foraminifera tests are silt to medium-sand size (20-300 μ), dinoflagellate cysts are generally silt to medium-sand size (25-250 μ), and radiolarian tests are coarse silt to medium-sand size (50-400 μ).

dissolution = "A process of chemical weathering by which minerals and rock material pass into solution" (AGI, 1980).

Seafloor dissolution changes the composition of sediments considerably; for example, only 2% of the biogenic opal produced by organisms is estimated to be retained in the sediment record (Kennett, 1982). Differential dissolution of microfossils can be used to estimate preservation of microfossil assemblages. According to Kennett (1982), coccoliths (see **calcareous nannoplankton**) and **benthic foraminifera** are generally more resistant to dissolution than the most resistant **planktonic foraminifera**. Among planktonic foraminifera, species that live high in the water column are usually more fragile than deeper dwelling species and are thus less likely to be preserved. Siliceous microfossils in order of increasing resistance to dissolution are **diatoms**, delicate **radiolarians**, robust radiolarians, and **sponge spicules** (Kennett, 1982). **Silicoflagellates** are rated variously by different authorities.

sedimentation rate = rate at which sediment accumulated. Many geologists prefer the term "accumulation rate" so as to clearly include sediment losses from sea-bottom transport or **winnowing**, periods of non-deposition, and **dissolution** on the seafloor and during early **diagenesis**.

Sedimentation rates in surface sediments are often expressed as thickness per unit time (e.g. cm/m.y.) for convenience, and this convention is also sometimes used for ancient sediments, though it is highly ambiguous in both cases. The reasons are that (1) surficial seafloor sediments are often so extremely porous that measured thicknesses are unreliable due to disturbances during sampling; and (2) sediments compact significantly during burial so that rock thicknesses are hard to compare with surficial values. In ancient sediments,

sedimentation rates expressed as thickness per unit time are sometimes corrected to "decompaction" values, which means that an estimate is made of the original thickness. This kind of calculation introduces considerable uncertainty in Monterey strata, because to "decompact" correctly requires much unavailable information. As illustration, laminated mud sediments on the seafloor of the Santa Barbara Basin today are estimated to have 94% porosity (Soutar and others, 1981), clayey diatomaceous sediments in the Bering Sea are estimated to have 87% porosity at the seafloor, calcareous pelagic sediments have 72% porosity at the seafloor (Hamilton, 1976), whereas quartzose Monterey strata (e.g. Lions Head) have about 15% porosity. What this means is that the Santa Barbara sediments are 6% solid, the Bering Sea sediments 13% solid, calcareous sediments 28% solid, and Lions Head rocks 85% solid (see **porosity**). "Decompaction" from Lions Head to calcareous sediment values simply means multiplying all thicknesses by 3.0, "decompaction" from Bering Sea values by 6.5, and "decompaction" from Lions Head to Santa Barbara Basin values by 14. "Decompaction" thus introduces a factor of 5 uncertainty depending on the assumption of original surficial values.

A more standardizable convention is to express sedimentation rates in weight per surface area per unit time (e.g. $g/cm^2/m.y.$), and this convention is always preferred (Kennett, 1982). Then the pertinent factors for determining accumulation rates are time span, dry bulk density, and strata thickness. In terms of uncertainty, the limiting factor is time span. Even in the most ideal circumstances in the Miocene of California, an increment of 300,000 years is the shortest time span that can be determined paleontologically, but any such increment is based on multiple levels of correlation from diverse evidence such as seafloor spreading rates on the opposite side of the planet (see **geologic time-scale**). In practice, any interval less than a million years has considerable uncertainty and even an interval of 4 million years would have more than 10% uncertainty. Reasonably certain estimates of accumulation rates in the Monterey (and most ancient sedimentary rocks), therefore, are restricted to long-term rates - averages over a period exceeding 1 million years, and preferably at least 4 million years.

What does the long-term rate mean when looking at a specific sample in an interval? A common simplifying assumption is that equal thickness represents equal time, so that all beds within an interval represent the same average rate. For some purposes, this is a reasonable assumption, but it is not a reasonable assumption for determining the rate of accumulation of any specific component (e.g. TOC) where major sediment components vary significantly among beds without the necessary corollary that all sediment component fluxes intimately co-vary in an almost miraculous way. The assumption requires, for example, the corollary that in every period when one component had more rapid influx, all other components adjusted downward to exactly compensate. Another corollary is that no two component fluxes might rapidly increase (or decrease) at the same time.

If the flux rate of a single major sediment component varies independently of other components, or if two or more components change simultaneously, then equal thickness does not represent equal time. In the Monterey Formation in the Santa Barbara coastal area, evidence indicates that sedimentation rates varied as much as an order of magnitude

between members, and also an order of magnitude *within* members (Isaacs, 1984, 1985). Thus sedimentation rates for specific samples are only vague guesses.

BURIAL AND DIAGENESIS

diagenesis = "All the chemical, physical, and biologic changes undergone by a sediment after its initial deposition, and during and after its lithification, exclusive of surficial alteration (weathering) and metamorphism....It embraces those processes (such as compaction, cementation, reworking, authigenesis, replacement, crystallization, leaching, hydration, bacterial action, and formation of concretions) that occur under conditions of pressure (up to 1 kb) and temperature (maximum range of 100° C to 300° C) that are normal to the surficial...part of the Earth's crust..." (AGI, 1980). The term is restricted by some to "the initial phase of postsedimentary changes, occuring in the zone where the sediment is still unconsolidated..." (AGI, 1980). Diagenesis includes **silica diagenesis, calcite diagenesis, dolomite authigenesis, apatite authigenesis, clay diagenesis,** and **porosity reduction.**

authigenesis = "The process by which new minerals form in place within an enclosing sediment or sedimentary rock during or after deposition, as by replacement or recrystallization..." (AGI, 1980).

silica diagenesis = **diagenesis** of biogenic silica (SiO_2). In the Monterey Formation, biogenic silica was originally mainly **diatom** frustules, but also included minor **radiolarian** tests, **silicoflagellate** tests, and **sponge spicules.**

Biologically synthesized silica is generally an unstable amorphous (non-crystalline) silica called opal-A. During diagenesis, opal-A usually dissolves and crystallizes to form another unstable silica form called opal-CT (Murata and Nakata, 1974; Murata and Larson, 1975). The structure of opal-CT is not perfectly known, but the most common idea is that it is interstratified α-cristobalite and α-tridymite, two high-temperature forms of SiO_2. Subsequently opal-CT recrystallizes to form quartz, the stable form of silica near the earth's surface.

In the Monterey Formation, the two silica phase transformations (opal-A/opal-CT and opal-CT/quartz) generally take place by nearly *in-situ* solution-precipitation processes. The main control is generally considered to be temperature, with the opal-A/opal-CT transformation occurring at 45-50° C and the opal-CT/quartz transformation at 75-85° C (Keller and Isaacs, 1985). The range in the transformation temperatures is mainly related to (though not necessarily caused by) lithologic composition, especially the ratio of clay minerals to biogenic silica (Isaacs, 1982) and organic matter abundance (Hinman, 1990). In highly siliceous calcite-bearing rocks, lower temperature formation of glassy cherts has also been documented (e.g., Behl, 1990), and in these cases quartz formation commonly

involved infilling and pore cementation. Silica phase transformations are often associated with seismic reflectors (see **porosity reduction**).

clay diagenesis = **diagenesis of clay minerals** during sediment burial.

Little work has been published on clay diagenesis in the Monterey Formation until very recently, in part because of the widespread opinion that the Monterey Formation has few clay minerals, although actually it contains averages in the range 15-30% in the Santa Maria and Santa Barbara areas. Recent work has shown the value of clay diagenetic studies, particularly in the progressive transformation with burial depth of smectite to illite. In addition to a progressive increase in the proportion of illite in mixed-layer illite/smectite, a distinct change from random to short-range ordering occurs at burial temperatures of about 100° C. Calibration of clay reactions with **silica diagenesis** in several Santa Maria subsurface sections shows that the distinctive clay ordering occurs at slightly higher temperatures than quartz formation (Pollastro, 1990).

Strata at Lions Head are entirely quartzose (Pisciotto, 1981a), but mixed-layer illite/smectite has only random order (R. M. Pollastro, unpublished data; see Chapter B, this report). The temperature exposure at the Lions Head section is thus tightly constrained by inorganic diagenesis at about 85-100° C.

calcite diagenesis = **diagenesis of calcite** with increased temperature and pressure during burial.

Despite the high abundance of calcite in much of the Monterey, little recrystallization of calcite occurred because both coccoliths (see **calcareous nannoplankton**) and tests of **planktonic foraminifera** are composed of low-magnesium calcite which is chemically stable. (Most tests of **benthic foraminifera**, by contrast, are composed of high-magnesium calcite which tends to recrystallize). However, some limestones are present locally. References: Scholle (1977), Garrison (1990).

dolomite authigenesis = formation of **dolomite** [mineral] during diagenesis.

There is a great deal of published literature on dolomite, including a volume on dolomite in the Monterey Formation (Garrison and others, 1984), but little consensus about the details of its formation. Many kinds of dolomite can be distinguished, the most prominent being nodules and concretions which formed relatively early in diagenesis as shown, for example, by compactional draping (e.g. KG-18). Early-formed dolomite can apparently reduce the permeability of some strata so much that normal diagenetic reactions are prevented. For example, **diatom** frustules can be found preserved in dolostones interbedded with highly siliceous strata in which there is no other trace remaining of the original diatom frustules. Many recent advances in **biostratigraphy** of the Monterey Formation have come from isolating diatom frustules from dolostones (e.g., White, 1989).

Other dolomite may form comparatively late in diagenesis, and about 50% of dolomite is present as disseminated crystals at low abundances rather than in discrete dolostones.

Early dolomite is thought to be associated with production of CO_2 during oxidation of organic matter early in diagenesis (Pisciotto, 1981b; Garrison and others, 1984). Because sulfate is a major inhibitor of dolomite formation, reduction of sulfate to sulfide is also critical (Garrison and others, 1984; Baker and Burns, 1985; Compton and Siever, 1986). There is much literature on this subject.

apatite authigenesis = formation of apatite during deposition or burial of sediment.

In the Monterey Formation, the most common phosphatic rocks are phosphatic marlstones (KG-2, KG-17) which formed from laminated organic-rich coccolith-foraminiferal-diatom mud mainly by replacement (Garrison and others, 1987). According to Garrison and others (1987), phosphatic marlstones formed in a wide variety of paleogeomorphic settings - outer shelves, slopes, basin floors, and the tops and flanks of deeply submerged banks. A common aspect of all such strata is slow pelagic deposition and low-oxygen water masses (Garrison and others, 1987). The apatite is thought to form relatively early in diagenesis, tens to hundreds of meters below the seafloor (Garrison and others, 1987). The phosphate in apatite is generally thought to be derived from organic matter.

Another rare phosphatic rock type is nodular phosphorite (present in the carbonaceous marl member at Naples), apparently formed by repeated cycles of burial, nodule growth, exhumation, and reburial during periods of non-deposition (Garrison and others, 1987). Apatite in the Rincon Shale (especially KG-3) is probably present as concentric phosphatic pellets.

porosity = "The percentage of the bulk volume of a rock or soil that is occuped by interstices, whether isolated or connected" (AGI, 1980). Porosity is often determined by measurement of (1) dry bulk density, the weight per unit volume including the volume of pore space; and (2) grain density, which is the weight per unit volume of the solid grains.

In the Monterey Formation, present porosity can vary from about 70% to negligible values (<1%). The most porous rocks are the purest diatomites, which can be so porous that they are lighter than water (<1.0 g/cm^3). The least porous rocks are glassy quartz cherts and certain dolostones. Dry bulk densities range from about 0.8 to nearly 2.8 g/cm^3, and dry grain densities range from about 2.0 g/cm^3 in very organic-rich rocks to 2.8 in g/cm^3 pure dolostones (Isaacs, 1981b, etc.).

porosity reduction = the process of reducing porosity especially during sediment burial, for example by compaction or cementation.

Compared to other sediment types, porosity of diatomaceous rocks is unusually high both at the seafloor and during the first 500 m or so of burial (Hamilton, 1976). Reported surficial values vary from as high as 95% (meaning that only 5% of the rock *volume* is solid

material) to about 87% (meaning that only 13% of the rock *volume* is solid material). During burial, the high porosity of diatomaceous rocks is also retained much deeper than in other sediment types (Hamilton, 1976). A major reduction in porosity is closely associated with silica diagenesis, especially the transformation of biogenic opal-A to crystalline opal-CT by solution-precipitation which is thought to cause compaction by collapse of the strong framework of diatom frustules (Isaacs, 1981b). In many places such as the Bering Sea this diagenetic reaction is so sharp that it causes a seismic reflector; because this seismic reflector cross-cuts stratigraphic reflectors and mimics the seafloor bottom, it is called a bottom-simulating reflector and is interpreted as a more or less isothermal surface (Scholl and Creager, 1973; Hein and others, 1978). A similar reflector is also associated with the opal-CT to quartz transformation, which also involves a sharp reduction in porosity.

Most other types of strata in the Monterey Formation have more gradual patterns of porosity reduction. An exception is dolostones, which in some cases seem to have formed by cementation of highly porous rocks early in burial (see **dolomite authigenesis**).

ACKNOWLEDGMENTS

Many people have contributed invaluable thoughts on these subjects over the years, and I am grateful to all. For extensive and searching discussions, I am particularly endebted to Timothy R. Baumgartner of CICESE (Ensenada, Mexico). I also specially thank Margaret A. Keller of the U.S. Geological Survey (Menlo Park, California), James C. Ingle of Stanford University (Stanford, California), Richard G. Stanley and Kenneth J. Bird of the U.S. Geological Survey (Menlo Park, California), and Robert E. Garrison of the University of California Santa Cruz (Santa Cruz, California).

Preliminary versions of the report were reviewed by James C. Ingle and Kenneth J. Bird.

REFERENCES

AGI, 1980 - see Bates and Jackson, 1980.

Alldredge, A. L., and Silver, M. W., 1988, Characteristics, dynamics and significance of marine snow: Progress in Oceanography, v. 20, p. 41-82.

Anderson, O. R., 1983, *Radiolaria*: Springer-Verlag, New York NY, 355 p.

Arends, R. G., and Blake, G. H., 1986, Biostratigraphy and paleoecology of the Naples Bluff coastal section based on diatoms and benthic foraminifera, *in* Casey, R. E., and Barron, J. A., eds., *Siliceous Microfossil and Microplankton of the Monterey Formation and Modern Analogs*: Pacific Section Society of Economic Paleontologists and Mineralogists Book 45, Los Angeles California, p. 121-135.

Baker, P. A., and Burns, S. J., 1985, Occurrence and formation of dolomite in organic-rich continental margin sediments: American Association of Petroleum Geologists Bulletin, v. 69, p. 1917-1930.

Barron, J. A., 1975, Marine diatom biostratigraphy of the upper Miocene-lower Pliocene strata of Southern California: Journal of Paleontology, v. 49, p. 619-632.

Barron, J. A., 1981, Late Cenozoic diatom biostratigraphy and paleoceanography of the middle-latitude eastern North Pacific, Deep Sea Drilling Project Leg 63: Initial Reports of the Deep Sea Drilling Project, v. 63, p. 507-538.

Barron, J. A., 1986, Updated diatom biostratigraphy for the Monterey Formation of California, *in* Casey, R. E., and Barron, J. A., eds., *Siliceous Microfossil and Microplankton of the Monterey Formation and Modern Analogs*: Pacific Section Society of Economic Paleontologists and Mineralogists Book 45, Los Angeles California, p. 105-119.

Barron, J. A., and Keller, G., 1983, Paleotemperature oscillations in the middle and late Miocene of the northeastern Pacific: Micropaleontology, v. 29, no. 2, p. 150-181.

Bates, R. L., and Jackson, J. A., eds., 1980, *Glossary of Geology*: American Geological Institute, Falls Church, Virginia, 2nd edition, 751 p.

Behl, R. J., 1990, Chertification in the Monterey Formation of California [abs.]: American Association of Petroleum Geologists Bulletin.

Berger, W. H., 1974, Deep-sea sedimentation, *in* Burk, C. A., and Drake, C. L., eds., *The Geology of Continental Margins*: Springer-Verlag, New York, p. 213-241.

Berger, W. H., and Soutar, A., 1967, Planktonic foraminifera: Field experiment on production rate: Science, v. 156, p. 1495-1497.

Bernal, P. A., and McGowan, J. A., 1981, Advection and upwelling in the California Current, *in* Richards, F. A., ed., *Coastal Upwelling*: American Geophysical Union, Washington D.C., p. 381-399.

Berry, L. G., and Mason, B., 1959, *Mineralogy*: W. H. Freeman, San Francisco, California, 630 p.

Bohacs, K. M., 1990, Sequence stratigraphy of the Monterey Formation, Santa Barbara County: Integration of physical, chemical, and biofacies data from outcrop and subsurface, *in* Keller, M. A., and McGowen, M. K., eds., *Miocene and Oligocene Petroleum Reservoirs of the Santa Maria and Santa Barbara-Ventura Basins, California*: Society of Economic Paleontologists and Mineralogists Core Workshop 14, p. 139-200.

Bramlette, M. N., 1946, The Monterey Formation of California and the Origin of Its Siliceous Rocks: U.S. Geological Survey Professional Paper 212, 57 p.

Buzas, M. A., Douglass, R. C., and Smith, C. C., 1987, Kingdom Protista, *in* Boardman, R. S., Cheetham, A. H., and Rowell, A. J., eds., *Fossil Invertebrates*: Blackwell Scientific Publications, Oxford.

Calvert, S. E., 1964, Factors affecting the formation of laminated diatomaceous sediments in the Gulf of California, *in* Van Andel, T. H., and Shor, G. G., eds., *Marine Geology of the Gulf of California*: American Association of Petroleum Geologists Memoir 3, p. 311-330.

Canfield, C. R., 1939, Subsurface stratigraphy of Santa Maria Valley oil field and adjacent parts of Santa Maria Valley, California: American Association of Petroleum Geologists Bulletin, v. 23, p. 45-81.

Compton, J. S., and Siever, R., 1986, Diffusion and mass balance of Mg during early dolomite formation, Monterey Formation: Geochemica et Cosmochimica Acta, v. 50, p. 125-135.

Crain, W. E., Mero, W. E., and Patterson, D., 1985, Geology of the Point Arguello discovery: American Association of Petroleum Geologists Bulletin, v. 69, p. 537-545.

Crawford, F. D., 1971, Petroleum potential of Santa Maria Province, California *in* Cram, I. H., ed., *Future Petroleum Provinces of the United States - Their Geology and Potential*: American Association of Petroleum Geologists Memoir 15, p. 316-328.

Dean, W. E., Stow, D. A. V., Barrow, E., and Schallreuter, R., 1984, A revised sediment classification for siliceous-biogenic calcareous-biogenic and non-biogenic components: Initial Reports DSDP 75, U.S. Government Printing Office Washington D.C.

DePaolo, D. J., and Finger, K. L., 1991, High-resolution strontium-isotope stratigraphy and biostratigraphy of the Miocene Monterey Formation, central California: Geological Society of American Bulleton, v. 103, p. 112-124.

Dibblee, T. W., Jr., 1950, Geology of the southwestern Santa Barbara County, California: California Division of Mines and Geology Bulletin 150, 95 p.

Dibblee, T. W., Jr., 1966, Geology of the central Santa Ynez Mountains, Santa Barbara County, California: California Division of Mines and Geology Bulletin 186, 99 p.

Dumont, M. P., 1986, The Miocene/Pliocene Epoch boundary as determined by diatom biostratigraphy in the California coastal region: University of California, Berkeley, unpublished M.A. thesis, 112 p.

Dunbar, R. B., and Berger, W. H., 1981, Fecal pellet flux to modern bottom sediment of Santa Barbara Basin (California) based on sediment trapping: Geological Society of America Bulletin, v. 92, pt. I, p. 212-218.

Dunham, J. B., and Blake, G. H., 1987, *Guide to Coastal Outcrops of the Monterey Formation of Western Santa Barbara County, California*: Pacific Section Society of Economic Paleontologists and Mineralogists Book 53, 35 p.

Dunham, J. B., and Cotton-Thornton, M. L., 1990, Lithology of the Monterey Formation in the western Santa Maria Valley field, Santa Maria basin, California, *in* Keller, M. A., and McGowen, M. K., eds., *Miocene and Oligocene Petroleum Reservoirs of the Santa Maria and Santa Barbara-Ventura Basins, California*: Society of Economic Paleontologists and Mineralogists Core Workshop 14, p. 202-243.

Edwards, L. N., 1971, Geology of the Vaqueros and Rincon Formations, Santa Barbara Embayment, California: University of California Santa Barbara, unpublished Ph.D. thesis, 421 p.

Edwards, L. N., 1972, Notes on the Vaqueros and Rincon Formations, *in* Weaver, D. G., ed., *Central Santa Ynez Mountains, Santa Barbara County, California*: Pacific Sections American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists Guidebook, p. 46-54.

Estrada, M. and Blasco, D., 1979, Two phases of the phytoplankton community in the Baja California upwelling: Limnology and Oceanography, v. 24, p. 1065-1080.

Flower, B. P., and Kennett, J. P. 1991, Middle Miocene stable isotopic records from DSDP Site 588A and Naples Beach, California [abs]: Geological Society of America Abstracts with Programs, v. 23, no.5, 1991 Annual Meeting, p. 337.

Garrison, R. E., 1990, Pelagic and hemipelagic sedimentary rock as source and reservoir rocks, *in* Brown, G. C., Gorsline, D. S., and Schweller, W. J., eds., *Deep-Marine Sedimentation: Depositional Models and Case Histories in Hydrocarbon Exploration and Development*: Pacific Section Society of Economic Paleontologists and Mineralogists Short Course Volume 66, p. 123-149.

Garrison, R. E., Kastner, M., and Kolodny, Y., 1987, Phosphorites and phosphatic rocks in the Monterey Formation and related Miocene units, coastal California *in* Ingersoll, R. V., and Ernst, W. G., eds., *Cenozoic Basin Development of Coastal California*: Prentice-Hall, Englewood Cliffs, New Jersey, p. 348-381.

Garrison, R. E., Kastner, M., and Zenger, D. H., eds., 1984, *Dolomites of the Monterey Formation and Other Organic-Rich Units*: Pacific Section Society of Economic Paleontologists and Mineralogists Book 41, 215 p.

Govean, F. M., and Garrison, R. E., 1981, Significanc of laminated and massive diatomites in the upper part of the Monterey Formation, California *in* Garrison, R. E., and Douglas, R. G., eds., *The Monterey Formation and Related Siliceous Rocks of California*: Pacific Section Society of Economic Paleontologists and Mineralogists Book 15, p. 181-198.

Graham, S. A., 1976, *Tertiary sedimentary tecontics of the central Salinian block of California*: unpublished Ph.D. thesis, Stanford University, Stanford, California.

Hamilton, E. L., 1976, Variations in density and porosity with depth in deep-sea sediments: Journal of Sedimentary Petrology, v. 72, p. 157-169.

Hein, J. R., Scholl, D. W., Barron, J. A., Jones, M. G., and Miller, J., 1978, Diagenesis of Late Cenozoic diatomaceous deposits and formation of the bottom simulating reflector in the southern Bering Sea: Sedimentology, v. 25, p. 155-181.

Hinman, N. W., 1990, Chemical factors influencing the rates and sequences of silica phase transitions: Effects of organic constituents: Geochimica et Cosmochimica Acta, v. 54, p. 1563-1574.

Honjo, S., and Roman, M. R., 1978, Marine copepod fecal pellets: production, preservation and sedimentation: Journal of Marine Research, v. 36, p. 45-47.

Hornafius, J. S., 1991, Facies analysis of the Monterey Formation in the northern Santa Barbara Channel: American Association of Petroleum Geologists Bulletin, v. 75, p. 894-909.

Ingle, J. C., 1980, Cenozoic paleobathymetry and depositional history of selected sequences within the southern California continental borderland, *in* Sliter, W., ed., *Studies in Micropaleontology*: Cushman Foundation for Foraminiferal Research Special Publication 19, p. 163-195.

Ingle, J. C., Jr., 1981, Origin of Neogene diatomites around the North Pacific rim, *in* Garrison, R. E., and Douglas, R. G., eds., *The Monterey Formation and Related*

Siliceous Rocks of California: Pacific Section Society of Economic Paleontologists and Mineralogists Book 15, p. 159-179.

Isaacs, C. M., ed., 1981a, *Guide to the Monterey Formation in the California Coastal Area, Ventura to San Luis Obispo*: Pacific Section American Association of Petroleum Geologists, v. 52, 91 p.

Isaacs, C. M., 1981b, Porosity reduction during diagenesis of the Monterey Formation, Santa Barbara coastal area, California *in* Garrison, R. E., and Douglas, R. G., eds., *The Monterey Formation and Related Siliceous Rocks of California*: Pacific Section Society of Economic Paleontologists and Mineralogists Book 15, p. 257-271..

Isaacs, C. M., 1982, Influence of rock composition on kinetics of silica phase changes in the Monterey Formation, Santa Barbara area, California: Geology, v. 10, p. 304-308.

Isaacs, C. M., 1984, Hemipelagic deposits in a Miocene basin, California: Toward a model of lithologic variation and sequence, *in* Stow, D. A. V., and Piper, D. J. W., eds., *Fine-Grained Sediments: Deep-Water Processes and Facies*: Geological Society [of London] Special Publication 15, p. 481-496.

Isaacs, C. M., 1985, Abundance versus rates of accumulation in fine-grained strata of the Miocene Santa Barbara basin, California: Geo-Marine Letters, v. 5, p. 25-30.

Isaacs, C. M., and Lagoe, M. B., 1987, Mid-Tertiary biogenous silica deposition in California - the pre-Monterey record, *in* Tsuchi, R., ed., *Pacific Neogene Event Studies*: International Geological Correlation Program Project No. 246 Publication, Shizuoka, Japan, p. 39-42.

Keller, M. A., 1984, Diagenesis and lithostratigraphy of the Monterey Formation near Ojai, California: California State University at Los Angeles, unpublished M.S. thesis, 111 p.

Keller, M. A., and Isaacs, C. M., 1985, An evaluation of temperature scales for silica diagenesis in diatomaceous sequences including a new approach based on the Miocene Monterey Formation, California, U.S.A.: Geo-Marine Letters, v. 5, p. 31-35.

Kennett, J. P., 1982, *Marine Geology*: Prentice-Hall, Englewood Cliffs New Jersey, 813 p.

Khan, S. M., Coe, R. S., and Barron, J. A., 1989, High-resolution magentic polarity stratigraphy of the Miocene Monterey Formation at Shell Beach, Pismo basin, California, *in* Garrison, R. E., ed., *Japan-US Seminar on Neogene Siliceous Sediments of the Pacific Region Syllabus and Fieldtrip Guidebook*, p. 106-117.

Lagoe, M. B., 1984, Paleogeography of Monterey Formation, Cuyama Basin, California: American Association of Petroleum Geologists Bulletin, v. 68, p. 610-627.

Lagoe, M. B., 1987, Middle Cenozoic basin development, Cuyama basin, California, *in* Ingersoll, R. V., and Ernst, W. G., eds., *Cenozoic Basin Development of Coastal California*: Prentice-Hall, New Jersey, p. 173-206.

MacKinnon, T. C., 1989, Petroleum geology of the Monterey Formation in the Santa Maria and Santa Barbara coastal and offshore areas, *in* MacKinnon, T. C., ed., International Geological Congress, 28th, Washington D. C. *Oil in the California Monterey Formation*; Field Trip Guidebook T311: Washington D.E., American Geophysical Union, p. 11-27.

Mazzullo, J. M., Meyer, A., and Kidd, R., 1988, New sediment classification scheme for the Ocean Drilling Program - a handbook for shipboard sedimentologists: ODP Technical Note No. 8, p. 44-58.

Murata, K. J., and Larson, R. R., 1975, Diagenesis of Miocene siliceous shales, Temblor Range, California: U.S. Geological Survey Journal of Research, v. 3, p. 553-566.

Murata, K. J., and Nakata, J. K., 1974, Cristobalitic stage in the diagenesis of diatomaceous shale: Science, v. 184, p. 567-568.

Murata, K. J., Friedman, I., and Cremer, M., 1972, Geochemistry of diagenetic dolomites in Miocene marine formations of California: U.S. Geological Survey Professional paper 724-C, 12 p.

Murata, K. J., Friedman, I., and Madsen, B. M., 1969, Isotopic composition of diagenetic carbonates in marine Miocene formations of California and Oregon:: U.S. Geological Survey Professional paper 614-B, 24 p.

Naeser, N. D., Naeser, C. W., and McCulloh, T. H., 1989, The application of fission-track dating to the depositional and thermal history of rocks in sedimentary basins, *in* Naeser, N. D., and McCulloh, T. H., eds., *Thermal History of Sedimentary Basins: Methods and Case Histories*: Springer-Verlag, New York, p. 157-180.

Ogle, B. A., Wallis, W. S., Heck, R. G., and Edwards, E. B., 1987, Petroleum geology of the Monterey Formation in the offshore Santa Maria/Santa Barbara areas, *in* Ingersoll, R. V., and Ernst, W. G., eds., *Cenozoic Basin Development of Coastal California*: Prentice-Hall, Englewood Cliffs, New Jersey, p. 382-406.

Paytan, A., Martin, E., Kastner, M., MacDougall, J.D., and Herbert, T. D., 1991, Barite: A monitor of the oceanic Sr isotopic ratio [abs]: Geological Society of America Abstracts with Programs, v. 23, no.5, 1991 Annual Meeting, p. 341.

Phleger, C. F., and Soutar, A., 1973, Production of benthic foraminifera in three east Pacific oxygen minima: Micropaleontology, v. 19, p. 110-115.

Pisciotto, K. A., 1981a, Notes on Monterey rocks near Santa Maria, California, *in* Isaacs, C. M., ed., *Guide to the Monterey Formation in the California Coastal Area, Ventura to San Luis Obispo*: Pacific Section American Association of Petroleum Geologists, v. 52, p. 73-81.

Pisciotto, K. A., 1981b, Review of secondary carbonates in the Monterey Formation, California, *in* Garrison, R. E., and Douglas, R. G., eds., *The Monterey Formation and Related Siliceous Rocks of California*: Pacific Section Society of Economic Paleontologists and Mineralogists Book 15, p. 273-283.

Pisciotto, K. A., and Garrison, R. E., 1981, Lithofacies and depositional environments of the Monterey Formation, California, *in* Garrison, R. E., and Douglas, R. G., eds., *The Monterey Formation and Related Siliceous Rocks of California*: Pacific Section Society of Economic Paleontologists and Mineralogists Book 15, p. 97-122.

Pollastro, R. M., 1990, The illite/smectite geothermometer - concepts, methodology, and application to basin history and hydrocarbon generation, *in* Nuccio, V. F., and Barker, C. E., eds., *Applications of Thermal Maturity Studies to Energy Exploration*: Rocky Mountain Section Society of Economic Paleontologists and Mineralogists, Denver, Colorado, p. 1-18.

Raymont, J. E. G., 1980, *Plankton and Productivity in the Oceans, v. 1 - Phytoplankton*: Pergamon Press, Oxford, 2nd ed., 489 p.

Reimers, C. E., Lange, C. B., Tabak, M., and Bernhand, J. M., 1990, Seasonal spillover and varve formation in the Santa Barbara Basin, California: Limnology and Oceanography, v. 35, p. 1577-1585.

Savrda, C. E., and Bottjer, D. J., 1986, Trace-fossil model for reconstruction of paleo-oxygenation in bottom waters: Geology, v. 14, p. 3-6.

Savrda, C. E., and Bottjer, D. J., 1987, The exaerobic zone, a new oxygen-deficient marine biofacies: Nature, v. 327, no. 6117, p. 54-56.

Savrda, C. E., Bottjer, D. J., and Gorsline, D. S., 1984, Development of a comprehensive oxygen-deficient marine biofacies model: Evidence from Santa Monica, San Pedro, and Santa Barbara Basins, California Continental Borderland: American Association of Petroleum Geologists Bulletin, v. 68, p. 1179-1192.

Scholl, D. W., and Creager, J. S., 1973, Geologic synthesis of Leg 19 (DSDP) results: far North Pacific, and Aleutian Ridge, and Bering Sea, *in* Creager, J. S., Scholl, D. W., and others, eds., *Initial Reports of the Deep Sea Drillling Project*: Washington D.C., U.S. Government Printing Office, v. 19, p. 897-913.

Scholle, P. A., 1977, Chalk diagenesis and its relation to petroleum exploration: oil from chalks, a modern miracle?: American Association of Petroleum Geologists, v. 61, p. 982-1009.

Schrader, H. J., 1971, Fecal pellets: Role in sedimentation of pelagic diatoms: Science, v. 174, p. 55-57.

Sholkovitz, E. R., 1973, Interstitial water chemistry of the Santa Barbara Basin sediment: Geochimica et Cosmochimica Acta, v. 37, p. 13-21.

Silva, K. A., and Corliss, B. H., 1991, Temporal variation in benthic foraminiferal populations in the California Borderlands [abs]: Eos, Transactions, American Geophysical Union, v. 72, no. 44, p. 265.

Soutar, A., Johnson, S. R., and Baumgartner, T. R., 1981, In search of modern depositional analogs to the Monterey formation, *in* Garrison, R. E., and Douglas, R. G, eds., *The Monterey Formation and Related Siliceous Rocks of California*: Pacific Section Society of Economic Paleontologists and Mineralogists Book 15, p. 123-147.

Stanley, S. M., 1986, *Earth and Life Through Time*: W. H. Freeman and Company, New York, New York.

Stow, D. A. V., and Piper, D. J. W., 1984, Deep-water fine-grained sediments; history, methodology and terminology, *in* Stow, D. A. V., and Piper, D. J. W., eds., *Fine-Grained Sediments: Deep-Water Processes and Facies*: Geological Society [of London] Special Publication 15, p. 3-14.

Tont, S. A., 1981, Temporal variations in diatom abundance off Southern California in relation to surface temperature, air temperature and sea level: Journal of Marine Research, v. 39, p. 191-201.

U.S. Geological Survey, 1974, Geology and reservoir characteristics of the Santa Ynez Unit, Santa Barbara Channel, off California: U.S. Geological Survey Final

1983, *Petroleum Generation and Occurrence in the Miocene Monterey Formation, California*: Pacific Section Society of Economic Paleontologists and Mineralogists Book 33, p. 111-130.)

Vork, D. R., 1984, Palynology of Recent Sediments of the California Continental Borderland: University of Southern California (unpublished) Ms. thesis, 128 p.

Werner, D., ed., 1977, *The Biology of Diatoms*: University of California Press, Berkeley and Los Angeles, 498 p.

White, L. D., 1989, Age of the Lions Head section, Santa Maria basin, California, *in* Garrison, R. E., ed., *Japan-US Seminar on Neogene Siliceous Sediments of the Pacific Region Syllabus and Fieldtrip Guidebook*, p. 121-123.

Williams, G. L., 1978, Dinoflagellates, Acritarchs and Tasmanitids, *in* Haq, B., and Boersma, A., eds., *Introduction to Marine Micropaleontology*: Elsevier, New York, p. 292-326.

Woodring, W. P., and Bramlette, M. N., 1950, Geology and paleoecology of the Santa Maria district, California: U.S. Geological Survey Professional Paper 222, 185 p.

Wyrtki, K., 1966, Oceanography of the eastern equatorial Pacific Ocean: Oceanography and Marine Biology Annual Review, v. 4, p. 33-68.