UNITED STATES DEPARTMENT OF THE INTERIOR
J. A. Krug, Secretary

GEOLOGICAL SURVEY
W. E. Wrather, Director

Professional Paper 212

THE MONTEREY FORMATION OF CALIFORNIA AND THE ORIGIN OF ITS SILICEOUS ROCKS

BY

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UNITED STATES
GOVERNMENT PRINTING OFFICE
WASHINGTON : 1946

For sale by the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C.
Price 60 cents

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By M. N. Bramlette

ABSTRACT

The Monterey formation is so thick and extensive, and has so much economic as well as scientific importance, that it constitutes a major element in the geology of California. The Miocene strata that consist predominantly of highly siliceous rocks have received a number of names in different areas, but intensive stratigraphic work in recent years, particularly that done by the oil companies, indicates that most of these locally named stratigraphic units are essentially equivalent. It appears advisable, therefore, to return to an early and convenient usage by extending the term Monterey formation to include many of these locally named units. This report contains stratigraphic sections representing most of the areas where local names have been applied, with their suggested correlation.

The siliceous rocks which characterize the formation belong to several widely varied but intergrading types. Diatomite and less pure diatomaceous rocks are conspicuous in the upper part of the formation in many areas. Harder siliceous rocks classed as porcelanite, porcelaneous shale, cherty shale, and chert constitute a large part of the formation. Preserved siliceous organisms are rare in the porcelaneous and cherty rocks, but various lines of evidence indicate that these silica-cemented rocks were formed in major part through an alteration of originally diatomaceous rocks similar to those now present in the upper part of the formation. The alteration seems to have been a process of solution of the relatively unstable silica of the delicate opaline shells and reprecipitation of the silica as a cement to form the porcelaneous rocks. Beds or lentils of dense chert were formed by the same process in parts of the strata that were originally purer diatomaceous rocks.

The time at which the alteration occurred and the fundamental causes of the alteration are problems not yet fully solved. These sediments appear to have been undergoing alteration at varying rates ever since they were deposited on the sea floor. Much of it occurred at an early stage in the compaction of the deposits and may be termed diagenetic; most of it, however, was subsequent to most of the compaction and seems to have been effected, in part at least, through load and deformation during late Miocene and early Pliocene time.

Sandstone and the finer clastic sediments of the formation are more briefly considered than some less abundant rocks such as the carbonate beds and concretions, because the carbonate concretions include preserved diatoms and show evidence of a diagenetic process of formation that bears on the origin of the associated siliceous rocks. The widespread occurrence of tuffaceous material also bears on the origin of siliceous rocks. Several earlier writers have considered the possible significance of the close association of volcanic rocks, particularly of tuffs, with highly siliceous deposits in many regions. Additional evidence is presented in this report that the alteration of tuffs may result in silicification of adjacent beds, and that an abundant supply of silica from tuffs commonly results in an unusually large development of the siliceous organisms.

Large parts of the formation are bituminous and are generally recognized as important source beds of many California oil fields. The character of the bedding and its mode of formation suggest a significant relationship with the conditions for formation of petroliferous strata, in that the thin rhythmic bedding or lamination was evidently formed at depths below that affected by appreciable wave or current action, and such conditions are favorable for the accumulation of the organic matter from which petroleum is formed. The bedding and fossil content differ from those of formations deposited in shallower or more agitated waters and indicate two distinct genetic types of rock. The rhythmically bedded type generally indicates greater crustal instability and geosynclinal deposition.

INTRODUCTION

NATURE OF THE INVESTIGATION

The wide extent of the Monterey formation in California, its distinctive lithologic character, and its importance to the petroleum industry as one of the major oil-producing formations of California, make a comprehensive study of the formation desirable. A study of both local details of character and regional features was accordingly undertaken in 1931 as one of the projects made possible through certain research funds then available to the United States Geological Survey. Subsequent plans made it impossible to carry out this program in full, but some of the data and conclusions obtained before the interruption of the work are presented in this report.

Because of the wide variety of problems involved, the rapid lateral changes in the strata, and the wide distribution of the formation, it is necessary to limit the discussion to some of the more outstanding geologic relations regarding which tentative conclusions appear justified. Some other problems that cannot be solved without additional data are briefly presented, however, for the consideration of the many geologists who are studying the formation in various areas and from various aspects.

During the field season of 1931, the writer was assisted by K. E. Lohman, of the Geological Survey, and R. M. Kleinpell in examining and measuring several sections and in collecting samples. Mr. Lohman has devoted part of his time to the study of the diatom floras collected, in order to determine their value in stratigraphic correlations, but this work is not yet com-

pleted. Mr. Kleinpell has studied many of the Foraminifera in continuance of his private work on the foraminiferal faunas and correlations in the California Tertiary, and the correlations presented in this paper are based largely on the results of his work.

Several subsequent periods of field work with W. P. Woodring have been spent in areas where the formation was examined and mapped, including the Palos Verdes Hills in Los Angeles County and the Purisima Hills in Santa Barbara County. Petrographic study and other laboratory work on the many rock samples collected was done during several intervals since 1931.

ACKNOWLEDGMENTS

This investigation by the Geological Survey was undertaken at the suggestion of Dr. Ralph D. Reed, who continuously promoted the work by suggestive discussion and criticism. Many other geologists in California, connected both with universities and with oil companies, have been helpful in various ways that can only in part be acknowledged here. Prof. J. P. Buwalda has at various times kindly made available office space and laboratory facilities at the California Institute of Technology. Prof. B. L. Clark and Prof. N. L. Taliaferro of the University of California, Prof. A. C. Waters and Prof. H. L. Schenck of Stanford University, and Dr. O. P. Jenkins of the State Division of Mines have contributed suggestive discussion and information. Among the many oil geologists who have furthered this work, particular mention should be made of Dr. W. S. W. Kew and other members of the staff of the Standard Oil Company of California, and of various members of the geologic staff of the Texas and Shell Companies of California. Dr. Harold Hoots, Mr. Max Krueger, Dr. Wayne Galliher and others have also been helpful in various ways.

The work was done under the general supervision of C. S. Ross, chief of the section of petrology of the Geological Survey, and he has aided in many ways. W. P. Woodring has made very useful suggestions on the stratigraphic problems of the California Miocene. K. E. Lohman assisted in some of the field work and with some data on the diatoms. R. C. Wells, Charles Milton, J. J. Fahey, and R. E. Stevens of the chemical laboratory made analyses of samples, and P. G. Nutting made specific-gravity determinations of several samples. The manuscript was carefully criticized with regard to expression by F. C. Calkins. Among others who have aided with suggestions and criticisms are W. H. Bradley, James Gilluly, W. W. Rubey, P. D. Trask, and Ralph Stewart.

GENERAL CHARACTER AND DISTRIBUTION OF THE FORMATION

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 total 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. But, despite all this variation, its siliceous character makes it one of the most distinctive and easily recognized of the formations in the thick Tertiary system of California.

The siliceous rocks locally include thick diatomaceous members, more widespread and in general thicker members of the hard but not very dense silica-cemented rocks termed porcelanite and porcelaneous shale, and large amounts of the harder and denser silica rocks classed as chert and cherty shale. Although the formation is characterized by these 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.

A diatomaceous member is not everywhere present in the formation, but where present it forms the upper part of the Monterey siliceous rocks. This upper diatomaceous member, however, is not everywhere of the same age. Porcelaneous and cherty rocks of some areas are equivalent in age to diatomaceous rocks of other areas, even though the diatomaceous rocks consistently form the upper part of the siliceous rocks of all areas where present. The diatomaceous deposits reach a maximum thickness of about 1,000 feet in an area south of Lompoc, Santa Barbara County, and they are several hundred feet thick in other places, including the type area near the town of Monterey, the Palos Verdes Hills of Los Angeles County, the southwestern San Joaquin Valley, and parts of the Salinas Valley.

Porcelanite and porcelaneous shale are more widespread, and in most areas, including the type area near Monterey, they are the dominant siliceous rocks of the formation. In many areas these rocks are several thousand feet thick, and at two widely separated localities, on Chico Martinez Creek and in Reliz Canyon, they are more than 5,000 feet thick.

Chert and cherty shale, though less abundant than the porcelaneous rocks, are of almost equally wide distribution and occur in most areas of the formation. They commonly form thin beds, alternating with beds of less siliceous rocks. The cherty rocks are particularly abundant in parts of the Berkeley Hills, as in the

Claremont Canyon exposures (pl. 6, *C*), from which the local name Claremont shale was adopted.

Although the siliceous rocks and the associated normal clastic rocks constitute most of the formation, interbedded deposits of pyroclastic materials are numerous and widespread. The purer beds of pyroclastic materials occur at many horizons, but they are generally thin and form only a small percentage of the total thickness. In a few areas, however, certain of these beds are scores of feet thick, and in part of San Luis Obispo County one of the beds is locally several hundred feet thick. The pyroclastic beds consist of unaltered vitric tuff or volcanic ash and of tuffs in various stages of alteration to beds of bentonite. Lava flows and associated intrusive bodies, mostly basaltic in composition, occur in the formation in a number of areas. Most of these bodies are sills, which apparently were intruded under little cover, and it is not always easy to distinguish the sills from the flows.

Carbonate rocks form a minor part of the formation but are widespread. They occur as dolomitic and calcareous beds and concretions. Many of the calcareous beds consist largely of Foraminifera, and much of the formation is more or less calcareous because of the disseminated remains of foraminiferal shells.

Parts of the formation are highly bituminous, and much of the dark color of the unweathered siliceous rocks is due to organic matter, which is recognizable in thin sections and fragments under the miscroscope. The rocks that have been lightened in color by weathering contain less recognizable organic matter, most of the organic matter having apparently been removed by oxidation and leaching. Oil accumulations are known in the formation in a number of widely separated areas, and in some other areas the formation is considered as the probable source of the oil in adjacent formations.

A widespread and conspicuous feature of the formation is a thin rhythmic bedding, which appears to have been an important factor in the markedly incompetent behavior of the rocks under deformation. The close folding and very complicated minor structural features commonly present in many areas (pl. 4, *A*, *B*) are probably in part a result of this bedding, which also makes these features especially conspicuous.

STRATIGRAPHY AND CORRELATIONS

STRATIGRAPHIC RELATIONS

The marked and abrupt lateral variations in lithology and the scarcity of macro-fossils have made correlations difficult in much of the Miocene of California, with the result that many local formation names have been used. The complex stratigraphic relations were well summarized in 1913 by Louderback.[1] Intensive study, in recent years of the abundant micro-fossils, especially of the Foraminifera, has greatly clarified the correlations, however, and the results have largely confirmed the views presented so long ago by Louderback.

In general the lower Miocene consists largely of clastic sediments, with sandstone dominant toward the base, and with a rather consistent decrease in grain size to mudstone in the upper part of the lower Miocene (Saucesian stage of Kleinpell). Calcareous shale and mudstone are commonly dominant in the lower part of the middle Miocene and siliceous rocks become much more common and widespread in the upper part of the middle Miocene. In many areas, particularly in the coast ranges and in southern California, the Monterey siliceous rocks are thus of late middle Miocene and upper Miocene age. The underlying mudstones and calcareous shales would preferably receive other formational names, as the Rincon mudstone and the Sandholdt formation. Though their contacts are gradational, these stratigraphic units are distinct and mappable over large areas.

Detailed paleontologic and stratigraphic studies tend to increase the number of recognized stratigraphic units in the vertical sequence, but they tend at the same time to eliminate some unit names that have been applied locally. The data now available seem to justify the extension of the early and well-known name Monterey formation to include a number of locally named formations that are lithologically similar to it but that, because of their occurrence in separate areas, are not demonstrably continuous with it and until recently were not definitely known to be approximately equivalent to it. Woodring,[2] in 1940, summarized the confusing status of the stratigraphic names in the California Miocene and advocated the wider extension of the name Monterey formation.

The correlation chart of plate 2 shows fourteen of the better-known stratigraphic sections in various parts of California, including the type Monterey section; and four additional sections in the San Joaquin Valley region are shown in plate 3. These sections represent most of the areas in which local names were applied to the Monterey formation and indicate their relations. The correlations are based largely on the results of the study of foraminiferal faunas by R. M. Kleinpell and his interpretation of their relationships to the more limited macro-faunas. These correlations are believed to agree in general with the views of other micropaleontologists, and essentially with the evidence from other lines of paleontologic and stratigraphic work. No correlation of the many foraminiferal zones recognized over much of this region is indicated, because no detailed discussion of Miocene stratigraphy is attempted in this paper and because the relations of these faunal zones are largely covered in a recent book by Kleinpell.[3] Some of the

[1] Louderback, G. D., The Monterey series in California: Univ. California Pub., Dept. Geol. Sci. Bull., vol. 7, no. 10, pp. 177-241, 1913.

[2] Woodring, W. P., Stewart, Ralph, and Richards, R. W., Geology of the Kettleman Hills oil field, Calif.: U. S. Geol. Survey Prof. Paper 195, pp. 117-118, 1940.

[3] Kleinpell, R. M., Miocene stratigraphy of California: Am. Assoc. Petroleum Geologists, 1938.

correlation lines shown in plates 2 and 3 represent the position of the base or top of some of the stages defined by Kleinpell. These are used because his attempt at a chronologic subdivision into stages, though based largely on the foraminiferal zones, includes interpretations from other lines of evidence; the individual zones within the stage units, moreover, are not always sufficiently well defined to warrant their use in these general correlations. The relation of Kleinpell's stages to his foraminiferal zones are shown in the following table.

Stage names and foraminiferal zones of the California Miocene as defined by R. M. Kleinpell

Upper Miocene	Delmontian stage	Upper	
		Lower	*Bolivina obliqua* zone
	Mohnian stage	Upper	*Bolivina hughesi* zone
		Lower	*Bulimina uvigerinaformis* zone
			Bolivina modeloensis zone
Middle Miocene	Luisian stage	Upper	*Siphogenerina collomi* zone
			Siphogenerina nuciformis zone
		Lower	*Siphogenerina reedi* zone
	Relizian stage	Upper	*Siphogenerina branneri* zone
		Lower	*Siphogenerina hughesi* zone
Lower Miocene	Saucesian stage	Upper	*Uvigerinella obesa* zone
		Lower	*Plectofrondicularia miocenica* zone
			Siphogenerina transversa zone
	Zemorrian stage	Upper	*Uvigerinella sparsicostata* zone
		Lower	*Uvigerina gallowayi* zone

The horizontal datum line of plates 2 and 3, with reference to which the stratigraphic sections are arranged, is the boundary between Kleinpell's Luisian and Relizian stages. This horizon was used as the datum because it is here, in most of the sections, that Foraminifera are most abundant and the faunal zones most satisfactorily determined.

Few lithologic units are persistent enough to be of much value in the general correlations, and some of these, such as that of the Temblor sandstone (pl. 3) are known to deviate markedly from correlations believed to represent more nearly chronologic horizons. But even though few individual lithologic units are of more than local extent, the correlations indicate that, in general, the widespread strata characterized by highly siliceous rocks are equivalent and largely of middle and upper Miocene age. Even in the few areas where these siliceous rocks extend in an uninterrupted sequence a little way up into strata that are probably Pliocene, or down into those that are lower Miocene, they may be regarded as part of the Monterey. Many other formations are thus defined as including strata that extend uninterruptedly above or below the chronologic equivalents of the beds at the type locality. In the area from which the Monterey formation received its name, these beds rest on an irregular surface of granodiorite, so that the base is not of exactly the same age even within a small area. Plate 2 shows that in other areas the strata lithologically similar to those of the type Monterey section, and apparently of the same age, are underlain by similar rocks that, although they contain faunal zones of earlier Miocene age, seem properly included in the Monterey formation because they are not separable on a lithologic basis from the overlying strata. In the Maricopa area (pl. 3), the Monterey formation includes older strata than it is known to include elsewhere. At the top of the Monterey formation, also, diatomaceous beds or the harder silica rocks extend at some places conformably up into the Pliocene. In the Purisima Hills, south of Santa Maria—a few miles north of the Lompoc quarry section (pl. 2)—there is an unusually large thickness of diatomaceous sediment of transitional Miocene-Pliocene age, apparently conformable with similar beds in the upper Miocene and therefore properly included in the Monterey formation. In some nearby areas, however, as in the Santa Maria oil field, there is a marked unconformity at the base of the transitional Miocene-Pliocene deposits. Detailed mapping may give a more satisfactory basis for delimiting the top of the Monterey formation in this region that presents such complex stratigraphic relations.

In the southern Salinas Valley, which includes the area of the Indian Creek section (pl. 2), the upper part of the Miocene consists of a thick sandstone unit which has long been known as the Santa Margarita sandstone. This sandstone is apparently equivalent in age to the upper part of the Monterey formation of some other areas, including that of the type area, but as it forms a lithologically distinct and extensive unit overlying the Monterey formation of the southern Salinas Valley area, it seems entitled to be recognized as a distinct formation.

In areas where the Miocene rocks are dominantly of the Monterey siliceous types but divisible into lithologic units distinct enough to be locally mappable, such units seem preferably considered as members of the Monterey formation. No new names for members are proposed here, because the units indicated in the stratigraphic sections were not mapped in these areas, and only with such areal mapping are the distinctive members properly differentiated and delimited. In the Puente Hills, the middle and upper Miocene consists of a thick succession of siliceous rock units alternating with sandstone and siltstone units that seem preferably classed as members of the Monterey formation, for, though locally thick and distinct, these members vary laterally to such a marked degree that most of them cannot be traced and mapped for more than short distances. Farther southeast in the Puente Hills these members show less and less similarity to the Monterey lithologic types, particularly in the upper part of the section of this area (pl. 2), and there some rather arbitrary division for the top of the Monterey formation is necessary. In such areas, where sandstone units become laterally more conspicuous than the interbedded siliceous rocks, an arbitrary decision is necessary as to whether the lithology of the formation as a whole makes the name Monterey appropriate. In areas where the rocks of equivalent age have little or no lithologic similarity to those of the Monterey formation, the use of that name is obviously inappropriate.

In a region such as that east of the Berkeley Hills, the middle and upper Miocene consist in part of rocks like those characteristic of the Monterey formation, but these rocks are separated into distinct stratigraphic units by thicker units of sandstone. All these thick and distinct units, being relatively persistent and mappable over a large area, have received formational names and have been grouped together as formations of the Monterey group.[4] The term "group" is used because of the inclusion of several formations of Monterey type, all of which are approximate equivalents of parts of the formation in other areas.

SECTION OF THE TYPE MONTEREY AREA

As is frequently the case, the locality from which the formation name was derived is unsatisfactory as a type locality. The formation in this area, near the town of Monterey in Monterey County, cannot be measured or examined in any unbroken sequence, and the complete succession can be worked out only by detailed mapping and by correlating several partial sections. This work has been done by Galliher,[5] and his published results form the basis for the section shown in plate 2. The lithologic description of the rocks in this section is modified to conform with the classification used in this report, as some details of the rocks were examined in the course of the present investigation.

At the base of the formation, sandstone, sandy shale, and calcareous shale in varying thickness rest upon an irregular surface of granodiorite. These clastic strata are included as a basal part of the Monterey formation because in places they are relatively thin or nearly absent and grade into the characteristic siliceous strata. The major part of the formation consists of thin-bedded porcelanite and porcelaneous shale, with only minor proportion of the denser siliceous rocks classed as chert. It would be difficult to subdivide these porcelaneous rocks, on the basis of any obvious lithologic differences, into mappable members, and Galliher depended largely on the foraminiferal zones to determine the position of isolated exposures within the thick section of similar rocks. An upper member (unnamed) consists mainly of diatomite and diatomaceous shale, but it contains some lenticular beds of opaline chert in the lower part, which thus grades into strata made up of interbedded diatomaceous and cherty and porcelaneous rocks that are transitional to the underlying member of porcelanite and porcelaneous and cherty shale. The transitional zone is not well exposed in the type area, but it is well exposed in the road cuts along the Laurelles grade, on the north slope of the hills north of Carmel Valley and near the east edge of Monterey quadrangle.

The correlation with other sections shown in plate 2 is based on the foraminiferal zones worked out by Galliher, which Kleinpell has restudied and compared with the faunal zones in the Monterey of other areas. Kleinpell took the upper part of the type Monterey, near Del Monte, as the type of his Delmontian stage.

SECTION OF THE BERKELEY HILLS-SAN PABLO BAY REGION

The section examined and measured east of the Berkeley Hills includes only the lower formations of the Monterey group of this area, and in the correlation chart (pl. 2) this partial section is combined with the partial section that includes the upper formations from the south side of San Pablo Bay. The section of the lower formations was measured on the southwest side of Lawson Hill, at the head of Bear Creek, in the Concord quadrangle. This section is on the northeast flank of the Sobrante anticline and includes strata of the Sobrante sandstone up to the Hambre sandstone.[6] The San Pablo Bay section was measured in the Mare Island quadrangle. It extends along the highway from the con-

[4] Lawson, A. C., U. S. Geol. Survey Geol. Atlas, San Francisco folio (No. 193), p. 9, 1914.

[5] Galliher, E. W., Geology and physical properties of building stone from Carmel Valley, Calif. Mining in California, Report 28 of the State Mineralogist, California Jour. Mines and Geology, vol. 28, no. 1, pp. 14-41, 1932.

[6] Lawson, A. C., op. cit., Map showing geology of the Concord quadrangle.

tact of the Tice shale and Hambre sandstone, about one-half mile northeast of the town of Pinole, to the junction of the highway with the Franklyn Canyon road, where lower Briones sandstone is exposed in the road cuts; and from there it continues along the Franklyn Canyon road, which parallels the railway, to the contact of the upper Briones sandstone and San Pablo formation just east of the railroad flag stop named Luzon. The thickness of the San Pablo formation was not determined, as the beds here flatten out, but in a nearby area the San Pablo is reported by Clark[7] to be more than 2,000 feet thick. The apparently gradational contacts at the base of the Briones sandstone and between its members, and the poor exposures of these contacts, make the indicated thickness of these members only approximate.

The two partial sections are correlated, as shown in plate 2, at the contact of the Tice shale and Hambre sandstone, because these formations are well defined and apparently persist from one area to the other. The correlation with other Monterey sections is based on the study by Kleinpell of foraminiferal faunas from the Sobrante, Claremont, Tice, and Rodeo formations, and on his interpretation of the relation of these faunas to the macro-faunas from the Briones sandstone and San Pablo formation.

RELIZ CANYON SECTION

The thick section exposed in Reliz Canyon, on the west side of the Salinas Valley, in the southeast corner of the Soledad quadrangle, which is all in Monterey County, has been carefully studied by Kleinpell,[8] and the data on the thicknesses of the units and on correlation as shown in the section in plate 2 are based on his results. The lithology of the rocks at this locality was further examined in the course of the present work, however, with the result that in plate 2 Kleinpell's terminology is somewhat modified and some of his minor subdivisions are merged. Most of this thick Monterey section consists of porcelaneous shale and porcelaneous mudstone, which is not easily divisible into distinctive or mappable members. A sequence of strata in the lower part of this section was taken by Kleinpell as the type of the Relizian stage.

INDIAN CREEK AND QUAILWATER CREEK SECTION

The section along the west side of Indian Creek across the so-called "Highland Monocline," in the northwestern part of the Pozo quadrangle of San Luis Obispo County,[9] was measured from the basal contact with granodiorite, south of the Highland School, to the center of the north line of sec. 29, T. 28 S., R. 15 E., Mt. Diablo meridian. The upper part of the section was measured along the creek about two miles to the west, known locally as Quailwater Creek, from the bridge northward through sec. 13, T. 28 S., R. 14 E., Mt. Diablo meridian. These two partial sections are correlated by means of distinctive lithologic units and foraminiferal zones. Correlation with other sections is based on the foraminiferal zones in the Monterey formation, and on the larger fossils and stratigraphic relations in the Santa Margarita sandstone and Temblor-Vaqueros sandstone sequence.

SAN LUIS OBISPO CREEK SECTION

The Monterey rocks along San Luis Obispo Creek, in the San Luis quadrangle, were examined in the road cuts of the highway on the west side of the valley. A section was measured whose top is in the Pismo formation,[10] which forms the upper beds in the trough of a syncline about 3,700 feet north of the highway bridge across San Luis Obispo Creek, and whose base is in a thick tuff exposed in road cuts southwest of the junction of Davenport Creek with San Luis Obispo Creek. The Pismo formation, which consists of a thick white sandstone underlain by silicified sandstone and siltstone, seems to be equivalent in large part to the Santa Margarita sandstone, as indicated by Fairbanks. The lower few hundred feet of the Pismo formation is distinctly tuffaceous, and may be equivalent to the thick bed of tuff occurring near the contact of the Santa Margarita and Monterey formations in the Indian Creek-Quailwater Creek section. The Monterey formation in this section is only about 330 feet thick exclusive of the thick tuff at the base, for which the name Obispo tuff member is proposed (p. 22). The thinness of the strata characteristic of the Monterey in this section is in remarkable contrast with their great thickness less than a mile to the west and with the nearly 1,400 feet of well exposed Monterey rocks about two and a half miles to the southwest, along the lower part of San Luis Obispo Creek. As shown in plate 2, no structural discordance between the Monterey and Pismo formations has been found here, the contact being apparently transitional. An unconformity at this contact in some other parts of this area is indicated by the work of Fairbanks,[11] but marked lateral variations in the Miocene beds within short distances account for an areal distribution of the formations, that suggests unconformable relations elsewhere on his map.

LOMPOC QUARRY SECTION

A rough section is presented of a part of the Monterey formation exposed in the area of the diatomite quarry about two miles south of Lompoc, Santa Bar-

[7] Clark, B. L., Fauna of the San Pablo group of middle California: Univ. California Pub., Dept. Geol. Sci. Bull., vol. 8, no. 22, p. 399, 1915.

[8] Kleinpell, R. M., Miocene stratigraphy of California, Am. Assoc. Petroleum Geologists, p. 7, 1938.

[9] Anderson, F. M., and Martin, B., Neocene record in the Temblor Basin, Calif., and Neocene deposits of the San Juan District, San Luis Obispo County: California Acad. Sci. Proc., 4th ser., vol. 14, pl. 10, 1914.

[10] Fairbanks, H. W., U. S. Geol. Survey Geol. Atlas, San Luis folio (No. 101), p. 4, 1904.

[11] Idem., p. 4.

bara County, in the Lompoc quadrangle. The thick diatomaceous deposits are being quarried in the trough of a syncline, on whose flanks the basal part of the formation is not exposed. No Foraminifera nor any larger invertebrate fossils were found in the upper part of the diatomaceous rocks that form the upper member (unnamed), which is nearly 1,000 feet thick, and further study of the diatoms and fish remains in this uppermost part may show it to be of Pliocene age. Beneath approximately another thousand feet of interbedded diatomaceous and cherty strata are porcelaneous and cherty rocks, whose base is not exposed. Throughout the thick zone of interbedded diatomaceous and cherty strata, good foraminiferal faunas were found that belong in the *Bolivina hughesi* zone of the upper Miocene, and largely on this basis the section is tentatively correlated as indicated in plate 2.

POINT CONCEPCION AND BIXBY CANYON SECTIONS

A section of the upper part of the Monterey formation was measured along the coastal cliffs near Point Concepcion, in Santa Barbara County, and combined with a section of lower strata in nearby Bixby Canyon. The sea-cliff section begins with the highest beds present in the trough of a syncline, about one mile north of Point Concepcion, and continues down to the lowest beds exposed in the slight reversal of a plunging anticline two miles farther north along the coast. The lower part of the Monterey formation, together with the underlying strata down to the Vaqueros sandstone, were measured in the middle branch of the first large canyon to the east of Point Concepcion, in which is located the Bixby ranch house, from which the canyon is named. An exact correlation between these two partial sections is difficult, but that shown in plate 2 is not believed to be in error by more than a few hundred feet.

The uppermost part of the Monterey formation as exposed along this coastal section may prove, as in some other sections of this region, to be of Pliocene age and equivalent to similar beds in the Santa Maria region to the north, which contain Pliocene fossils. Study of the diatoms which are the only abundant fossils in these uppermost beds may settle this question of age. This part of the formation is increasingly silty and massive toward the top, as in many other Monterey sections. The thick tuff bed at the base of the Monterey formation is correlated with the Obispo tuff member of the Monterey by both the distinctive lithologic sequence and foraminiferal zones.

NAPLES AND GAVIOTA CANYON SECTIONS

The section beginning with the uppermost beds exposed in the sea cliffs below Naples, in Santa Barbara County, and extending west beyond the mouth of Dos Pueblos Creek includes strata to the base of the Monterey formation, but it is combined with a section in Gaviota Canyon in order to indicate the relations of the Monterey to the Miocene deposits beneath it. The uppermost beds exposed in the cliffs below Naples consist of diatomaceous mudstone, probably equivalent to similar beds in the upper part of the section at Point Concepcion. The sea-cliff exposures continue down in the stratigraphic section to the west, but west of the mouth of Dos Pueblos Creek the calcareous mudstone with siliceous limestone reefs that forms the lower part of the formation is affected by small faults and folds, which make it impossible to calculate the thickness of this part of the section very closely. The Obispo tuff member of the Monterey, at the base of this section, serves to correlate it with the Gaviota Canyon section, which includes lower strata and was measured along the highway on the east side of Gaviota Canyon. This correlation is checked by foraminiferal zones, which also form the basis of correlation between these and other Monterey sections. The dark mudstone formation between the Obispo tuff member of the Monterey and the Vaqueros sandstone is a distinctive and persistent formation in several counties in this part of California, and it includes several foraminiferal zones. Kerr,[12] who studied it in Ventura County, named it the Rincon formation.

GRIMES CANYON SECTION

A section of the Monterey formation is well exposed in road cuts along the east side of Grimes Canyon,[13] in the central part of the Piru quadrangle, in Ventura County. The comparatively thin Monterey formation is here overlain without apparent unconformity, or at least without obvious structural discordance, by sandstone of Pliocene age, which contains a Pico (upper Pliocene) foraminiferal fauna only about 200 feet above its base. The calcareous shales forming the basal part of the Monterey formation grade down into sandy beds of the Vaqueros sandstone. This basal part is not exposed in the canyon section, but is found along the strike of the beds less than one-half mile to the east. The small thickness of the Monterey in this section is in striking contrast to its unusually great thickness in the Modelo Canyon area, which lies on the other side of the Santa Clara River Valley and is about 10 miles distant; but the difference appears to be due to a difference in the thickness of equivalent beds rather than to unconformity or to non-deposition in the Grimes Canyon area during much of the Miocene period. However, additional collecting and study of the foraminiferal faunas is necessary to determine whether any equivalent of the Rincon mudstone is present in the Grimes Canyon section.

[12] Kerr, P. F., Bentonite from Ventura, California: Econ. Geol., vol. 26, no. 2, p. 156, 1931.

[13] Kew, W. S. W., Geology and oil resources of a part of Los Angeles and Ventura Counties, Calif.: U. S. Geol. Survey Bull. 753, p. 61, 1924.

MODELO CANYON SECTION

The thick Miocene section above the Vaqueros sandstone (lower Miocene) was all included by Kew[14] in the Modelo formation, named from Modelo Canyon, a branch of Piru Creek, which is in the northeast part of the Piru quadrangle, in Ventura County. The thick mudstone forming the lower part of Kew's Modelo formation is not exposed in Modelo Canyon but is exposed in nearby areas. It is correlated with the Rincon mudstone. The Modelo Canyon section was measured, and Foraminifera collected from it and reported on, by geologists of the Texas Company, and the section shown in plate 2 is mainly based on their data;[15] the lithologic descriptions are modified, however, as a result of observations made in the course of the present study. The lithologic units, though thick and locally distinct, vary rapidly along the bedding, and it therefore seems best to consider them as members rather than formations. The sandstone members (unnamed) are locally as thick as or thicker than the intervening members of siliceous rock, but the use of the name Monterey formation for all the Miocene strata above the Rincon mudstone seems appropriate in this area, even though the conditions here closely approach those in areas where the name is not appropriate.

BEVERLY GLEN PASS SECTION

Several well exposed sections on the north side of the Santa Monica Mountains of Los Angeles County were examined. One of these, along the Topanga Canyon road, has been described in a report by Hoots,[16] and a part of the strata in this section was taken by Kleinpell as the type of the Mohnian stage. Only the section along the highway from Van Nuys to Beverly Glen is shown in plate 2. The upper part of this section, down to the base of the second sandstone (260 feet thick), was measured along the cuts of the small road on the west side of the Valley Park Country Club, in the first canyon east of that followed by the present highway. The lower part of the section was measured from Mulholland Drive, at the crest of the mountains, southward along the highway toward Beverly Glen. The beds above the top of the Topanga formation were assigned to the Modelo formation in the report by Hoots,[17] but it now seems preferable to include them in the Monterey formation.

PUENTE HILLS SECTION

The thick succession of siliceous shale and sandstone members in the Puente Hills of Los Angeles County—named the Puente formation in an early report[18]—varies so greatly within short distances that the stratigraphic section from the southeastern part of the Puente Hills shown in plate 2 is somewhat generalized, the thickness of units as there shown being only approximate. The rapid variation and the presence of locally thick sandstone members, as in the area of Modelo Canyon, make the appropriateness of the name Monterey formation questionable. The name seems more obviously appropriate, however, in a part of the Puente Hills that lies only a short distance northwest of the area represented by the section.

The position of the top of the Monterey formation in this section is questionable, and even after additional stratigraphic work and mapping it would probably have to be placed arbitrarily, because of the transitional character of a thick upper part, some of which is thought to be Pliocene in age. The lower part of the formation is not exposed in this area; the age of the lowest beds exposed, which are included in the lower Puente by English,[19] is mainly upper Miocene but perhaps in part late middle Miocene. Older Miocene strata are present, however, on the south side of the Santa Ana River valley.

PALOS VERDES HILLS SECTION

The general section for the Palos Verdes Hills shown in plate 2 is composite, being made up of several incomplete sections based on the recent mapping of this area. The section and its correlation with other areas has been published.[20] The subdivision into the named members is probably applicable only to a local area. The Monterey formation here rests upon the Franciscan formation (Jurassic ?), and its lower strata pinch out northward in an overlap on the Franciscan rocks.

DANA POINT SECTION

The section along the sea cliffs north of Dana Point, in Orange County, is taken from the report on this area by Woodford,[21] although, as in other sections which have been previously described, the lithologic terms for the rocks are somewhat modified as a result of the present investigation. Correlation with other Monterey sections is less satisfactory than in most of the sections, because good foraminiferal faunas were not found, but the relations indicated are believed to be approximately correct. A good foraminiferal fauna is found immediately above the San Onofre breccia in an area two or three miles north of the sea-cliff section, and forms part of the basis for the correlation indicated.

[14] Op. cit. (Bull. 753), p. 55.

[15] Hughes, D. D., unpublished paper.

[16] Hoots, H. W., Geology of the eastern part of the Santa Monica Mountains, Los Angeles County, Calif.: U. S. Geol. Survey Prof. Paper 165-C, p. 103, 1931.

[17] Idem., p. 102.

[18] Eldridge, G. H., and Arnold, Ralph, The Puente Hills oil district, southern California: U. S. Geol. Survey Bull. 309, p. 103, 1907.

[19] English, W. A., Geology and oil resources of the Puente Hills region, southern California: U. S. Geol. Survey Bull. 768, p. 33, 1926.

[20] Woodring, W. P., Bramlette, M. N., and Kleinpell, R. M., Miocene stratigraphy and paleontology of Palos Verdes Hills, California: Am. Assoc. Petroleum Geologists Bull., vol. 20, no. 2, pp. 125-149, 1936.

[21] Woodford, W. O., The San Onofre breccia: Univ. California Pub., Bull. Dept. Geol. Sci., vol. 15, no. 7, pp. 212-213, 1925.

BIG TAR CANYON SECTION

Four additional stratigraphic sections in the San Joaquin Valley region are shown in plate 3. The section in Big Tar Canyon of Reef Ridge, in the Coalinga quadrangle, has been described, and its relation to other Miocene sections indicated, in a report on the Kettleman Hills.[22] Only the porcelaneous mudstone member known as the McLure shale member is included in the Monterey formation of this area, and the upper part of the Temblor sandstone is equivalent to part of the Monterey formation to the south.

CHICO MARTINEZ CREEK SECTION

One of the best-exposed and thickest sections of the Monterey formation occurs in Chico Martinez Creek, in the northern part of the McKittrick quadrangle, in Kern County. The section was measured along the south side of the creek. It begins at the unconformable contact of the diatomaceous upper member of the Monterey formation with the conglomerate of the Tulare formation (Pliocene), and continues stratigraphically downward to the mouth of a small tributary of Chico Martinez creek, near the center of Sec. 9, T. 29 S., R. 20 E., Mt. Diablo meridian. The lower part of the section was measured by going up this branch (Zemorra Creek, type locality of Kleinpell's Zemorrian stage) southwestward to the base of the Miocene, there underlain by the so-called "Cavernous sandstone," which is of Eocene age except perhaps in the uppermost part. Correlation with other sections is largely based on Kleinpell's interpretation of the foraminiferal faunas. Here, as in most other areas, Foraminifera are rare in the upper part of the Monterey, and the diatomaceous member at the top of the formation may prove to be in part of Pliocene age.

MARICOPA TYPE SECTION

The Miocene siliceous shales in the hills south of Maricopa, Kern County, were described in an early report[23] under the name "Maricopa shale." The section of this type area shown in plate 3 indicates the lithologic similarity and equivalence of most of this formation with strata in Chico Martinez Creek and the similar relations with the Monterey sections of plate 2, so that the name "Monterey formation" may properly replace the local designation "Maricopa shale." The siliceous rocks characteristic of the Monterey formation extend to a somewhat lower horizon here than in any other area known. The formation is overlapped by Pliocene beds, and the upper part of the Monterey is cut out by an unconformity.

The section was measured along the small canyon extending through secs. 13 and 24, T. 11 N., R. 24 W., San Bernadino meridian, on the north flank of the anticline that is shown on the map by Pack[24] as a westward extension of the Pioneer anticline. The correlation is based on the foraminiferal faunas examined by Mr. Boris Laiming of the Texas Company.

SECTION OF THE BAKERSFIELD AREA

A generalized section of the Miocene strata of the Kern River area, in Kern County, northeast of Bakersfield, shown in plate 3, indicates the stratigraphic relationships, though the name Monterey formation is not applicable to the relatively thin strata of equivalent age in this area. This generalized section is based on data presented by Ferguson,[25] and the correlations with other sections shown in plate 3 agree, in general, with Kleinpell's interpretation of the foraminiferal faunas and of their relations to the several larger fossil faunas of this area.

ECOLOGIC SIGNIFICANCE OF THE FOSSILS

The abundant Foraminifera in the Monterey formation have proved to be of great value in stratigraphic correlation and have been studied largely for that purpose. Ecology is necessarily involved in the stratigraphic interpretations, but very few ecologic data had been published prior to the appearance of Kleinpell's[26] book in 1938. Although the ecology of modern foraminiferal faunas is not adequately known, Kleinpell attempted some interpretations from it regarding the Miocene faunas. He concludes that the foraminiferal faunas represent temperate-zone conditions, ranging from subtropical in the middle Miocene to cool temperate in the upper Miocene, and that most of the faunules indicate "depths between the upper limits of the neritic zone and the edge of the continental shelf (about 25 to 500 fathoms)."

Most of the Foraminifera are bottom dwellers, and it is difficult to understand their abundance in some of the Monterey strata, that other evidence suggests were accumulated in bottom water that was unfavorable for most benthonic organisms. The relative scarcity of larger fossils in the laminated siliceous rocks seems probably to be due, in part at least, to the low oxygen content of the bottom water, which would be expected where there was no appreciable wave or current action (p. 35), and it seems improable that Foraminifera would require less oxygen than most other benthonic organisms. The delicate diatom shells are so easily drifted that an abundance of shallow-water benthonic diatoms might be expected to accumulate in the bottom

[22] Woodring, W. P., Stewart, Ralph, and Richards, R. W., Geology of the Kettleman Hills oil field, Calif.: U. S. Geol. Survey Prof. Paper 195, pl. 47, 1940.

[23] Pack, R. W., The Sunset-Midway oil field, California: U. S. Geol. Survey Prof. Paper 116, p. 35, 1920.

[24] Idem.

[25] Ferguson, G. C., Correlation of oil field formations on east side San Joaquin Valley: California Div. of Mines, Bull. 118, pt. 2, pp. 240-41, 1943.

[26] Kleinpell, R. M., Miocene stratigraphy of California, pp. 11-19, Am. Assoc. Petroleum Geologists, 1938.

sediments of stagnant basins, and perhaps the empty foraminiferal shells could likewise be drifted into such basins if the bottom slopes were relatively steep.

The buoyancy of the empty foraminiferal tests, even when "water-logged," is evident in washing, as they are easily panned off from much smaller grains of sand. Their common occurrence in thin layers within the Monterey formation, and their association with an increased proportion of very fine sand and silt, suggest in such occurrences that their deposition was a result of drifting, even though the currents were generally not appreciable at the immediate surface of the bottom sediment. This transportation of the empty shells on the sea floor may be one factor in the relative uniformity of depth facies that is apparent in most of the Monterey foraminiferal zones over large areas.

Hanna has offered brief ecologic interpretations on a few diatom floras, which, however, are too limited to serve as the basis for any general interpretations. He states that the deposit from Malaga Cove [27] contains diatoms indicating an accumulation in shallow water, many of the genera being shallow-water, bottom-dwelling forms. However, the frequent drifting of diatoms by waves and currents seems to make ecologic conclusions of questionable value as applied to the area where these diatoms have accumulated, for littoral forms would commonly be carried out and deposited in deeper waters. Dr. Mann is quoted as follows by Jordan [28] regarding the diatoms from the Lompoc deposit: "Practically all of the forms are characteristic of northern waters; in fact, the Lompoc diatoms are, as a class, brought down from northern latitudes." The loss of the more delicate planktonic forms through solution in the sea water, both before and after reaching the bottom (p. 51), is also an important factor for consideration in any ecologic interpretation based on the diatoms.

Mollusca are generally rare in the siliceous rocks of the formation, being represented by only a few species; small species of *Arca* and of the Pectinidae are the only common forms, and these are mostly represented only by molds of the shells. Local sandy facies occasionally contain a more varied fauna, such as that found at a locality in the Palos Verdes Hills, which according to Woodring [29] is a shallow-water fauna with a number of species of tropical aspect. Miocene sandstone formations underlying and overlying the Monterey formation more commonly contain a larger molluscan fauna, this being true, for example, of the Temblor, Santa Margarita, and San Pablo formations, and these formations are at least in part equivalent to the Monterey formation of other areas. The limited fauna of generally small and thin-shelled forms usual in the Monterey formation suggests relatively deep and cool waters, and the larger faunas of associated sandstones are more littoral assemblages of warmer-water aspect. Such differences are to be expected in seas with large ranges in depth.

Fish remains are common in both the diatomaceous and the harder siliceous beds of the formation; beautifully preserved specimens are commonly found where quarrying operations expose the bedding surfaces. The lamination or fissility of the beds is doubtless a factor in the frequency with which these fish remains are observed, as the scales and smaller bone fragments are conspicuous only on bedding surfaces. It seems evident, however, that fish remains are much more abundant here than in most marine formations, even those of comparably fine texture that are composed of normal clastic sediments. The well-known relation between abundance of fish and abundance of micro-planktonic food supply in modern seas suggests an explanation for the presence of so many fish in this formation; records of an abundant micro-plankton are obvious in the diatomaceous deposits and are indirectly evident in much of the other siliceous rock. The extraordinary abundance of the single species of herring (*Xyne grex*) in a certain thin stratum in the Lompoc quarry deposit is partciularly noteworthy. Regarding the fossil fish fauna or the Monterey formation in general, Jordan [30] says: "No species either distinctly tropical or distinctly subarctic appear among the Tertiary fishes of southern California. We must, therefore, conclude that the Miocene temperature differed little from that which obtains at present."

Less common fossils of the formation include bones of whales, bones and teeth of a sea cow (Desmostylus), bird skeletons, rare remains of land animals, including horse teeth and a dog's skull, and leaves of land plants. Most of these rare fossils are largely of local ecologic significance only, being related to the position of the shore line and to other conditions at the particular time and place of their occurrence; the published accounts of them, therefore, need not be reviewed here.

The evidence available seems, on the whole, to indicate conditions of temperature and rainfall not markedly different from those now existing along the California coast, and, as was suggested by Mann, the colder-water diatoms may have drifted down from more northern latitudes.

PALEOGEOGRAPHIC INTERPRETATIONS

Many features of the formation, to be described in some detail, will appear obviously related to conditions in the Monterey sea. Some of the more general of these conditions are considered first, even though the data are insufficient to permit more than generalized and in

[27] Hanna, G. D., The age of the diatom-bearing shales at Malaga Cove, Los Angeles County, Calif.: Am. Assoc. Petroleum Geologists Bull., vol. 12, no. 11, p. 1111, 1928.

[28] Jordan, D. S., The fish fauna of the California Tertiary: Stanford Univ. Pub., Univ. Series, Biol. Sciences, vol. 1, no. 4, p. 293, 1921.

[29] Op. cit., p. 138.

[30] Op. cit., p. 238.

part speculative interpretations. Much additional information regarding both the extent and the lithology of more exact chronologic subdivisions within the thick formation must be obtained before any clear views as to paleogeographic conditions can be developed.

Maps by Reed showing the distribution and thickness of the lower, middle, and upper Miocene deposits in the southern part of California were published,[31] in 1936, and these maps, though necessarily generalized, embody enough surface and subsurface data to indicate some pertinent facts regarding the Miocene seas. The sea was less extensive in lower Miocene time than in the middle and upper Miocene, but throughout the Miocene it included deep basins wherein great thicknesses of sediment accumulated. These basins were more or less separated by land areas, or by shallower sea areas where much less sediment was accumulated. The basins show little relation to the present coast line, and apparently were connected in part with the open ocean by relatively shallow and narrow seaways. The deeper basins and shallower-water divides off the present coast in the region of the Channel Islands,[32] constitute such conditions of bottom topography as are postulated for the Monterey seas.

Certain areas, such as one in the southwestern San Joaquin Valley and a smaller one near Ventura, were persistently negative throughout most of the Miocene time, so that thick Miocene sedimentary deposits accumulated in them, though some shifting of the centers of maximum deposition is indicated by the maps of Reed.[33] In the area of the Los Angeles basin, the shifting of the area of maximum deposition during the Miocene was more marked; the area of maximum deposition shifted widely between early and middle Miocene time, and then shifted back in late Miocene time to about the same position it had occupied in the early Miocene. Other areas, such as one west of Coalinga, between the San Joaquin Valley and Salinas Valley, appear to have remained positive, so that they were not covered by the sea until late in the Miocene. The area of the middle Salinas Valley seems to have been occupied throughout the Miocene by a shallow seaway connecting deeper basins of accumulation.

The mere shape and distribution of the areas of maximum sedimentary accumulation, and their changes and shiftings through Miocene time, suggest that they were tectonic basins of subsidence. The thickness of the deposit in a given place appears to reflect the amount of subsidence that permitted accumulation rather than the supply of sedimentary material locally available, and this seems even more probable for that large part of the sediment which is not of clastic origin. Here as in many other regions, it seems more probable that the thick deposition was the result of subsidence than that the subsidence was largely a result of the accumulating load of sediment. The shifts of the areas of maximum deposition indicate that, in general, the basins of subsidence were not originally depressed to their total depth and gradually filled with all subsequent Miocene deposition.

The results of the work on Pliocene Foraminifera by Natland[34] and of that on Pliocene larger fossils by Woodring[35] suggest that the thick Pliocene deposits of the Los Angeles and Ventura basins may have been formed by a gradual filling of initially deep basins. The ecologic data available on the Miocene faunas do not, however, support such an interpretation for the Monterey formation.

The general distribution of land and sea shown in Reed's paleogeographic maps indicates that the Monterey siliceous rocks do not represent deep-sea deposits formed in areas far removed from land, such as those that have received the more extensive accumulations of siliceous organic deposits in present oceans. The relatively small proportion of clastic material, particularly of the coarser materials, in the thick Monterey deposits of many areas requires an explanation other than remoteness from any terrigenous source of sediment. An explanation suggested long ago was that in Miocene time the land was arid and without large streams. One weakness of this hypothesis is the lack of evidence of unusual aridity in the Miocene, and even if arid conditions had existed large streams arising in the interior might have flowed across the arid coastal regions as they so commonly do today. Another view has postulated that the Miocene land areas were nearly at base level, but this view is opposed by evidence that the crust of the region was unstable and contained subsiding basins in Miocene time, and by the rapid variations from nonclastic to the coarse clastic sediments which are locally common in the Monterey formation. Land of low relief might have contributed large amounts of silt and clay to the depositional areas, as it does in many places at the present time. The widespread mudstone deposits, including the Rincon mudstone, that generally followed the deposition of the lower Miocene sandstones are perhaps more suggestive than the typical Monterey sediments of conditions approaching base level.

A more recent suggestion by Reed[36] seems to account better for the conditions of deposition of the Monterey

[31] Reed, R. D., and Hollister, J. S., Structural evolution of southern California: Am. Assoc. Petroleum Geologists Bull., vol. 20, no. 12, figs. 17, 19, and 20, 1936.

[32] Trask, P. D., Sedimentation in the Channel Islands region, California: Econ. Geology, vol. 26, no. 1, pp. 24-43, 1931.

[33] Idem.

[34] Natland, M. L., The temperature and depth distribution of some recent and fossil Foraminifera in the Southern California region: California Univ., Scripps Inst. Oceanography Bull., Tech. Ser., vol. 3, no. 10, pp. 225-30, 1933.

[35] Woodring, W. P., Lower Pliocene mollusks and echinoids from the Los Angeles Basin, Calif.: U. S. Geol. Survey Prof. Paper 190, pp. 12-22, 1938.

[36] Reed, R. D., Geology of California, p. 186, Am. Assoc. Petroleum Geologists, 1933.

non-clastic rocks. He points out that the disturbance, including faulting and much volcanic activity, at about the beginning of the middle Miocene seems to have disintegrated many of the major drainage systems, with the result that vast deposits of continental sediments, such as those in the Mojave region, were accumulated. In the Coalinga area,[37] the continental deposits containing *Merychippus* have been correlated with the marine middle Miocene. Disintegration of the through-flowing drainage in middle and upper Miocene time may thus have caused most of the material that otherwise would have been carried into the adjacent seas to stay on the land. Support for the view that a disintegration of the larger drainage systems may have been an important factor is afforded by present conditions of sedimentation in the tropical Pacific island areas. Organic deposits, consisting of coral reefs and sands formed from calcareous organisms, are accumulating around many of these islands and in such bays as Pago Pago harbor,[38] despite the strong topographic relief and heavy rainfall, because of the small drainage area of the streams. In Pago Pago harbor the sand brought down by the streams is dumped near their mouths, and no large quantity of fine clastic sediment is contributed to the bay. Organic deposits are dominant in this region, and there is little deposition of clastic material except for the local accumulations of sand near the mouths of streams, which apparently correspond with the local interfingering, in the Monterey formation, of comparatively clean arkosic sands with diatomaceous deposits.

Seas that had deeper basins, formed by local subsidence, within which all the sediment available from land or areas of shallower water could accumulate but which received relatively small supplies of terrigenous material, would be particularly favorable for the accumulation of thick organic deposits. The relatively small proportion of clastic material in these deposits may have resulted, however, from an unusually rapid supply of the diatomaceous sediment as well as from the relatively small supply of terrigenous sediment. The origin of the diatomaceous deposits is considered on p. 37 and leads to the conclusion that the organic accumulation was rapid as compared with the rate commonly assumed, and that it probably was not very much slower than the rate of accumulation of many clastic deposits. Among the factors favoring an unusually large supply of diatoms for this rapid accumulation, perhaps the most important was the drifting of this micro-plankton by currents from the open ocean into catchment areas of deeper water and into cul-de-sacs along the coast. J. P. Smith suggested that an oceanic circulation similar to that now active along the west coast of North America would have favored a drifting of diatoms by currents from the open ocean to the northwest and accumulation in cul-de-sacs in the Monterey sea.[39]

LITHOLOGY OF THE FORMATION

SILICEOUS ROCKS

The various types of siliceous rocks, all distinguished by a much higher content of silica than normal clastic shale or mudstone, constitute a large and characteristic part of the formation. The terminology used by Cayeux[40] for the many types of siliceous rocks described in his comprehensive volume on the siliceous rocks of France is not followed in this paper, because of the rather artificial distinction between many of the types, few of which are recognized by common American usage. As there is complete gradation between the various types of siliceous rocks and from them to the ordinary sedimentary rocks that have a normal content of silica, any classification within this gradational series must be rather arbitrary. An obvious distinction can be made only between the diatomaceous rocks, which are comparatively soft and contain abundant well preserved remains of diatoms, and the porcelaneous and cherty rocks, which are hard and cemented by silica, and in which well preserved diatoms are rare.

Chemical analyses of some of the various types of siliceous rocks are given in the following table. These indicate the high proportion of silica compared to alumina. An exception is the sample from Graciosa Ridge (column No. 3), which is more properly classed as a diatomaceous mudstone—a massive rock, much less than half of which generally consists of diatoms. This rock from Graciosa Ridge is now assigned to a formation unconformably overlying the Monterey, but similar diatomaceous mudstone is also common in the Monterey formation. The calcium carbonate which is present in some of the samples and abundant in a few is eliminated by recalculation, because it is clearly an admixed constituent and the object of making and tabulating the analyses was to compare the significant ratio of silica to alumina.

DIATOMACEOUS ROCKS

Diatomaceous rocks are common in the upper part of the Monterey formation in many areas, and the formation includes the thickest diatomaceous deposits known. These show all gradations from nearly pure deposits of diatoms, through diatomaceous shales, diatomaceous mudstones, and siltstones, to rocks without appreciable quantities of these siliceous organisms. The

[37] Idem, p. 211.

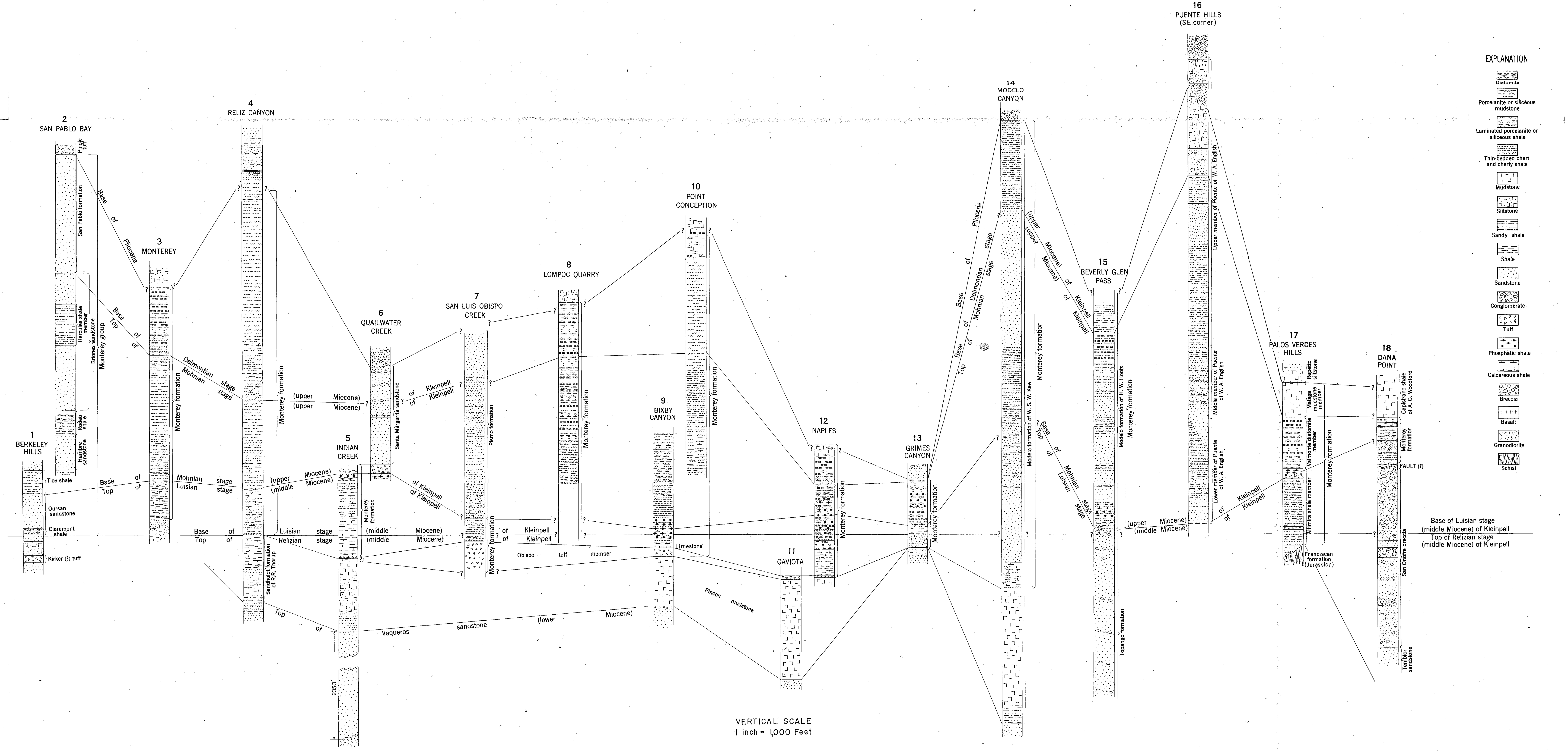
[38] Bramlette, M. N., Some marine bottom samples from Pago Pago Harbor, Samoa: Carnegie Inst. Washington Pub. No. 344, Dept. Marine Biol. Papers, vol. 23, pp. 1-35, 1926.

[39] Louderback, G. D., The Monterey series in California: Univ. California Pub., Dept. Geol. Sci. Bull., vol. 7, no. 10, p. 235, 1913.

[40] Cayeux, L., Les Roches Sedimentaires de France—Roches Siliceuses, Imprimerie Nationale, Paris, 1929.

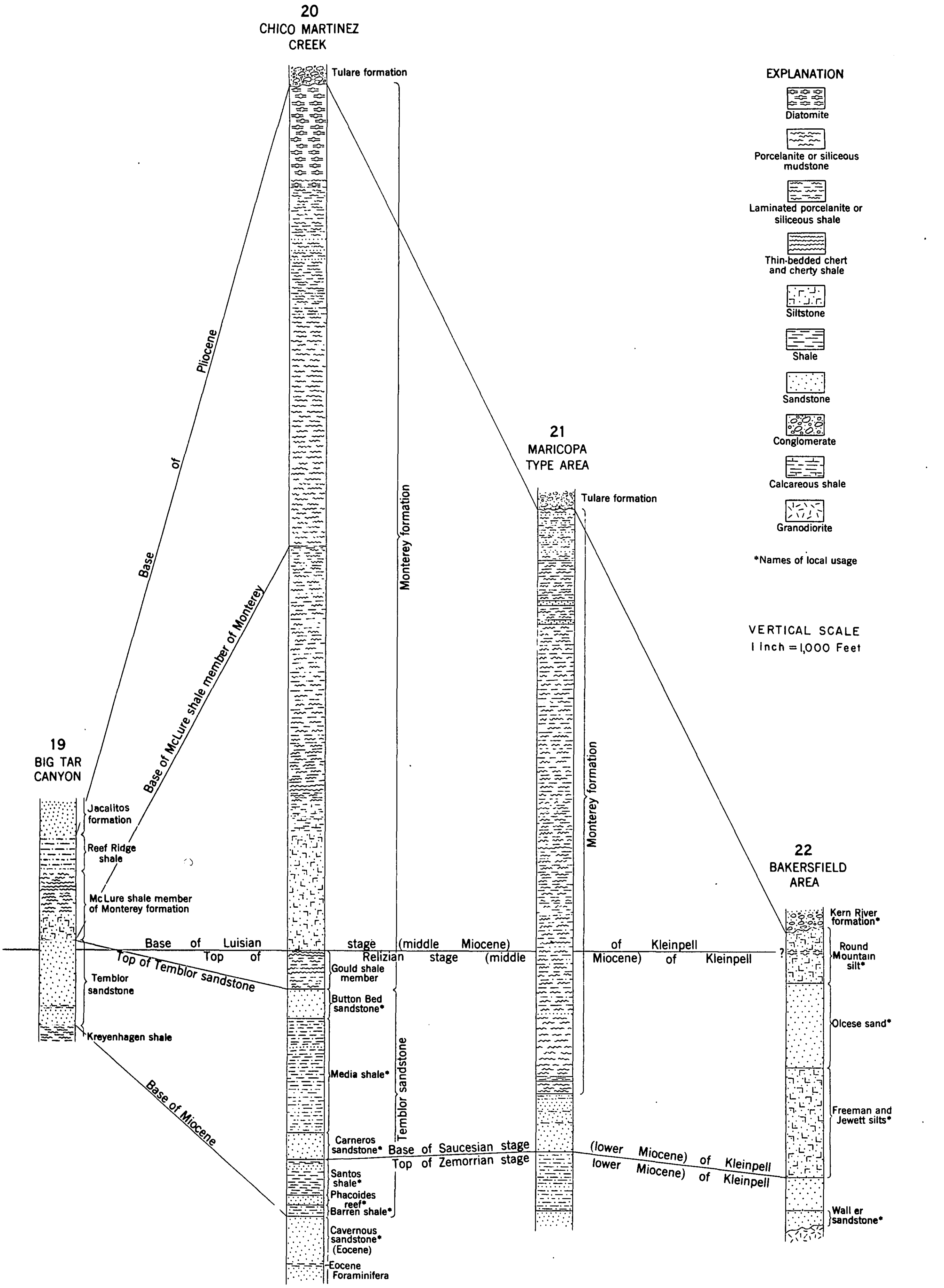
INDEX MAP SHOWING LOCATION OF STRATIGRAPHIC SECTIONS OF THE MONTEREY FORMATION IN CALIFORNIA

696489 O - 46 (Face p. 12) No. 1



STRATIGRAPHIC RELATIONS OF MIOCENE SECTIONS OF WESTERN CALIFORNIA FROM THE CENTRAL TO THE SOUTHERN PART OF THE STATE

696489 O - 46 (Face p. 12) No. 2



STRATIGRAPHIC RELATIONS OF MIOCENE SECTIONS OF THE SAN JOAQUIN VALLEY, CALIFORNIA

696489 O - 46 (Face p. 12) No. 3

Chemical analyses of siliceous rocks of the Monterey formation of California

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	71.80	73.71	72.50	87.20	84.45	78.70	82.55	88.90	86.89	86.92	92.37
Al_2O_3	5.02	7.25	11.71	1.86	4.14	5.83	4.82	2.28	2.32	4.27	2.46
Fe_2O_3	2.45	2.63	2.35	1.06	1.48	1.92	.90	.87	1.28	....	....
FeO	.35	.44		.33	.51	.62	.13	.20			
MgO	1.69	1.47	.83	1.14	.52	.71	....	....	Trace	Trace	....
CaO	[1]1.45	1.72	.32	[1].05	[1]1.25	[1]2.59	1.30	1.05	1.43	1.60	1.70
Na_2O	1.81	1.19	1.88	.53	.46	.56	1.09	.49	3.58	2.48	....
K_2O	3.55	1.00		2.75	.64	1.06					
H_2O-	4.64	2.88	9.54	2.78	3.25	3.64	5.53	3.10	4.89	5.13	2.74
H_2O+	5.50	6.94		2.23	3.11	4.26	2.90	2.80			
TiO_2	....	.50	....	....	.35	.35	....	....	....	....	....
CO_2	[1]	Trace?	....	[1]	[1]	[1]	....	....	....	....	....
P_2O_5	.17	.24	....	.22	.28	.34	....	....	....	....	....
SO_3	....	.16	....	....	.18	Trace?	....	....	....	....	....
Cl	1.34	....	....	.16	....	....	.81	.27	....	....	....
Organic carbon	Small	.00	....	Small	.12	.23	....	....	....	....	....
	99.77	100.13	99.13	100.31	100.74	100.81	100.03	100.06	100.39	100.40	99.27
$CaCO_3$ (calculated[1])	9.20	....	....	5.16	13.51	29.1	....	....	....	....	....

[1] CO_2 and a corresponding proportion of CaO to combine as $CaCO_3$ are calculated out of the composition.

1. Composite sample of 10 diatomaceous rocks of the Monterey formation. R. C. Wells, analyst.
2. Diatomaceous shale from road near Hollywood Country Club: U. S. Geol. Survey Prof. Paper 165-C, p. 108, 1931.
3. "Diatomaceous shale", Graciosa Ridge, 3 miles southeast of Orcutt, Santa Barbara County, Calif.: U. S. Geol. Survey Bull. 322, p. 45, 1907.
4. Composite sample of 10 cherty shales of the Monterey formation. R. C. Wells, analyst.
5. Cherty shale, Mulholland Highway, Santa Monica Mountains: U. S. Geol. Survey Prof. Paper 165-C, p. 108, 1931.
6. Cherty shale ("hard platy shale"), Mulholland Highway, Santa Monica Mountains: U. S. Geol. Survey Prof. Paper 165-C, p. 108, 1931.
7. "Fairly soft cherty shale", Palos Verdes Hills, Los Angeles County, Calif.: Unpublished dissertation at California Institute of Technology, by Hampton Smith. G. Eisenhauer of Los Angeles, analyst.
8. "Very hard cherty shale", Palos Verdes Hills, Los Angeles County, Calif.: Unpublished dissertation at California Institute of Technology, by Hampton Smith. G. Eisenhauer of Los Angeles, analyst.
9. "White shale", Monterey, Monterey County, Calif.: Univ. California, Dept. Geology Bull., vol. 1, p. 25, 1893.
10. "White porcelain shale", region of Point Sal, Santa Barbara County, California: Univ. California, Dept. Geology Bull., vol. 2, no. 1, p. 12, 1896.
11. "Opaque flint", Point Sal, Santa Barbara County, Calif.: Univ. California, Dept. Geology Bull., vol. 2, no. 1, p. 12, 1896.

name diatomite is used for the purer diatomaceous rocks in commercial as well as geological usage, though the term implies no very definite degree of purity and is often used loosely by geologists for any of the soft "punky" rock in which diatoms are conspicuously present. Diatom shells are the predominant siliceous remains in these deposits, but the remains of radiolaria and silico-flagellates are also common. Sponge spicules are usually present, but are scarce except in some of the more silty deposits; where silt is abundant the spicules are commonly also abundant. A fine lamination is common, particularly in the purer diatomaceous deposits (pl. 5, *A*), though the thickness and distinctness of the laminae are variable.

The porosity of the purer diatomite is very high because of the minute pore spaces within and between the diatoms. Air-dried samples of this material have a specific gravity of only about 0.5, whereas the less pure diatomaceous shales and mudstones commonly have a specific gravity between 0.8 and 1.0. The silica content of a composite sample of ten diatomaceous rocks from different areas is 65.20 percent, the alumina content only 4.56 percent, and the $CaCO_3$ content 9.20 percent. The $CaCO_3$ is largely in Foraminifera. Some deposits, however, contain many beds of diatomite that are more nearly pure silica. Microscopic examination shows that some of this material contains only about 10 percent of impurity, which consists largely of minute clay particles and includes no calcium carbonate.

Most of the diatomaceous deposits are at present of no commercial value, the unusually pure deposits in a few areas being so large that the only important economic factor controlling production is the size of the market. Only three quarries have been operating during recent years in diatomite deposits of the Monterey formation, though several others have operated at times

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on a small scale. The properties and uses of diatomite have been described in many publications; one of the most comprehensive, which includes summaries of the known deposits, is that by Eardley-Wilmot.[41]

The Johns-Manville Products Company operates the largest quarry, which is about two miles south of the town of Lompoc, in Santa Bárbara County. The material is given such treatment at the large mill on the property as will prepare it for the uses to which it will be put; the diatomite products are then shipped under special trade names.[42] The principal uses of diatomite are for insulation and filtration. Large quantities of diatomaceous rock having a relatively high clay content are used by the iron industry. Diatomite having properties that make it especially suitable for specific uses occurs in distinct and rather persistent beds, and these are quarried separately over large faces, which are carefully stripped by means of hand picks (pl. 4, *C*). Some of these beds contain an unusually large proportion of certain hair-like diatoms, such as the genus *Thalassiothrix*, and are particularly suitable for filtration.

Beds of purer diatomite, usually a few feet thick, alternate with thicker zones of twenty feet or more that are less pure, being classified in part as diatomaceous mudstone. This alternation of beds is not obvious on casual inspection. Calcium carbonate is almost entirely lacking in the thick diatomaceous deposit at Lompoc, and no Foraminifera were found there. The fine lamination that is particularly well developed in the purer diatomaceous beds is illustrated in plate 5, together with small step faults, which are confined within particular beds but occur at many horizons. These thin zones of step faulting that do not extend into beds above and below can be traced for scores of feet along the same horizon and are obviously due to slip movements parallel to the bedding. Thin but persistent beds of dark opaline chert occur at a few horizons, as do other more lenticular beds and nodular masses of opaline chert. A few thin but sharply delimited and persistent beds of volcanic ash occur in the diatomite (pl. 5, *C*). Rare shards of volcanic glass are scattered through the diatomite, becoming common only in the massive-bedded upper part of the deposit. Fish scales are commonly observed on bedding planes, and quarrying along bedding planes has exposed many beautifully preserved skeletons of fish.

This large deposit of diatomite near Lompoc occurs in the trough of a syncline and forms approximately the upper 1,000 feet of the Monterey formation of this area. The uppermost part of this diatomite may prove to be of lower Pliocene age. The relatively pure diatomite grades upward through diatomaceous mudstone to a silty mudstone, containing fewer diatoms, which forms the highest strata remaining in this synclinal trough. Underlying this 1,000 feet of diatomaceous rock is about 1,000 feet of strata consisting of alternating zones of cherty rock, which range from about 2 to 20 feet in thickness, and zones of diatomaceous shale having about the same thickness (pl. 4, *D*). Beneath these alternating zones is a great thickness of porcelaneous and cherty shale, the base of which is not exposed in the area.

A second large quarry, that of the Dicalite Company, is located in the diatomite beds that crop out along the north side of the Palos Verdes Hills, in Los Angeles County. This diatomite is several hundred feet thick, attaining its maximum thickness of about 500 feet in the vicinity of the quarry. Most of the features displayed in the Lompoc deposit are also present here, including thin beds of dark opaline chert, thin volcanic ash beds—called "silver sand" by the quarrymen—and alternating zones of purer and less pure diatomite a few feet in thickness. In this deposit, however, there is no thick member made up of alternating zones of diatomaceous and cherty rocks, such as underlies the diatomite near Lompoc. The contact with the underlying porcelaneous and cherty shales is rather sharp and definite, though this contact does not remain at the same stratigraphic horizon even within the area of the Palos Verdes Hills: the lower part of the diatomite in the northeastern part of the hills is equivalent to some of the cherty and porcelaneous shale occurring farther southwest.[43] The diatomaceous strata of the Palos Verdes Hills are darkest—gray rather than the usual nearly white—where they have apparently been least affected by near-surface surface weathering and leaching, as in the lower part of the sea-cliff exposures at Malaga Cove and in the sea-level tunnel driven through the Hills for sewage disposal. They are very dark where saturated with water.

The third locality where diatomite is being quarried is in the Salinas Valley, about five miles northwest of the town of Bradley, in Monterey County. Several hundred feet of diatomite here forms the upper part of the Monterey formation, and is underlain by a thick succession of porcelaneous and cherty rocks.

Another quarry was formerly operated in the diatomite forming the upper member of the formation in the type area near Monterey; this old quarry is south of the highway along Canyon del Rey, about three and one-half miles southeast of Del Monte. In the southwestern San Joaquin Valley, also, and in several other areas, diatomaceous beds constitute the upper part of the formation, as is indicated in the section of some

[41] Eardley-Wilmot, V. L., Diatomite, its occurrence, preparation, and uses: Canada Dept. Mines, Mines Branch, Pub. no. 691, 1928.

[42] Mulryan, H., Geology, mining and processing of diatomite at Lompoc, Santa Barbara County, Calif.: Am. Inst. Min. Met. Eng. Tech. Pub., no. 687, p. 27, 1936.

[43] Woodring, W. P., Bramlette, M. N., and Kleinpell, R. M., Miocene stratigraphy and paleontology of Palos Verdes Hills, California: Am. Assoc. Petroleum Geologists Bull., vol. 20, no. 2, p. 143, 1936.

of these areas in plates 2 and 3; but most of these diatomaceous strata are much less pure than the diatomite now being quarried.

PORCELANEOUS ROCKS

Porcelanite is the name used by Taliaferro[44] and others and adopted here for designating the silica-cemented rocks that are less hard, dense, and vitreous than chert. Such rock has minute pore spaces, which usually give it a dull or matte lustre resembling that of unglazed porcelain. Porcelanite is commonly of light color in surface exposures, but its range of color is great, and some of the variation is obviously due to bleaching and leaching effects of surface alteration. No color, therefore, is implied in the term. The rock is not conspicuously laminated or fissile, though it is commonly rather thin bedded; siliceous beds from less than one inch to several inches in thickness alternate with thin partings of less siliceous rock.

Porcelaneous rocks that are finely laminated or fissile are classed as porcelaneous shale, although all gradations to a non-fissile porcelanite are found, so that the distinction must commonly be arbitrary. The finely laminated porcelaneous rocks are not necessarily fissile and perhaps should not be classed as porcelaneous shale, but no distinction seems practicable, because the fissility of the laminated rocks is accentuated by surface leaching and weathering. By an increase in the proportion of clay and silt, the porcelanite grades into porcelaneous mudstone, which resemble crude pottery more than porcelain, and this in turn grades into normal, unsilicified mudstone. The porcelaneous rocks constitute the major part of the siliceous rocks of the formation in the type area near Monterey and in most other areas. Their intergradation makes it difficult in many areas to distinguish the several varieties of porcelaneous rocks, however, the distinctive terms can usefully be applied to particular strata in certain areas. In the thick Monterey section in Reliz Canyon most of the rock is classed as porcelanite and porcelaneous mudstone, the latter being dominant, and these two types are interbedded, and intergrade, to a degree that makes it impossible to divide much of the section into mappable lithologic units. The distinction between porcelaneous shale and porcelaneous mudstone, however, is commonly quite obvious. Porcelaneous mudstone forms some distinctive units, such as the McLure shale member of the Monterey in the western San Joaquin Valley.

The porcelaneous rocks consist essentially of a mixture of clay or silty clay with a large but variable proportion of opaline silica. The chemical composition is accordingly variable, but the ratio of silica to alumina, as indicated in the analyses on page 13 is much higher than in ordinary clay shale or mudstone. Calcium carbonate, occurring in part as Foraminifera, varies greatly in amount; it may be considered an admixed accessory, best eliminated by recalculation in comparing analyses of the siliceous rocks. The relatively light weight of the porcelaneous rocks indicates their high porosity, though their pore spaces are very minute. The specific gravity of some representative samples range from 0.9 to 1.4, the lighter ones thus being no heavier than some of the less pure diatomaceous rocks. With decreasing pore space, there is complete gradation to the denser and more vitreous types classed as chert and cherty shale. Impressions or molds of the largest discoid diatoms, such as *Cosinodiscus,* are often observable with the hand lens in the porcelaneous rocks, and commonly are abundant on bedding surfaces of the more fissile porcelaneous shales. Examination of many of these samples in the laboratory shows that the original diatoms are not preserved in these rocks, but the molds are abundant. Microscopic examination, with high magnification, makes it obvious that much of the fine porosity of these porcelaneous rocks is due to the molds of various small diatoms and other siliceous organisms. The finer pore spaces are obscure, however, in thin sections, because of the impregnation of the fine pore spaces with Canada balsam and the intimate mixture of fine clay particles and opaline matrix; only by reheating the Canada balsam and introducing some air bubbles by lifting an edge of the cover glass are the shapes of the finer pore spaces, thus filled with air, made easily recognizable. In this way molds of even the very delicate forms, such as the silico-flagellates, may be seen.

The porcelaneous shale that shows the most abundant impressions of diatoms is usually of a markedly fissile type, relatively soft, porous, and of light weight, and is therefore classed by some field geologists as diatomaceous shale. But the distinction from true diatomaceous shale containing well-preserved diatoms is ordinarily not difficult to make in the field with a hand lens, and the distinction is obviously significant. The so-called "poker chip shale" of the drillers is a platy porcelaneous shale which splits from the cylindrical core samples into thin discs. These core samples are generally dark in color, largely because of organic matter, and so are the porcelaneous rocks of surface samples that have been exposed for so short a time as to have undergone little surface alteration or weathering (p. 36).

Calcareous Foraminifera range from abundant to entirely absent in the porcelaneous rocks, as in other types of siliceous rocks of the Monterey formation. In some of the porcelaneous rocks the Foraminifera originally present have been leached and occur only as molds. This leaching seems to have been effected largely by ground waters related to the present topographic surface, and occurs more commonly in the porcelaneous than in the cherty rocks. Fish scales are abundant in the porcelaneous rocks, as in the other types of

[44] Taliaferro, N. L., Contraction phenomena in cherts: Geol. Soc. America Bull., vol. 45, p. 196, 1934.

siliceous rocks. Further details of similarity and contrast with the other siliceous rocks, which bear on the origin of these rocks, will be discussed later.

CHERT AND CHERTY SHALE

The name chert is applied to the relatively pure silica rocks of the Monterey formation that are dense and vitreous, regardless of whether they consist mainly of opal or mainly of chalcedony, and regardless of their color, which varies greatly. Some of the darker chert resembles rock that has been termed flint, but there seems to be no satisfactory basis for the definition of flint, and the more widely used term chert seems preferable for all such rocks in the Monterey formation. The chert is generally thin-bedded and has partings of clay shale, carbonate (usually dolomite), or more rarely sandstone. The chert beds, in general ranging from less than one inch to several inches in thickness, usually show a fine lamination (pl. 5, *D*) but little or no tendency to part along the laminae. The term cherty shale is used for somewhat less pure cherty rocks in which some of the fine laminae contain enough non-siliceous material to make the rock split into plates. The cherty shale is almost as dense and vitreous as the chert, and it is not commonly practicable to distinguish the two, because of the large influence that the degree of weathering seems to have on the extent of parting along laminae. Weathering also tends to make the cherty shale resemble porcelaneous shale in some surface outcrops. The thin-bedded chert and cherty shale are similar to rocks termed Kieselschiefer in Germany and phthanite in France.

The partings of shale or other rock are usually more prominent in the thin-bedded chert and cherty shale than in the porcelaneous rocks and diatomaceous rocks; the partings in them are not uncommonly as thick as the chert beds and occasionally are thicker. The beds of chert and cherty shale are usually persistent and regular as far as any continuous exposure extends (pl. 6, *A*), which is a hundred feet or more in some outcrops, but in places they are lenticular or vary greatly in thickness, as in Claremont Canyon (pl. 6, C) and in the sea cliffs northwest of Pismo (pl. 6, *B*).

The chert and cherty shale usually contain a larger proportion of chalcedonic silica and cryptocrystalline quartz than the porcelaneous rocks, but in general they are dominantly composed of opaline silica. Some of the purer cherts are more than 90 percent silica, as indicated in the chemical analyses on page 13. The interiors of Foraminifera and of the larger diatoms, and other original pore spaces, have been filled with chalcedony and cryptocrystalline quartz in much of the cherty rock, whose density stands in contrast with the high porosity of the porcelaneous rocks; and dark-colored chalcedonic silica commonly fills small cross-cutting fissures and partings along bedding planes in the cherty rocks. In some specimens of the laminated chert and cherty shale, an occasional lamina about 0.1 millimeter thick of nearly amorphous but minutely granular material, which seems to have been originally an especially clayey lamina, contains delicate diatoms preserved in their original opaline state.

In the lower part of some of the thickest Monterey sections, as in those of Chico Martinez Creek and Bixby Canyon, the silica matrix of the cherty shale and chert is largely chalcedony and cryptocrystalline quartz rather than opal. Some of the calcareous Foraminifera in these rocks have been replaced by silica, and their outlines are made visible only by slight differences in index of refraction between the chalcedony and the cryptocrystalline quartz.

Chert composed largely of opal occurs in concretionary or nodular masses, though much less commonly than in beds. These concretionary masses are most conspicuous where they occur in diatomaceous strata; but they also occur in the cherty and porcelaneous beds in some areas, and usually at rather definite horizons. Distinctive bedding features and even the thin lamination where present can be traced from the adjacent strata into these chert concretions, indicating that they were formed by impregnation of the strata with additional silica. Where the opaline concretions occur in diatomite, the bedding extends from the adjacent strata into the concretions without much warping (pl. 7, *A*), but the concretions in bedded chert or cherty shale commonly show a marked warping of the stratification planes, because, after the concretions were formed, the material outside them was compacted to a greater degree than that within them. The concretionary masses of opal commonly show a concentric banding as well as the original bedding, and in some of them the concentric banding is more marked than the bedding (pl. 7, *B*, *C*). Some of these concentrically banded opal concretions were described by Taliaferro,[45] with particular attention to the evidence that the opal contracted during its dehydration. Contraction of concentric shells and introduction of additional silica along the openings thus developed seems to have accentuated the concentric banding; but this banding seems also to be related to growth of the concretions through the impregnation of the strata with additional opal added in successive layers, as illustrated by the part of one of these concretions that is shown in plate 17, *C*. In this concretion and in some others composed of very dark opal, fine lamination, small faulting, or other such textural features, though not conspicuous on unweathered faces of the opal, can be brought out clearly by leaching with caustic solution. Further consideration of these opal concretions, as it bears on the mode of origin of the siliceous rocks, is presented on page 46.

[45] Op. cit.

THE SILICA MINERALS OF THE SILICEOUS ROCKS

The most abundant form of silica in the Monterey siliceous rocks is opal, though chalcedony is common and cryptocrystalline quartz is usually associated with it. No entirely reliable means of distinguishing, in the field, between the opaline and chalcedonic silica was found, but the predominance of opal is evident from microscopic study of a large number of thin sections and of a yet larger number of thin slivers chipped from samples. A slight difference in lustre between the opal and chalcedony is usually observable, and the mode of occurrence is in part suggestive; chalcedony more commonly has filled openings and fractures, though veinlets of opal occur also. Color apparently has no significance, for both chalcedony and opal range from nearly black to nearly white.

Only three distinct types, grouped as opal, chalcedony, and quartz, are distinguished, with no attempt to differentiate minerals within the chalcedonic type. Some chalcedony (quartzine) elongated perpendicular to the C axis was recognized, and perhaps other forms of silica that are distinguished optically, especially by French petrographers, are present. These varieties are, however, far less abundant in these rocks than normal chalcedony, and are closely associated with it insofar as they occur; just which of these varieties are present, and how abundant each one is, therefore, seems unimportant. The greater stability of the less hydrous forms of silica probably accounts for the relative scarcity of opal as compared with chalcedony and quartz in pre-Tertiary siliceous formations, particularly in those of Paleozoic age; and this tendency of opal to alter to the more stable forms of silica seems to be well shown in the Monterey formation.

The term opal is used to designate all of the apparently amorphous and isotropic silica, though it is now recognized that opal commonly includes small quantities of cristobalite, which can be determined only by X-ray diffraction patterns. A paper by Taliaferro [46] discusses the properties of opal as a solidified gel or glass and the relations of varying water content to the index of refraction and density of opal. These relations are illustrated in the following table by Kokta.[47]

Relations of water content, index of refraction, and density in opal

Percent H_2O	Index of refraction	Density
3.55	1.4592	2.160
4.71	1.4567	2.139
4.76	1.4512	2.104
5.08	1.4520	2.100
5.25	1.4501	2.122
5.30	1.4425	2.116
5.36	1.4528	2.046
5.36	1.4518	2.098
5.58	1.4496	2.055
6.05	1.4499	2.056
6.17	1.4478	2.070
6.27	1.4499	2.075
6.33	1.4531	2.096
7.05	1.4491	2.074
7.40	1.4445	2.038
8.36	1.4425	2.025
8.97	1.4465	2.036
9.16	1.4410	2.008

[46] Taliaferro, N. L., Some properties of opal: Am. Jour. Sci., 5th ser., vol. 30, no. 179, pp. 450-474, 1935.

[47] Kokta, Jaroslav, On some physico-chemical properties of opals and their relation to artificially prepared amorphous silicic acids (abstract): Mineralogical Abstracts, vol. 4, no. 11, p. 517, 1931.

The composition of the opal of organic origin in the various types of siliceous organisms is rather uniform, as indicated by the index of refraction, which varies little from 1.440±.002. A chemical analysis of the opal forming the skeleton of a siliceous sponge shows 88.56 percent silica and an ignition loss of 10.26 percent,[48] and according to Kokta's data the water content of opal with an index of refraction near 1.440 would be about 9 percent. In some experiments on the solubility of siliceous organisms in alkaline solution, Samoilov and Rozhkova [49] found diatoms more readily soluble than sponge spicules, as might be expected from the relative stability and degree of preservation of the remains of each in siliceous formations; but the greater solubility of the diatoms may be due only to their much greater delicacy of structure, rather than to any difference in the opal of the two groups of organisms.

The index of refraction of the opaline matrix in the cherty and porcelaneous rocks is somewhat variable but is generally near 1.46. Under high magnifications, however, this opaline matrix does not appear perfectly homogeneous and glassy, like the opal of the siliceous organisms, but finely granular, and it usually can be seen to contain appreciable quantities of minute clay particles, which produce an aggregate effect on the index of refraction. Some of the finely granular material is not resolvable into discrete particles and may be an amorphous mixture approaching, at least, the state of a solid solution of opal and alumina. In a recent study of the Monterey siliceous rocks of the Palos Verdes Hills, Hampton Smith [50] found that one of the thin laminae of such impure opaline material contained 6.95 percent alumina, 84.96 percent silica, and 5.60 percent ignition loss. The recognizable clay minerals seemed inadequate for this proportion of alumina. The hardness of this thin lamina, moreover, was less than that of the purer opal laminae, and its index of refraction was near 1.464. For these reasons, and because its properties resemble those of the artificially prepared silica-alumina

[48] Clarke, F. W., and Wheeler, W. C., The inorganic constituents of marine invertebrates: U. S. Geol. Survey Prof. Paper 124, p. 4, 1922.

[49] Samoilov, Y. V., and Rozhkova, E. V., Deposits of silica of organic origin (abstract): Mineralogical Abstracts, vol. 3, no. 3, p. 147, 1926.

[50] Smith, Hampton, Unpublished dissertation at California Inst. of Technology.

gels studied by Splichal,[51] Smith concluded that the material represents a silica-alumina gel. The difficulty, however, of recognizing an amorphous silica-alumina gel intimately mixed with opal, and of determining how much of it is present, is illustrated in a recent study of artificially prepared silica-alumina gels by Hellmers and Köhler.[52] These investigators found a regular increase in index of refraction with increase in proportion of alumina to silica, and they attempted to correlate this relation with possible equivalents occurring in nature. The influence of water content was assumed to be rendered negligible by comparing only air-dried samples. Extended tests were made in order to determine how the index of refraction of the silica-alumina gel was affected by absorbed alkalis, organic acids, and iron oxide. It was concluded that absorbed alkalis present in such quantity as might be expected in natural occurrences would not greatly influence the indices of refraction, and that absorbed organic acids or iron oxide would noticeably color the mixture whenever they were present in such quantity as to have a marked effect on the index of refraction. The complexity of the factors influencing the index of refraction of such possible solid solutions of alumina with opal are thus evident. It seems probable that variations in the index of refraction of the matrix of the siliceous rocks is due not so much to variations in a silica-alumina gel as to (1) a variable proportion of water in the opaline silica, and (2) the aggregate influence of very fine particles of clay and other substances, visible only in part even under high magnifications. Any attempt to relate hardness to the purity of the opal is also difficult, as hardness appears to depend largely on state of aggregation and porosity, particularly where the rocks have been weathered and leached. The presence of alumina in solid solution in an opaline cement is therefore difficult to establish. The alumina in such form is necessarily scarce, for the total percentage of alumina in the siliceous rocks is generally relatively low, and most of it can be accounted for as contained in recognizable clay particles. In the main, therefore, the siliceous cement must be essentially opal.

Chalcedony and cryptocrystalline quartz, though distinctly less abundant than opal in most of the Monterey rocks, are the dominant silica minerals in the cherty shale of the lower part of the formation in some areas where the formation is unusually thick, as on Chico Martinez Creek and in Bixby Canyon. In the chert and cherty shale of Claremont Canyon, the rocks seem to be exceptionally altered and indurated, as might be expected from their occurrence in almost vertical strata next to a fault of large throw,[53] and they there contain more than the usual proportion of chalcedony and quartz. Even the few siliceous organisms preserved in calcareous concretions in these beds have been altered to chalcedonic silica. The diatoms, obtained by dissolving the carbonate concretions in acid, were identifiable even though partly corroded and altered to chalcedony. The chalcedony associated with rocks largely composed of opal usually occurs as vein fillings (pls. 7, *D*; 8, *A*, *B*) in the easily fractured opaline rocks, or fills the larger pore spaces, such as the chambers of Foraminifera (pl. 8, *C*, *D*) and the interiors of the largest diatoms (pl. 9, *B*, *C*). Only diatoms thus filled with chalcedony are easily recognizable in the opaline rocks, but it is difficult to determine whether the chalcedony has filled mere molds of the original diatoms, such as commonly occur in the porcelaneous shale, or has filled the interior of the original opaline shells, which are not easily distinguished from the surrounding opaline matrix.

Granular quartz is perhaps less abundant than chalcedony in the cherty rocks of the formation, but cryptocrystalline aggregates of quartz are commonly associated with the chalcedony, particularly in the vein fillings of fractured rocks, where the quartz usually forms a central mass bordered by the chalcedony. This mode of occurrence indicates that the quartz commonly forms the final deposit which completes the filling of the larger openings.

An unidentified mineral is so intimately associated with the opal and chalcedony that it is here described with them, though it is probably not a silica mineral. It occurs in such microscopically thin layers that no sample sufficient for chemical tests was obtainable. Its index of refraction is lower than that of the opal, having a mean value near 1.42, but its birefringence is higher than that of chalcedony. The mineral forms aggregates of fine fibers lying normal to the layers. These fibers have approximately parallel extinction and show positive elongation. These properties approach nearer to those of erionite (a lime-potash-soda zeolite) than to those of any other known mineral, but spectrographic tests of a sample of the mineral in which it is intimately interbanded with opal, made by Dr. Steiger of the chemical laboratory of the Geological Survey showed only the spectrographic bands for silica and a little magnesia and iron. Tests on a larger spectroscope might show additional elements, but the lack of appreciable calcium and alumina seems to show that the mineral is not erionite. In the opaline cherts thin films of this mineral line some of the cavities, some of them filled in later with chalcedony. Where these cavities are the interiors of diatoms, a surrounding film of this fibrous mineral makes it particularly difficult to determine whether any of the original opal of the shells

[51] Splichal, J., Contribution to the knowledge of colloidal clays (abstract): Mineralogical Abstracts, vol. 1, no. 9, p. 288, 1922.

[52] Hellmers, J. H., and Kohler, R., Die Bestimmung von Tonerde und Kieselsauregel in Boden auf optischem Wege: Preuss. geol. Landesanstalt, Lab. Mitt., Heft 21, pp. 22-54, 1935.

[53] Lawson, A. C., U. S. Geol. Survey Geol. Atlas, San Francisco folio (no. 193), 1914.

is present. This mineral is common in the concretionary opal masses that occur in diatomaceous strata. Some of the material filling concentric cracks in these concretions consists largely of tiny spherules made up of concentric layers of opal alternating with thinner layers of this fibrous mineral (pl. 9, *A*). The nearly parallel extinction of the radiating fibers produces the cross seen in each spherule under crossed nicols. Such material was examined by Taliaferro[54] and illustrated in his paper. He interpreted the concentric shells as layers of opal with thin void films between, but similar material from the same locality shows alternating shells of opal and this unknown mineral, which is more readily examined in thin chips immersed in index of refraction liquids than in thin sections.

Another undetermined mineral has replaced the shells of large discoid diatoms, preserving well their original form; these shells occur in a thin layer interbedded with the silty porcelaneous shale, exposed in road cuts south of the large diabase sill of the Miraleste area, in the Palos Verdes Hills. This rock is not silica-cemented, and the diatoms may readily be removed from their matrix. The original opal of these diatoms has been altered or replaced by a soft, white material, which is apparently amorphous and isotropic and has an index of refraction of 1.476±.003. Not enough of this material was obtained to serve for chemical analysis, but it may be allophane.

CLASTIC SHALE, MUDSTONE, AND SANDSTONE

Although the characteristic siliceous rocks constitute most of the Monterey formation, large quantities of normal clastic rocks are interbedded with them in a number of areas, and where the siliceous rocks grade laterally into strata consisting dominantly of these clastic rocks the name Monterey is not appropriate. Besides the decidedly siliceous rocks and the normal clastic rocks, there are intermediate or gradational rocks, such as the porcelaneous mudstone, which may form such large stratigraphic units as the McLure shale member of the Monterey formation. These intermediate rocks are commonly very fine-grained, but in a few places the siliceous rocks grade into sandstone. In the lower part of the Pismo formation, for example, the sandstones are commonly opal-cemented and grade into beds of sandy chert (p. 6). As the noraml clastic rocks of the Monterey formation are not, in general, significantly different from the usual sedimentary rocks of these types, little discussion of them is necessary here, though certain significant features of their bedding are considered in some detail in connection with rhythmic bedding.

Clay shale forms numerous thin beds and partings in some of the siliceous rock. Most of the argillaceous rock, however, particularly that forming thick beds, is better classed as mudstone; little of it is fissile enough to be properly called shale, and, as it contains much silt and some fine sand, the term claystone is inappropriate. The mudstone is generally gray to almost black in fresh exposures, but where weathered it is usually chocolate brown. Because of its lack of fissility it forms debris with a hackly to somewhat conchoidal fracture. Yellow films of jarosite are rather common in the weathered mudstone, and gypsum is often conspicuous along fractures. A thick mudstone formation immediately underlying the Monterey formation over a large area in Ventura and Santa Barbara counties has been named the Rincon formation.[55] Thinner units of similar mudstone are commonly interbedded in the Monterey, and beds of it a foot to several feet thick alternate with siliceous shale or siliceous carbonate beds that have a similar range of thickness.

The sandstones of the Monterey formation are generally feldspathic; much of the feldspar is fresh, and the grains are commonly angular, only the larger ones being more or less rounded. These features are common to most of the Tertiary sandstone of California.[56] Little if any of the Miocene sandstone found in this region is chiefly composed of quartz; much of it contains enough feldspar to be classed as arkose, though its arkosic character may not always be obvious in its megascopic appearance. The heavy mineral content of the sandstones varies widely both laterally and vertically, as might be expected from the different character of the source rocks in different areas. The published data on this subject need not be summarized here, being of little significance except for particular areas.

The sandstone forming the upper Miocene over a large part of the Salinas Valley and adjacent areas is of rather uniform and distinctive character, and in this region it is known as the Santa Margarita sandstone. The formation consists of light-colored sandstone, commonly almost white, generally massive-bedded and coarse-grained. It contains relatively little clay or mud. Fossils, chiefly large oysters and echinoids, are rather abundant at some horizons, and the fossils as well as the character of the bedding suggest accumulation in shallow water. The sandstone is distinctly arkosic, and in the type area, near the town of Santa Margarita, it contains nearly as large a proportion of feldspar as the large granodiorite mass to the east, from which it was evidently in large part derived. Its close similarity to the granodiorite in mineral composition is evident not only in the lighter minerals—largely orthoclase and sodic plagioclase with some quartz—but also in the heavier minerals—biotite, ilmenite, magnetite, apatite, sphene, epidote, and garnet. Vitric volcanic ash occurs

[54] Taliaferro, N. L., Some properties of opal: Am. Jour. Sci., 5th ser., vol. 30, no. 179, p. 465, 1935.

[55] Kerr, P. F., Bentonite from Ventura, Calif.: Econ. Geology, vol. 26, no. 2, p. 156, 1931.

[56] Reed, R. D., The occurrence of feldspar in California sandstones: Am. Assoc. Petroleum Geologists Bull., vol. 12, no. 10, pp. 1023-1024, 1928.

in the lower part of the formation but is scarce in most of it. The unusually light color of these beds seems to be due in general not to admixed ash but to the abundance of nearly white feldspar, part of which is finely divided as a result of disintegration without much decomposition, combined with a scarcity of muddy admixture in the form of finely divided clay and hydrous iron oxide.

In some areas this Santa Margarita sandstone interfingers with the Monterey formation, and on the San Joaquin Valley side of the Temblor range, coarse white sandstone of this formation is interbedded with nearly pure diatomite. The Santa Margarita sandstone thus appears to have accumulated in clear littoral waters that were not receiving much mud from extensive land drainage systems. Similar conditions except for generally deeper, offshore water are suggested for the accumulation of the equivalent diatomaceous rocks of the Monterey formation.

Sandstone dikes are common in the Monterey formation in some areas. The sand has evidently been forced along fractures in the porcelaneous and cherty shales, probably because these siliceous rocks are unusually brittle (pl. 14, *A*). Some of the sandstone dikes have evidently cut through a great thickness of beds. In the outcrops just north of Chico Martinez Creek, sandstone dikes extend through a great thickness of porcelaneous shale which contains no sandstone beds for many hundreds of feet above and below the horizon of the dikes. Some of the sandstone intrusions are locally concordant with the bedding and might be mistaken in small exposures for sandstone beds; such an occurrence is well illustrated in a report by Hoots [57] on the Santa Monica Mountains. Many of the sandstone dikes are impregnated with dead oil, which has suggested that oil and gas under pressure may have been a factor in forcing up the sand that formed the dikes;[58] some oil, however, would be likely to impregnate cross-cutting sandstone dikes in more or less bituminous strata, regardless of how these dikes may have been intruded.

CARBONATE BEDS AND CONCRETIONS

Limestone is remarkably scarce in the thick Tertiary deposits of California, but impure calcareous and dolomitic rocks occur as thin beds, or more commonly as concretions, in a large part of the Monterey formation. In an area including parts of Santa Barbara and San Luis Obispo Counties, a limestone member constitutes the lower part of the formation and is rather thick and conspicuous in some localities,[59] though it is thin or absent in intermediate areas. This limestone occurs near the contact of the lower and middle Miocene foraminiferal zones, and thin beds of less pure limestone and dolomite are common at various horizons in the middle Miocene part of the formation in many areas. Most of the calcium carbonate in the formation, however, is disseminated, and much of it occurs as Foraminifera shells, which form the greater part of some thin beds. In fresh exposures, as in the sea cliffs along the coast of the Palos Verdes Hills area and in the measured section near Naples, impure carbonate beds are unusually conspicuous and form hard reefs a foot or more in thickness, alternating with thicker zones that contain much less carbonate. In most of the hard beds the shells of Foraminifera are relatively rare and the carbonate occurs largely as rhombic crystals. Much of the carbonate is more or less magnesian, and part of it is dolomite. The varying proportions of calcite and dolomite in concretions and beds make it necessary to use the broad term carbonate rock, especially since it is often difficult, because of the obscuring effect of silicification, to distinguish the carbonates in the field by applying hydrochloric acid. Additional data on the calcium-magnesium ratios in these rocks, with relation to their areal and stratigraphic distribution, might well prove significant. Carbonate with considerable iron seems to be relatively scarce, though some of the cherty rocks near intrusive contacts of basalt contain crystals of ankerite, obviously formed as a result of contact alteration.

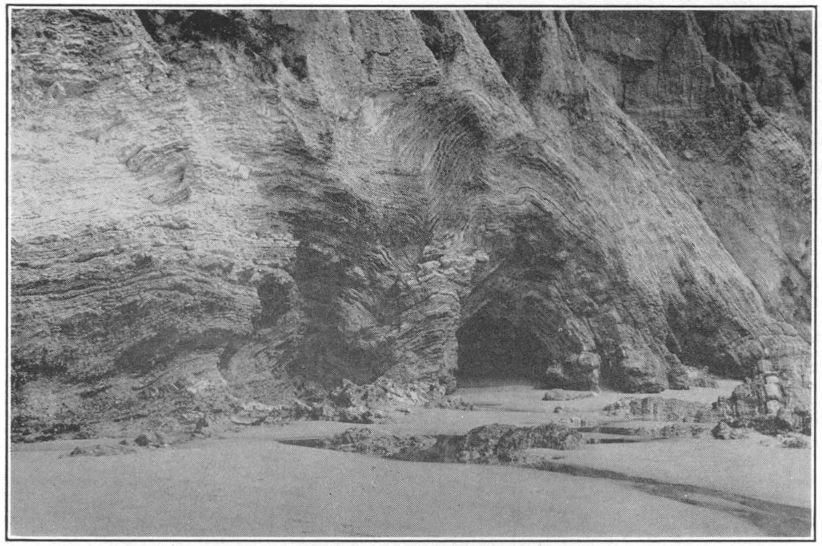
Carbonate concretions are distributed through much of the formation, especially its lower part, in many areas; their absence in certain areas, such as the type area near Monterey and the Lompoc quarry area, is exceptional. Although the concretions are apparently of an ordinary type that is common in many other formations, they seem worth describing because they show some features bearing on their mode of origin with special clearness, and also because they throw light on the origin of the siliceous rocks.

The concretions are generally oblate ellipsoids that have their longer axes parallel to the bedding. They are more or less abundant at rather definite stratigraphic horizons, the intervals between which range from a few feet to scores of feet and in many sections average about twenty feet. The maximum diameter of the concretions ranges from a few inches to several feet but is usually not far from uniform in any particular zone. The relations of the concretions to the bedding in the enclosing strata are well shown in thin-bedded siliceous strata (pl. 10); the beds continue through the concretions but are thicker within them than elsewhere, so

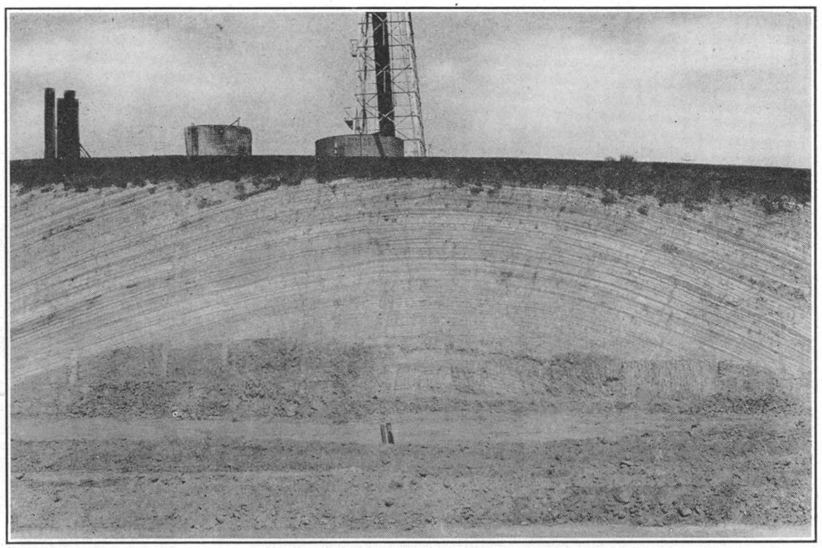
[57] Hoots, H. W., Geology of the eastern part of the Santa Monica Mountains, Los Angeles County, Calif.: U. S. Geol. Survey Prof. Paper 165-C, pl. 24, C, 1931.

[58] Jenkins, O. P., Sandstone dikes as conduits for oil migration through shales: Am. Assoc. Petroleum Geologists Bull., vol. 14, no. 4, pp. 411-421, 1930.

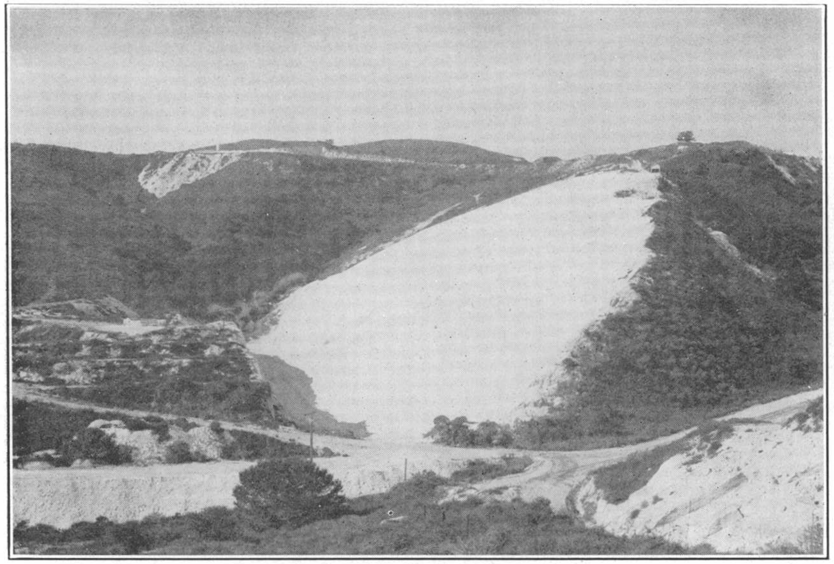
[59] Arnold, Ralph, and Anderson, Robert, Geology and oil resources of the Santa Maria oil district, Santa Barbara County, Calif.: U. S. Geol. Survey Bull. 322, p. 34, 1907.



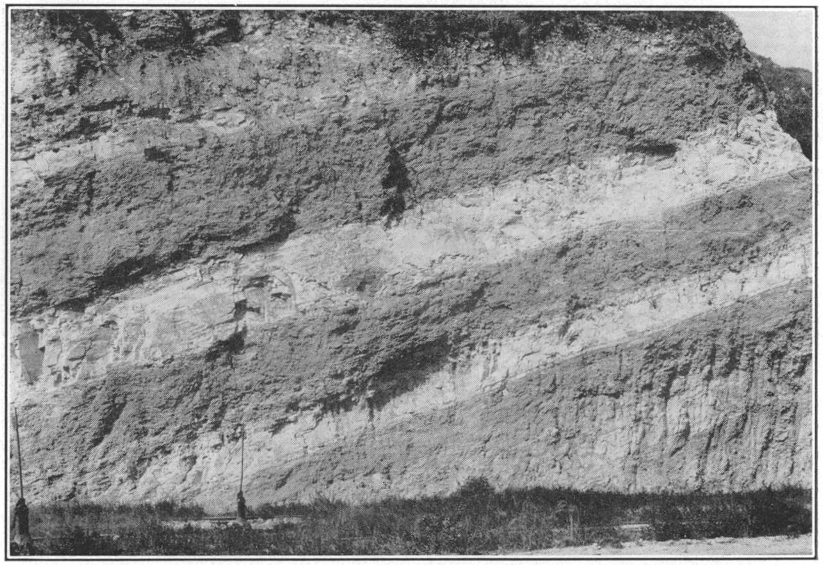
A. CLOSE FOLDING OF THE THIN-BEDDED SILICEOUS ROCKS OF THE MONTEREY FORMATION IN SEA CLIFFS ABOUT 3 MILES NORTHWEST OF PISMO, SAN LUIS OBISPO COUNTY.



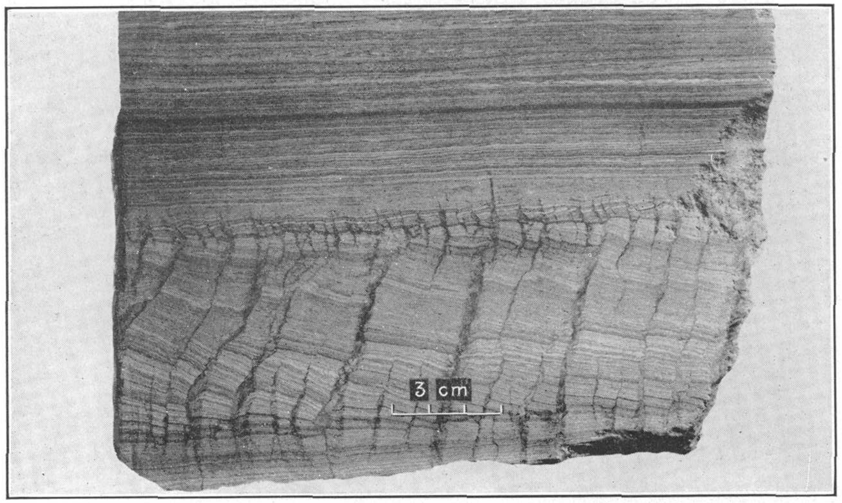
B. CREST OF SMALL FOLD IN THE THIN-BEDDED MONTEREY FORMATION IN ROAD CUT ON SOTO STREET, NORTH OF ALHAMBRA AVENUE, LOS ANGELES.



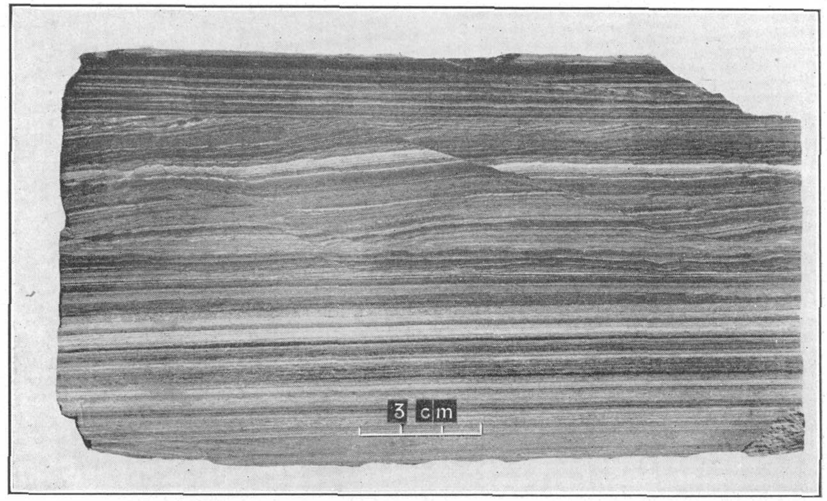
C. QUARRYING OF PARTICULAR STRATA IN THE DIATOMITE QUARRY OF THE JOHNS-MANVILLE CORPORATION, NEAR LOMPOC, SANTA BARBARA COUNTY.



D. ALTERNATING ZONES OF DIATOMACEOUS AND CHERTY ROCKS, AVERAGING 5 TO 10 FEET IN THICKNESS, ENTRANCE ROAD TO THE DIATOMITE QUARRY NEAR LOMPOC.

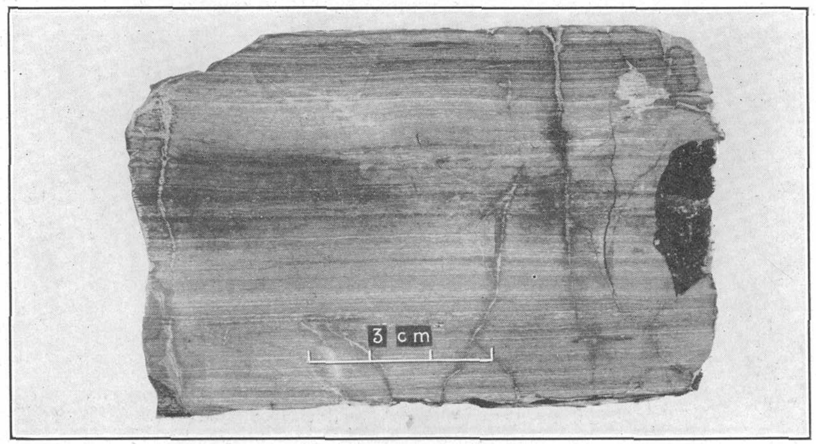


A. SMALL STEP FAULTS CONFINED WITHIN CERTAIN BEDS IN LAMINATED DIATOMITE.



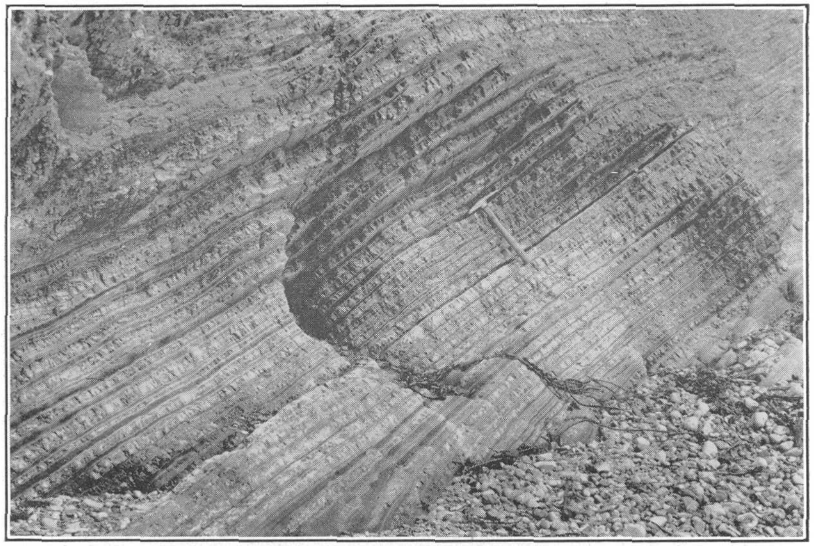
B. LOW ANGLE FAULTS IN LAMINATED DIATOMITE.

C. VOLCANIC ASH BED SHOWING SMALL DRAG FOLD IN LAMINATED DIATOMITE.

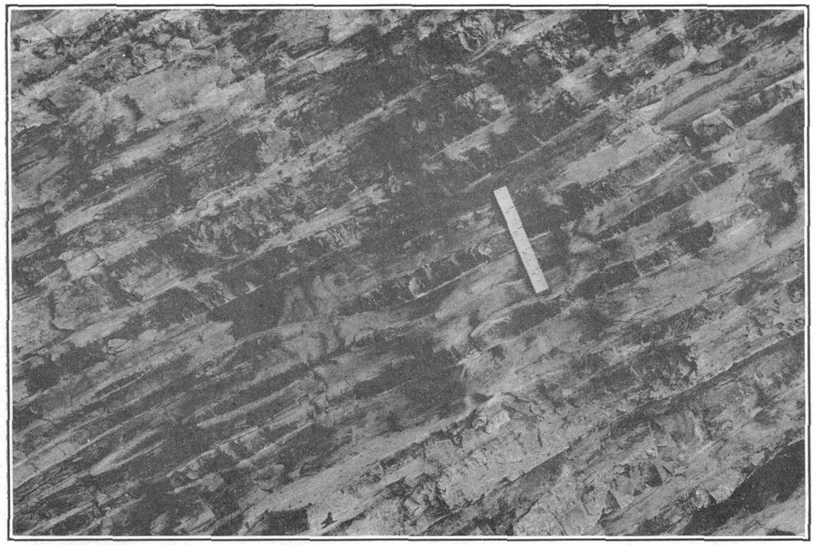


D. FINE LAMINATION IN CHERT.

Chipped edge at right shows dense black opal that is not etched.

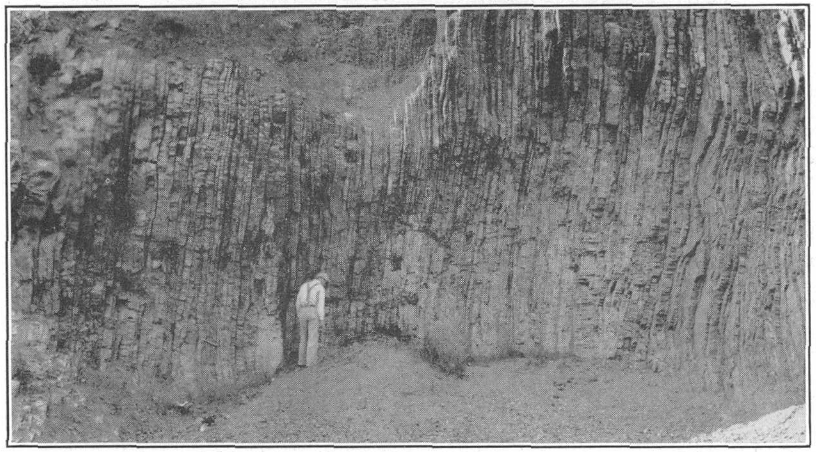


A. LATERAL UNIFORMITY OF BEDDING IN RHYTHMICALLY BEDDED CHERT.



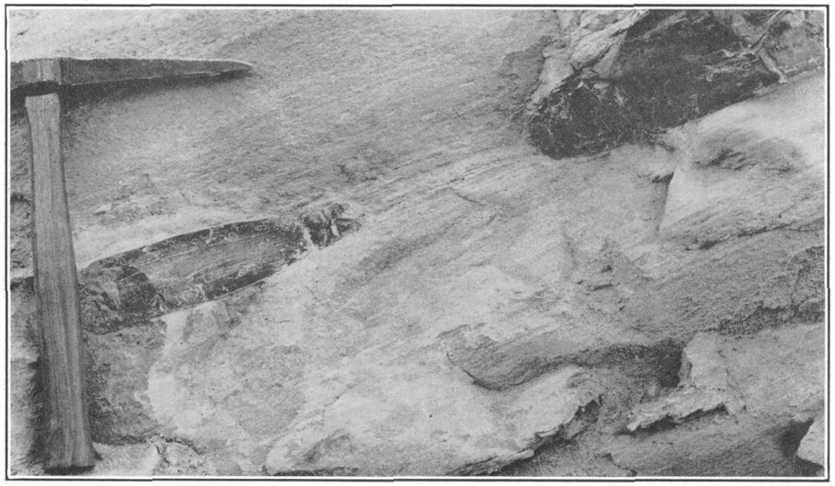
B. LENTICULARITY OF CHERT BEDS, PARTICULARLY OF THOSE IN MIDDLE PART OF PHOTOGRAPH.

Scale is 5 inches long.

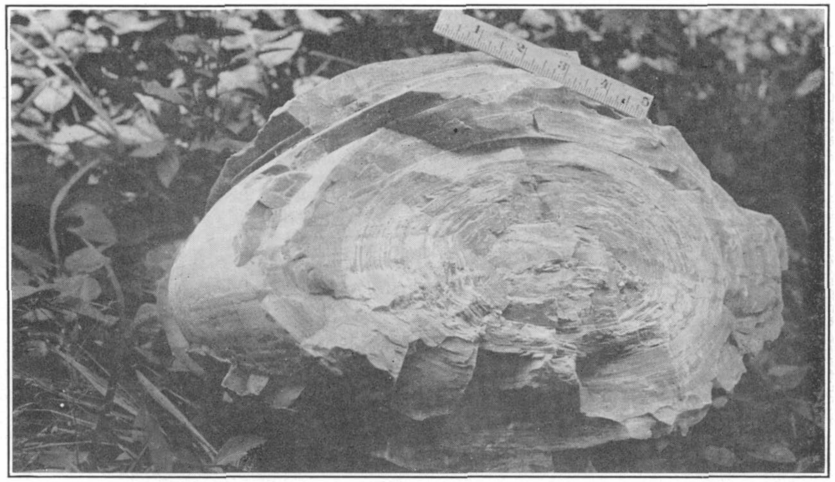


C. CHERT BEDS OF IRREGULAR THICKNESS, SOME OF WHICH PINCH OUT ABRUPTLY, IN CLAREMONT CANYON OF THE BERKELEY HILLS, ALAMEDA COUNTY.

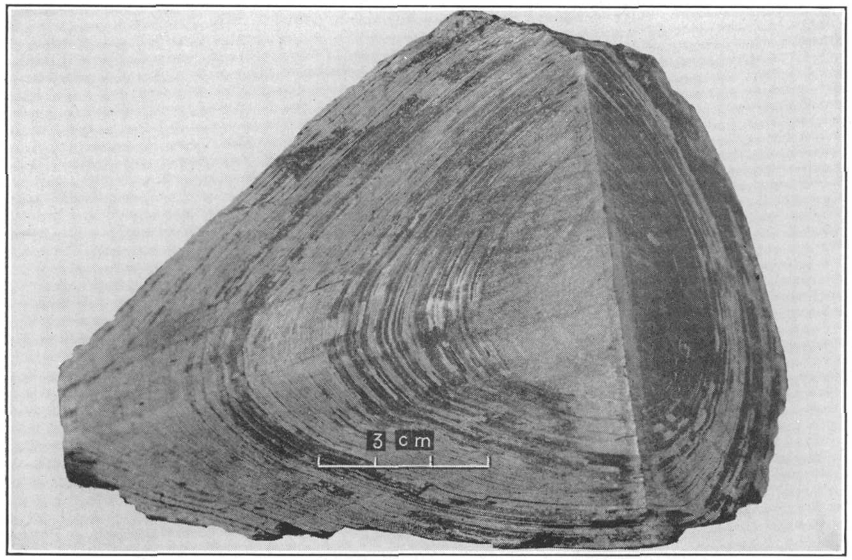
D. LENTICULAR OPALINE CHERT IN DIATOMITE.



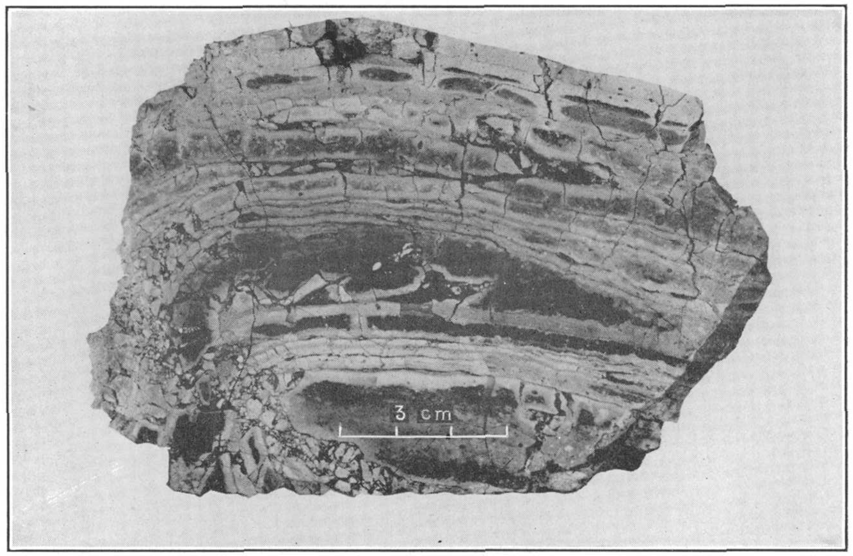
A. LENTILS OF DARK OPALINE CHERT WITH LAMINAE CONTINUOUS FROM DIATOMITE INTO CHERT.



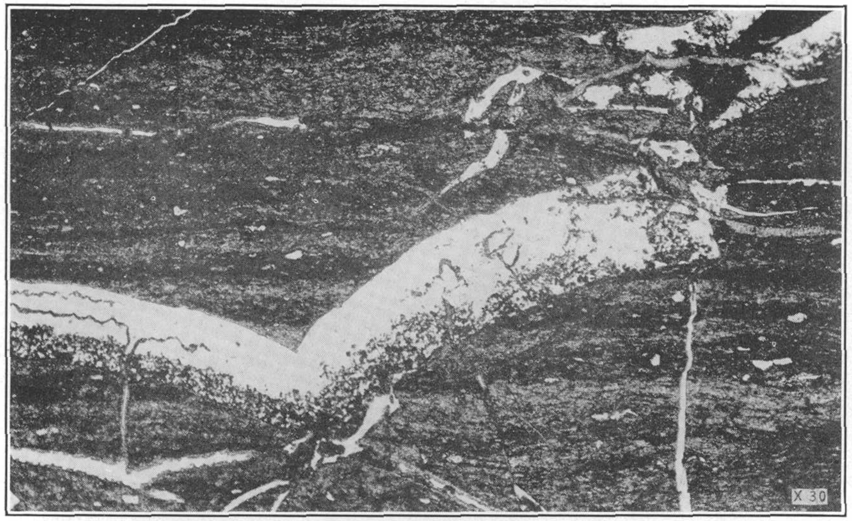
B. CONCENTRIC BANDING IN AN OPAL CONCRETION.



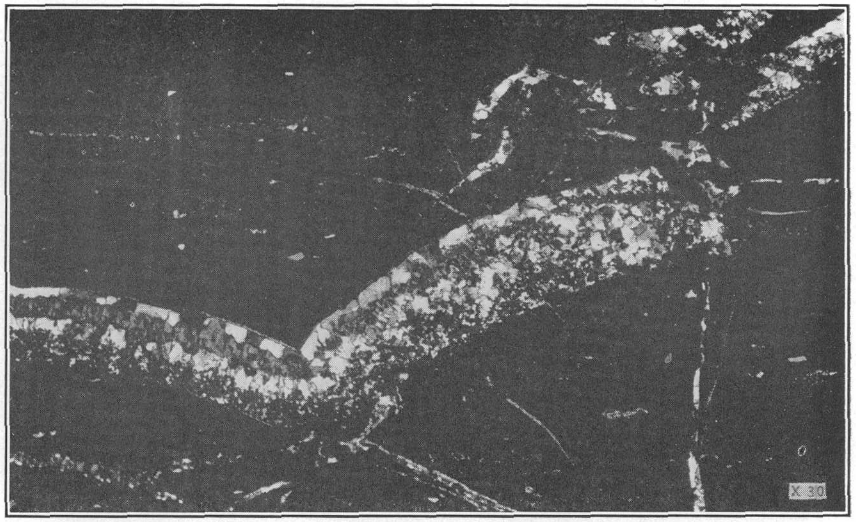
C. CONCENTRIC BANDING AND FAINT BEDDING SHOWN ON POLISHED AND ETCHED FACES OF AN OPAL CONCRETION FROM SAME LOCALITY AS IN PLATE 7, *B*.



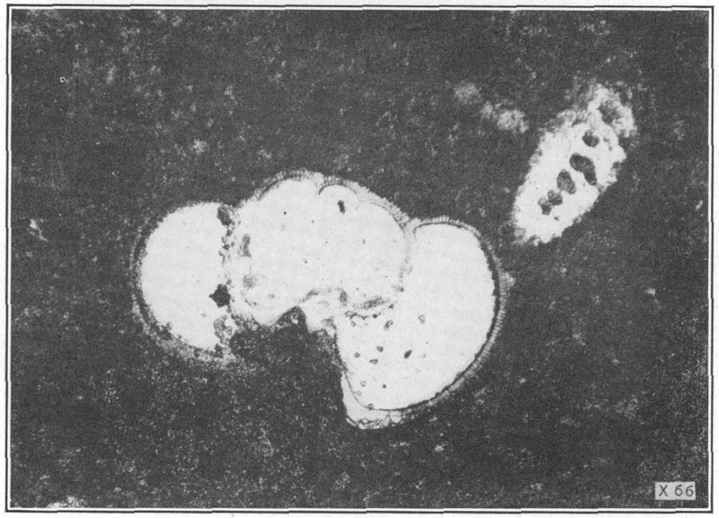
D. BRECCIATED AND RECEMENTED CHERT, ENTRANCE ROAD TO JOHNS-MANVILLE QUARRY NEAR LOMPOC.



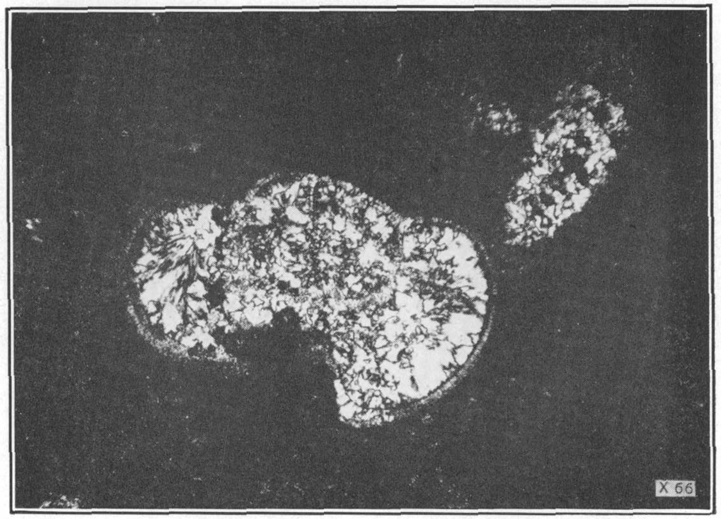
A. THIN SECTION SHOWING CHALCEDONY AND QUARTZ FILLING FRACTURES IN OPALINE CHERT.



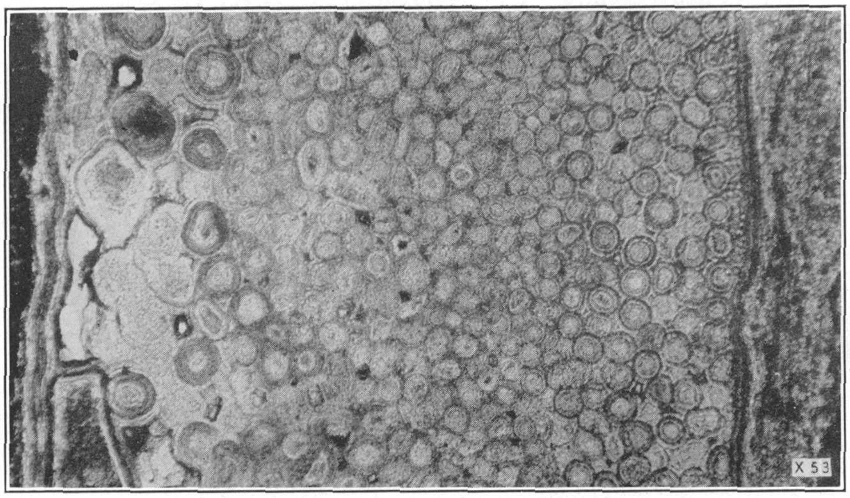
B. SAME AS 8, *A*, UNDER CROSSED NICOLS.



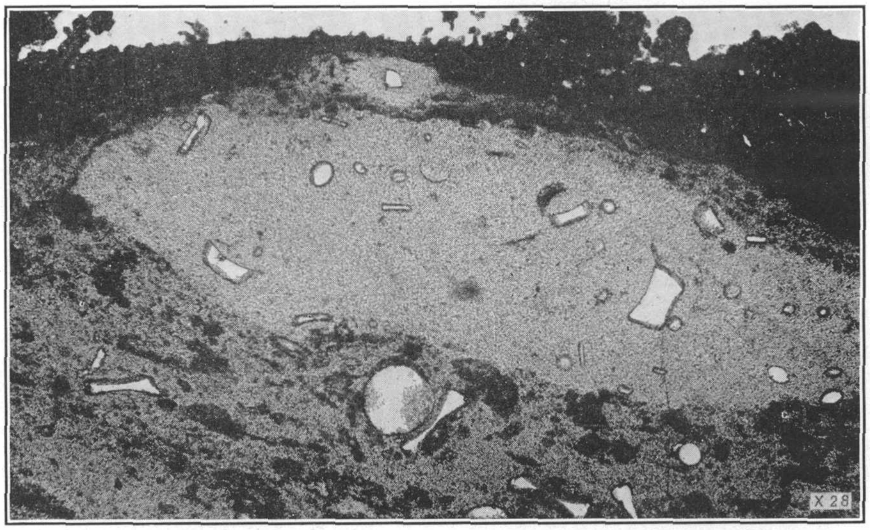
C. CHALCEDONY AND QUARTZ (CLEAR AREAS) FILLING AND PARTLY REPLACING CALCAREOUS FORAMINIFERAL SHELLS IN PORCELANITE.



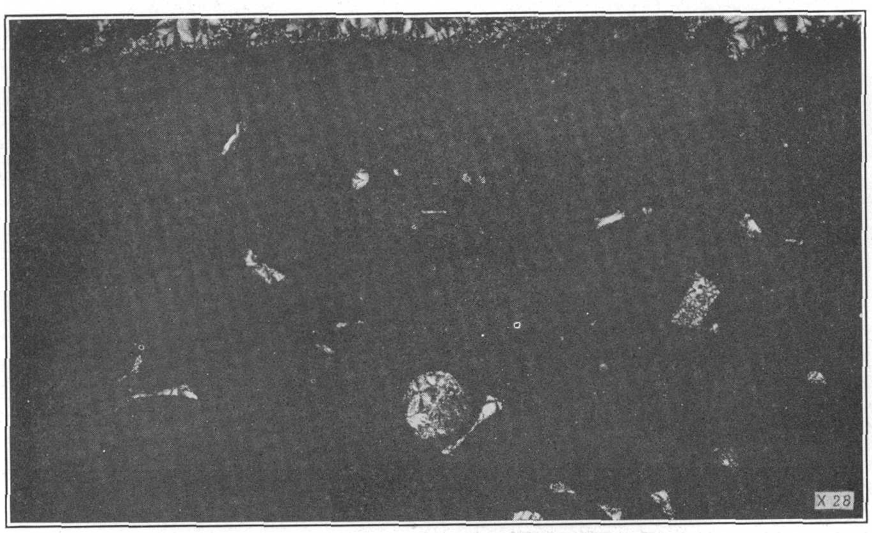
D. SAME AS 8, *C*, UNDER CROSSED NICOLS.



A. THIN SECTION OF SPHERULITIC OPAL FROM A VEINLET IN THE OPAL CONCRETION SHOWN IN PLATE 7, *C*.

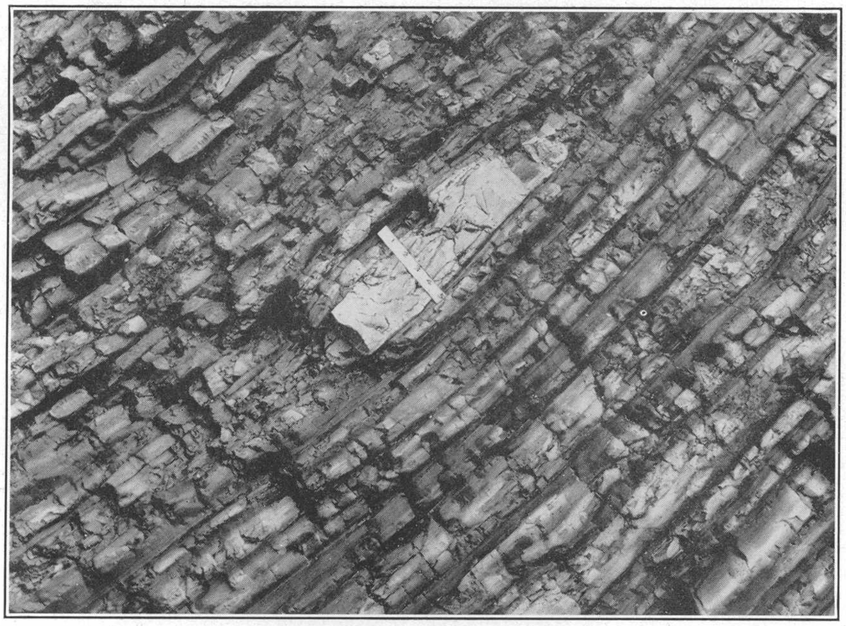


B. CHALCEDONY (CLEAR AREAS) FILLING THE INTERIOR OF LARGE DIATOMS IN OPALINE CHERT.
Irregular dark splotches are brown organic matter.

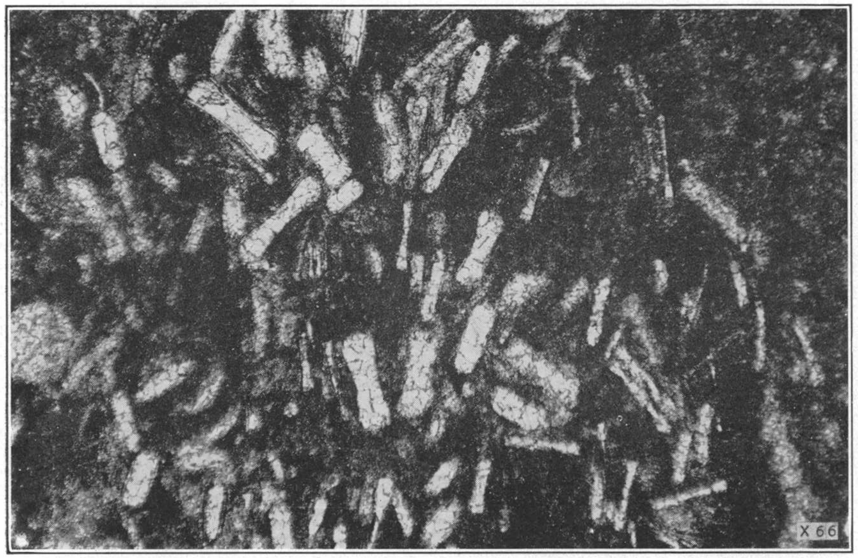


C. SAME AS 9, *B*, UNDER CROSSED NICOLS.

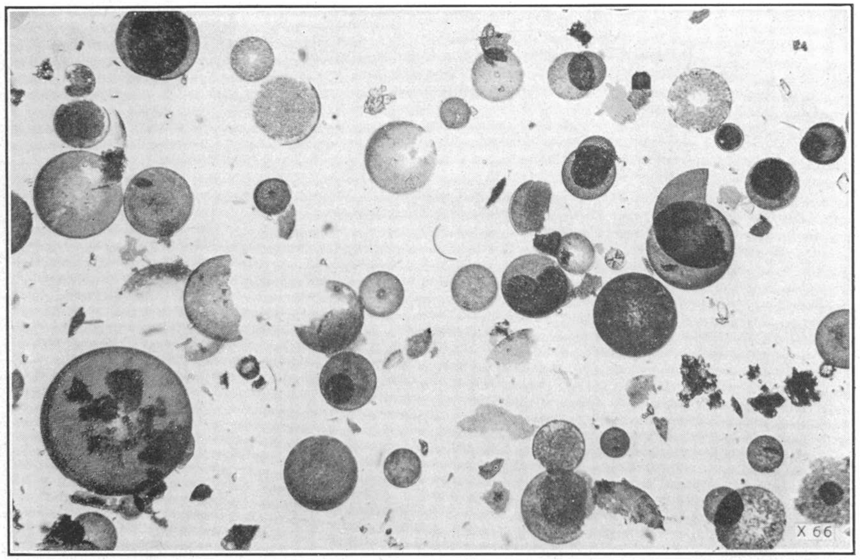
A. LARGE CALCAREOUS CONCRETIONS IN CHERTY SHALE IN ROAD CUT NEAR HOLLYWOOD COUNTRY CLUB, ON NORTH SIDE OF SANTA MONICA MOUNTAINS, LOS ANGELES COUNTY.



B. CALCAREOUS CONCRETION IN CHERTY SHALE IN SEA CLIFF ABOUT 2½ MILES NORTHWEST OF PISMO, SAN LUIS OBISPO COUNTY.

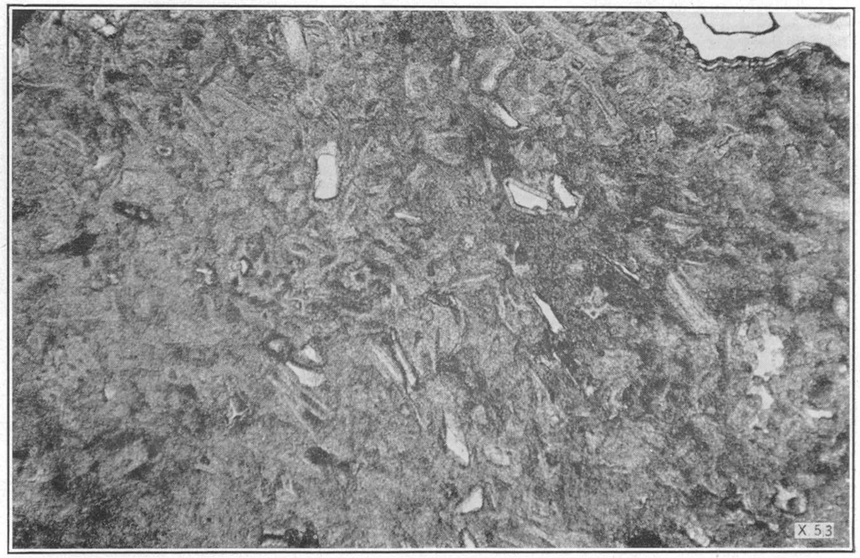


A. DIATOMS IN THIN SECTION FROM THE CALCAREOUS CONCRETION SHOWN IN PLATE 10, *B*, WITH CLEAR AND MORE COARSELY CRYSTALLINE CALCITE FILLING THE INTERIOR OF DIATOMS.



B. OPALINE DIATOMS OBTAINED FROM THE DIGESTION WITH ACID OF PART OF THE SAME SPECIMEN SHOWN IN 11, *A*.

C. THIN SECTION OF TUFF FROM THE OBISPO TUFF MEMBER OF THE MONTEREY FORMATION FROM THE VALLEY OF SAN LUIS OBISPO CREEK, SAN LUIS OBISPO COUNTY.



D. THIN SECTION OF A SILICIFIED BED IN THE OBISPO TUFF MEMBER OF THE MONTEREY FORMATION AT SOUTH POINT, ABOUT 2 MILES NORTHWEST OF PISMO, SAN LUIS OBISPO COUNTY.

that the beds immediately above and below the concretions bulge outward. All the concretions include more or less sedimentary material similar to that forming the adjacent beds, and most of them are little more than carbonate-cemented nodular masses of the sedimentary material forming these adjacent beds. The relations are particularly obvious where a variety of thin beds, including some of sandstone, pass through a concretion. A study of thin sections of carbonate-cemented sandstone under the microscope shows that the carbonate has not merely filled spaces between the sand grains but has also pushed the grains apart. Concretions in a light-colored diatomite are themselves light colored, as they contain little of the clay or other iron-bearing constituents which impart the usual rusty brown color to most weathered concretions. Such concretions contain many opaline diatoms. In thin section, the diatoms appear to have been replaced by carbonate, for the very thin opal walls are not distinguishable in the highly refringent calcite surrounding them and filling the interior of their frustules; but when the carbonate has been dissolved away with hydrochloric acid the original opal skeletons of the diatoms are seen to have been perfectly preserved (pl. 11, *A*, *B*).

The concretions in siltstone consist of carbonate-cemented silt. Some specimens of them contain [60] well-preserved grains of the less stable minerals, such as augite and hornblende, and shards of volcanic glass, which are absent or altered in the enclosing rock. Thin laminae in rhythmically bedded sediments can be clearly traced through the concretions. These relations to the enclosing rocks indicate how the concretions were formed. If the carbonate concretions had been formed syngenetically as nodular masses growing on the sea floor, as some that were dredged from the bottom of Auckland Harbor, New Zealand,[61] appear to have been, some of the adjacent sediment might well have been incorporated in them as they grew, but it is very improbable that layers of unconsolidated sediment would pass through growing masses of carbonate with little change in texture and composition. Where the concretions occur in thin alternating laminae of sand and finer sediment, it is particularly clear that they were formed after the strata were deposited.

Although these concretions are secondary, it seems clear that they were formed during the early stages of compaction and lithification and may thus be termed diagenetic products. The fact that the concretions occur at definite stratigraphic horizons indicates that they are not late secondary developments, related to present topographic and ground-water conditions. The individual beds are thicker in the concretions than in adjacent strata, and thus give evidence that the concretions were formed before the compaction of the beds was far advanced. When the enclosing rock is fine-grained, the beds are usually about three to four times as thick in the concretions as in the adjacent rock, but where the enclosing rock is sandy there is less difference in thickness. The beds immediately above and below the concretions are warped around them, owing largely to subsequent compaction; though without the other evidence the warping might equally well be interpreted as due to a secondary growth of the concretions after the consolidation of the beds. As already mentioned, some separation of grains by the growth of the introduced carbonate in the partially compacted beds is recognizable, and this growth evidently accounts in part for the greater thickness of beds within the concretions. Most of this difference, however, is probably due to pressure. At many places the Foraminifera, particularly the larger and thinner-shelled forms, in clay shale or siliceous shale are largely crushed or "pancaked," whereas within the concretions the Foraminifera in the same beds are not deformed, having evidently been protected from the pressures due to load and deformation. Abundant well-preserved diatoms are included in the concretions that occur in porcelaneous and cherty beds, which outside the concretions contain no recognizable diatoms. The diatoms within the concretions have apparently been protected not only from deformation but from solution and other agencies of alteration. This matter is considered further in the discussion of origin of the siliceous rocks (p. 48).

The physico-chemical conditions governing the development of the carbonate concretions are not evident, and they must in large part be inferred from theoretical considerations. Some, perhaps most, of the carbonate of the concretions may have been held in solution by the sea water included in the sediments, and precipitated at more or less regular intervals within the strata as conditions changed during the compaction of the beds. Part or most of the carbonate may represent finely divided calcite and aragonite that have been leached from nearby strata and reprecipitated in the form of relatively large and stable masses. No obvious leaching of the carbonate from strata adjacent to the concretions was noted, but such leaching might not be perceptible without detailed study if only minute particles of carbonate had been thus transferred. In these concretions no nuclei of carbonate or other material that may have served as a center for localizing the precipitation are evident; and the rather regular spacing of the zones of concretions suggests that their distribution may have been largely determined by differential concentration of solutions and the extent to which these solutions were diffused within the beds.

Many of the impure limestone beds forming hard reefs between thicker zones that contain less carbonate appear, like the concretions, to be secondary in the sense that

[60] Bramlette, M. N., The stability of minerals in sandstone: Jour. Sedimentary Petrology, vol. 11, no. 1, pp. 32-36, 1941.

[61] Bartrum, J. A., Concretions in the recent sediments of the Auckland Harbor, New Zealand: Trans. New Zealand Inst., vol. 49, pp. 425-428, 1916.

they were not deposited on the sea floor in their present form. The many small faults and the brecciation that commonly occur within these carbonate beds are of a type that could have formed only before the beds were lithified. The beds probably contained, originally, more carbonate than those adjacent to them, and were cemented through recrystallization. Calcite from adjacent beds was probably added, however, for evidence of leaching of Foraminifera and other calcareous material in adjacent beds is not uncommon. These impure limestone beds appear to have been formed in much the same way as the carbonate concretions, except that the relative abundance of carbonate along certain horizons tended toward the production of continuous beds rather than of nodular masses. A similar mode of formation for thin alternating beds of limestone and shale in several formations in the Alps has been suggested by Wepfer.[62] He applied the term auslaugungs-diagenese to this process of concentration of carbonate in certain beds through leaching of adjacent beds.

PYROCLASTIC MATERIAL IN THE MONTEREY FORMATION

Pyroclastic material occurs in much of the Monterey formation. It consists of unaltered vitric ash or tuff beds, partially altered tuffaceous beds, and the more thoroughly altered tuffaceous material known as bentonite, composed largely of the clay mineral montmorillonite. Some pyroclastic material is also disseminated in various kinds of sedimentary rocks. The character and stratigraphic relations of these pyroclastic materials not only bear on the problem of the origin of the siliceous rocks in the formation, but offer some additional information on the ways in which tuffaceous deposits may become altered. When more is known regarding their areal and vertical distribution, they should help in the making of more accurate stratigraphic correlations.

Pyroclastic material occurs in the pre-Miocene Tertiary [63] strata of California, but it is much more common and widespread in the Miocene and Pliocene, particularly above the base of the middle Miocene. In some areas pyroclastic material has been recognized in the lower Miocene, but it apparently is not so widespread nor so abundant here as higher in the section. In the Berkeley Hills, tuff and highly tuffaceous sandstone form the lower 100 feet of the Sobrante sandstone of Lawson,[64] but this is correlated with the Kirker tuff and is considered by Clark [65] to be Oligocene. Some of the lower Miocene part of the Temblor sandstone along Reef Ridge, on the west side of the San Joaquin Valley, contains admixed tuffaceous material of andesitic composition,[66] and the lower Miocene formation known locally as the Jewett silt of the Bakersfield area (pl. 3) is reported to be tuffaceous. Thick tuffaceous deposits are most widespread, however, near the contact of the lower and middle Miocene. Thinner beds are numerous above this horizon throughout much of the middle and upper Miocene deposits, though many of them are apt to escape observation except in fresh exposures, such as may be seen in road cuts, sea cliffs, or steep-walled stream cuts.

The thick tuff bed recognized at many places in San Luis Obispo and Santa Barbara Counties is the lowest and thickest in the Monterey formation of this region. It lies near the top of the lower Miocene, or about at its contact with the middle Miocene. This tuff is here designated the Obispo tuff member of the Monterey, since it is well exposed, with nearly its maximum thickness of several hundred feet, on the east side of San Luis Obispo Creek about four miles south of the town of San Luis Obispo. Correlated with it is the thick tuff exposed along the coast at Avila Beach and South Point, and at many other localities in the San Luis quadrangle.[67] This tuff is underlain by a dark mudstone formation, which is correlated (pl. 2) with the lower Miocene dark mudstone in the Ventura quadrangle, termed by Kerr [68] the Rincon formation. The tuff is considered to be the basal bed of the Monterey formation which above the tuff in this region consists of limestone, calcareous and siliceous shales, and thinner interbedded layers of tuff. Though the Obispo tuff member is widespread, it is apparently absent or unrecognizable at some places within the general region of its occurrence—as in parts of the Santa Maria area—perhaps because of non-accumulation or of dilution with sandy material that represents local shallow-water deposits.

The general character and the sparse crystals contained in the Obispo tuff member of the Monterey indicate that it is most probably rhyolitic, but may have the composition of a quartz latite or dacite. The crystals consist of a fresh plagioclase near oligoclase, less abundant quartz, which is in part euhedral, and accessory zircon and biotite. These minerals, however, form only a few percent of the tuff, which is chiefly composed of vitric shards (pl. 11, *C*). In the type area, where the formation is thickest, much of this vitric material shows little or no alteration, though some of it is partially devitrified and contains secondary crystals of a zeolite and of gypsum. The freshest glass, which appears entirely isotropic, has an index of refraction of 1.496±

[62] Wepfer, E., Die Auslaugungs-Diagenese, ihre Wirkung auf Gestein und Fossilinhalt: News Jahrb. fur Min., Beilage-Band 54B, pp. 17-94, 1926.

[63] Taliaferro, N. L., The relation of volcanism to diatomaceous and associated siliceous sediments: Univ. California Pub., Dept. Geol. Sci. Bull., vol. 23, no. 1, p. 19, 1933.

[64] Lawson, A. C., U. S. Geol. Survey Geol. Atlas, San Francisco folio (no. 193), p. 10, 1914.

[65] Clark, B. L., The San Lorenzo series of middle California: Univ. California Pub., Dept. Geol. Sci. Bull., vol. 11, no. 2, p. 75, 1918.

[66] Bramlette, M. N., Heavy mineral studies on correlation of sands at Kettleman Hills, Calif.: Am. Assoc. Petroleum Geologists Bull., vol. 18, no. 12, p. 1567, 1934.

[67] Fairbanks, H. W., U. S. Geol. Survey Geol. Atlas, San Luis folio (no. 101), areal map, 1904.

[68] Kerr, P. F., Bentonite from Ventura, Calif.: Econ. Geology, vol. 26, no. 2, p. 156, 1931.

.002. In other areas, such as those at Avila Beach and at South Point, the tuff is more largely devitrified and contains many silicified, cherty layers, about an inch to several feet in thickness, the thicker of which have somewhat the appearance of intercalated rhyolite flows. Thin sections of this cherty rock show the original pyroclastic texture—partially devitrified shards imbedded in an opaline cement (pl. 11, *D*).

The source of this tuff appears to be in the vicinity of the type area in San Luis Obispo County, where the thickness of the material is greatest and its texture coarsest. A general decrease in size of the fragments upward in the bed suggests that most of this tuff was the product of a single eruption and came from a single vent, though minor and inconspicuous breaks may occur in the tuff and some of it may be derived from nearby vents of nearly contemporaneous activity. The thickness and grain size of the Obispo tuff member decrease toward the south; any vents other than the main one, therefore, probably lay to the north, or perhaps west of the present coast. Thick tuffaceous deposits that probably correlate with the Obispo tuff member occur in the Adelaida quadrangle,[69] and these may have come from a local source in this more northern area. The tuff was deposited in marine waters, for it is immediately underlain and overlain by marine beds and contains in some places a few Foraminifera and diatoms.

The thick tuff bed at the mouth of the Cuyama River, in Santa Barbara County, is believed to be the Obispo tuff member of the Monterey though its base is not exposed and its stratigraphic relations are therefore somewhat uncertain. In the Bixby Canyon section, near Point Concepcion (pl. 2), this tuff is 120 to 130 feet thick. Here, although its tuffaceous character is obvious, especially in the lower and coarser part of the bed, the rock is more altered than in the San Luis Obispo area; it contains a greater quantity of zeolites and clay minerals, and the glass is more devitrified. In the Gaviota section this tuff, together with the immediately adjacent beds, is poorly exposed and partly covered with landslides, which commonly occur on thick beds of altered tuff; its thickness, however, is at least 50 feet and perhaps nearer 100 feet. Farther to the southeast, in the coast section at Naples, this tuff is only about 30 feet thick and is largely altered to the clay mineral montmorillonite. Thin sections of this bentonitic tuff show clearly the outlines of the original vitric shards. These are altered in part to the clay mineral, but the larger ones, which are nearly isotropic, have altered to a zeolitic mineral—probably clinoptilolite.[70] The pyroclastic grains are much smaller than in the San Luis Obispo region. Farther southeast, in the Ventura quadrangle, there is a bentonite near the top of the Rincon formation which has been described by Kerr.[71] This bed, though only a few feet thick, has apparently been identified at several localities. Its stratigraphic position and relation to foraminiferal faunas indicate that it is equivalent to the Obispo tuff member of the Monterey. This tuff horizon is in the upper part of Kleinpell's *Uvigerinella obesa* zone, which he regards as the upper zone of the lower Miocene; and it is not far below his *Siphogenerina hughesi* zone, which he regards as the lowest zone of the middle Miocene (p. 4).

This tuffaceous horizon will probably be identified over a yet larger area, particularly to the east and north of the type area, though it probably will not be recognized much farther to the southeast, having thinned to a few feet in the Ventura area. In this direction it has thus become inconspicuous, and it is not very distinctive here because there are several other layers of bentonite above this horizon; most of these are thin, but some of them, which will be described later, are locally thick. Over the large area in which it may be definitely identified, the Obispo tuff member of the Monterey serves as a particularly good chronologic horizon marker. A tuff that is nearly pure and sharply delimited from adjacent beds seems to be the only sort of lithologic unit that can safely be considered contemporaneous throughout its lateral extent, as it is an ash that fell into marine waters and was deposited rapidly enough to contain very little other admixed sediment.

A possible equivalent of the Obispo tuff member of the Monterey may be present in the Chico Martinez Creek section of the San Joaquin Valley region (pl. 3). Here a moist, greenish-gray, soap-like clay about 60 feet thick occurs a little above the middle of the formation known locally as the Media shale and, to judge by foraminiferal correlations, at the horizon of the Obispo tuff member. This bed resembles a bentonite and is quite distinct from the adjacent normal shales, but the poor exposures in the creek bottom are so much weathered that the identification of the bed as an altered tuff is not entirely established. In Coffee Canyon of the Bakersfield area, also, an ash bed several feet thick and ash that has been reworked into overlying sands in the upper part of the formation known locally as the Olcese sandstone were shown to the writer by Wayne Galliher; and the paleontologic correlations of Kleinpell indicate that this ash bed is approximately at the horizon of the Obispo tuff member (pl. 3).

VOLCANIC ASH BEDS

Numerous beds of nearly pure volcanic ash occur in the Monterey formation above the horizon of the Obispo tuff member. Most of these beds are from less than an inch to a few inches, or at most a few feet, in thickness, though in a few areas there are some of much greater thickness. These volcanic ash beds are composed

[69] Taliaferro, N. L., personal communication.

[70] Bramlette, M. N., and Posnjak, E., Zeolitic alteration of pyroclastics: Am. Mineralogist, vol. 18, no. 4, pp. 167-171, April 1933.

[71] Kerr, P. F., op. cit., pp. 153-168.

almost entirely of vitric shards, with few crystals, and, except for some tuffaceous material in the upper Miocene of central California (p. 25), they commonly include little admixed material of non-volcanic origin.

The most nearly fresh glass, which appears to be entirely isotropic, generally shows an index of refraction near 1.50, though in samples from many horizons and many areas it ranges between 1.495 and 1.505. A chemical analysis of one of the most nearly pure and fresh of these vitric ash beds is shown below, along with that of an average for rhyolites.

Chemical analysis of a volcanic ash interbedded with upper part of diatomite in the Lompoc Quarry of the Johns-Manville Corporation, Santa Barbara County, compared with average composition of 64 rhyolites as given by R. A. Daly

	1	2
SiO_2	72.11	72.6
Al_2O_3	11.62	13.9
Fe_2O_3	1.01	1.4
FeO	1.19	0.8
MgO	0.16	0.4
CaO	0.38	1.3
Na_2O	2.13	3.6
K_2O	4.35	4.0
H_2O-	0.22	1.5
H_2O+	6.44	
TiO_2	0.37	0.3
BaO	0.15	----
MnO	0.01	0.1
	100.14	99.9

1. Volcanic ash from Lompoc Quarry. J. J. Fahey, analyst.
2. Mean of 64 analyses of rhyolites and liparites from Daly, R. A., Igneous Rocks and their Origin, 1914, p. 19.

The index of refraction of this vitric ash is 1.503± .002. Admixed material is thought to make up less than 5 percent of the rock, but a close estimate is impossible because it is uncertain whether certain of the crystals are foreign or not. The chemical analysis indicates that the ash is rhyolitic.

Most of the volcanic ash beds examined show a very small proportion of crystals, usually estimated at nearer 1 than 5 percent. The most numerous crystals are of fresh plagioclase ranging between oligoclase and andesine in composition, but there is some quartz, partly in the form of six-sided double pyramids, and a little biotite and zircon. Some of these crystals can be definitely identified as of volcanic origin by the thin, ragged films of glass which may be observed on parts of their surface. Some of them, however, are interpreted as volcanic only because of their rather uniform distribution and because they all belong to a few species that commonly occur in rhyolite. As these volcanic crystals are so scarce even in the tuffs, they would obviously be scarce and hard to identify in rocks that were largely clastic; in such rocks, fragments of glass would be the only evidence of volcanic admixture.

A few microfossils, such as diatoms and sponge spicules and less commonly Foraminifera, are present in the ash beds, but they are usually scarce in those beds even where the adjacent beds consist mainly of such organic remains. The ash beds commonly show a decrease of grain size from bottom to top and are sharply marked off from the overlying as well as the underlying beds except where the adjacent strata are massive siltstone or sandstone. In massively bedded strata the ash beds are likely to be impure and largely mixed into the overlying clastic sediments; but where the ash is interbedded with fine-grained and laminated diatomaceous sediment, microscopic study of many samples has revealed remarkably little reworked ash in the overlying beds. Samples taken less than an inch above the top of nearly pure ash beds several inches thick show only rare grains of the volcanic ash, certainly amounting to less than 1 percent of the overlying sediment. This seems to indicate that the ash beds were deposited in water below the depth of effective wave or current action, a condition that seems to have been usual where the Monterey beds that are evenly laminated (p. 34) were being laid down.

The thickest bed of relatively pure vitric volcanic ash that was found in the Monterey formation above the Obispo tuff member occurs near the base of the upper Miocene in the southern Salinas Valley. In the section measured along Quailwater Creek (pl. 2) this ash bed is more than 100 feet thick, though the upper part is impure and shows a gradation and reworking into the overlying Santa Margarita sandstone. It is underlain by diatomaceous shale, which contains a foraminiferal fauna classed by Kleinpell as the lowest zone of the upper Miocene; and beneath a few feet of this diatomaceous shale are porcelaneous and cherty shales that contain a fauna considered representative of the upper part of the middle Miocene. This ash bed is conspicuous for several miles in this area, and it seems to correlate with the bed exposed on the west side of the Salinas Valley north of Paloma, in the San Luis quadrangle.[72] Pyroclastic beds, some of them fresh and some of them altered to bentonite, are particularly common about at this horizon near the base of the upper Miocene, but they are generally thin, and so numerous that individual beds cannot be correlated for any great distance.

The vitric volcanic ash in the Monterey formation is not all in these distinct beds; some of it is disseminated through other rocks. Where the uppermost part of the Monterey consists, as it does in many areas, of poorly sorted diatomaceous mudstone and siltstone, it includes layers several feet thick that contain 5 percent or more of volcanic ash. Both the character of the sediments and the distribution of this volcanic ash suggest that such deposits accumulated in shallower or more agitated water than that in which distinct beds of nearly pure ash were formed.

Pyroclastic material is especially conspicuous and

[72] Fairbanks, H. W., op. cit.

abundant in much of the upper Miocene of central California, but that which occurs in this region is apparently different in composition and source from most of that in the more southern areas. In the Berkeley Hills-San Pablo Bay area (pl. 2), all the formations above the Tice shale, which is considered to be of early upper Miocene age, contain tuffaceous material, which becomes increasingly abundant upward in the section, and this material appears to be chiefly andesitic. The massive sandstones constituting most of the upper Miocene of this area contain disseminated shards of more or less altered glass, and in general a fairly large proportion of mineral grains that appear to be of pyroclastic origin. These are dominantly of fresh plagioclase ranging from andesine to labradorite; they also include much hornblende and also, in the upper part (San Pablo), much augite.

These minerals are characteristic of certain andesites, but there may be some question whether they can be singled out and identified as pyroclastic, mixed as they are with so decidedly greater a proportion of obviously clastic material. The belief that they are pyroclastic rests on the following facts. The few samples of the Oursan sandstone examined were found to contain no appreciable amount of vitric pyroclastic materials or of the andesitic minerals. They consist mainly of various feldspars and quartz, but contain the heavy minerals magnetite, zircon, garnet, tourmaline, sphene, and rarer grains of glaucophane. All these minerals appear to be in ordinary clastic grains. Samples above the base of the Hambre sandstone, on the other hand, contain not only grains like these, but also appreciable though varying quantities of partially altered volcanic glass shards and larger quantities of fresh plagioclase ranging from andesine to labradorite, much of it zoned, and of green hornblende. The andesine-labradorite and hornblende have a volume, in each sample, that is roughly proportional to the volume of the vitric shards, and as these are obviously volcanic the quantitative relation just noted strongly suggests that the fresh feldspar and hornblende are also volcanic. The most nearly fresh glass, which is completely isotropic, has an index of refraction near 1.50, which would be consistent with a dacitic or even rhyolitic composition (p. 24), but this index of refraction is not necessarily too low for the glassy part of an andesite. Most of the shards of glass are more or less altered, and these altered shards commonly have a weak birefringence and an index of refraction between 1.48 and 1.49, which is the same as that of the associated crystals of zeolite.[73] It is believed that this relatively low index is a result of alteration and does not indicate the original composition of the glass.

All three members of the Briones sandstone contain admixed vitric shards, together with mineral grains that appear andesitic; and in much of the overlying San Pablo formation such materials become more conspicuous. All these upper Miocene sandstone formations show massive bedding and other features that suggest deposition in shallow waters, or at least in waters subject to wave or current action. It may be because of such conditions that the pyroclastic materials are here disseminated rather than concentrated in purer beds; even ash that fell directly into marine waters, if these waters were continually agitated, would inevitably mingle with clastic sediment that was being deposited at nearly the same time.

How much of the andesitic material in the upper Miocene of central California fell thus directly into the sea, or whether any did so, can hardly be decided from the facts now available, which are open to various interpretations. Certain relations pointed out by Louderback[74] suggest that the andesitic material, or at least that forming fragments of gravel sizes, was largely brought into the area by streams from the east and north and derived from the andesitic rocks of the Sierra Nevada. Fragile shards of glass, however, would be less likely to survive so long a journey. Perhaps the andesitic mineral grains were thus brought in by streams from the northeast while most if not all of the vitric material represents ash falls, as it does in most of the pyroclastic material farther south. Some reasons for believing they have a common source and mode of derivation have been mentioned, however, and another possible interpretation may be suggested.

The proportion of crystals to glass will vary in a given fall with distance from the source—the farther the distances drifted from the source, the sparser will be the crystals. Such a variation was noted in ash thrown out by the great explosion of Krakatoa. It seems possible, therefore, that the pyroclastic material of the upper Miocene, not only in the central part of California but also, to a larger extent than is now recognized, further south, was erupted from andesitic volcanoes, and that in areas nearer the source these pyroclastic materials would contain relatively numerous crystals of andesitic rocks, whereas the thin shards of glass would be carried far to the south. This may account not only for the relatively small quantity of pyroclastic material in the upper Miocene of southern California but also for the lack of recognizable andesitic pyroclastic materials in this region. The Obispo tuff member of the Monterey, as already indicated, evidently had a different source and is more silicic in composition, and the pyroclastic beds in the overlying middle Miocene resemble it in composition. Some of the beds of pyroclastic material in the upper Miocene of southern California are also silicic in composition, as is illustrated by the analysis of the fresh ash from the Lompoc Quarry (p. 24), and an ash from the Santa Moncia Mountains (p. 28); but

[73] Bramlette, M. N., and Posjnak, E., op. cit.

[74] Louderback, G. D., Period of scarp production in the Great Basin: Univ. California Pub., Dept. Geol. Sci. Bull., vol. 15, no. 1, pp. 1-44, 1924.

even in central California, the dominantly andesitic pyroclastic materials of the upper Miocene are associated with more silicic ash beds. The available evidence is thus not conclusive as to the quantity of pyroclastic material from andesitic volcanoes that is present in the upper Miocene of southern California. The areal extent of this material may prove of some importance, as the stratigraphic correlations in the upper Miocene and Pliocene may be partly substantiated from data on the composition of the dominant types of pyroclastic material, which in the tuffaceous sandstones of the Coalinga area show a rather definite eruptive sequence.[75]

BENTONITE BEDS

Bentonite beds are numerous in the middle and upper Miocene of California. As pointed out in discussing their relation to the unaltered pyroclastics (p. 27), they occur in strata underlying those that contain the unaltered ash beds. The derivation of some of the bentonite beds from tuffs is clearly shown by the well-preserved pyroclastic texture seen in thin sections, which abound in relict shards altered to the clay mineral montmorillonite. But in most of the beds regarded as bentonite no pyroclastic texture is preserved. Since the term bentonite is defined by Ross and Shannon[76] as implying a derivation from tuff, evidence of the pyroclastic origin of these beds must be considered. Relict pyroclastic texture would, of course, easily be effaced in these thin waxy beds, wherein movement along bedding planes has so commonly caused marked pinching and swelling, and localized bedding slips and other minor deformation features are often obviously associated with these particular beds (pl. 12, *B*). In certain localities, bentonite beds not showing any preserved pyroclastic texture are known to be equivalent to beds of vitric tuff elsewhere (pp. 27-28), and it is thus evident that some bentonites fail to show the relict texture which is the most direct evidence of derivation from glassy volcanic ash.

Certain distinctive physical characteristics may be used as suggestive, though not definite, criteria for the recognition of bentonite independently of relict textures. These characteristics depend on the fact that bentonites, wherever found and whether or not they show pyroclastic texture, are usually composed of the clay mineral montmorillonite. The beds classed as bentonite in the Monterey formation consist of a homogeneous clay, waxy or soap-like in consistency, pieces of which, when fresh and moist, are slightly translucent on thin edges. On exposure to air, the fresh clay dries and cracks markedly on the surface. When placed in water, especially after drying, the bentonite rapidly slakes or sloughs down into a flocculent gel-like mass, with an increase in volume that is often very marked. The color varies widely, ranging from almost white through creamy and yellowish tints to green or brown, depending apparently on the amount of iron present and its state of oxidation.

The mode of occurrence of these distinctive clay beds in the Monterey formation is also somewhat suggestive of their origin. Most of them are thin—an inch or less to several inches in thickness—and are sharply separated at both base and top from the adjacent beds, which may consist of normal clastic mudstones, of calcareous or porcelaneous shales, or of some other rock (pl. 12, *A*). In their homogeneity and sharp contacts with adjacent beds, which clearly record abrupt changes in the character of sedimentary deposition, they resemble the beds of vitric ash (pl. 5, *C*).

The clay mineral of which these bentonite beds are largely composed is identified by its refringence and birefringence as montmorillonite. Other minerals are generally very minor constituents. The most common, in the bentonites as in the fresh vitric tuffs, are fresh plagioclase—ranging from oligoclase to andesine—and quartz. Euhedral crystals of gypsum are common in the weathered outcrops of bentonites. Distinct silicification of the immediately adjacent beds is seen at some places; usually this affects the underlying bed more than the overlying one, and seems to be an impregnation with silica derived from the alteration of the tuff to bentonite (p. 44). That such silicification of adjacent beds was not more commonly recognized is probably due to the usual occurence of the bentonites in the porcelaneous and cherty strata, where any additional silicification would be difficult to distinguish.

The few bentonites from this formation that were tested by P. G. Nutting of the Geological Survey's chemical laboratory proved to have very poor bleaching qualities both in their raw state and after acid treatment.

RELATIONS OF THE UNALTERED VITRIC TUFFS AND THE BENTONITE BEDS

The Obispo tuff member of the Monterey, as already indicated, is little altered in the type area, where it consists mainly of almost fresh vitric material; southeastward the bed is progressively more altered as it becomes thinner and more fine-grained; and along the Santa Barbara coast down to a place near Ventura it is largely a bentonitic clay. Such a relation between degree of alteration on the one hand and thickness and grain size on the other is to be expected; action by solutions would become more effective as the size of the particles decreased and as the ratio of the volume of available solution to the quantity of material acted on increased. Equally significant, however, is the relation between degree of alteration and character of enclosing

[75] Bramlette, M. N., Heavy mineral studies on correlation of sands at Kettleman Hills, Calif.: Am. Assoc. Petroleum Geologists Bull., vol. 18, no. 12, pp. 1570-71, 1934.

[76] Ross, C. S., and Shannon, Earl V., The minerals of bentonite and related clays and their physical properties: Jour. Am. Ceramic Soc., vol. 9, no. 2, pp. 77-96, 1926.

beds. The unaltered volcanic ash generally occurs in strata that are but little indurated, such as the diatomite and less pure diatomaceous strata that occur in the upper part of the formation in many areas; the more altered pyroclastic beds, including the bentonites, are never found in these diatomaceous deposits, but occur in underlying, more lithified strata, such as the porcelaneous and cherty shales or the clay shales and mudstones associated with them. This relation holds for all the sections that were examined carefully and that are shown in plates 2 and 3, and they hold also for a much greater number of partial sections examined in other areas. No exceptions are known, but the following qualification is important: although no beds of bentonite, or even of partially bentonitized tuff, were found in any of the diatomaceous deposits, some few beds of vitric tuff that are not appreciably altered are found in lower strata interbedded with porcelaneous and cherty rocks. The Obispo tuff member in the type area is such a bed; the influence of its especially great thickness and the coarseness of its texture have apparently outweighed the influence of stratigraphic position. An ash bed on Mulholland Drive, along the crest of the Santa Monica Mountains, which is interbedded with porcelaneous shale strata but lies not far below the transition to overlying diatomaceous strata, is only slightly altered but grades laterally into a bentonite (pp. 27-28). In a zone of interbedded diatomaceous and cherty rocks such as occur in the Naples and the Lompoc Quarry sections, the ash beds are in part nearly fresh. These beds are transitional, however, both in their degree of alteration and in their occurrence within a zone of alternating diatomaceous and cherty rocks. The significance of the consistent occurrence of fresh vitric material—without any bentonitic tuffs—in the diatomaceous deposits, combined with the almost as consistent occurrence of more altered tuffs in underlying strata that are associated with the porcelaneous and cherty rocks, is considered in the discussion of the origin of these siliceous rocks. Some additional occurrences described below show the relations particularly well, because they represent occurrences in equivalent strata at different localities.

In the Palos Verdes Hills of southwestern Los Angeles County, a vitric tuff bed, though only a few feet thick, has been given a name—the Miraleste tuff bed—because its distinctive character makes it useful as a key bed in mapping the area.[77] This bed, which occurs in the Altamira shale member of the Monterey formation, contains numerous lapilli of brown, rather basic pumice, having a refractive index of about 1.54, scattered in a light matrix of impure fine ash that has a refractive index of about 1.50. In many exposures on the north flank of the hills, where it is associated with soft diatomaceous strata, this tuff is unaltered; but in several exposures of the same bed less than a mile to the south, where it is interbedded with porcelaneous and cherty shale strata, it is so altered that both the matrix and pumiceous lapilli are almost a bentonitic clay, though the lapilli are clearly distinguishable from the matrix. Both the field mapping and foraminiferal faunas indicate that the strata of these two areas are equivalent.

On the north flank of the Santa Monica Mountains, in Los Angeles County, a pyroclastic bed about two feet thick is exposed in a road cut along the Mulholland Drive, at the locality marked No. 57 on the geologic map of this area made by Hoots.[78] The middle 16 inches of this volcanic ash bed is very little altered, and is seen under the microscope to consist largely of isotropic glass with an index of refraction of 1.504±.002. Nearer the base and top of this bed the glass shows more evidence of devitrification, the shards being coated with thin anisotropic films; and for a thickness of about an inch at both top and bottom the bed is altered to a bentonitic clay. About a mile to the west, this bed is composed enirely of bentonite. The basis for correlating this bed in these localities is shown in the following detailed sections, and a similar sequence was found in several exposed sections in nearby canyons, including one between the localities of the sections described below.

[77] Woodring, W. P., Bramlette, M. N., and Kleinpell, R. M., Miocene stratigraphy and paleontology of Palos Verdes Hills, Calif.: Am. Assoc. Petroleum Geologists Bull., vol. 20, no. 2, p. 134, 1936.

[78] Hoots, H. W., Geology of the eastern part of the Santa Monica Mountains, Los Angeles County, Calif.: U. S. Geol. Survey Prof. Paper 165-C, pl. 16, 1931.

Stratigraphic sections showing lateral change of volcanic ash into bentonite

Section at locality No. 57 of Hoots and in immediately adjacent canyon to the northeast

Porcelaneous shale.		
Volcanic ash bed (sample A)	inches	23
Platy, porcelaneous shale	feet	20
Rusty brown bentonite	inches	2
Porcelaneous and silty shale	"	6
Greenish-yellow bentonite	"	½-1
Porcelaneous shale	feet	12
Buff bentonite	inches	6
Porcelaneous shale	feet	22
Sandstone.		

Section in cut on west side of hill 1,215 feet high, 1.18 miles N. 77° W. from locality No. 57

Porcelaneous shale.		
Rusty-brown bentonite (sample B)	inches	4
Platy, porcelaneous shale	feet	18
Rusty-brown bentonite	inches	2
Porcelaneous shale	"	5
Greenish-yellow bentonite	"	½
Porcelaneous shale	feet	11
Yellow bentonite	inches	8
Porcelaneous shale	feet	16
Sandstone.		

Chemical analyses of samples A and B from the above sections are shown in the following table. The specific gravity of the vitric ash of sample A was determined by P. G. Nutting of the Geological Survey Laboratory as 2.297.

Chemical analyses of vitric volcanic ash and of equivalent bed of bentonite from north side of Santa Monica Mountains, Los Angeles County, Calif.

	1	2	3	4
SiO_2	70.30	65.66	50.03	51.53
Al_2O_3	[1]12.82	12.71	16.75	17.92
Fe_2O_3	.42	1.94	5.83	4.24
FeO	1.80	1.60	.47	0.14
MgO	.27	.71	2.78	1.98
CaO	1.18	1.44	1.20	1.22
Na_2O	2.10	1.10	.26	.50
K_2O	2.48	1.73	.60	.09
H_2O-	.68	4.34	13.53	} 21.86
H_2O+	7.12	8.03	7.52	
TiO_2	.32	.40	.65	.47
P_2O_5	....	.06	.24	None
MnO	.07	.00	.01	....
BaO	.17	.17	.16	None
	99.73	99.89	100.03	99.95

[1]Includes P_2O_5

1. Washed concentrate of largest and least altered shards of vitric volcanic ash from sample A, taken at Hoots' locality No. 57. R. E. Stevens, analyst.
2. Untreated vitric ash from sample A, including finer ash and thin films of bentonitic material. Charles Milton, analyst.
3. Bentonite, sample B, taken 1.18 miles from locality of sample A. Charles Milton, analyst.
4. Bentonite from cut along Topanga Canyon Highway about 800 feet northwest of crest of Santa Monica Mountains, believed from similarity of sequence to be from same bed as samples A and B. J. J. Fahey, analyst.

These analyses are interesting because they represent fresh material and altered material from the same pyroclastic bed, so that the chemical changes involved are more certainly indicated than those merely assumed for other bentonites. Analysis no. 1 represents a nearly fresh glass of rather silicic composition. The chemical changes involved in the slight alteration observable microscopically in the untreated ash of Sample A are shown in analysis no. 2 to include some loss of silica and alkalies and an increase of water. Analysis no. 3 shows a marked decrease of silica, loss of most of the alkalies, and a large increase of water below 110° C. As indicated by Ross and Kerr,[79] these seem to have been the most important changes involved in the formation of most bentonites. The increase in magnesium is also usual in the formation of bentonite. The sample of bentonite represented by analysis no. 4 is not certainly from the same bed as the others. It is yellow, rather than rusty brown like the one represented by analysis no. 3, yet the iron content of the two samples is not greatly different.

[79] Ross, C. S., and Shannon, E. V., op. cit.

Sample no. 2 appeared from a casual field examination to be a fresh ash. A slight alteration was noted on examination under the microscope, but only after the analysis showed more water and less alkalies than might be expected in fresh ash. Sample no. 1 was therefore analyzed after washing part of the original sample to eliminate the thin films and fine particles of bentonitic clay on the glass shards. This observation suggests that some other analyses of apparently fresh ash may not represent the original composition, particularly if the water content is above normal.

The upper 450 feet of the well-exposed section along the sea cliffs at Naples (pl. 2) consists mainly of diatomaceous mudstone, but it contains some disseminated volcanic ash. In the underlying 1,000 feet of strata—which consist of alternating zones of porcelaneous and cherty shale and zones of diatomaceous and phosphatic shale of varying thickness—volcanic ash forms numerous thin, well-defined beds that show little or no alteration. The index of refraction of the glass shards in different beds ranges between 1.500 and 1.505. Lower strata contain partly altered ash beds, and the rock immediately underlying several of these is obviously silicified. The Obispo tuff member, at the base of the Monterey formation, here consists of nearly white bentonite. About 16 miles to the west, in the Gaviota Pass section, equivalent strata are recognizable from their distinctive lithologic features, from their place in the sequence, and from their large foraminiferal faunas. In this section the rocks, including the highest strata present along the coast west of the mouth of Gaviota Creek, are more generally lithified; the 1,000 feet of interbedded cherty, diatomaceous, and phosphatic shales in the Naples section are represented here by cherty, porcelaneous, and phosphatic shales that contain no zones in which diatoms are preserved. The thin beds of vitric pyroclastic material in the section along the Naples coast are represented by bentonitic beds in the more lithified strata of the Gaviota section.

A similar relation is found between two sections, only about four miles apart, in the Highland Monocline area, in the northwestern part of the Pozo quadrangle. In the Indian Creek section (pl. 2), the Monterey formation consists of calcareous and porcelaneous shale and porcelanite. At its top is a thick bed of volcanic ash, which is overlain by the Santa Margarita sandstone. Some thin bentonite beds are interbedded with the porcelaneous and calcareous rocks, being most numerous in the lower part of the formation. The equivalent strata in the canyon about four miles to the west—the type locality for Kleinpell's[80] Luisian stage—consist of soft calcareous and diatomaceous deposits, with some

[80] Kleinpell, R. M., Miocene stratigraphy of California, fig. 11, p. 122. Am. Assoc. Petroleum Geologists, 1938.

thin beds of vitric ash that show little or no alteration. The correlation of these two sections is particularly well established.

As Ross and Shannon [81] have pointed out, the facility with which a volcanic glass is altered depends in part upon its original composition. In some deep-sea deposits,[82] basaltic glass has been largely altered to palagonitic and clay minerals, whereas interbedded silicic volcanic ash is not observably altered. Basaltic tuffs, however, are generally of local occurrence and associated with lavas and do not constitute such thin and widespread layers as are common in the Monterey. Factors other than original composition have obviously been important in the alteration of the vitric material, since the same beds may be unaltered in one place and altered to bentonite in another. In some outcrops of the Miraleste tuff bed (in the Altamira shale member of the Monterey) in the Palos Verdes Hills, the more basic pumice fragments and the silicic ash matrix are both fresh, while in others they are both altered. Texture is doubtless a factor; so, also, is the thickness of the bed where there is not essentially unlimited supply and free circulation of the solutions effecting the alteration. In the two-foot pyroclastic bed described on page 23 only the top inch and the bottom inch were largely altered to bentonitic clay. The composition of the solutions and the readiness with which they gained access to the vitric material are no doubt additional factors. Few tuff beds of the Monterey are so much thicker and coarser-grained than the average, however, that the influence of these factors on alteration dominates over that of stratigraphic position, and this stratigraphic relation is apparent in most tuffaceous beds. So far as the writer is aware, no pyroclastic beds altered to bentonite are known in the Quaternary, though fresh volcanic ash beds are not uncommon in Quaternary as well as in Tertiary strata. Tuffaceous beds are largely altered in parts of the Tertiary and are generally altered in pre-Tertiary formations. Parts of tuffaceous beds that have been silicified into dense cherty rock may be thus preserved with little further alteration in much older strata. These stratigraphic relations suggest that much of the alteration is related to age, load, and deformation, and in this sense may be considered an early stage of metamorphism.

A suggestion by Taliaferro [83] that the alteration of tuff to bentonite may have occurred before or during accumulation on the sea floor was based on some occurrences of bentonite beds that could be traced into dikes of bentonitic tuff, which were regarded as the feeders of the pyroclastic material through a "rent in the wet sediment" of the sea floor. But the bentonite dike and even the bed may have been injected after the rocks were consolidated, in the same manner that many dikes and connecting sill-like beds of sandstone in the Monterey formation (p. 20) must have been formed; or wet volcanic ash may have been so injected and subsequently altered to bentonite. Dikes of fresh volcanic ash extending from beds of this material into fractures of both overlying and underlying strata of the Monterey have been found in the Palos Verdes Hills.

Taliaferro's view that tuff is altered to bentonite on the sea floor is opposed not only by the described stratigraphic relations, but by the common silicification of beds immediately above as well as below the altered tuff. It is almost inconceivable, moreover, that pyroclastic texture could be preserved in an alteration on the sea floor, as bentonite characteristically swells and sloughs when immersed in water. Preservation of the texture could be expected, however, if the tuff were altered within confining strata and by the relatively scant water within these strata.

The chemical changes in the alteration of tuffs are considered further in discussing the origin of the porcelaneous and cherty rocks.

LAVAS AND INTRUSIVE IGNEOUS ROCKS

The widespread pyroclastic beds in the Monterey formation have been considered in some detail, partly because they form an integral part of the formation and may prove of value in stratigraphic work, but especially because of their probable bearing on the origin of the siliceous rocks of the formation. Nonfragmental igneous rocks also are common in the formation in many areas, but they require little discussion in this paper. In large part they are intrusive, though probably in general of Monterey age, but in some areas there are large quantities of lava. These rocks are mainly basaltic, contrasting strongly in composition with the widespread silicic tuffs, but andesitic lavas and others of alkalic composition occur in the Monterey, especially in San Luis Obispo County and northward.[84]

As the lavas and intrusive rocks bear less directly than the pyroclastic rocks on the problems considered in this report, they will not be described here, and no summary of the numerous publications in which they are described will be presented. Only a few facts regarding them need be noted. Irregular chert masses, either of deuteric or of later origin, commonly occur in the basaltic rocks, particularly in the more brecciated flows, but they show little resemblance to the bedded cherts in the Monterey formation. In some areas, such as the Palos Verdes Hills, the basaltic dikes and sills have locally modified the immediately adjacent siliceous

[81] Ross, C. S., and Shannon, E. V., op. cit., p. 84.

[82] Bramlette, M. N., and Bradley, W. H., Geology and biology of North Atlantic deep-sea cores, part 1, Lithology and geologic interpretations: U. S. Geol. Survey Prof. Paper 196-A, 1940 [1941].

[83] Taliaferro, N. L., The relation of volcanism to diatomaceous and associated siliceous sediments: Univ. of California Pub., Dept. Geol. Sci. Bull., vol. 23, no. 1, p. 46, 1933.

[84] Taliaferro, N. L., Geologic history and structure of the central Coast Ranges of California: California Div. Mines, Bull. 118, pt. 2, pp. 142-44, 1941.

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rocks by an increased development of chalcedonic silica, and secondary ankerite crystals occur in contact zones of chert, which are rarely more than a few feet in thickness.

RHYTHMIC BEDDING

A conspicuous feature of the Monterey formation in many areas is a rhythmic bedding that shows remarkably well the regular recurrence or alternation in the character of the sedimentary deposition. The Pliocene of California also shows rhythmic bedding in some areas, as in the thick deposits of the Ventura basin, and such bedding is common in the thick Cretaceous sediments in the Coast Range.[85] The rhythmic bedding in the Monterey formation seems worthy of being discussed in some detail. Even though the discussion may lead to no final conclusions regarding the processes or geological agencies of periodic character that produce this type of bedding, the formation illustrates particularly well many features that should throw some light on the origin of such bedding that is likewise characteristic of many other formations.

Several distinct types of rhythmic bedding are indicated by the superposition of those of relatively great thickness upon others of much less thickness (pl. 14, *A*). The thinnest laminae are to be measured in fractions of a millimeter. In general, however, beds about one inch thick are most conspicuous and best show the characteristic features of the rhythmic bedding, and they are therefore described first. This type of rhythmic bedding is well developed along the north side of the Santa Monica Mountains, and is well exposed there on the many road cuts in the small canyons south of Ventura Boulevard.

Plate 13 illustrates some of this bedding, with the individual beds averaging between one and two inches in thickness, together with some details of two beds. These are made up of a clastic and an organic layer, and alternations of such materials form the rhythmic sequence. In plate 13, *B*, the lower layer, about 21 mm. thick, consists of fine sand and silt, which decreases upward in grain size to the thin layer of clay-size material that immediately underlies the lighter-colored layer of organic sediment, which is about 7 mm. thick. Above this the same sequence is repeated. The organic layers consist largely of diatoms but include also some silicoflagellates, Radiolaria, Foraminifera, and some admixed fine clastic sediment. Some admixture of the organic remains is likewise scattered through the clastic layers.

These couplets of a clastic layer and an organic layer, each a unit of rhythmic bedding, indicate a repeated process, initiated rather abruptly by the accumulation of clastic material, which gradually decreased in grain size and was succeeded by the accumulation of more dominantly organic sediment, apparently deposited in clearer water.

These beds resemble varves formed in glacial lakes, but though the term varve may be applied to marine beds,[86] as its definition implies only a seasonal sequence of sedimentary accumulation forming annual deposits, a broader term, without any time connotation, is needed for similar beds whose mode of formation is uncertain. The word "rhythmite," used by Sander[87] for the individual units of rhythmic beds, will be adopted here as a brief term to designate the couplet of distinct sedimentary types of rock, or the graded sequence of sediments, that form a unit bed or lamina in rhythmically bedded deposits. No definite limit on the thickness of the bed or lamina called a rhythmite seems desirable, but it seems preferable not to let the term include those more complex units, consisting of several distinct beds or groups of beds, which have been termed cyclothems.[88] A varve would be a rhythmite of a special class, known or believed to consist of the sediment deposited in a year.

The rhythmites illustrated in plate 13 show well the character of the recurrent sequence of sedimentary accumulation. The lower part of each rhythmite consists of clastic material, whose base is sharply defined, though there is seldom any evidence that the underlying deposit has been appreciably scoured. The grain size of the clastic material decreases upward, and the clastic material is overlain by sediment that is dominantly organic. The presence of a thin layer of mud just below the base of the organic layer indicates that the organic material was deposited in clearer water than the mud, rather than that the rate of deposition of organic sediment was increased. Some significant variations in the character of the rhythmites should be described, however, before considering possible causes of such a recurrent process.

The upper rhythmite in plate 13, *B*, shows, about 3 millimeters from the top, a thin layer of dark silty clay within the white organic layer; the uppermost 4 mm. thus forms a minor rhythmite. Such minor layers are not generally present in the rhythmites, however, and where present they consist either of a single thin clastic intercalation, as illustrated in plate 13, *B*, or of two or even three thin layers. The thickness of the compound rhythmites thus formed is not notably greater than that of the simple rhythmites. These less regularly occurring minor layers thus appear to be the result of significant but minor variations or interruptions in the dominant process that forms the rhythmites. In certain areas where the thickness of the rhythmic bedding is less regular, the distinction between the minor

[85] Reed, R. D., Geology of California, p. 105, Am. Assoc. Petroleum Geologists, 1933.

[86] Bradley, W. H., Nonglacial marine varves: Am. Jour. Sci., 5th ser., vol. 22, p. 318, 1931.

[87] Sander, Bruno, Beitrage zur Kenntnis der Anlagerungsgefuge: Mineralogische und petrographische Mitteilungen, vol. 48, pp. 27-139, Leipzig, 1936.

[88] Wanless, H. R., and Weller, J. M., Correlation and extent of Pennsylvania cyclothems: Geol. Soc. America Bull., vol. 43, no. 4, p. 1003, 1932.

breaks within unit beds and the rhythmites of varying thickness is less clear (pl. 14, *B*) than in plate 13, *B*, and may appear entirely confused.

A thickness of about one inch is most common for this type of rhythmite, and there is a greater range of difference in the relative thickness of the clastic and organic layers than in the total thickness of the rhythmites. Either the clastic or organic layer may dominate in a particular succession of the rhythmites. This variation is not entirely irregular, however, as the rhythmites in a particular zone are fairly uniform. The rhythmites that consist largely of the organic layer are usually about an inch thick, as are those that consist more largely of silt and fine sand, with only a thin organic layer at the top.

The rhythmites in the sandstone members of the Monterey, unlike those in the finer-grained members, do not show this uniformity in thickness that is largely independent of composition. In the same area, on the north flank of the Santa Monica Mountains, in which the siliceous rocks are so regularly banded (pl. 13, *A*), the sandstone members contain rhythmites that are thicker and less regular, and their thickness is roughly proportional to the coarseness of the sand. The well-exposed beds at the crest of the mountains on the Girard-Topanga Canyon road average about two or three inches in thickness but show much variation (pl. 12, *C*). Each is composed dominantly of medium- to fine-grained sand but includes an upper layer of silt and clay. Organic material forms only a thin uppermost part, or more commonly forms no distinct layer, but is most abundant in the finer-grained upper part of the beds. The graded sequence in size of sediment is not apparent in this photograph, but it is generally present in these beds, though less well developed than in the more uniform rhythmites. Ripple marks and evidence of scour are relatively common in these sandstone beds. In sandstone members higher in this same section, the sand is much coarser, and individual beds range from several inches to several feet in thickness, probably averaging more than a foot. A graded sequence is evident in these beds also. The coarse to medium sand in the lower part of each grades upward to finer sand; and though little or no organic sediment is apparent in the upper part, the gradation in each of these thick rhythmites is broadly similar in character to that in the thinner, more largely organic rhythmites, and indicates a general similarity of origin.

In some areas, as in the southeastern part of the Puente Hills, where the Miocene strata are dominantly sandstone, it seems hardly appropriate to apply to them the name Monterey formation, even though they include some thin-bedded siliceous rocks (p. 8). Much of the sandstone here is in beds one foot to several feet thick, each of which shows a similar gradation from coarse at the bottom to fine at the top. Bailey [89] has described and discussed the significance of similar graded bedding of sandstones in Scotland.

In the much larger alternation of sandstone and finer-grained members of the formation that occurs in some areas, the units show no such regularity of thickness and other features, and they suggest no definitely rhythmic process of deposition. This irregular large-scale alternation seems probably due to changes in base level accompanying earth movements.

Superimposed on the rhythmic sequence of beds one or two inches thick is a much thicker cyclic bedding which, though conspicuously developed in relatively few places, has a significant bearing on the origin of the several types of rhythmic bedding. It is well seen in road-cut exposures in a canyon just east of Beverly Glen Boulevard, on the north side of the Santa Monica Mountains. Several hundred feet of strata here show a regular alternation of zones five to eight feet thick. Zones including about forty to fifty rhythmites consisting dominantly of fine clastic material alternate with zones including a similar number of rhythmites that consist dominantly of organic sediment. Five of these alternating zones are shown in plate 12, *D*; the uppermost, middle, and lowest zones include rhythmites that are relatively rich in diatoms, and the two intermediate zones include rhythmites that are largely composed of clastic material. Plate 14, *A*, shows a larger number of the alternating zones of rhythmites. The individual rhythmites are of about the same thickness regardless of composition.

The boundaries between zones of dominantly organic origin and zones of dominantly clastic rhythmites are not so sharp as those between individual rhythmites but is rather gradational, which makes it difficult to determine exactly how many rhythmites are to be included in each of these larger alternating zones. An attempt was made, however, to count the number of rhythmites in each of several zones, and the range in number seems too great to be due entirely to this doubtful delimiting of the beds to be grouped in one of the zones; the number of rhythmites in a zone, whether of dominantly organic or dominantly inorganic material, ranges from about 20 to about 50. A near view of the rhythmites within this larger alternation is shown in plate 14, *B*. The details of a specimen representing a single rhythmite are shown in plate 15, *A*.

Very fine laminae, usually a small fraction of a millimeter in thickness, are common in both the diatomaceous and the harder siliceous rocks of the formation, and these fine laminae also represent a type of rhythmite, as they show a definite alternation of layers that contain abundant organic matter with those that contain less. Lamination that apparently is only a fissility due to

[89] Bailey, E. B., New light on sedimentation and tectonics: Geol. Mag., vol. 67, no. 788, pp. 77-92, 1930.

orientation of the sedimentary particles parallel with the bedding—a kind of lamination that tends to form in many fine-grained sediments during their accumulation and compaction [90]—is also common in the Monterey formation, but it is not to be confused with the fine laminae illustrated in plate 5, *A* and *D*, which represent a rhythmic alternation of different kinds of sediment. In thin sections (pl. 15, *B*) and thin chips of the fresher siliceous rocks, it may be seen that the laminae consist of thin layers relatively rich in brown organic matter alternating with layers, usually somewhat thicker, that contain relatively little organic matter. The couplets forming this type of rhythmite are variable in thickness, but their thickness is generally a small fraction of a millimeter and probably averages between 0.1 and 0.2 millimeter. They appear identical with the rhythmic laminae interpreted as marine varves by Bradley.[91] Indeed, one specimen from Los Angeles County examined and so classed by him was from the Modelo formation, now called Monterey.

The fine rhythmic lamination is common in the diatomaceous deposits, but is more apparent in the cherty rocks of the formation, particularly those that also show the larger type of rhythmic bedding. These thin rhythmites are of a distinctly lower order of magnitude from those that average between one and two inches—many of these finer rhythmic laminae occur within a single one of the larger rhythmites—and it is thus evident that they were formed by a different process. The thin laminae, the more conspicuous one- to two-inch rhythmites, and the alternations several feet thick represent three superposed rhythms.

The remarkably clear-cut sequence of sedimentation shown in some of the rhythmic bedding in the Monterey formation, the variations in its character, and the superposition of different rhythms, all seem to offer an unusually good opportunity for determining the mode of formation of such bedding. Similar bedding is common in many other formations, but in them it seldom shows such well-defined and varied characteristics. A diagenetic or later rearrangement of the originally deposited sediments seems to have played a part in the formation of some types of rhythmic bedding, but the bedding here described shows textural gradations that obviously cannot be thus accounted for and that must be due to the nature of the depositional process.

It is in the rhythmites an inch or two in thickness that the characteristic features of such beds are especially obvious; these rhythmites, therefore, seem to offer the best opportunity to ascertain what processes were involved in their formation. They show clearly a repeated sedimentary sequence that involves a periodic influx of clastic material to the area of deposition; this influx gradually decreases as the grain size of the material decreases, and is usually succeeded by an increase in the proportion of organic remains. A new cycle is then begun by the next influx of clastic material. The general lack of disturbance of the underlying layers, illustrated in plate 13, *B*, *C*, indicates that each layer was formed by an actual influx of additional sediment to the area rather than a mere agitation and resettling of bottom sediment. It seems evident that these beds were deposited below depths of much wave or current action, for each bed commonly shows remarkable uniformity of both character and thickness in exposures that may be traced continuously for distances of a hundred feet or more. Sudden pinching or cutting out of beds, ripple marks, and signs of scour by waves or currents are uncommon. Plate 15, *C*, illustrates an exceptional example of scour. Only in the rhythmic beds that are dominantly sandy is such scour and ripple-marking fairly common (see pl. 12, *C*), and here the wave or current action was not sufficient to prevent the accumulation and preservation of thin beds with graded texture.

Processes that might produce rhythmic bedding have been discussed by a number of writers. These have been reviewed and analyzed by Rubey,[92] and they will therefore be considered here only briefly, with regard to their possible application to the origin of such bedding in the Monterey. Among the more definitely periodic processes, those involved in the annual change of seasons or of several longer climatic cycles are recognized. Other processes that seem capable of producing the individual graded beds include exceptionally heavy storms, shiftings of ocean currents, unusually heavy rain storms on the adjacent land areas, and slumping of bottom sediment on steep submarine slopes. In these processes, however, no long-continued periodicity has been recognized, nor would it be expected. Topographic changes or earth movements are obviously inapplicable as a cause of the repeated sequence of such thin beds as those considered here.

Since the beds generally show little or no sign of scour, storm waves could not have produced this bedding through a mere stirring up of the bottom and resettling of sediments, and the upper, chiefly organic, layer of one bed would not supply enough sand through such wave disturbance to form the succeeding bed. But where the sea floor was of irregular topography, as it is off the present coast of California in the Channel Islands region, and conditions of sedimentation were essentially as described in that area by Trask,[93] unusual storm waves might act on some of the ridges down to depths not ordinarily affected, carry off relatively coarse sedi-

[90] Lewis, J. V., Fissility of shale and its relation to petroleum: Geol. Soc. America Bull., vol. 35, no. 3, pp. 557-590, 1924.

[91] Bradley, W. H., op. cit., p. 324.

[92] Rubey, W. W., Lithologic studies of fine-grained Upper Cretaceous sedimentary rocks of the Black Hills region: U. S. Geol. Survey Prof. Paper 165, p. 40, 1930.

[93] Trask, P. D., Sedimentation in the Channel Islands region, California: Econ. Geology, vol. 26, no. 1, pp. 24-43, 1931.

ment, and drop it from suspension in adjacent waters of greater depth. Such a process could perhaps produce the type of graded bed described, and other evidence (p.11) suggests that such physiographic conditions on the sea floor were not improbable in the Monterey sea. However, the regular repetition of these beds of nearly uniform character and thickness would require a periodicity in the intervals between larger storms that does not exist at present. A more probable effect of storm wave action would be to form sandy layers, alternating with layers of finer or more organic sediment, at rather widely varying intervals.

Rhythmic bedding might likewise be produced by water flowing over an uneven sea floor similar to that postulated for the action of storm waves. Under these conditions, the ridges might supply relatively coarse sediment that the submarine currents would carry on and drop in nearby basins of deeper water. Off the coast of South America there is some evidence of a periodic shifting of current,[94] but it seems improbable that currents could shift in particular areas for a long period of geologic time with such regularity as is indicated in the rhythmites of the Monterey formation.

Periods of unusually heavy rainfall on adjacent lands, other than those determined by annual or other climatic cycles, would also presumably come at too irregular intervals to produce this regular and uniform bedding. Even greater irregularity would be expected in submarine slides or slumping of sediments on the steeper slopes of a basin.

The annual change of seasons is an established cause of rhythmic bedding in glacial lake deposits. Varves are forming, because of seasonal changes, in some modern lakes where the relationship to glacial action seems a minor if not negligible factor. Nipkow[95] seems to have demonstrated very clearly that the laminated sediments in some of the Swiss lakes are varves formed by seasonal changes. Stagnant parts of some of the Norwegian fiords are also accumulating laminated sediment that Strφm[96] has interpreted as varves. In a core from the little-compacted sediment of Drammensfjord, these varves average about 2.6 mm. in thickness in the upper 130 mm. of the core, about 0.8 mm. in the lower part, and about 1 mm. for the whole core. Similar varves might form in more or less stagnant marine basins under certain conditions. In a region of marked seasonal rainfall, the rivers would carry out far greater loads of clastic material during the rainy season, when they were swollen, than during the dry season. Comparatively little of the sediment would be carried in suspension into deep sea water, but some of the finer portion might be thus transported to relatively deep basins near shore. The gradual decrease in the volume of the rivers and their load of sediment in the dry season would be accompanied by a relative increase of organic material. The uniformity of the rhythmic bedding therefore seems most plausibly explained as the result of such a seasonal weather cycle, or of longer climatic cycles.

These long cycles are of course less well established than the seasonal ones; several of them, however, have been suggested as explaining certain types of rhythmic bedding, among them being the Brückner cycle of about 33 years, the 21,000 year cycle of the precession of the equinoxes, and others. Rhythmic bedding in a Jurassic formation of the Alps was attributed by Winkler[97] to some one of these longer climatic cycles, because he believed the annual cycle too brief for the deposition of beds about 7 centimeters thick. The precessional period of about 21,000 years was suggested by Gilbert[98] for a cyclic sequence with alternations several feet thick in the Cretaceous of Colorado. The annual climatic cycle, however, is the only one that has yet been definitely shown to be of sufficient intensity to produce a clear record in the rocks deposited in certain periods and areas. The thickness of the rhythmic beds, within a range of a small fraction of a millimeter to several centimeters, seems to be an inadequate criterion for distinguishing an annual from some longer climatic cycle; varying conditions might cause annual deposits, even in marine sediments, to differ that much in thickness. Pleistocene glacial varves at least 14 centimeters in thickness have been described,[99] but they could hardly be formed in marine waters except possibly in very localized accumulations.

Even so much as an inch of marine deposition in a year would seem possible only under exceptional and localized conditions—where, for example, a small basin of accumulation is supplied through by-passing of sediment from large areas of shallower water. Rough calculations from the measured load of sediment in the Colorado river indicate that this river system carries about 2,180 tons of sediment per year for each square mile of drainage area, or about 43,600 cubic feet, figured at 20 cubic feet per ton. Assuming that all this sediment is deposited over an area equal to that drained by the river, it would form a layer .019 inch thick each year. An annual deposit one inch thick would therefore require a localized area of accumulation about 1/60 as large as the drainage area. The wide distribution of the Monterey formation seems inconsistent with such extremely localized accumulation, and, conversely, the

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94 Murphy, R. C., Oceanic and climatic phenomena along the west coast of South America during 1925: Geogr. Rev., vol. 16, pp. 26-54, 1926.

95 Nipkow, F., Uber das verhalten der Skelette planktisher Kieselalgen in geschichteten Tiefenschlamm des Zurich- und Baldeggersees: Revue d'Hydrologie. Annales, vol. 4, nos. 1-2, pp. 71-120, 1927.

96 Strom, K. M., Land-locked waters: Skrifter utgitt av Det Norske vidensk.-akad. Oslo, Mat.-Naturv. Klasse, no. 7, pp. 67-69, 1936.

97 Winkler, A., Zum Schichtungsproblem; Ein Beitrag aus den Sudalpen: Neues Jahrb., Beilage-Band 53, Abt. B, p. 309, 1926.

98 Gilbert, G. K., Sedimentary measurement of Cretaceous time: Jour. Geology, vol. 3, pp. 121-127, 1895.

99 Sauramo, Matti, Studies on the Quaternary varve sediments in Southern Finland: Comm. geol. Finlande Bull. 60, p. 85, 1923.

assumption of a very extensive area of supply for the sediments seems inconsistent with the hypothesis of a disintegrated drainage system during much of Miocene time (p. 12). Though diatomaceous deposits from a large part of the Monterey, they apparently accumulated at a rate not far different from that of the clastic sediments (p. 38).

But if the rhythmic beds that are one or two inches thick are assumed to be annual deposits, the accumulation of the entire 3,000 feet of Monterey strata on the north flank of the Santa Monica Mountains, which represent upper Miocene time, would have required only about 24,000 years. This figure does not appear to be even of the right order of magnitude; and it cannot be very greatly increased, for in no more than a small part of these strata is the rhythmic bedding so obscure that it might represent a much slower rate of deposition, nor does the section show evidence of long periods of non-deposition. It thus appears improbable that these most conspicuous rhythmites are annual deposits, however strongly their regularity and sharp definition suggest a correlation with the annual weather cycle with which we are familiar.

We therefore seem led to the conclusion that the annual cycles are represented by the thinnest rhythmic beds or laminae, whose average thickness lies between 0.1 and 0.2 mm. If these are assumed to be annual deposits, the 3,000 feet of upper Miocene strata would represent about 7,000,000 years if all the strata were laminated. Actually, not more than about one-third shows this lamination, because of the interbedded sand, which presumably accumulated more rapidly, so that about 2,000,000 or 3,000,000 years would probably be a closer estimate. This is of the right order of magnitude, at least, for the latest estimates indicate that the whole of Miocene time amounted to about 15,000,000 or 20,000,000 years.[1]

An additional reason—a negative one as it were—for regarding the laminae that are a fraction of a millimeter thick as annual deposits is that no pronounced periodic process or cycle within the annual weather cycle would seem reasonably to account for them. Lamination of sandy deposits that is due to tidal action has been described and illustrated by Häntzschel;[2] but, as would be expected, this lamination is very lenticular and irregular. The very thin and regular laminae of the diatomaceous deposits could not be formed nor preserved where appreciable tidal currents were acting. Tidal currents in the water above that at the bottom of basins might, however, cause variations in the settling of diatoms and other sediment and thus might form the thin laminae.

[1] Urry, W. D., Ages by the helium method: Geol. Soc. America Bull., vol. 47, no. 8, p. 1229, 1936.

[2] Hantschel, Walter. Tidal flat deposits, in Recent marine sediments, pp. 197-198, Am. Assoc. Petroleum Geologists, 1939.

If the thinnest laminae represent annual deposits, it is necessary to account for the thicker and more conspicuous rhythmites by some cyclic process whose period was of the order of magnitude of 100 years, and that was more conspicuous in its effect on the accumulating sediments than the annual weather cycle. A year or two with very extraordinary rains and floods occurs occasionally along the west coast of South America. The rainy periods appear to be related to a shift of the marine currents off the coast,[3] and there is a slight suggestion that they are periodic; the last three, at least, have occurred at intervals of about 35 years. Some such climatic change, if it occurred at fairly regular intervals near 100 years, might account for the one- to two-inch rhythmites in which the lower part consists of graded clastic sediment and the upper part consists of finely-laminated organic sediment. Incidentally, the steep submarine slope along the coast of Ecuador and Peru, with deep water relatively near land, would seem a particularly favorable environment for the formation of such beds. The yet larger cyclic alternation evident in some parts of the Monterey seems to be the result of some more gradual climatic oscillation, with a period of perhaps 2,000 or 3,000 years, for it is represented by about that many of the thinnest rhythmic beds.

Many features of the rhythmic bedding are exceptionally well shown in the Monterey formation, but definite conclusions as to the periodic processes that could have produced them do not seem justified from the data available. A climatic control is strongly suggested, however, by the regularity of the processes, and by the compounding into larger cycles that are superimposed on the smaller ones. A more detailed study and analysis of the several types of rhythmic bedding seem to offer interesting possibilities. But regardless of the processes and their periods, some definite and significant conclusions about certain conditions of the sedimentary basins can be drawn from the mere presence of the rhythmic bedding.

EVIDENCE ON CONDITIONS IN DEPOSITIONAL BASINS

Although the precise nature of the periodic processes that caused the rhythmic bedding in the Monterey formation is problematic, the mere presence of such bedding marks a distinctive type of sedimentary accumulation, which contrasts in many important features with the more common type that has either massive or irregular bedding. The formation and preservation of the rhythmic bedding implies deposition below wave base and below any marked current action, though not necessarily in very deep water, for the amount of water agitation and movement is often more closely related to local topographic irregularities of the bottom than to absolute depth. A great thickness of rhythmically bedded

[3] Murphy, R. C., op. cit., pp. 26-54.

sediment must have accumulated in a basin that either was originally very deep or that underwent long-continued subsidence. The rate of subsidence need not have kept in close balance with the rate of deposition, but must merely have been so rapid that the basin was generally not filled with sediment up to the level of wave and current action.

The more familiar type of sedimentary deposition, at wave base rather than below it, was considered by Barrell[4] in formulating his ideas on diastems and discontinuous deposition. He says: "The maintenance of shallow water conditions during the accumulation of a formation means that there has been nearly always an excess of sediment above what was needed to maintain the surface at base level." He points out that such conditions are common and that, therefore, "The sediment deposited at any one point is only a small fraction of that which is carried past." The carrying past of much of the sediment under such conditions was given the useful designation of by-passing by Eaton,[5] in an interesting paper that further emphasizes and enlarges some of the concepts suggested by Barrell. The results of by-passing and discontinuous deposition were thought by Eaton to be well shown in the Pliocene deposits of the Ventura Basin. Examples of such effects are indeed obvious in these deposits, but they are much less common than the regular rhythmic bedding and graded sandstone beds that characterize formations accumulated below wave base, with a minimum of by-passing and discontinuous deposition. Only the latter conditions permitted the accumulation of the extraordinary thickness of about 15,000 feet of Pliocene strata in the Ventura basin.

The deposits that show regular rhythmic bedding were obviously not subjected to much scour and by-passing of sediment; they represent a maximum of accumulation, limited only by the rate of supply of sediment to the basin of deposition. Under these conditions of deposition the mollusks and other benthonic organisms would have a somewhat unfavorable habitat, for water below wave or current action would be poorly aerated and there might be some smothering of the less actively moving bottom dwellers by uncompacted ooze, which would be abundant on a sea floor where there was no by-passing of the finest sediment. Such conditions may account for the paucity of macro-fossils in the Monterey and other rhythmically bedded formations. The San Pablo group and the Santa Margarita sandstone of central California represent a different facies of the upper Miocene deposits, wherein the sandstones do not show graded bedding but are characteristically massive or irregularly bedded, and these strata contain more macro-fossils.

[4] Barrell, Joseph, Rhythms and the measurement of geologic time: Geol. Soc. America Bull., vol. 28, p. 783, 1917.

[5] Eaton, J. E., The by-passing and disctontinuous deposition of sedimentary materials: Am. Assoc. Petroleum Geologists Bull., vol. 13, no. 7, p. 713-761, 1929.

Larger fossils are thus apt to be relatively rare under the conditions of deposition below wave base or much current action, but micro-fossils are often abundant, because the lack of water agitation favors the accumulation of the small pelagic organisms, which are not swept on to greater depths. The remains of the abundant plankton organisms that had no hard parts and that are therefore not apparent as fossils would accumulate with the diatoms and other micro-fossils. The lack of aeration would largely prevent oxidation and destruction of this organic matter. Conditions resulting in the formation and preservation of rhythmic bedding or lamination would thus also be favorable for the accumulation of deposits that, being unusually rich in organic matter, may constitute source beds of petroleum (p. 37).

Rhythmic bedding or lamination is common in thick formations in regions of long-continued crustal instability such as the coastal region of California, and in regions of geosynclinal deposition such as the former seaway of Tethys in Eurasia. Regions of less crustal unrest, in which there have been few or no deep and rapidly subsiding basins of sedimentary deposition, are illustrated by the Atlantic Coastal Plain. There the Tertiary sediments are massive or irregularly bedded, having evidently accumulated in shallow seas on the continental shelf, where by-passing and discontinuous deposition were usual. The contrast between the two types of formation with respect to character of bedding has been emphasized by Bailey;[6] and the contrast in their fossil content and other features likewise indicates that they were deposited under very different conditions, which reflect the tectonic history.

SOURCE BEDS OF PETROLEUM

Many of the earlier papers on the Monterey formation describe it as consisting in large part of bituminous shale, and most of the oil fields that were discovered early were in Monterey strata or closely associated with them. These relationships apparently led to an early view that the Monterey was the only important source of petroleum in California, and its importance was thus overemphasized. The many questions that remain unsettled about such factors as the extent of lateral and vertical migration of petroleum make it difficult to evaluate the importance of particular strata as a possible source of oil, but the discovery of many important oil fields in thick Pliocene strata, particularly in the Los Angeles and Ventura Basins, has made it seem probable that these Pliocene rocks are the source of much or most of the oil within them. Oil accumulations in pre-Miocene formations of the California Tertiary are also becoming increasingly well known. These discoveries, together with a natural reaction against the

[6] Bailey, E. B., New light on sedimentation and tectonics: Geol. Mag., vol. 67, p. 77, 1930.

early view, may have tended for a time to depreciate unduly the importance of the Monterey as a source of oil. The fact seems to remain that a great deal of oil originated in this formation, and it certainly contains many of the greatest oil pools in California.

The abundance of diatoms in parts of the Monterey formation has suggested that these organisms may have been the source of much of the oil of the formation. Tolman [7] has emphasized this view, and he had charge of a research project of the American Petroleum Institute for the investigation of diatoms as a source of oil, but a final report on this work has not appeared.

Parker D. Trask, of the United States Geological Survey, has made extensive investigations of source beds of petroleum in cooperation with the American Petroleum Institute, and in this work he had large collections of Monterey rock samples for study. The results of this study, together with many data on the organic content of the samples, were published [8] in 1942.

Strata that may be termed bituminous shale because of their high content of organic matter are common in parts of the Monterey formation in several areas, and other parts of the formation are commonly much higher in organic matter than might be supposed from their appearance when weathered. The dark color usual in the unweathered porcelaneous and cherty shales of the formation is due primarily to a high content of organic matter, but weathering leaches or oxidizes much of the organic matter, so that the rocks become light-colored. Thin sections of the dark, unweathered siliceous rocks show abundant small areas of dark-brown organic matter, either disseminated or largely concentrated in definite laminae, but organic matter is less conspicuous or largely absent in weathered rock. Where the dense opaline rocks have been weathered only in a thin outer zone (pl. 17, *C*), individual laminae also show this local removal of organic matter by weathering. When the dark and fresher rocks are leached with sodium or potassium hydroxide solution, they are lightened as they are by weathering (pl. 5, *D*), and the caustic solution is darkened with the organic matter that has been extracted. This result, together with study of thin sections, indicates that the dark color is due in major part to organic matter. Black iron sulphide is noted in thin sections, but is usually much less abundant than recognizable organic matter, though the two materials are apt to be associated and thus combine to cause the dark color. The bleaching effected by caustic solutions and by weathering indicates that organic matter is generally more abundant than iron sulphide in these rocks, and the buff stains—due to iron oxide derived from the iron sulphide—that are common on the weathered surfaces of many dark strata are not usually conspicuous in the light-weathering porcelaneous rocks.

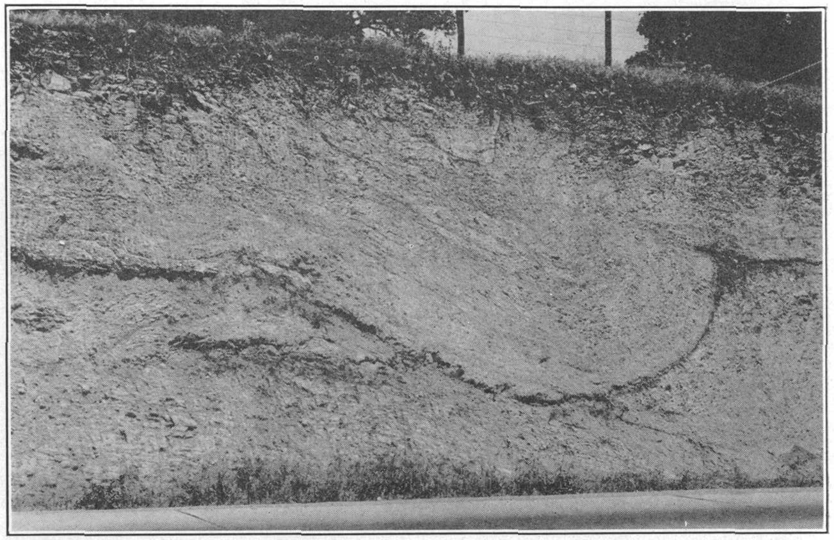
Perhaps some of the porcelaneous and cherty rocks of the formation were originally of light color, because of their containing little admixed organic matter at the time they were deposited, but the surface leaching and bleaching of originally darker rocks is evidently responsible for much of the nearly white to mauve-colored rock that is so common in surface exposures. For example, the Monterey rocks as mapped at the surface in the Palos Verdes Hills are generally light colored and do not appear to be particularly high in organic matter, but where these same strata were encountered in the tunnel recently driven through the hills for the Los Angeles sewage-disposal project they were all dark gray to almost black, and it is found by study of thin sections and chips of these fresh rocks that the color is largely due to organic matter. Heavy tar or asphalt is common in the fractured siliceous rocks in the tunnel, though it is not conspicuous at the surface. The beds of cherty and porcelaneous rock in the lower parts of sea-cliff exposures that are being actively eroded by the waves are likewise relatively dark, as they contain more brown organic matter than the equivalent but more thoroughly weathered beds that extend up the cliffs to old terrace surfaces, and the dark rock is found, by study of rock chips and thin sections, to contain much organic matter. Localities on the coast at which these relations were observed include San Juan Capistrano Point, Palos Verdes Hills, Naples, and Point Concepcion; other such localities where sections were not measured include South Point west of Pismo, Point Buchon, a locality near Santa Cruz, and a locality near Point Reyes. The same relation is noted in some narrow deep canyons, where erosion has been so rapid as to expose beds in the canyon bottoms that have not been conspicuously weathered. Drill cores from many areas show that the cherty and porcelaneous Monterey rocks are consistently darker far below the surface than they are in the surface exposures directly above.

The diatomaceous shales, also, are usually darker in unweathered than in weathered exposures, as may be seen in the cliffs at Malaga Cove in the vicinity of Palos Verdes Hills, and at Naples, but this difference is due in part to saturation with water; samples of this rock are a much lighter gray when dried than when moist, though not as nearly white as the more weathered diatomaceous deposits. Although he believed that diatoms may be in part the source of Monterey oil, Tolman noted that the diatomaceous members in general contain less organic matter than much of the harder siliceous rock. This may be due in part to the high porosity and permeability of the diatomaceous deposits, which facilitates leaching of the original organic material by surface or ground-water solutions. Many beds and lentils of opaline chert are dark from their or-

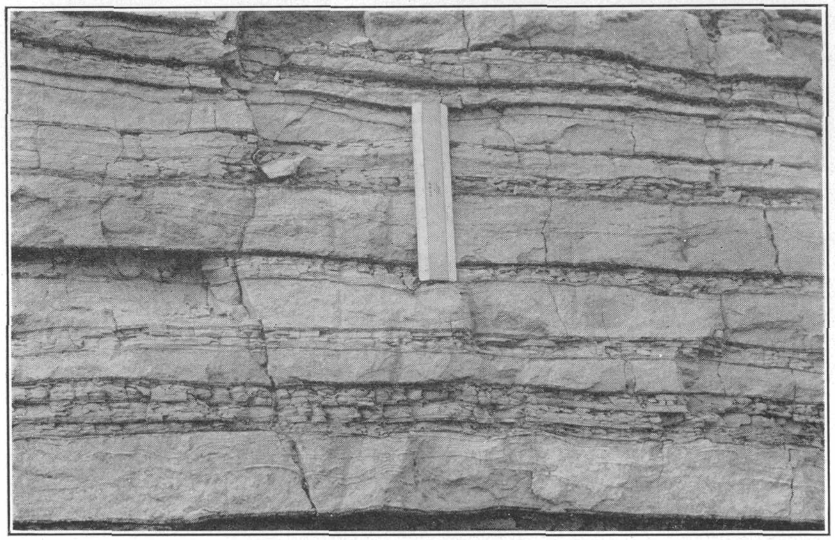
[7] Tolman, C. F., Biogenesis of hydrocarbons by diatoms: Econ. Geology, vol. 22, no. 5, pp. 454-74, 1927.

[8] Trask, P. D., and Patnode, H. W., Source beds of petroleum, Am. Assoc. Petroleum Geologists, 1942.

A. BENTONITE BED SHOWING ABRUPT CONTACTS WITH PORCELANEOUS ROCKS, CARMEL VALLEY, MONTEREY COUNTY.

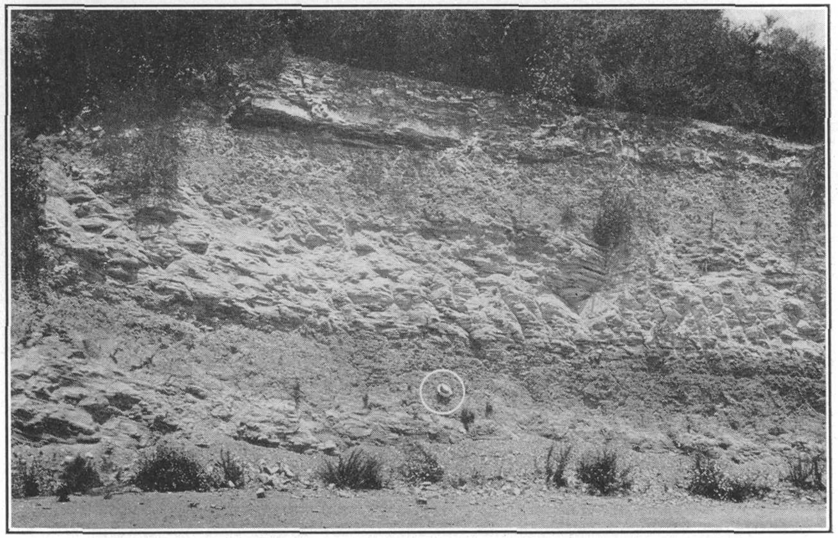


B. BENTONITE BED IN PORCELANEOUS SHALE SHOWING SQUEEZING AND LOCAL THICKENING OF THE DARK BENTONITE BED, SOUTHEAST OF DEL MONTE, MONTEREY COUNTY.

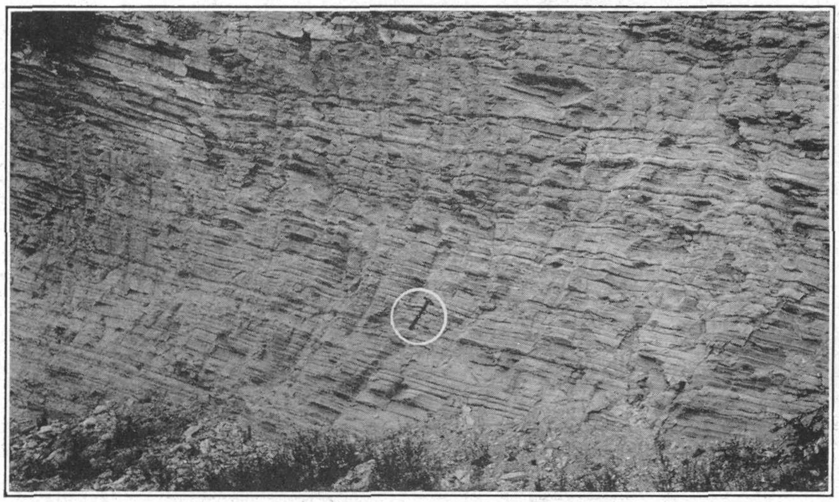


C. IRREGULAR ALTERNATION OF SANDSTONE AND SANDY SHALE ON TOPANGA CANYON ROAD NEAR CREST OF SANTA MONICA MOUNTAINS, LOS ANGELES COUNTY.

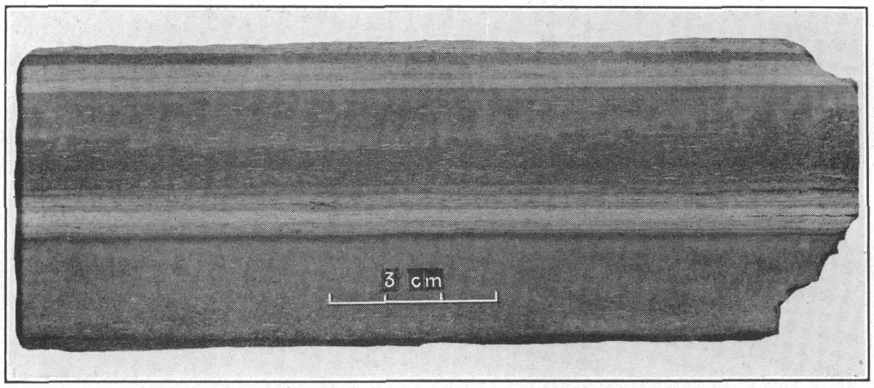
Scale is about 6½ inches long.



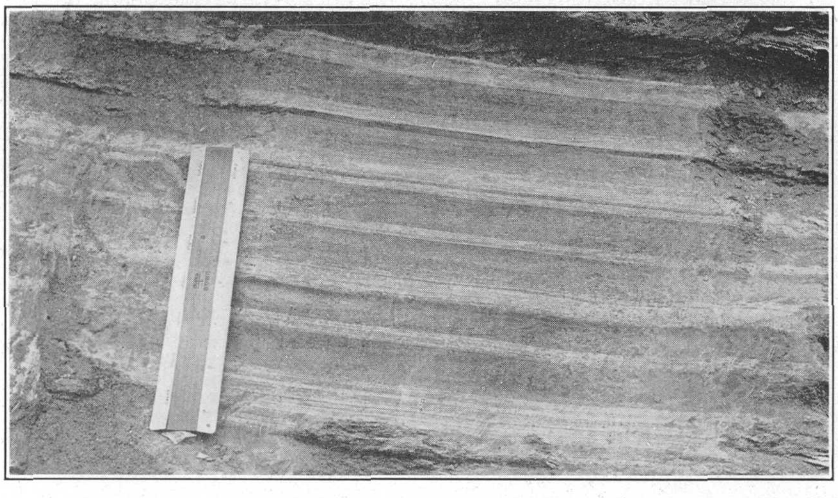
D. LARGER ALTERNATION SUPERIMPOSED ON THE THINNER RHYTHMIC BEDDING, ABOUT 1,100 FEET SOUTH OF ENTRANCE TO VALLEY PARK COUNTRY CLUB, ON NORTH SIDE OF SANTA MONICA MOUNTAINS, LOS ANGELES COUNTY.



A. RHYTHMIC BEDDING IN ROAD CUT NEAR ENTRANCE TO VALLEY PARK COUNTRY CLUB, NORTH SIDE OF SANTA MONICA MOUNTAINS, LOS ANGELES COUNTY.

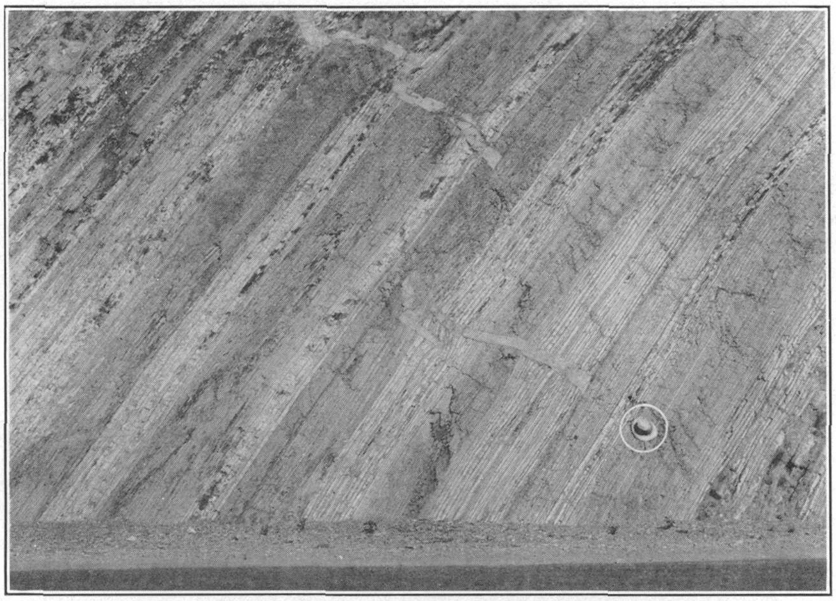


B. SPECIMEN SHOWING DETAILS OF TWO OF THE RHYTHMIC BEDS FROM SAME LOCALITY.



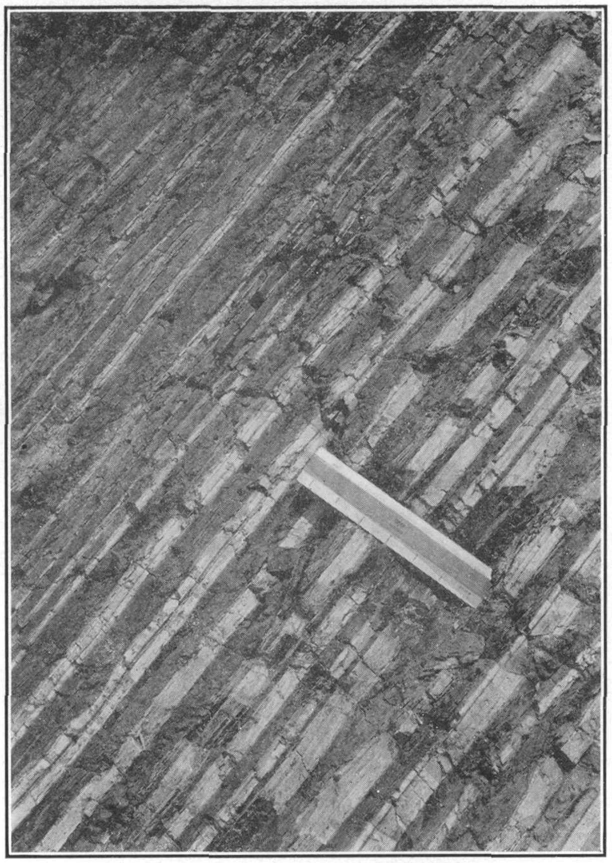
C. DETAILS OF RHYTHMIC BEDDING ON A SCRAPED SURFACE IN ROAD CUT ALONG VAN NUYS-BEVERLY GLEN ROAD ON NORTH SIDE OF SANTA MONICA MOUNTAINS, LOS ANGELES COUNTY.

Scale is about 6½ inches long.



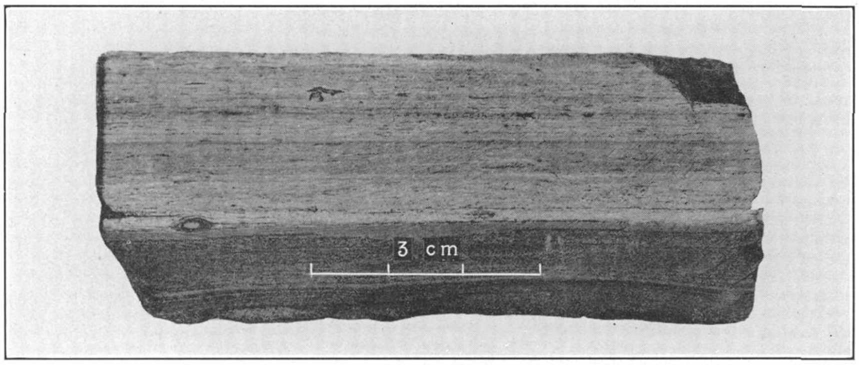
A. LARGER ALTERNATION SUPERIMPOSED ON THE THINNER RHYTHMIC BEDDING ON THE TOPANGA CANYON ROAD SOUTH OF GIRARD, LOS ANGELES COUNTY

Note sandstone dike that is offset along bedding plane slips.

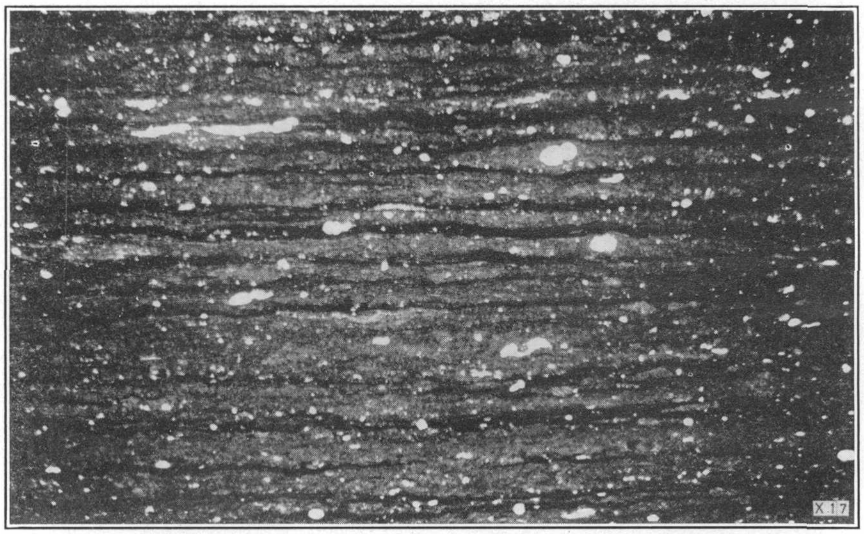


B. DETAILS OF BEDDING AT SAME LOCALITY.

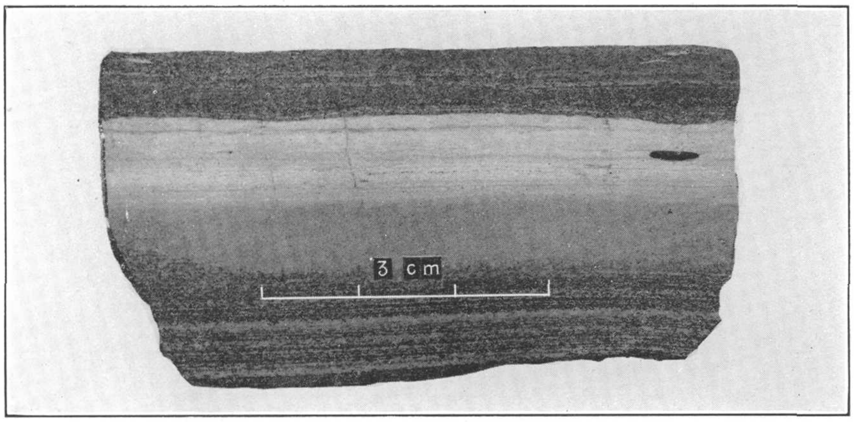
Note change from rhythmites that are dominantly siliceous rock to those of a zone in which they are dominantly clastic sediment. Scale is about 6½ inches long.



A. POLISHED FACE OF ONE OF THE RHYTHMIC BEDS FROM LOCALITY OF PLATE 14, *B*.
Upper part is cherty shale.



B. FINE LAMINATION IN CHERTY SHALE, WITH DARKER LAYERS RICHER IN BROWN ORGANIC MATTER.



C. SLIGHT SCOUR AT TOP OF DIATOMACEOUS UPPER LAYER OF A RHYTHMITE.

ganic content, though immediately adjacent and equivalent beds in the porous diatomite are nearly white and obviously contain very little organic matter (pl. 7, *A*). It seems probable, however, that little of the diatomaceous shale was ever as rich in organic matter as the porcelaneous and cherty rocks commonly called bituminous shale, which occur lower in the Monterey formation in certain areas. These bituminous, siliceous shales are believed to have been originally diatomaceous (p. 50), but the importance of the diatoms as a source of the bituminous matter remains an open question, for abundant microplankton organisms without hard parts would also be expected to accumulate under the same conditions as the diatoms.

The strata that are most conspicuously bituminous and that show the most organic matter in thin sections are in general the distinctly laminated porcelaneous and cherty shales. The sands that are impregnated with free oil or its inspissated products are obviously to be excepted; they are reservoirs in which oil has accumulated, rather than source beds. Fine lamination or other thin rhythmic bedding may, as previously pointed out, be a common characteristic of source beds of petroleum, since the conditions that allowed these features to be formed and preserved would be favorable for the accumulation of unusual amounts of organic matter (p. 35); the lack of appreciable wave of current action indicated by the preserved lamination implies a minimum renewal of oxygen in the bottom waters and, consequently, little destruction of finely-divided organic matter. Furthermore, the organic matter would also be supplied to the bottom sediment more rapidly here than in more agitated waters, where it would tend to be swept away.

Fine lamination or thin rhythmic bedding are characteristic of many deposits regarded as probable source beds of petroleum, but it is difficult to determine how close the relation between character of bedding and organic content may be, because relatively few source beds can be reasonably well identified as such. One of the more obvious exceptions to any such relation is afforded by the lower Pliocene Repetto formation of the Los Angeles basin, which is considered a probable source bed of much of the large Pliocene production of this area. This formation is generally a rather fine-grained siltstone and mudstone, and though it was formed in relatively deep water [9] it is massive-bedded, with no obvious lamination.

Trask [10] has emphasized the correlation between fine texture and accumulation of organic matter. Lamination would generally occur only in fine-grained sediments, and it is suggested that the lamination may be as significant as mere grain size, or even more so, in deposits unusually rich in organic matter. Many fine-grained deposits do not show such lamination. Some of these are known to form in relatively shallow and wave-agitated waters, under conditions of bottom topography [11] where much oxidation of organic matter might be expected even though the sediment is fine-grained. As already mentioned, the Repetto formation is one of the exceptions to any such possible relation, and doubtless many other source beds lack fine lamination; such lamination, however, may prove to be characteristic of the richest source beds.

The most conspicuously bituminous strata are commonly associated with phosphatic material. Hoots [12] has emphasized the close association of petroliferous beds and bituminous matter with the phosphatic shale of the Monterey formation near the base of the upper Miocene in the Playa del Rey oil field. Other places in which this association has been observed are the Palos Verdes Hills, the Grimes Canyon area, the Naples section, and the Bixby Canyon section. It has been suggested that large accumulations of phosphate are favored in areas of rapid destruction of marine life where surface currents of different temperatures meet, as along the Agulha Banks off the South African coast.[13] Such a situation would seem equally favorable for increased accumulation of organic matter, especially if the currents met where the depth of the water and the character of the bottom topography were such as to prevent such active movement of bottom currents as would result in rapid oxidation.

ORIGIN OF THE SILICEOUS ROCKS

ORIGIN OF THE DIATOMACEOUS DEPOSITS

Some data bearing on the mode of formation of the diatomite and less pure diatomaceous rocks that form extensive deposits in the upper part of the Monterey have already been presented in describing these materials, and this problem was also considered more broadly in discussing paleogeographic conditions and certain lithologic features such as rhythmic bedding. The problem will now be considered more explicitly.

Large diatomaceous or other organic deposits can have accumulated only under one of the following conditions: (1) growth of the organisms in such unusually great abundance as to completely dominate normal deposition of clastic sediments; (2) deposition of clastic sediment so nearly lacking that organic material dominates even though it accumulates very slowly; or (3) a combination of 1 and 2, large development of the organisms being combined with the deposition of relatively little

[9] Woodring, W. P., Lower Pliocene mollusks and echinoids from the Los Angeles Basin, Calif., and their inferred environment: U. S. Geol. Survey Prof. Paper 190, 1938.

[10] Trask, P. D., Origin and environment of source sediments of petroleum, pp. 67-95, Gulf Pub. Co., Houston, Tex., 1932.

[11] Idem, p. 163.

[12] Hoots, H. W., Blount, A. L., and Jones, P. H., Marine oil shale, source of oil in Playa del Rey field, Calif.: Am. Assoc. Petroleum Geologists Bull., vol. 19, no. 2, pp. 172-205, 1935.

[13] Murray, John, Challenger Report, Deep sea deposits, p. 396, 1891.

clastic material. As the following discussion will show, the diatomaceous deposits of the Monterey formation appear to be due to the combination of conditions last mentioned rather than to either of the first two conditions alone.

The larger diatomaceous deposits of modern seas—those, for example, of the north and south Pacific Ocean—occur in deep water and seem to represent relatively slow accumulations in areas nearly free from terrigenous material. Hence it has been inferred that ancient diatomaceous deposits accumulated under similar conditions, this view being implied in the following statement on the Monterey formation by Fairbanks:[14] "The time required for the deposition of 4,000 feet of such material, which so far as we know accumulates at an exceedingly slow rate, must have been enormous." Very little more is known at present about the absolute rate of accumulation of such sediments than when Fairbanks made this statement. Reasons have been given, however (pp. 11-12), for believing that these diatomaceous deposits, though laid down where little clastic material was being deposited, were not formed in abyssal waters far from land; and some details of occurrence suggest that the accumulation of the organic material was relatively rapid.

The discussion of rhythmic bedding indicated that, whatever the agency producing such bedding, the alternation is so regular that some process of nearly uniform period is involved. The rhythmic beds, like the superimposed larger cycles (p. 31), are not markedly thinner in material consisting largely of diatoms than in associated material that is largely composed of silt and fine sand. Only in the coarser sandstone members of the formation are the rhythmites, or graded beds of sandstone, generally and conspicuously thicker than in the diatomites. No systematic relation is apparent between the thickness of the formation at a given place and the proportion of clastic sediment in it at that place. Some of the thickest sections of the Monterey deposits, such as those at Point Concepcion, Chico Martinez Creek, and Reliz Canyon, consist largely of the non-clastic sediments. Other thick sections representing about the same period of time consist largely of clastic sediment, as in the Puente Hills and Modelo Canyon areas. These relations indicate that the clastic sediments did not ordinarily accumulate many times faster than the non-clastic siliceous sediments; in general they apparently did not accumulate even twice as fast. The thousands of feet of rhythmically bedded Miocene deposits in many basin areas indicate relatively little by-passing of sediment and comparatively rapid accumulation in those areas, of the entire formation.

As already pointed out, the rapid accumulation of the thick diatomaceous deposits may have been due in part to a concentration of the slowly settling diatoms by current drifting. Coastal currents might thus carry these diatoms from a large area of the open sea and deposit them in embayments or in the less agitated bottom waters of the deeper basins along the coast. The importance of current drift in some diatom deposits is indicated by Philippi,[15] who shows that in a part of the South Pacific affected by northward-flowing currents, the extensive bottom accumulations of diatoms lie north of the areas in which these organisms are growing most abundantly in the surface waters. Branner[16] suggested that the large diatomaceous deposits of the Monterey formation might represent material that was drifted by colder currents flowing southward from Alaska and that was caught in cul-de-sacs, such as probably existed in the area now occupied by the southern part of the San Joaquin Valley. This view seems to be supported by the statement of Dr. Mann that the diatoms in the Lompoc deposit are characteristic of northern waters (p. 10).

In considering the possibility that unusually thick diatomaceous deposits may have accumulated rapidly from the immediately overlying waters, without much influence from current drifting, some rough calculations from available data were attempted. During a spring diatom epidemic in Grays Harbor, Washington, the surface water[17] was found to contain about 12,000,000 diatom cells per liter. This would be equivalent to about 200,000 cells per cubic inch of surface water. Lohman[18] has calculated that a cubic inch of diatomite of the Monterey formation contained about 21,000,000 cells. If the observed density of diatoms in Grays Harbor extended through a depth of 100 inches of water, 20,000,000 diatoms would be floating over every square inch of sea bottom. If these diatoms were of the same size as those in the Monterey and fell vertically to the bottom, they would form nearly an inch of diatomaceous sediment during one seasonal epidemic. But several factors in this calculation are obviously inaccurate. In the first place, the *Chaetoceras* which dominated the Grays Harbor epidemic is much smaller on the average than the forms found in the Monterey diatomites. The assumption, moreover, that the surface density of the diatoms would continue to a depth of 100 inches may be largely in error. During an epidemic such densities may extend only an inch or two from the surface, though under normal conditions the diatoms generally develop most abundantly at depths of about 50 to 100 feet and decrease downward to the limits of the phototropic zone, the depth of which ranges between 90 and 400 feet,

[14] Fairbanks, H. W., U. S. Geol. Survey Geol. Atlas, San Luis folio (no. 101), p. 10, 1904.

[15] Philippi, E., Die Grundproben der Deutschen Sudpolar Expedition: Deutsche Sudpolar Exp., Bd. 2, Hft. 6, p. 614-15, 1912.

[16] Branner, J. C., Influence of wind on the accumulation of oil bearing rocks (abstract): Geol. Soc. America Bull., vol. 24, p. 95, 1913.

[17] Trask, P. D., Origin and environment of source sediments of petroleum, p. 299, Gulf Pub. Co., Houston, Texas, 1932.

[18] Lohman, K. E., personal communication.

depending on the season, latitude, and other factors. Johnstone [19] mentions a haul in the Bay of Kiel from a depth of 20 meters that, according to the data of Brandt, indicated a density of growth equivalent to about 98,000 diatoms per cubic inch. Finally, the most serious error in the calculation is probably in the assumption that all the delicate diatoms, such as *Chaetoceras*, eventually reach the bottom. Such delicate-shelled forms, though they dominate in most surface planktons, are scarce in the bottom sediment; presumably, therefore, their thin shells are so soon dissolved after death that few of them reach the sea floor. Brockmann [20] in a paper published in 1935 calculates the yearly production of diatom plankton for the Baltic sea at 6,750 cc. per square meter of surface, an amount that, if it all reached the bottom, would form a deposit 7 mm. thick. He finds, however, that the actual rate of accumulation is far less than this, because the more abundant forms are the delicate ones whose shells dissolve before reaching the bottom.

It seems improbable that an adequate source of silica in marine waters would be available for a long-continued accumulation of diatomaceous sediment from the immediately overlying water at a rate even approaching that indicated in the preceding discussion. Some such rate of accumulation might be attained locally, however, through concentration of diatoms from large areas of the sea by current drifting.

The remains of siliceous organisms in the Monterey deposits include Radiolaria, silico-flagellates, and sponge spicules, but the diatoms are in general so dominant, that conditions must have been particularly favorable for their growth during a great part of Monterey time. Such favorable conditions would have included suitable temperature and salinity of water, and availability of all necessary nutrients.

In a comprehensive paper on the plankton of the Gulf of Maine, Bigelow [21] says:

> Perhaps no phenomenon in the natural economy of the gulf so arrests attention (certainly none is so spectacular) as the sudden appearance of enormous numbers of diatoms in early spring, and their equally sudden disappearance from most of its area after a brief flowering period. As precisely this same phenomenon takes place in northern European waters where biologists have long occupied themselves with the marine plankton, no wonder the possible factors, hydrographic and seasonal, or the physiology of the diatoms themselves, which first permit and then stop their almost inconceivably rapid multiplication and finally even prohibit their further existence, have been the subject of much study and discussion. Nevertheless, as Herdman has recently declared, "The factors governing this phenomenon still remain imperfectly understood."

Most oceanographers, however, including Bigelow, seem to agree that under normal conditions in modern seas the development of phytoplankton as a whole is limited in the main by the available phosphate and nitrogen in sea water, but that for the diatoms in particular the supply of silica may more commonly limit development. No agreement has been reached even in the studies of modern seas as to which of these three nutrients is generally scarcest relatively to the needs of the diatoms and thus plays the critical part in limiting their development. Before considering the significance of the oceanographic data available, therefore, some geologic evidence on the question, suggested by the mode of occurrence and the associations of diatomaceous deposits, may be summarized.

The frequent association of siliceous organisms and volcanic ash was noted by Ehrenberg [22] as early as 1844. In 1867, J. D. Whitney [23] emphasized this common association in the many diatomaceous deposits of California and adjacent states, and suggested that the unusual supply of silica available in the ash might have favored the growth of diatoms. A similar view was advanced by de Lapparent [24] in 1923. More recently, in 1933, Taliaferro [25] has reviewed the many examples of the association of diatomaceous and volcanic rocks, which include most of the larger diatomaceous deposits known, and he also concluded that this association was due to the large supply of silica made easily available for the development of the siliceous organisms.

In the course of the present study the writer adopted a similar interpretation.[26] Before doing so he compiled a review of all described occurrences, but this review need not be repeated here, being largely covered in the recent (1933) paper by Taliaferro. The important diatomaceous (tripoli) deposits of North Africa were not known by Taliaferro to be associated with volcanic ash, as they have since been shown to be in a paper by Anderson.[27] Another such association in the Miocene of central China was described by Juan [28] in 1937. An undescribed occurrence of siliceous organisms, composed more largely of Radiolaria than of diatoms, associated with vitric pyroclastics in the Tertiary of the Santa Elena Peninsula of Ecuador is known to the writer. There is also a marked increase in diatoms at the horizon of a thin volcanic ash bed occurring in some deep-

[19] Johnstone, James, Conditions of life in the sea, p. 163, Cambridge Univ. Press, 1908.

[20] Brockmann, Chr., Diatomeen und Schlick im Jade-Gebiet: Senckenbergischen Naturf. Gesell., Abh. 430, p. 18, 1935.

[21] Bigelow, H. B., Plankton of the offshore waters of the Gulf of Maine: U. S. Bur. Fisheries Bull., vol. 40, pt. 2, Document no. 968, p. 465, 1926.

[22] Ehrenberg, C. G., On the remains of infusorial animalcules in volcanic rocks: Geol. Soc. London Quart. Jour., pp. 73-91, Aug. 1846.

[23] Whitney, J. D., On the fresh water infusorial deposits of the Pacific coast and their connections with the volcanic rocks: California Acad. Nat. Sci. Proc., vol. 3, pp. 319-324, 1867.

[24] de Lapparent, J., Lecons de Petrographie, p. 322, Masson et Cie, Paris, 1923.

[25] Taliaferro, N. L., The relation of volcanism to diatomaceous and associated siliceous sediments: Univ. California Pub., Dept. Geol. Sci. Bull., vol. 23, no. 1, 1933.

[26] Bramlette, M. N., Origin of the Monterey siliceous rocks of California (abstract): Washington Acad. Sci. Jour., vol. 23, no. 12, p. 573, 1933.

[27] Anderson, R. V., The diatomaceous and fish-bearing Beida stage of Algeria: Jour. Geology, vol. 41, no. 7, p. 685, 1933.

[28] Juan, V. C., Diatomaceous earth in Shanwang, Linchii, Shantung. Geol. Soc. China Bull., vol. 17, no. 2, pp. 183-192, 1937.

sea cores from the North Atlantic.[29] The association of volcanic rocks, and particularly of pyroclastic rocks, with the thicker and more extensive deposits of siliceous organisms is thus found to be so general, both in geologically recent and older strata, that it must have some genetic significance.

Modern deep-sea deposits commonly contain much pyroclastic material, which is so widely distributed by transportation through the air that it falls into deep seas where other sedimentary materials accumulate but slowly. This fact suggests the possibility that the diatomaceous deposits of the Monterey contain associated pyroclastic material because they may represent comparable deep sea deposits. This hypothesis is contradicted, however, by the various lines of evidence which indicate that the Monterey deposits were not accumulated in deep seas and at an exceptionally slow rate. Volcanic ash is just as commonly associated with nonmarine diatomaceous deposits formed in shallow lakes.

As Reinhold [30] has pointed out, the common association of diatoms and volcanic ash may be due, in part at least, to the fact that delicate opaline shells would be less readily dissolved and hence more commonly preserved in beds containing volcanic ash than elsewhere, because the water within the beds contained so much silica derived from the ash that it had little solvent effect on the diatoms. But though this may be a factor in preserving some diatoms in the ash interbedded with normal sediments not largely composed of diatoms, it obviously cannot account for the larger accumulations originally consisting chiefly of diatoms.

One of the earliest and quantitatively most important effects of the alteration of vitric pyroclastics, is a loss of silica. Great quantities of silica would thus be dissolved in sea water from volcanic ash, supplying one element highly favorable to the growth of diatoms. This condition seems a probable cause of the common association of diatoms with volcanic ash, and some support for this view is found in the results of recent oceanographic studies.

The most abundant diatom planktons of modern oceans occur most widely in high latitudes, where their development seems to be favored, in general, by the low temperature and salinity of the sea water. More temperate waters, however, show an equally great abundance of diatoms in certain places where streams from the land or the upwelling of deeper ocean waters rapidly replenish the supply of nutrients. An abundance of nutrients is thus shown to be of paramount importance.

Bigelow [31] says:

On the whole, with successive observations and experiments, it grows more and more probable from year to year that, given temperatures, salinities, and alkalinities in which diatoms can exist, with sunlight sufficient for photosynthesis, their regional and seasonal abundance depends chiefly on the richness of the water in dissolved food substances, organic and inorganic . . .

Some investigators have concluded that of the three nutrients occurring in least abundance in an available form in sea water, nitrogen was the limiting factor to all plankton growth, others that the supply of phosphate was the critical factor, and still others that, for the diatoms, it was the silica supply. Since these investigations lead to no general agreement, and since many of them seem inconclusive because of the difficulty of controlling and evaluating all the factors, no review of them seems necessary.

Bigelow [32] concludes, after considering all the evidence,

* * * in the long run probably the supply of nitrogenous compounds chiefly determines the regional richness and poverty of the phytoplankton as a whole.

But in considering the diatom plankton he [33] also says:

The obvious dependence of diatoms on silica (which is present in only very minute quantities in sea water) for the construction of their shells has naturally tended to focus attention on the fluctuations in concentration of that substance as probably governing the abundance of marine diatoms, and several recent authors, among them Michael, have definitely accepted it as the chief determinant. Diatoms require more silica than nitrogen, the disparity between these two substances being much greater in the dry matter of these plants than in the sea water in which they live.

He[34] says further:

But after the flowerings have abounded for a few weeks in this particular location, they so reduce the supply of silica (as the analyses show) by converting it into an unavailable form (that is, their own shells) that the water becomes unable to support their active multiplication.

These conclusions are similar to views expressed by Johnstone [35] as follows:

So far as the diatoms are concerned, it would appear that it is the proportion of silica in the sea water that determines the production.

The problem of which nutrient material may have been critical for the long-continued development of the diatoms that have formed thick deposits seems less complex than the question of which nutrients may temporarily or locally limit production in the modern seas. The siliceous deposits make it evident that much of the silica was being permanently removed from the sea water, so that in a long period of time, replenishment of silica was more likely to have been critical than replenishment of any other nutrient. Such equally necessary nutrients as the less stable phosphate and nitrogenous compounds more largely move in a cycle of organic and inorganic forms, these constituents being returned to the near-surface waters, where they could

[29] Bramlette, M. N., and Bradley, W. H., Geology and biology of North Atlantic deep-sea cores, part 1, Lithology and geologic interpretations: U. S. Geol. Survey Prof. Paper, 196–A, p. 21, 1940 [1941].

[30] Reinhold, Th., Fossil diatoms of the Neogene of Java and their zonal distribution: Verhandlungen Geol. Mijnbouwkundig Genootschap voor Nederland en Kolonien, Geol. Ser. Deel XII, blz. 1-132, eerste stuk, Dec. 1937.

[31] Op. cit., p. 467.

[32] Idem, p. 468.

[33] Idem, p. 473.

[34] Idem, p. 482.

[35] Johnstone, James, Conditions of life in the sea, p. 236, Cambridge Univ. Press, 1908.

be used again by the phytoplankton, through oceanic circulations, such as upwelling and turbulence.

The very low concentration of silica in sea water, and the relatively large amount of this constituent required by the diatoms, suggested to Murray and Irvine[36] that these organisms may obtain part of the necessary silica from fine clay material in suspension. Their experiments with controlled diatom cultures, and later experiments by Coupin,[37] seem to support this view. The silica of a clay complex has however been shown by Nutting[38] to be readily soluble; the silica used by the diatoms in these cultures was therefore probably taken from solution rather than directly from the clay complex. A replenishing of the supply of silica from silicates or other sources, even though the silica then occurs in such extreme dilution as one part per million, is evidently sufficient for diatom growth in sea water. Johnstone[39] has pointed out the reasons that permit the microplankton to utilize silica and other nutrients in solutions that are so dilute as to be entirely inadequate for supporting larger and more complex organisms.

Other necessary nutrients, such as phosphate and nitrogen, enter more largely than silica into the organic cycle in marine waters. Additional nitrogen may also be supplied through the action of nitrogen-fixing bacteria, and possibly to some extent through volcanic activity, for it is well known that some volcanic exhalations include notable quantities of ammonia, which, in soluble salts, might be added to the marine waters. Any appreciable increase in phosphate through such a source seems less probable. However, the great fertility of volcanic-ash soils is generally recognized, and all the essential nutrients for diatoms as well as for land plants may be especially available in volcanic materials.

An unusually large supply of available silica and possibly of some other necessary nutrients from the most finely divided particles of relatively unstable volcanic ash would therefore seem highly conducive to abundant and long-continued development of siliceous organisms, and this seems the most probable reason for the close association of volcanic materials with the larger deposits of siliceous organisms. Even the comparatively fresh-looking volcanic ash that commonly occurs in the diatomaceous deposits may have yielded enough silica to supply the needs of countless diatoms, through alteration of the most finely divided particles and of the outer surfaces of the larger shards. Silica tends to be lost in the alteration of ash to bentonite, and the effects of this alteration in its early stages would hardly be apparent on casual inspection, as is indicated in the various stages of alteration described on page 28.

But the enormous abundance, in the Monterey formation, of rocks that have a silica content and silica-alumina ratio much higher than those of any original volcanic rock cannot be accounted for by this process alone, any better than it could by an inorganic process of rearrangement of the silica in tuffaceous deposits. These vast accumulations of siliceous rocks with a silica content greater than that of the source material evidently require some process of concentration of the silica during the deposition of the sediments. Such a concentration might result from the drifting of the delicate siliceous plankton by currents and its settling in protected or comparatively deep basins—a process that is known to be an important factor in the accumulation of some diatomaceous deposits.

ORIGIN OF THE PORCELANEOUS AND CHERTY ROCKS

Porcelanite, porcelaneous and cherty shales, and cherts constitute in the aggregate a much larger part of the Monterey formation than the diatomaceous rocks. Their mode of formation is more obscure than that of the rocks consisting largely of recognizable siliceous organisms but is of more general interest, because similar cherty rocks, which might have had a similar origin, occur in many other regions in formations ranging in age from pre-Cambrian to Tertiary. Chemically, the distinctive feature of these rocks is a ratio of silica to alumina much higher than is usual in fine-grained clastic rocks, most of which are largely composed of clay and other silicate minerals. The unusual proportion of silica is due to its original presence in abnormal amount or to its later introduction, since neither theoretical considerations nor observed facts indicate that it is due to removal of any part of the chemically more inert alumina.

REVIEW OF ALTERNATE THEORIES OF ORIGIN

A great many papers have been written regarding the source of the silica in various siliceous formations, and the conclusions from this extensive literature on the subject indicate that siliceous rocks probably have been formed in various ways. It would be impracticable to review all these papers here, but a summary, in outline form, of the various theories that have been proposed—most of them in various interpretations of the Monterey siliceous rocks—is presented below in order to consider their applicability to the Monterey formation.

Tentative genetic grouping of the various theories regarding the source of silica in siliceous formations

I. Inorganic source of silica
  - A. Deposition of sediment unusually high in clastic silica
  - B. Inorganic precipitation from siliceous waters
    - 1. Syngenetic
      - (a) Siliceous emanations from volcanic rocks

[36] Murray, John, and Irvine, Robert, On silica and the siliceous remains of organisms in modern seas: Roy. Soc. Edinburgh Proc., vol. 18, pp. 229-250, 1889.

[37] Coupin, Henri, Sur l'origin de la carapace siliceuse des diatomees: Acad. Sci. (France), Compte Rendu 175, pp. 1226-1229, 1922.

[38] Nutting, P. G., The solution and colloidal dispersion of minerals in water: Washington Acad. Sci. Jour., vol. 22, no. 10, pp. 261-267, 1932.

[39] Johnstone, James, op. cit.

(b) Silica in solutions and as colloids introduced by streams
2. Epigenetic
(a) Secondary introduction of silica by ground or surface waters

C. Chemical alteration and redistribution of silica of tuffaceous sediments
1. Syngenetic
(a) Halmyrolysis or "submarine weathering"
2. Epigenetic
(a) During compaction and lithification or later

II. Organic source of silica
A. Organic precipitation and accumulation of siliceous organisms
B. Chemical alteration and redistribution of silica of organisms
1. Syngenetic
(a) Halmyrolysis or "submarine weathering"
2. Epigenetic
(a) Diagenetic alteration during compaction and lithification
(b) Metamorphic alteration during deformation and igneous intrusion
(c) Alteration by ground or surface waters

DEPOSITION OF SEDIMENT UNUSUALLY HIGH IN CLASTIC SILICA

Many of the sedimentary formations that contain an unusually high percentage of silica consist of such rocks as quartzite, sandstones, or siltstone, the main constituent of which is quartz, in grains that are obviously clastic. The St. Peter sandstone of the Mississippi Valley region is a well-known example of a formation that is unquestionably clastic and highly siliceous. Griswold [40] interpreted the Arkansas novaculite as a deposit of very fine-grained clastic quartz, but from the evidence available it seems possible that the cryptocrystalline quartz of this formation may have been formed by alteration of originally opaline silica rocks. English [41] suggested that the siliceous shales now included in the Monterey formation of the Puente Hills area may be fine-grained clastic silica rocks. Microscopic examination of these rocks, however, shows that much of the silica is in an opaline cement or matrix, and that the recognizable clastic grains are largely feldspar, clay, and other silicate minerals rather than quartz. The sandstone interbedded with the siliceous shale generally contains more feldspar than quartz, and there is no reason to assume that the finer-grained sediments would be more quartzose. Indeed the work of Grout [42] on the relation of chemical composition to grain size in clastic rocks shows a decrease, rather than an increase, in the proportion of silica in the finer-grained rocks, as might be expected from the relatively high proportions of clay minerals in these rocks.

[40] Griswold, L. S., The origin of the Arkansas novaculites: Boston Soc. Nat. History Proc., no. 26, pp. 414-21, 1895.

[41] English, W. A., Geology and oil resources of the Puente Hills region, southern California: U. S. Geol. Survey Bull. 768, p. 31, 1926.

[42] Grout, F. F., Relation of texture and composition of clays: Geol. Soc. America Bull., vol. 36, no. 2, pp. 393-415, 1925.

SILICA PRECIPITATED FROM VOLCANIC EMANATIONS

Volcanic rocks are so commonly associated with bedded chert formations as to suggest that the chert is a precipitate of silica-rich emanations from the volcanic rocks. This hypothesis was thoroughly discussed by Davis [43] in his study of the cherts in the Franciscan formation of California, wherein he suggested that this explanation might apply not only to the cherts in the Franciscan but also to the bedded cherts in the Monterey formation. A similar origin for the cherts in the Monterey formation has recently been suggested by Taliaferro,[44] and he has interpreted some silica pipes in volcanic rocks underlying the Monterey formation in southern San Luis Obispo County as conduits for siliceous emanations. There seems to be little direct evidence, other than the association with volcanic rocks, to support this hypothesis even for the cherts of the Franciscan formation. Its adoption is based in large part on the objections to alternate hypotheses rather than to direct evidence, though this lack of direct evidence might be expected from the limited exposures available for examination and the great structural complications in these exposures. The extensive outcrops of the thin-bedded cherts and porcelaneous rocks of the Monterey formation, on the other hand, permit a more thorough test of the hypothesis.

Except for the siliceous pipes in volcanic rocks underlying the Monterey formation observed by Taliaferro at a single locality, no structures resembling conduits for siliceous springs or emanations have been reported in the extended examinations of this widespread formation, even though in many areas it contains intrusive sills, above which similar conduits would appear most likely to occur. No thickening of chert beds toward known or postulated local vents has been observed. On the contrary, the beds appear in general to be remarkably persistent and uniform considering the thinness of the individual beds, except in a few places such as Claremont Canyon in the Berkeley Hills (pl. 6, *C*); and even in such places the chert beds do not thicken in one direction only but are markedly irregular. Furthermore, there is no obvious concentration of cherty and porcelaneous strata in areas where intrusive rocks are present or especially abundant, and as these rocks are usually of basaltic composition and undersaturated with silica, they could hardly be expected to give off as emanations the vast volumes of free silica represented in the Monterey formation. The relatively small amount of chert that occurs as nodules and stringers in associated basalts in the few occurrences examined appears to have been formed by alteration of the basalt, though this alteration may be largely a deuteric process involved in the

[43] Davis, E. F., The Radiolarian cherts of the Franciscan group: Univ. California Pub., Dept. Geol. Sci. Bull., vol. 11, no. 3, pp. 235-432, 1918.

[44] Taliaferro, N. L., The relation of volcanism to diatomaceous and associated siliceous sediments: Univ. California Pub., Dept. Geol. Sci. Bull., vol. 23, no. 1, p. 52, 1933.

late stages of consolidation rather than a later or surface alteration. Even silicic intrusive rocks would not be expected to furnish adequate supplies of free silica of magmatic origin to account for the huge volume of siliceous sediment in the Monterey, unless they are far more abundant than there is any reason to suppose from their known distribution. Theoretical considerations and some direct evidence seem to oppose this hypothesis, but these need not be followed further at this point, as the direct evidence of a different origin for the Monterey siliceous rocks presents additional objections to this view.

PRECIPITATION OF SILICA INTRODUCED BY STREAMS

So much silica is carried in solution and colloidal suspension by streams, and so little is present in sea water, that a very large amount must be precipitated in the sea. The amount of silica contributed annually to the sea by streams has been estimated by Clarke[45] at about 319,000,000 metric tons—a contribution intermediate between that of calcium, estimated at about 557,000,000 metric tons, and that of sodium, estimated at 258,000,000 metric tons.

An undetermined part of the silica introduced by streams into the oceans is evidently removed by siliceous organisms, but it is commonly assumed that most of the silica is precipitated inorganically through the action of electrolytes in the sea water. Much additional work is needed to determine the relative importance of organic and inorganic precipitation of silica in sea water, or even to establish definitely that inorganic precipitation occurs there under existing conditions. Similar problems regarding calcium carbonate have received considerable attention, and, though these problems are far from being wholly solved, it now seems probable that much deposition of calcium carbonate has been an inorganic process. Ocean waters, however, are commonly almost saturated with calcium carbonate but apparently not with silica, unless perhaps near the mouths of some streams and in some deep basins. The silica content of 255 streams given by Clarke,[46] when recalculated, shows an average of 16.4 parts per million. The usual silica content of sea water at the surface is only about one part per million, though in some regions[47] the sea water at greater depths contains at least six or seven parts per million.

Experiments on the precipitation of silica in dilute solution have been made by several investigators, including Tarr,[48] Correns,[49] Lovering,[50] Gruner,[51] and Moore and Maynard.[52] The results obtained by these men appear very conflicting, but that seems understandable in view of the large number of variables involved. The influence of the alkalinity of sea water was emphasized by Correns, and that of associated organic colloids by Gruner. Other factors, such as temperature and nature of electrolytes, are obviously important. Schwarz[53] has reviewed the results of some of the experiments and has pointed out their unsatisfactory status. These laboratory experiments do not indeed appear to justify any definite conclusions regarding the inorganic precipitation of silica in sea water under natural conditions. Direct study of these natural conditions, on the other hand, yields information that may bear upon the problem. Some saline lakes contain several hundred parts per million of silica, and deeper ocean waters contain several times as much silica as most of the surface water. Some data from oceanographic studies (p. 40) have indicated a seasonal variation in the silica content of sea water, produced particularly in the waters near shore by seasonal diatom epidemics. These facts suggest that electrolytes are not the prime factor in accounting for surface-water concentrations of about one part per million of silica.

The relative importance of organic and inorganic agencies in precipitating the large amounts of silica contributed by streams to the oceans seems difficult to evaluate without additional data—particularly for the past, when conditions were perhaps in some respects markedly different from those of the present. Accordingly it seems impossible to determine the extent to which the large normal supply of silica from streams has contributed to the diatomaceous and other silica rocks of the Monterey formation. However, the close association of the larger diatomaceous deposits with pyroclastic materials appears to indicate that such an additional source of silica is of prime importance in the accumulation of unusually thick and extensive deposits of this type; and the porcelaneous and cherty strata were derived in large part from diatomaceous strata (p. 50) and not formed mainly by inorganic precipitation of silica contributed by streams.

[45] Clarke, F. W., Data of Geochemistry: U. S. Geol. Survey Bull. 695, p. 134, 1920.

[46] Idem.

[47] Phelps, Austin, The variation in the silicate content of the water in Monterey Bay, California * * * : Am. Phil. Soc. Trans., new ser., vol. 29, pt. 2, p. 157, 1938.

[48] Tarr, W. A., Origin of the chert in the Burlington limestone: Am. Jour. Sci., 4th ser., vol. 44, pp. 434-36, 1917.

[49] Correns, C. W., Beitrage zur Petrographie und Genesis der Lydite (Kieselschiefer): Mitt. d. Abt. fur Gesteins-, Erz-, Kohle-, und Salz-Untersuchungen, Preuss. geol. Landesanstalt, Abh. Heft. 1, Berlin, 1926.

[50] Lovering, T. S., The leaching of iron protores: Solution and precipitation of silica in cold waters: Econ. Geology, vol. 18, no. 6, pp. 523-40, 1923.

[51] Gruner, J. W., Organic matter and the origin of the Biwabik iron-bearing formation of the Mesabi Range: Econ. Geology, vol. 17, no. 6, pp. 407-60, 1922.

[52] Moore, E. S., and Maynard, J. E., Solution, transportation, and precipitation of iron and silica: Econ. Geology, vol. 24, no. 3, pp. 272-303, 1929.

[53] Schwarz, A., Die Natur des culmischen Kieselschiefers: Senckenbergischen Naturf. Gesell. Abh., Bd. 41, Lief. 4, pp. 191-241, 1928.

SECONDARY SILICIFICATION BY SURFACE OR GROUND WATERS

The various facts opposed to any theory of strictly secondary or late silicification of the cherty rocks of the Monterey and Franciscan formations have been reviewed by Davis [54] and need little further consideration. Such a theory is indeed sufficiently controverted by pointing out that these thick and extensive siliceous deposits are distributed, like most stratigraphic units, without any relation to the present topographic surface or to any imaginable older one. The many oil wells that penetrate the Monterey siliceous rocks to depths of several thousand feet show that, except for their darker color, these rocks have the same character in depth as on the surface. Secondary changes seem largely confined to leaching and bleaching by surface weathering and to some filling of cavities and fractures in the brittle siliceous rocks with opal or, more commonly, with chalcedony and cryptocrystalline quartz. The obviously secondary filling both of fractures across the bedding and of partings along the bedding is particularly common in lower parts of the formation, especially in areas of more intense structural deformation. They apparently were formed during such deformation as well as through subsequent ground-water circulation.

ALTERATION AND REDISTRIBUTION OF SILICA IN TUFFACEOUS SEDIMENTS

The genetic significance of the common association of pyroclastic materials with diatomaceous deposits has already been considered. Tuffaceous beds, more or less altered, are also commonly associated with the porcelaneous and cherty strata of the Monterey formation, and also with siliceous formations in other regions. The siliceous Mowry shale in Wyoming affords an instance of this same association that has been carefully studied and described by Rubey.[55] He concluded that the large amount of silica in these rocks, which occurs in part as a cementing matrix in the siliceous shale, was derived from the alteration of the included tuffaceous material. Evidence of a similar process in the Monterey formation was presented on pp. 26-28, which included chemical analyses that show the loss of silica involved in the alteration of the tuffs. The free silica was shown to have impregnated other parts of the tuffs as well as some beds immediately adjacent to the tuffs. Further consideration is necessary, however, in order to judge of the quantitative importance of this process in the origin of the siliceous rocks of the Monterey formation.

In a paper on the geology of the Carmelo Bay area, Lawson [56] suggested that the siliceous shales of the Monterey may represent more or less altered fine-grained tuffs, but his brief discussion indicates that this conclusion was based largely on general similarities in appearance and on two other criteria which now seem of doubtful value. One is the abundance of angular, fresh feldspar grains that appeared suggestive of crystals in tuff. It is now recognized that feldspar, much of it fresh, is the dominant mineral in many of the ordinary clastic sandstones of the California Tertiary (p. 19), and that the feldspar commonly shows little or no rounding, particularly in the smaller grains in the shales. The suggested similarity in chemical composition of a sample of siliceous shale with a rhyolitic tuff was based on an analysis showing 86.89 percent silica and only 2.32 percent alumina. This ratio of silica to alumina is far higher than that of even the most silicic tuff, unless of tuff that has been impregnated with silica derived from adjacent beds or from other sources. The analysis was obviously considered fairly representative of the rocks as a whole rather than a silicified part of the tuff; otherwise the evidence from this analysis would be of no significance, since a more silicified part of the tuff would have derived the additional silica from adjacent more altered beds and would not have changed the gross composition of the formation as a whole.

Various stages may be observed in the alteration of definitely recognizable tuffs, such as the thick Obispo tuff member of the Monterey and many thinner ones, from virtually fresh vitric ash to soft bentonitic clay. The most important chemical changes involved in this alteration are loss of silica, and hydration. Precipitation of free silica is shown in some places by marked silicification of beds adjacent to the tuff. Moreover, in some of the thicker tuffs, such as the Obispo tuff member of the Monterey, silica apparently derived from more altered parts of the adjacent tuff has impregnated numerous thin layers within the tuff. Some of the silicified tuff is as dense and hard as other chert beds in the Monterey formation, but in all samples that were examined in thin sections and thin chips the original pyroclastic texture was well preserved, partially altered shards being embedded in an opaline matrix (pl. 11, *D*). Tuff that is thus silicified generally has a much smaller volume than the adjacent altered material from which the silica seems to have been derived (pl. 16, *A*). This relation would be expected from the percentage of silica shown by chemical anlyses to have been lost during the alteration. The lower half of a tuff bed 50 to 60 feet thick, exposed in a road-cut below La Venta Inn, in the Palos Verdes Hills, has been so thoroughly silicified that it is as hard and dense as a rhyolite, but thin sections of it reveal a well-preserved pyroclastic texture. Only the upper half of this tuff consists of soft bentonitic material. The unusually large proportion of silicified tuff, apparently a single thick unit, seems to be only a local development, for no other outcrops of the rock were found. Silicification of immediately adjacent strata by

[54] Davis, E. F., op. cit., pp. 295-298.
[55] Rubey, W. W., Origin of the siliceous Mowry shale of the Black Hills region: U. S. Geol. Survey Prof. Paper 154, pp. 153-70, 1929.
[56] Lawson, A. C., Geology of Carmelo Bay: Univ. California Pub., Dept. Geol. Sci. Bull., vol. 1, pp. 1-59, 1893.

silica derived from thin beds of altered tuff is perhaps more common than can be definitely proved, for it would be hard to recognize such silicification in beds that were originally rich in silica.

Definitely recognizable tuffs, in part much altered, are common in the Monterey in many areas, but they constitute only a small part of the formation as a whole, the thicknes of most of them being measurable in inches rather than in feet. The possibility that much of the porcelaneous and cherty rock may also represent more or less altered tuffs is suggested by the superficial similarity in general appearance—especially the similarity, in weathered exposures, of non-laminated porcelanite—to slightly silicified fine-grained volcanic ash. The tuffs have been shown to be usually altered where they are associated with the porcelaneous and cherty rocks and to be virtually unaltered volcanic ash only in the diatomite and other rocks that are not cemented with silica. Moreover, the alternating thin beds of more siliceous and less siliceous rocks might be interpreted as the silicified layers and bentonitic layers within altered tuff, though this thin-bedded alternation is not conspicuous in the porcelaneous rocks that most resemble a fine-grained tuff.

More detailed examination, however, does not support such an interpretation. If the thin-bedded cherty and porcelaneous rocks represent silicified layers of tuff, they have not preserved the pyroclastic texture which is recognizable in the cherty beds in tuffs, such as those described as occurring in the Obispo tuff member of the Monterey; commonly, moreover, they show a very fine lamination that is not found in the silicified tuffs. The cherty beds are generally about as thick as, or thicker than, the alternating less siliceous beds, and most of the latter do not resemble altered tuff or bentonite; in some areas, indeed, they consist largely of carbonate or of silt and sand. More commonly these less siliceous partings consist of mudstone or shale, but they differ so much from one another in appearance and admixture of other constituents that chemical analyses, except in large number, would be of little significance. Many of these, when examined petrographically, seemed to be normal fine-grained clastic sediments, not resembling bentonite either in optical properties or in other physical properties. The partings in the cherty rocks are distinct and commonly consist of somewhat silicified clay shale or mudstone; those in porcelaneous rocks are, as a rule, but slightly less siliceous than the beds just above and below, and in much of this rock they are quite obscure or entirely absent.

The few chemical analyses available and the petrographic examination of a large number of the porcelaneous and cherty rocks, are believed to indicate that the average composition of these rocks would be approximately represented by the mean analysis (No. 4) on page 13. The mean silica percentage is certainly not much less than that in this analysis, and the mean silica-alumina ratio appears to be far higher than that of the most silicic volcanic rocks. A rearrangement of silica through alteration of tuffaceous material, even though it were assumed that the formation originally was composed entirely of silicic tuff, would therefore not account for such a high ratio of silica to alumina in the rocks as a whole.

The inadequacy of such an interpretation is further emphasized if, as has been concluded, tuffaceous material, fresh or altered, is not the dominant constituent of these rocks. The purer beds of pyroclastic materials, fresh or altered, are generally distinctive and easily recognized, but the proportion of altered tuffaceous material contained in the porcelaneous and cherty rocks is not easy to determine. Some indirect evidence as to its relative amount is afforded, however, by the following observations.

Nearly pure ash beds occur in the finely laminated diatomaceous deposits and little of this ash has been reworked into the immediately overlying beds (p. 24). This relationship indicates, as the fine lamination does, that both ash and diatomite accumulated below the depths of effective wave or current action. Disseminated volcanic ash, therefore, seldom constitutes more than a few percent of the diatomaceous deposits—not more than one or two percent, as estimated for most of the samples examined. The finely laminated porcelaneous and cherty rocks also were formed below effective wave or current action, and the sharply defined limits of the beds of bentonite in these strata indicate, as in the case of the ash beds, that there was little reworking of the pyroclastic material from which the bentonite was derived. This similarity in the distribution of pyroclastic material in the cherty rocks to that in the diatomaceous rocks is even more evident where diatomaceous strata of one locality can be traced into cherty strata at another (pp. 27-28). The volcanic ash in the diatomaceous strata is unaltered and easily recognized, occurring both as thin beds and as sparsely disseminated particles. In the equivalent strata composed of cherty and porcelaneous rocks the sharply defined bentonite beds are still distinguishable, and the siliceous rocks presumably contain about as much disseminated pyroclastic material as occurs in the diatomaceous strata, though this material is so altered as to be unrecognizable.

The general association of the more altered pyroclastic materials with the harder siliceous rocks (p. 27) must be significant; but the quantity of altered tuffaceous material included in the Monterey formation is obviously inadequate to have supplied all, or even most, of the cement in harder siliceous rocks. And, as has been indicated, this material could not account for the high ratio of silica to alumina in the formation as a whole. Another possible significance of this relationship is considered (p. 53) in discussing evidence that the porce-

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laneous and cherty rocks were formed by alteration of diatomaceous rocks.

SILICA DERIVED FROM SOLUTION OF SILICEOUS ORGANISMS

Many deposits of siliceous rock in which the siliceous organisms preserved are not sufficient to class them as organic deposits are believed by some investigators to have derived their silica from the siliceous organisms originally present in the rocks. Some of these same deposits have been interpreted by other investigators as of inorganic origin, the preserved siliceous fossils in them being regarded as more or less incidental. Evidence for either interpretation seems inconclusive in many cases. The many papers on an organic source of the silica of other deposits will therefore not be reviewed, but some of the facts and conclusions given in these studies will be considered in so far as they bear on the evidence of origin derived from the examination of the Monterey siliceous rocks.

Fairbanks [57] was apparently the first to interpret the cherts and other hard siliceous rocks of the Monterey formation as altered diatomaceous sediments, and his interpretation was accepted by Arnold and Anderson,[58] though Fairbanks presented no evidence for such an origin. More recently, in 1927, Tolman [59] has suggested the same origin for the porcelaneous rocks or "cemented opal shales" of the Santa Maria region. Microscopic examination of some of these rocks led him to conclude that they contained abundant diatom debris. The writer's examination of porcelaneous and cherty rocks of the Monterey from many areas has led him to conclude (p. 15), on the contrary, that recognizable diatoms or diatom debris are not in general abundantly preserved in the indurated or silica-cemented rocks, though molds of diatoms are commonly very abundant.

Some of the upper part of the Monterey formation is obviously of organic origin, being dominantly composed of diatoms and other siliceous organisms, but the greater part of the formation contains relatively few recognizable siliceous organisms. This part may be considered of organic origin, however, in the sense that it represents altered deposits of siliceous organisms, even though it has reached its present state through an inorganic process of solution and reprecipitation of silica within the rocks.

EVIDENCE OF FORMATION FROM DIATOMACEOUS ROCKS

EVIDENCE FROM THE CHERT OCCURRING IN THE DIATOMACEOUS DEPOSITS

Nodular concretions and lenticular beds of opaline chert are rather common in some of the diatomaceous deposits of the Monterey formation. Their mode of occurrence is illustrated in plates 6, *D*, and 7, *A*. They occur most commonly in the lower part of the diatomaceous deposits and in a transition zone where the diatomaceous rocks are interbedded with the underlying porcelaneous and cherty rocks.

Polished surfaces showing the relations of these lentils of dense opaline chert to the adjacent diatomite are illustrated in plate 16, *C*. In thin sections, differences in the texture and constitution of the fine laminae may be seen to pass from the diatomite into the chert without appreciable distortion of the bedding planes, a relation that clearly shows the equivalence of the two sorts of rock. Well-preserved large diatoms are abundant in the white porous diatomite, but they are not recognizable in the chert, even when the thin sections are examined under the microscope with dark-field illumination. The obvious continuity of the laminae, without appreciable changes in thickness or in their clastic constituents, strongly suggests that the cherty lentils were formed by impregnation of the diatomite with additional opal. Such continuity of laminae probably would not exist if the chert represented an inorganically precipitated mass of silica gel that was surrounded and buried by the diatomaceous sediment. Equally improbable is the view that silica was inorganically precipitated as thin laminae in local small areas on a sea floor that elsewhere accumulated similar laminae of diatomite, especially as the small area of the different deposits must first have increased and then decreased to have formed the lenticular masses of chert (pl. 16, *C*). The lack of recognizable diatom outlines in the opaline chert might conceivably be due to similarity in refringence between the delicate organic forms and the opaline matrix: the mean index of refraction of the opal in the matrix is about $1.450 \pm .003$, which is not very different from that of the organic opal—about $1.440 \pm .003$. It seems more probable, however, that the diatoms originally present may have completely lost their identity in an intimate intergrowth with the secondary opal. Etching with a caustic solution brings out the fine lamination of the chert, but it does not reveal any such distinction between opaline matrix and original opaline diatoms as might be expected if the tests of these organisms had been preserved.

Opal masses having the ellipsoidal form that is typical of concretions occur in the diatomaceous deposits in several areas but are not so common as the lenticular beds. These ellipsoidal masses are especially conspicuous at a rather definite horizon in the Lompoc diatomite deposit, and also in the diatomaceous strata in the canyon at the type of locality of Kleinpell's Luisian stage.[60] Similar ones are also found in the porcelaneous

[57] Fairbanks, H. W., U. S. Geol. Survey Geol. Atlas, San Luis folio (no. 101), p. 4, 1904.

[58] Arnold, Ralph, and Anderson, Robert, Geology and oil resources of the Santa Maria oil district: U. S. Geol. Survey Bull. 322, pp. 45-47, 1907.

[59] Tolman, C. F., Biogenesis of hydrocarbons by diatoms: Econ. Geology, vol. 22, no. 5, pp. 454-74, 1927.

[60] Kleinpell, R. M., Miocene stratigraphy of California, p. 122, fig. 11, Am. Assoc. Petroleum Geologists, 1938.

and cherty rocks of several areas, being unusually abundant along the coast of Drakes Bay, in the Point Reyes quadrangle. Taliaferro[61] has described these opal concretions in detail and discussed their origin. He suggests that they grew on the sea floor as masses of gel, and he presented interesting evidence of contraction in these concretions by gradual dehydration of the opal. Clear evidence of their early formation was given by certain outcrops near Point Reyes, where fragments of opaline concretions occur in an intraformational conglomerate, which is closely associated with strata containing zones of similar concretions and was clearly formed by a reworking of these opal concretions. This occurrence does indeed indicate an early development of these opal masses, but it does not preclude the possibility that they were formed by concretionary growth within the bottom sediment, and that within a relatively short time they were uncovered, moved, and broken by some such agency as submarine slump or bottom scour. Intraformational debris is not uncommon in other areas, and in other rocks of the Monterey formation (pl. 17, *A*, *B*). Growth of the concretions within the sediment soon after deposition would have been in a chemical environment distinctly different from the chemical environment of the overlying sea water (p. 52). Taliaferro's evidence of contraction in the concretions seems equally consistent with the evidence that they grew by an impregnation of the diatomaceous strata with additional opal, which is indicated by the uninterrupted continuation of the original bedding through the opal masses. In many specimens of these concretions the original bedding is not obvious, because of the marked bands formed by concentric growth; but it is discernible in the more weathered specimens and in those etched with caustic solution. Concentric banding is strikingly illustrated in plate 7, *C*. The specimen there depicted was taken from a concretion in rather massive diatomaceous strata, but it shows bedding planes marked by more than average amounts of phosphatic and other materials, which were seen to extend into the enclosing diatomite without much distortion or much variation in thickness. Similar concentric growth in a fragment of an opal concretion that was enclosed in diatomite is illustrated in plate 17, *C*. This chert clearly formed not only within the strata but even after the laminae had been displaced by tiny step faults, which were equally visible in the enclosing laminated diatomite.

The process and time of formation of these lentils and concretions of chert are considered in a following section, together with that of the other cherty and porcelaneous rocks of the formation. Discussion is here being focused only on the evidence that these concretionary masses do not seem to represent an opal rock of entirely different source and process of formation from that of the enclosing diatomaceous strata. On the contrary, their mode of occurrence (see pl. 16, *C*) indicates that they were formed by impregnation of the diatomaceous beds with additional opal.

DIATOMACEOUS STRATA AND EQUIVALENT STRATA OF PORCELANEOUS AND CHERTY ROCKS

A change from diatomaceous to cherty rocks on a small scale, along observable stratigraphic planes, is illustrated by the lenticular concretions described above. A similar change on a much larger scale can be shown to have occurred in certain areas, and additional detailed stratigraphic work seems likely to prove that such lateral change is commoner than is now generally recognized. In field mapping, however, the lack of easily identifiable stratigraphic markers usually makes it necessary to assume that the contact of diatomaceous and harder silica rocks represents a definite stratigraphic horizon. Lateral variation in the stratigraphic position of this contact in the Palos Verdes Hills has been mentioned in describing the alteration of the Miraleste tuff bed (in the Altamira shale member of the Monterey) (p. 27). Several hundred feet of diatomaceous shale in the northeastern part of these hills is represented on the south side of the hills, less than a mile distant, by strata consisting of cherty and porcelaneous shales without recognizable diatoms. A similar relation seems to exist, though it is less clearly established, in a nearby area at the town of San Pedro, where diatomaceous strata in the western part of the town are apparently represented by porcelaneous rocks to the southwest.[62]

A more obvious and well established example is found in the middle Miocene strata of the Highland Monocline area. Here about 400 to 500 feet of hard porcelaneous rocks exposed on Indian Creek (pl. 2) are traceable into soft diatomaceous beds with only a few lenticular and concretionary masses of cherty rock, exposed in a small canyon about four miles to the west of Indian Creek. This latter place was taken by Kleinpell as the type for his Luisian stage.[63] These two sections are particularly well correlated by abundant foraminiferal faunas and by distinctive lithologic sequences recognizable in both areas.

A lateral variation is also made evident by comparing two sections along the Santa Barbara County coast. In the Naples section (pl. 2), the middle Miocene strata are soft diatomaceous and phosphatic shales interbedded and alternating with zones of cherty and porcelaneous shales. The equivalent strata in the section at the mouth of Gaviota Creek, about 16 miles to the west, consist of cherty, porcelaneous, and phosphatic shales without preserved diatoms. The correlation of these two sections

[61] Taliaferro, N. L., Contraction phenomena in cherts: Geol. Soc. America Bull., vol. 45, no. 2, pp. 194-207, 1934.

[62] Woodring, W. P., Bramlette, M. N., and Kew, W. S. W., Geology and paleontology of the Palos Verdes Hills, Calif.: U. S. Geol. Survey Prof. Paper 207, p. 31, 1946.

[63] Kleinpell, R. M., Miocene stratigraphy of California, p. 122, fig. 11, Am. Assoc. Petroleum Geologists, 1938.

is well established both by the faunal and the lithologic sequence.

Along the north flank of the Purisima Hills of Santa Barbara County the writer, in his areal mapping, found that a thick deposit of diatomaceous mudstone in the eastern part of the hills grades westward into porcelaneous mudstone that contains no preserved diatoms, though it does contain abundant diatom molds. Still farther along, in the western part of the hills, the porcelaneous rock grades back again into soft diatomaceous mudstone.

A similar change, described by Reed,[64] is shown by the so-called Indicator Bed of the Coalinga anticline. Here a bed of diatomite about 20 feet thick, sharply separated from adjacent sandstone beds, was traced into a thinner bed of cherty shale without recognizable diatoms. The change occurs within a few hundred feet along the southwest limb of the anticlinal nose. Similar changes appear to occur, though they are less easily demonstrated, in the subsurface strata of the upper Miocene in the Los Angeles basin area and in the southwestern San Joaquin valley region, where diatomaceous beds in the outcropping strata at the edges of the basins are equivalent to hard, platy, porcelaneous shale encountered in wells drilled in the basins.

VERTICAL CHANGES IN STRATIGRAPHIC SECTIONS

At every place where diatomaceous deposits are present in the Monterey, they occur in what constitutes the upper part of the formation at that particular place, although, as is shown in plates 2 and 3, the diatomaceous deposits at one place may differ in age from those at another. In no area do the diatomaceous rocks form the lower part of the formation and the porcelaneous and cherty rocks form the upper part. The few areas in which diatomaceous deposits occur in the lower part of the formation offer no exceptions to this rule, for in these areas the overlying strata are not dominantly composed of the porcelaneous and cherty rocks. The same is true of some areas illustrated by the sections at Naples and Lompoc (pl. 2), where the diatomaceous upper part of the section and the cherty and porcelaneous shales of the lower part are separated by an unusually thick transitional zone, in which diatomaceous and cherty rocks are interbedded but in comparatively thin layers. In most areas no such thick intermediate zone of the interbedded rocks is present, the transition from diatomaceous strata to underlying harder rocks being so abrupt that there is little difficulty in mapping the contact locally, although the basal part of the diatomaceous member commonly includes a zone several feet or a few tens of feet thick that contains lentils and beds of chert, which increase downward in abundance.

Another type of transitional change downward from the diatomaceous deposits is found in some areas—for example, along Chico Martinez Creek (pl. 3) and in the nearby North Beldridge oil field. The nearly continuous sequence of cored strata from the Bear State No. 23 well gave a particularly good set of samples for examination. In these sections the upper diatomaceous strata are underlain by a rather light and porous porcelaneous shale in which impressions of diatoms are common, especially molds of the large discoid types, which are visible under a hand lens. Although the diatoms are represented only by molds, the heavier siliceous tests of radiolaria and sponge spicules are at least partly preserved. With increasing depth in the section, the diatom molds are increasingly difficult to recognize and the sponge spicules increasingly attacked by solution, their axial canals being commonly so much enlarged that their walls are very thin, and finally the spicules are entirely dissolved, so that only molds remain. The porcelaneous and cherty rocks in the lower part of the thick Chico Martinez Creek section consist largely of chalcedonic rather than opaline silica, and in these rocks no siliceous organisms, nor even molds of them, are recognizable, though they are present in the associated carbonate concretions.

DIATOMS IN CARBONATE CONCRETIONS

The carbonate concretions were formed after the deposition of the enclosing beds (pp. 20-21), though before the beds had been much compacted and lithified. The distinctive constituents and variations in beds extend laterally into the concretions, so that those in diatomaceous deposits include abundant diatoms.

The carbonate concretions which occur abundantly in the porcelaneous and cherty shales at many places, likewise generally contain diatoms, although the adjacent beds contain only molds of diatoms or are entirely devoid of their recognizable remains. Other characteristics of the bedding, however, may be clearly traced from the enclosing beds into the concretions. Plate 10, *B*, shows a carbonate concretion in cherty shale. Thin sections from this concretion and from equivalent beds in the cherty rock show that there are no recognizable diatoms in the cherty rock but many in the calcareous concretion. Diatoms in a thin section are illustrated in plate 11, *A*, and some of those obtained by digestion with acid are shown in plate 11, *B*. Diatoms are generally preserved in the calcareous concretions within the porcelaneous and cherty strata, presumably because of the relative impermeability of these concretionary masses to the solutions and their resistance to the pressures that have affected the enclosing beds. The carbonate concretions in the Monterey formation thus yield good diatom floras for micro-paleontologists to study, although great masses of the cherty and porcelaneous rocks that enclose the concretions are otherwise largely barren of identifiable diatoms. Rarely, as in a concretion from the Claremont shale of the type locality in

[64] Reed, R. D., Geology of California, pp. 173-174, Am. Assoc. Petroleum Geologists, 1933.

the Berkeley Hills, the diatoms in concretions have been replaced or altered to chalcedony, though they have retained their form. In this occurrence the strata are vertical and are next to a fault of large displacement. Moreover, the strata appear to be more altered than usual and the chert beds themselves are largely composed of chalcedony and quartz.

TEXTURAL AND STRUCTURAL SIMILARITIES BETWEEN DIATOMACEOUS AND CHERTY ROCKS

The diatomaceous rocks are remarkably similar in many details to the porcelaneous and cherty rocks. Perhaps no one of these resemblances is very striking in itself, but the consistency with which a number of the distinctive features of the diatomaceous rocks are duplicated in the harder silica-cemented rock types is highly significant.

The very fine lamination of cherty and porcelaneous shales, so common in many areas and well illustrated in the polished and etched specimen of plate 5, *D*, is apparently identical with the fine lamination common in the diatomite and diatomaceous shale (pl. 5). Some of the diatomaceous deposits are not finely laminated but consist of massive diatomaceous mudstone, and similarly massive porcelaneous mudstone is common in certain areas and certain parts of the formation. In the few areas where diatomaceous rocks are known to be exactly equivalent to hard siliceous rocks occurring near-by, the bedding has the same character in one rock that it has in the other.

In many areas a well marked rhythmic bedding an inch or two in thickness is found both in diatomaceous strata and in porcelaneous and cherty strata. The gradation within each bed is similar in both kinds of rock except that the upper part of each rhythmite in the diatomaceous sediment is rich in diatoms, whereas in the cherty rocks it is hard silica-cemented material in which no diatoms have been preserved (pl. 15, *A*, *C*).

Step faults on a very small scale, generally confined to particular beds and apparently due to slip movements along the bedding, are rather common in the diatomaceous shale of many areas (pl. 5, *A*). Similar faults are also found in both the porcelaneous and cherty rocks (pl. 18, *C*, *D*), but there they are not likely to be obvious except in weathered exposures or in specimens that have been etched with caustic solution.

Foraminifera, abundant fish scales, and some other organic remains are equally abundant, and show the same mode of occurrence, in the diatomaceous and cherty strata. In both types of rock the Foraminifera may be well preserved or may be leached and be represented only by molds. Foraminifera, or molds of them, appear to be in general less common in the diatomaceous strata than in the harder strata, though notable exceptions are found in some areas; but the distribution of these organisms appears to be correlated with stratigraphic position rather than lithologic character. Foraminifera are less abundant, and unaltered diatomite more bundant, in the upper part of the Monterey than in the lower part. Where diatomite occurs in the middle Miocene—that is, in the lower part of the Monterey—it contains abundant Foraminifera; and where, as in Reliz Canyon, porcelaneous and cherty rocks extend to the uppermost part of the Monterey, they contain few Foraminifera.

RELATIONS OF THE CHEMICAL COMPOSITION OF THE SILICEOUS ROCKS

Only a few chemical analyses of siliceous rocks from the Monterey formation are available (p. 13), and these differ so greatly that a large number of additional analyses would be required to give even an approximate idea of the average composition of these rocks. For this reason only two analyses, representing composite samples from two types of rock, were made for this report. One of these is an analysis of a mixture of ten samples of fairly representative diatomaceous rocks, selected from various areas; the other represents a mixture of samples of cherty shale similarily selected.

As other lines of evidence suggest that the cherty rocks were formed from the diatomaceous rocks through alteration involving concentration of the silica into denser beds, the theoretical composition was calculated of a cherty rock such as might be formed by impregnation of diatomaceous rock with additional opal.

Analyses of Monterey siliceous rocks and of one theoretically calculated

	1	2	3
SiO_2	65.20	82.69	82.60
$Al2O_3$	4.56	1.76	2.28
Fe_2O_3	2.22	1.00	1.11
FeO (?)	.32	.31	.16
CaO	6.47	2.93	3.23
MgO	1.54	1.08	.77
Na_2O	1.64	.50	.82
K_2O	3.22	2.61	1.61
P_2O_5	.15	.21	.07
MnO	.009	.012	.005
CO_2	4.05	2.28	2.03
Cl	1.22	.15	.61
Ignition, minus CO_2 and Cl	9.31	4.75	———
Organic matter	Small	Small	4.66
	99.909	100.282	99.955
H_2O—	4.26	2.64	———
Loss at 350°	8.52	4.14	———
Loss, at faint red heat	14.58	6.73	———
Loss, at full red heat	14.58	7.18	———
Loss or blasting	16.58	7.26	———

1. Composite sample of 10 diatomaceous rocks of the Monterey formation of California. R. C. Wells, analyst.
2. Composite sample of 10 cherty rocks of the Monterey formation of California. R. C. Wells, analyst.
3. Theoretically calculated composition of a cherty rock.

The theoretical composition shown in column No. 3 was calculated as follows: The average specific gravity of the impure diatomite or diatomaceous shale is approximately 0.8, and that of the cherty shale between two and three times as large; an additional 100 percent of silica was therefore added to the composition shown for the diatomaceous rocks, and the resulting figures were then halved so as to bring back the total to about 100 percent. The correspondence between the theoretical composition thus obtained and the composite analysis of cherty rocks shown in column No. 2 is so close as to be probably somewhat fortuitous; it probably would not be so close in another case based on such limited data. It may fairly be regarded, however, as supporting the hypothesis that the cherty rocks were formed by addition of silica to the diatomites.

The decrease in volume or thickness of strata implied in this change to the more dense cherty rocks is not generally apparent, nor is it easily determined from the available field data. The "Indicator Bed" on the Coalinga anticline affords the only known instance in which the relations are quite evident (p. 48). This is a distinctive thin bed overlain and underlain by sandstone. In Oil Canyon, it consists of soft diatomaceous shale and is about 20 feet thick. Within about half a mile along the strike, near the crest of the anticline, it is a dense cherty bed less than half as thick. This single example, however, is not very adequate evidence, as the original thickness may have had a corresponding lateral variation.

The more common alteration forming the porcelaneous rocks appears to involve the solution of diatoms and local deposition of the silica derived from them in the more clayey matrix, but in these rocks abundant molds of the opaline shells have been preserved. This alteration seems to have caused relatively little change in volume, and, as already indicated (p. 15), the density of the porcelaneous rocks is commonly not much greater than that of the diatomaceous rocks.

PORCELANEOUS AND CHERTY ROCKS FORMED CHIEFLY BY ALTERATION OF DIATOMACEOUS ROCKS

Evidence suggesting that the harder siliceous rocks were formed by alteration of diatomaceous rocks was observed in many localities and different types of occurrence. In some beds of the cherty rock the added silica was evidently derived from adjacent altered tuffs, but such beds appear to be few and relatively thin. Lateral transition of a thick body of diatomaceous strata to cherty and porcelaneous strata can be demonstrated in only a few places, but thousands of instances of the same change on a smaller scale can be seen in the lenticular masses of chert in diatomaceous deposits. Carbonate concretions containing well-preserved diatoms are common throughout great thicknesses of cherty and porcelaneous rocks that otherwise contain few or no recognizable diatoms. Equally common and widely observed are the striking similarities of the diatomaceous and the cherty rocks in details of lamination, large rhythmic bedding, and other features. The conclusion thus seems justified that most of the cherty and porcelaneous rocks were formed by rearrangement of the silica of originally diatomaceous rocks.

The ultimate source of much of the silica in these vast accumulations of diatomaceous sediment is believed, for reasons discussed on pages 39-41, to have been the Miocene pyroclastic rocks. The conclusion that the cherty and porcelaneous rocks represent altered diatomaceous rocks thus indicates the same source for nearly all the Monterey siliceous rocks. As the deposits contain a far higher proportion of silica than is present in even the most silicic volcanic rocks, it is necessary to suppose that the silica was derived from volcanic accumulations more extensive than those within the Monterey formation, and that it was concentrated by current drifting of the diatoms; some currents may have brought pelagic diatoms from the open sea into coastal embayments, while other currents may have concentrated the benthonic and pelagic diatoms of the shallower waters in the deeper water of local basins.

TIME OF ALTERATION

Evidence that most of the porcelaneous and cherty rocks of the Monterey were formed from diatomaceous rocks is more adequate than the evidence on the precise nature of the process of alteration and the time at which it occurred. The time of alteration cannot be limited entirely to a particular period during or following the deposition of the sediments; there is some evidence that the process has gone on more or less continuously since deposition, or since a time soon thereafter. It seems probable, however, that most of the alteration occurred in one or more definite stages and was largely completed in Pliocene time. Pebbles and boulders of typical porcelaneous and cherty rocks of the Monterey occur abundantly in Pliocene and Pleistocene conglomerates at many places and form the dominant constituent of some of these conglomerates, such as those in the extensive Paso Robles formation. The alteration obviously took place in large part before the accumulation of these conglomerates. Pebbles of the cherty rocks are also found, though less abundantly, in the upper Miocene sandstones which in some areas overlie Monterey formation—in the Santa Margarita sandstone of the southern Salinas valley, for example, and in the Pismo formation of the San Luis quadrangle. Plate 18, *A*, illustrates an occurrence of cherty shale pebbles at the contact of the Pismo formation with the Monterey formation. Many of these pebbles are angular and show little or no rounding by attrition.

Intraformational conglomerates composed largely of chert fragments have been seen at a few places in the

Monterey formation. Such a conglomerate is very conspicuous in the coastal cliffs just west of the mouth of Gaviota canyon (pl. 18, *B*). Here the chert fragments are obviously derived from the Monterey rocks, as shown by lithologic similarity and included Foraminifera. Many of the angular fragments have sharp edges and must have been deposited as brittle cherty rock and not as soft diatomaceous rock that was later altered to chert. At approximately the same horizon in the Naples section, diatomaceous beds with some interbedded chert contain a few scattered chert pebbles of Monterey formation. One of these pebbles, shown in plate 17, *D*, contains borings like those made by present-day boring mollusks in pebbles of chert and other rocks along this coast. After the holes were bored the pebble was buried in the diatomaceous sediment, which was then compacted around it and squeezed into the cavities. This chert pebble is underlain by the finely laminated bed shown in the illustration, which after compaction was altered to chert. The soft diatomaceous sediment which rested on the upper part had been partly eroded, so that the specimen was exposed in the wave-cut cliff, but enough of the upper part of the chert pebble was still embedded in the diatomaceous shale to show that the diatomite likewise was compacted around the pebble and filled some of the bored cavities. These relations, as well as the occurrence of the specimen above present high-water levels, make it evident that the boring was not done by modern organisms living on the present coast. A fragment of chert of the Monterey that had similar borings was found embedded in the Malaga mudstone member of the Monterey (upper Miocene) of the Palos Verdes Hills.

At least a part of the alteration of diatomite to chert was thus early enough to furnish pebbles that were reworked into succeeding Miocene deposits. It should be emphasized, however, that these intraformational pebbles consist of dense cherty rock; pebbles of the more common porcelaneous rocks are absent, though they are dominant in many Pliocene conglomerates in areas where these overlie Monterey rocks. So far as the writer has observed, the strata classed as Santa Margarita in the Salinas Valley that contain abundant pebbles of porcelaneous shale are of Pliocene age; pebbles of such rock are rare or generally absent in the part of the Santa Margarita that contains upper Miocene fossils. The pebbles of dense chert in the intraformational conglomerate at Gaviota are strikingly different from the immediately underlying beds of porcelaneous shale. This distribution of the pebbles suggests that only the beds of chert were available as hard rock to form the intraformational conglomerates, and that the porcelaneous rocks were formed in a later period of alteration (pp. 53-54).

The beautifully preserved lamination of the porcelaneous and cherty rocks indicates that they were altered after their accumulation as laminated diatomaceous deposits, for it seems improbable that an opal gel formed on the sea floor would possess a fine lamination identical with that of the diatomite. Identical lamination would be expected, on the other hand, if additional opal simply impregnated the laminated diatomite. It is noteworthy that the chert pebbles in the intraformational conglomerates show little or none of the fine lamination, and this chert would be less apt to show it if it formed on the sea floor or in the immediately underlying uncompacted diatomaceous deposits. The contrast between the earlier-formed chert pebble and the enclosing laminated chert is evident in plate 17, *D*.

The fact that diatoms are well preserved in calcareous concretions though absent or represented only by molds in adjacent porcelaneous rocks, indicates that the alteration was subsequent to the growth of these concretions; the concretions were evidently formed within the deposited sediment (pp. 20-21), though before that part of the compaction which has warped the beds around them.

It thus appears that most of the alteration took place within the diatomaceous sediments but, in part at least, soon after their accumulation, since fragments of the cherty rocks occur as intraformational conglomerates. These conglomerates represent interruptions of the sedimentation and reworking of underlying strata, or of strata not far below the surface of deposition in nearby areas, either through submarine slumps or through increased wave and current action. This alteration and lithification during accumulation and compaction of the beds may thus be classed as a diagenetic process. Evidence that much alteration occurred subsequent to these early diagenetic changes—alteration that is apparently related to the effects of load and deformation and perhaps appropriately termed metamorphic—will be considered after some discussion of the chemical conditions of the alteration.

PHYSICO-CHEMICAL CONDITIONS OF ALTERATION

That diatoms are to some extent dissolved by sea water is indicated by the work of Cooper;[65] and also by that of Brockmann,[66] Hustedt,[67] and others, all of whom have noted that many common pelagic diatoms, most of which have unusually delicate shells, are not commonly found among the diatoms of the bottom sediment. Even in the relatively shallow water of the North Sea, the more delicate of the pelagic forms are completely dissolved during their slow descent to the bottom. The very much thicker shells of some other pelagic forms,

[65] Cooper, L. H. N., Chemical constituents of biological importance in the English Channel, November 1930 to January 1932: Jour. Marine Biol. Assoc. of United Kingdom, new ser., vol. 18, no. 2, p. 697, 1933.

[66] Brockmann, Chr., Diatomeen und Schlick im Jade-Gebiet: Senckenbergischen Naturf. Gesellschaft, Abh. 430, p. 18, 1935.

[67] Hustedt, F., Vorlaufige Ergebnisse vergleichender Untersuchungen der Diatomeen holsteinischer Seen: Vorhandlungen der Intern. Vereinigung fur theoretische und angewandte Limnologie, Kiel, p. 103, 1922.

and of most shallow-water benthonic forms, accumulate in the bottom sediment without being noticeably corroded, though removal of a nearly uniform thin surface film from these diatoms would perhaps be unrecognizable. Appreciable solution of opaline organic remains by sea water is also indicated by Schulze's [68] observation that the axial canals in spicules from benthonic sponges are often seen to be enlarged by solution. This solution by bottom waters would perhaps be favored, as Hustedt [69] has suggested, by relatively sparse distribution of opaline shells in a highly calcareous bottom sediment. Solution by bottom waters is evidently not sufficient, however, to affect appreciably the large diatoms, at least where they accumulated rapidly or in great abundance, since many large deposits of them remain.

The silica dissolved from opaline shells in sea water, particularly that dissolved from the more delicate pelagic diatoms while they are settling in the water, would in part at least move in a cycle, through oceanic circulation and upwelling, along with the more soluble of the nutrients required by diatoms. Whether concentrations of silica approaching saturation may develop in the deeper ocean waters is not known, though silica content is known to increase with depth.[70] A unique occurrence of an irregular concretionary mass of opal in the diatom and radiolarian ooze of the north Pacific is recorded by Andree.[71] This mass may represent a precipitate in saturated bottom waters, but it seems equally possible that this opal mass was dredged from somewhat below the surface of the diatomaceous bottom sediment.

Alterations by included sea water within the sediment may occur early, and may therefore be essentially contemporaneous with processes occurring at the surface of the bottom sediment, but the results produced in the two environments may be quite different. The physicochemical conditions would certainly differ. The relatively small quantity of much less mobile water within the sediment would inevitably become more nearly saturated with some constituents than the more mobile overlying sea water. Under these conditions, simultaneous solution and reprecipitation of the opaline silica in the sediment are not incompatible processes. Particularly vulnerable to solution is the finely divided opal in the small diatoms that have a very delicate mesh structure, so that their surface area is large relative to their mass. What Harker [72] says of crystals would apply to diatoms:

Crystals of the same kind but of different sizes, in presence of their saturated solution and within the range of effective diffusion, constitute a sensitive system, in that a slight cause may suffice to bring about corrosion of some crystals with correlative addition of material to others. Such a cause is found in surface tension. Since the pressure due to surface tension is proportional to the curvature of the surface, a small crystal is under greater stress than a larger one. Increased stress, as we shall have occasion to point out later, causes increased solubility. Material is, therefore, dissolved from the smaller crystals and deposited upon larger ones in their neighborhood, until the smaller have disappeared.

Under such chemical conditions, alteration within some of the diatomaceous sediments seems to have begun with their deposition, and some opaline chert was formed at this early stage in some of the Monterey deposits. There are, however, large deposits of diatomite showing little or no such alteration, and that fact indicates that conditions were not always favorable for this diagenetic alteration. What conditions favored early alteration is not yet apparent, but some suggestions may be offered. Among the various factors that might further a diagenetic alteration of the diatomaceous deposits, the relative proportion of associated carbonate may prove to be the most significant. In general, the unaltered diatomaceous deposits are less rich in carbonates than the porcelaneous and cherty rock parts of the formation, though there are many exceptions to this rule. The proportion of organic matter is likewise generally greater in the silica-cemented rocks than in the diatomaceous strata, though the correlation may originally have been less close than it is now, because the more porous diatomaceous beds may have been more largely leached of their original organic matter (p. 36) than the denser siliceous rocks.

Reed [73] has suggested that the extent of alteration may have been controlled by differences in the composition and other properties of the sea waters related to their depth, and that the relatively great depth of the earlier Monterey seas and their later shallowing may, respectively, have determined the general prevalence of silica-cemented rocks in the lower part of the formation and of unaltered diatomaceous deposits in the upper part. Some facts appear to support this suggestion, but perhaps as many are in apparent conflict with it. Not until the ecology of the Foraminifera and other fossils is much better understood than it is at present can this hypothesis be tested adequately. Differences of depth cannot, at any rate, account for lateral transitions from diatomaceous strata to the harder silica rocks at places where, as along the north flank of the Purisima Hills, the two types of rock are similar in character of bedding, in proportion of clastic sediment, and, so far as can be judged from the limited fossils, in their macro- and micro-faunas. The vitric pyroclastic beds in the diatomaceous deposits are little altered, whereas those in the porcelaneous and cherty strata are largely converted to bentonite. This contrast suggests that the loss of silica and alkalies from the tuffs during

[68] Schulze, F. E., Report on the Hexactinellida, Challenger Rept., Zoology, vol. 21, pp. 26-27, 1887.

[69] Hustedt, F., op. cit., p. 103.

[70] Phelps, Austin, The variation in the silicate content of the water in Monterey Bay, California, during 1932, 1933, and 1934: Am. Phil. Soc. Trans., new series, vol. 29, pt. 2, p. 157, 1938.

[71] Andree, K., Geologie des Meeresbodens, Band 2, p. 358, Leipzig, 1920.

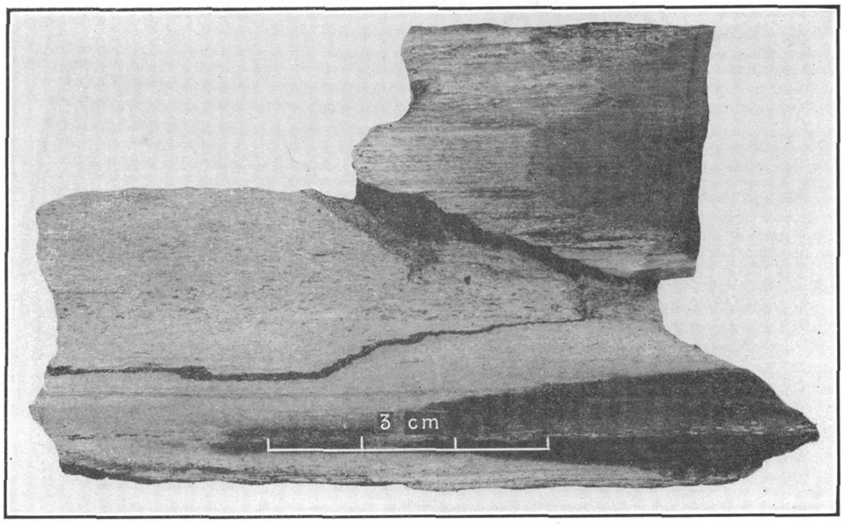
[72] Harker, Alfred, Metamorphism, p. 20, Methuen & Co., London, 1932.

[73] Reed, R. D., personal communication.

A. CHERT BEDS OF SILICIFIED TUFF WITHIN THE OBISPO TUFF MEMBER OF THE MONTEREY FORMATION.

Scale is 5 inches long.

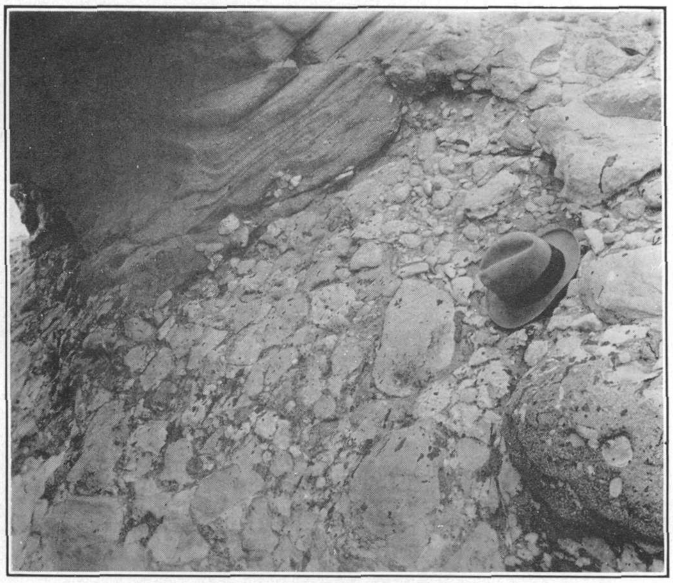
B. LENTILS OF CHERT IN THE DIATOMACEOUS ROCKS ALONG ENTRANCE ROAD TO JOHNS-MANVILLE QUARRY NEAR LOMPOC, SANTA BARBARA COUNTY.



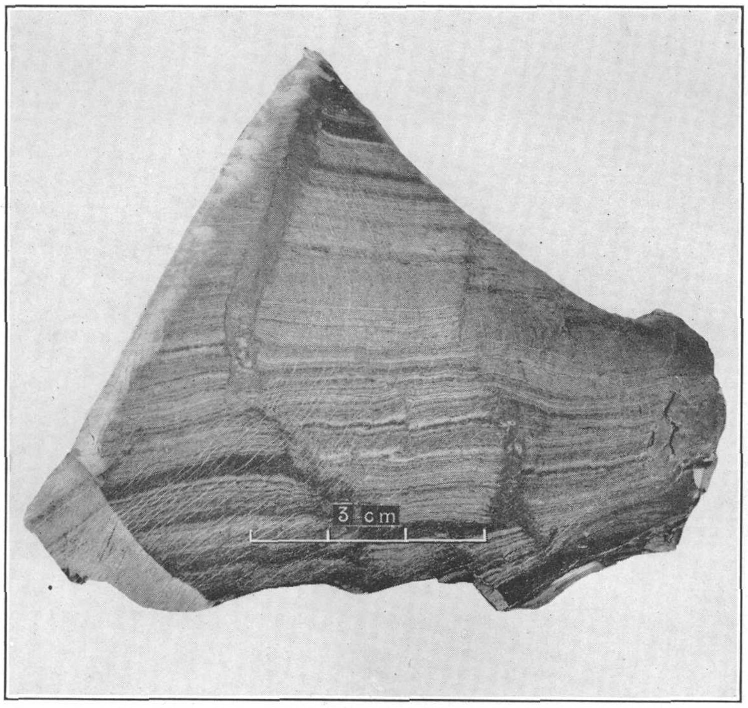
C. POLISHED FACES OF TWO SPECIMENS SHOWING CONTINUITY OF BEDDING LAMINAE FROM DIATOMACEOUS TO DENSE, CHERTY ROCK.

Dark crack in lower specimen is due to accidental break.

A. INTRAFORMATIONAL CONGLOMERATE IN SANDSTONE AND DIATOMACEOUS SHALE BEDS SOUTH OF GIRARD, ON NORTH SIDE OF SANTA MONICA MOUNTAINS, LOS ANGELES COUNTY.



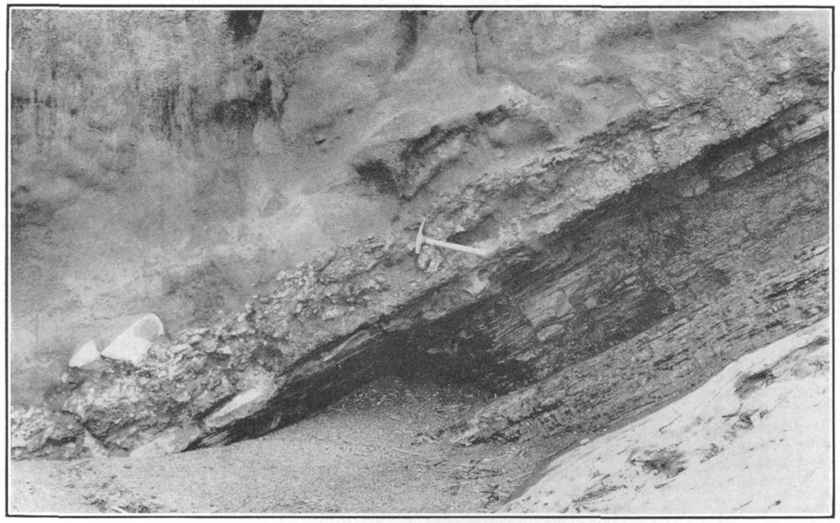
B. INTRAFORMATIONAL CONGLOMERATE WITH BOULDERS OF SOFT MUDSTONE AT MOUTH OF DOS PUEBLOS CREEK, SANTA BARBARA COUNTY.



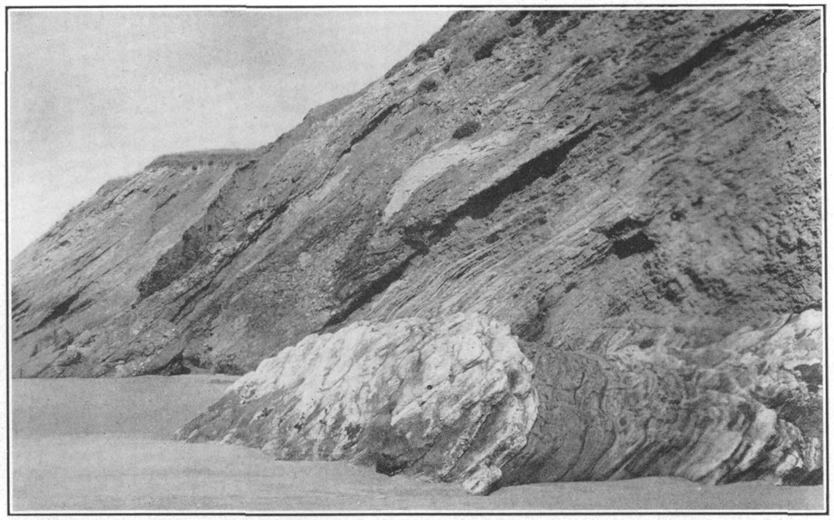
C. FINE CONCENTRIC BANDING AND STEP-FAULTING SHOWN ON A POLISHED AND ETCHED PIECE OF OPAL CONCRETION.

Lighter-colored edge at left shows surface weathering.

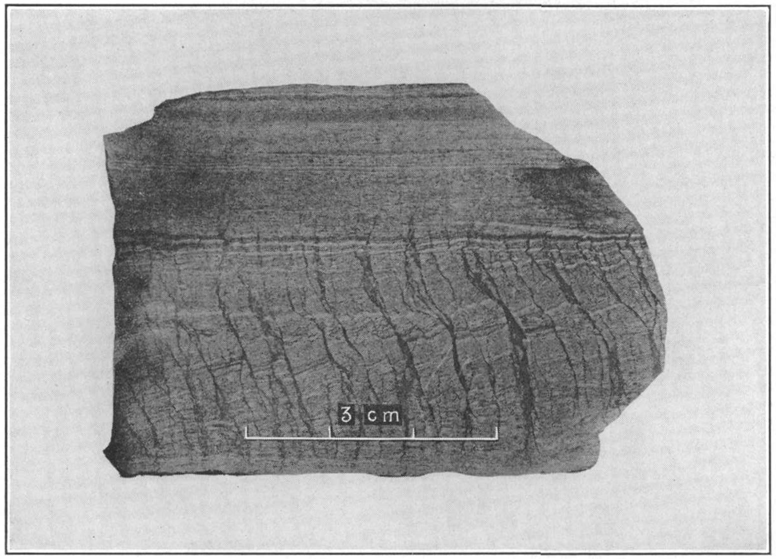
D. CHERT PEBBLE WITH MOLLUSCAN BORINGS, SHOWING COMPACTION INTO THE ADJACENT LAMINATED ROCK (NOW CHERT).



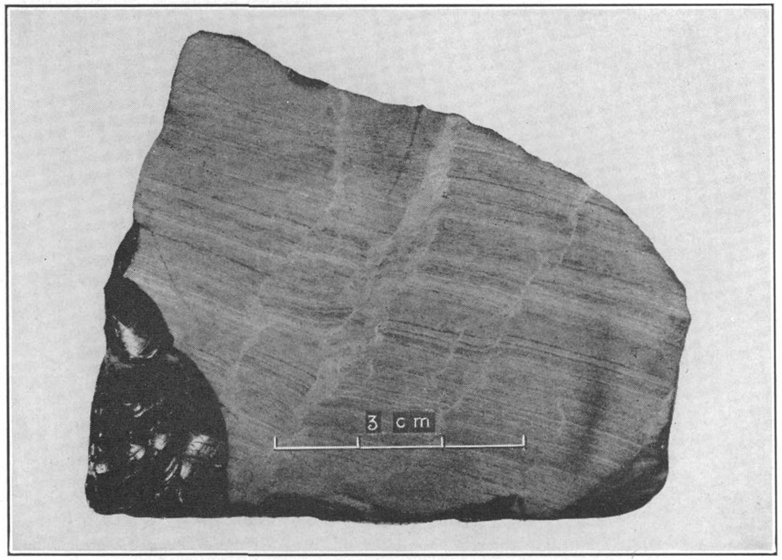
A. CHERT PEBBLE CONGLOMERATE AT CONTACT OF MONTEREY FORMATION AND TAR SANDS OF BASAL PISMO FORMATION.



B. CHERT-PEBBLE CONGLOMERATE AND TAR SAND WITHIN THE MONTEREY FORMATION, WEST OF THE MOUTH OF GAVIOTA CREEK, SANTA BARBARA COUNTY.

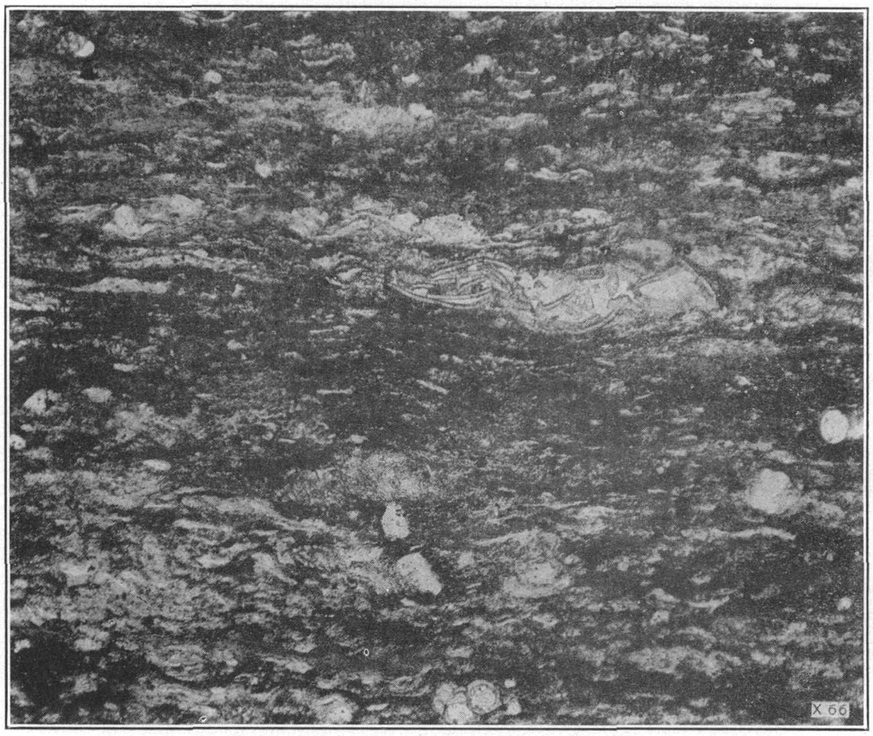


C. SMALL STEP FAULTS IN PORCELANEOUS SHALE FROM THE MIDDLE PART OF THE MONTEREY FORMATION ON CHICO-MARTINEZ CREEK, KERN COUNTY.

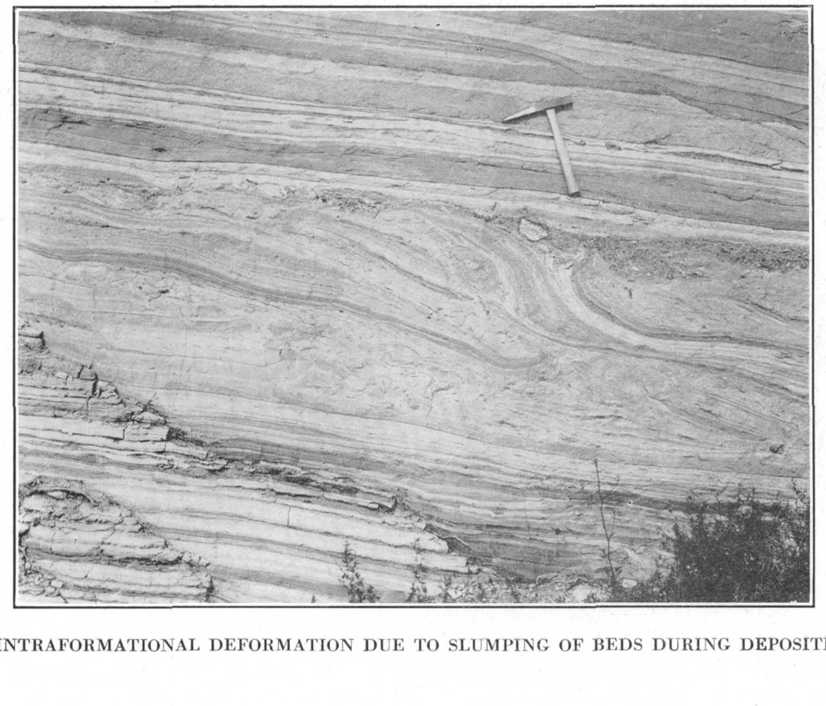


D. SMALL STEP-FAULTS IN BLACK OPALINE CHERT OCCURRING IN DIATOMACEOUS ROCK AT MALAGA COVE, PALOS VERDES HILLS, LOS ANGELES COUNTY.

Chipped corner at left shows dense black opal that is not etched.



A. MASHED FORAMINIFERAL SHELLS IN DENSE CHERTY SHALE.



B. INTRAFORMATIONAL DEFORMATION DUE TO SLUMPING OF BEDS DURING DEPOSITION.

their alteration is related to the alteration of the diatomaceous deposits. The conditions that caused an alteration of the pyroclastics may therefore have been of primary importance, though the same factors may possibly have influenced both these alterations about equally and yet independently. The amount of silica lost from the pyroclastics in the formation appears to be quite inadequate to account for most of the silica cement of the rocks of the formation as a whole. The alkalis which were also liberated from the tuffs early in the process of alteration, though much less in quantity than the free silica, may be a more important factor, because of their influence on the solubility of the opaline organisms within the sediments.

ALTERATION DUE TO LOAD AND DYNAMIC METAMORPHISM

The continuance of bedding laminae without warping from diatomite to chert (pl. 16, *C*) indicates that part of the silicification occurred later than most of the compaction of the sediments. The small step faults in cherty and porcelaneous rocks (pl. 18, *C, D*), obviously formed before the silica cementation of these rocks, show that part of the silicification was subsequent to some deformation of the beds. These small faults at certain horizons may however have been formed soon after the beds were deposited, for there is reason to believe that some deformation of the Miocene deposits took place during their accumulation, though much of this seems to have been only local and minor deformation, perhaps largely related to slumping of sediment on the sea floor (pl. 19, *B*).

In some areas and in some parts of the formation, particularly in fine-grained and fissile or shaly beds, the larger and thinner-shelled Foraminifera are "pancaked" or mashed down parallel to the bedding. This deformation of the Foraminifera is common in both the siliceous shales and the more normal clay shales, though not in the associated carbonate concretions, which formed before most of the compaction. Plate 19, *A*, shows this mashing of the Foraminifera in a hard cherty shale in which the silica matrix is in large part chalcedony. This deformation of the Foraminifera obviously occurred before the silicification.

The fact that the diatomaceous deposits occur only in the upper part of the Monterey formation, and never underlie the dominantly porcelaneous and cherty part, suggests that depth of burial and age may be important factors in much of the alteration. In many areas the formation is several thousand feet thick, and where the thickness of the post-Miocene deposits does not greatly exceed the thickness of the Monterey, the relative load on the upper and the lower parts of the Monterey would be very different. During deformation—and there are few areas in which the Monterey is not considerably deformed—this difference in overlying load might be an important factor in the low-grade metamorphism that would probably suffice to change the diatomaceous sediment to more stable silica rocks.

At some places, as in Reliz Canyon and Modelo Canyon, there are no diatomaceous beds, and even the upper part of the Monterey consists of porcelaneous and cherty rock. A quantitative comparison of the probable load of later sediments and intensity of deformation at such localities with those at places where diatomaceous deposits occur in the upper part of the formation might give significant results. Sufficient data for making such a comparison are not yet available, but oil wells in the deeper parts of such basins as the Los Angeles Basin and the southern San Joaquin valley encounter hard rocks classed as porcelaneous shale in the upper Miocene, whereas diatomaceous beds of the same age are found in wells nearer the margins of the same basins and crop out in the bordering areas. The limited data known to the writer indicate that diatomite or highly diatomaceous and "punky" rocks are not encountered in wells at depths much greater than 3,000 or 3,500 feet. But even though thickness of overburden probably influences the vertical distribution of the hard and soft rocks, other important factors have doubtless been involved, such as relative intensity of deformation, permeability of the beds to included solutions, and composition of the solutions. The suggested relationship of alteration to load and intensity of deformation seems nevertheless to justify further consideration as data become available, for the significance of such a possible relationship in many of the structural and stratigraphic problems regarding these rocks is obvious.

Other occurrences of rocks similar to the Monterey formation offer no evidence against the idea that much of the alteration is due to load and dynamic metamorphism; they seem rather to lend it some support. The siliceous rocks in the Miocene of Japan [74] are similar in many respects to the Monterey, and they likewise include diatomaceous strata overlying harder siliceous rocks, though the latter are not known to be altered diatomaceous rocks. The Kreyenhagen shale of California is also lithologically similar to the shale of the Monterey formation, and in it also a diatomaceous member overlies the harder siliceous rocks. Although this formation is of Eocene-Oligocene age, it is not overlain by Miocene rocks of the porcelaneous and cherty type in the area along Monocline Ridge, where its diatomaceous member is well developed. The thickness of the strata overlying this diatomite of the Kreyenhagen at the time of its major deformation is not determinable, but overlapping and thinning of formations indicate that the thickness of overburden was much

[74] Takahashi, J., The marine kerogen shales from the oil fields of Japan: Tohoku Imperial Univ., Science Reports, 3d ser., vol. 1, no. 2, pp. 63-156, 1922.

less than that present in the basin a short distance to the east of the outcrops of the Kreyenhagen.

Diatoms are not known to have existed earlier than mid-Mesozoic time, but other siliceous micro-fossils are known in strata as old as pre-Cambrian. It seems significant that in these older formations the siliceous fossils are preserved only in a dense, cherty matrix, usually of chalcedonic silica or quartz. Softer, "punky" rocks that contain siliceous remains in an uncemented matrix from which the siliceous shells may be separated are not known in strata older than Cretaceous, and nearly all of them are Tertiary or Quaternary.

The general relation, in the Monterey, of alteration to depth suggests that moderate load and dynamic metamorphism tend to produce the porcelaneous shale, in which the original diatoms are seldom recognizable except as molds, and that greater metamorphism tends to produce the denser, cherty rocks containing a greater proportion of chalcedonic silica. Some alteration, however, has been shown to occur in the early stages of compaction and lithification of the rocks, through what may be considered a diagenetic process. No sharp separation seems possible between the processes or between their products, but some tentative conclusions regarding them are suggested.

SUGGESTED PROCESS OF ALTERATION

The alteration of the siliceous rocks is believed to have been effected largely through redistribution of silica, the relatively unstable finely divided opal in the porous diatomaceous deposits having been dissolved, then re-precipitated near by to form denser and more stable silica rocks. Where the composition or other properties of the water were favorable, this process began soon after the deposition of the sediment. Because of abundant included solutions and high permeability at this early stage, parts of the diatomaceous sediment were thoroughly impregnated with the opal from adjacent sediment and converted into dense opaline chert and cherty shale. The diatoms appear in general to have been dissolved most readily in those thin beds or laminae in which they were relatively scarce, and the silica derived from them was reprecipitated in adjacent beds in which these organisms were relatively abundant (pl. 16, *B*). Ellipsoidal masses of dense opaline chert were formed in some of the more massive deposits of diatomite, whose relatively uniform composition and lack of bedding variations tended to favor this normal form of concretionary growth.

Strata not much affected by the diagenetic or early alteration—including the diatomaceous deposits remaining as such up to the present time—were subjected to varying degrees of metamorphism during subsequent periods of deformation. Where load and intensity of deformation were sufficient to further the tendency of the finely divided opal of the diatom shells to assume a more stable form, a redistribution of silica without extensive movement is believed to have formed the porcelaneous types of rock. During this low-grade metamorphism the rocks would be less permeable, and would contain a much smaller quantity of solutions, than in the early diagenetic period of alteration. Less transfer of silica to other beds or centers or precipitation might be expected to occur, therefore, at this stage than occurred in the early period of alteration that resulted in the formation of dense cherty rocks. The porcelaneous rocks show relatively little differentiation into distinct beds of greater and less silica content. They seem to have been formed by solution of the opaline shells and redeposition of the silica as a cementing matrix without appreciable transfer and redistribution, and they are minutely porous, because they contain abundant molds of dissolved siliceous shells. Some light is thrown on this process by the following statement of Harker:[75]

> Even recrystallization of a single mineral, where no chemical reaction is implied, must usually be brought about by solution. The presence of some solvent medium pervading the rocks is, therefore, to be presumed as an essential part of the mechanism of metamorphism of any kind. It is no less important to observe, however, that the solvent must be present in general only in very exiguous quantity. The kind of solution to which we appeal is a local and temporary solution.

Harker says further: [76]

> In general the conditions prohibit flowing movement of the solvent medium, and any redistribution of material must be effected, not by molar, but by molecular flux, that is, by diffusion.

Field observations appear to support the view that there were two rather distinct kinds and periods of alteration. The siliceous rock fragments in intraformational conglomerates within the Monterey formation are of dense chert such as seems to have formed in the diagenetic alteration, whereas the siliceous rock pebbles of the Monterey in later conglomerates (Pliocene and Pleistocene) are chiefly of porcelaneous rocks. The gradational change that is apparent in the porcelaneous rocks is evidently related to depth. In areas where the formation is exceptionally thick, the porcelaneous rocks become increasingly dense and hard with depth, and the molds of siliceous tests become correspondingly more obscure.

However, this distinction between two periods of alteration and between the resulting types of siliceous rocks is not evident in all occurrences. The later metamorphism has been superimposed on any earlier diagenetic alteration, and in some areas the two were probably not far separated in time, and were therefore less distinct in character and results. Where metamorphism has been greatest, the lower parts of the Monterey contain a relatively large proportion of cherty rock and are

[75] Harker, Alfred, Metamorphism, p. 14, Methuen & Co., London, 1932.
[76] Idem, p. 18.

distinctly differentiated into beds of greater and less silica content. Here, also, the proportion of chalcedony and cryptocrystalline quartz gradually increases downward, and that of opal decreases. Some of the dense cherty rocks thus appear to have been formed from the porcelaneous rocks by increased metamorphism, and these are not always distinguishable from the chert formed by diagenetic alteration. The relative amounts of opal and crystalline quartz may be suggestive evidence, however, even for specimens without relation to their field occurrence, as the early-formed chert consists largely of opal, which in dense beds or ellipsoidal masses would be relatively little altered to crystalline quartz.

Other factors have doubtless influenced the degree of alteration and the extent to which the reprecipitated silica has been segregated into distinct beds or masses. These factors include differences in the original proportion of admixed clay, which would have affected the permeability, and of silica. Some of the rhythmites that have been little altered differ very markedly in silica content.

Certain minor changes in the Monterey rocks record still later alterations, in part related to present surface processes; among these are part of the shattering of the brittle beds and redeposition of silica (usually chalcedony) in the fractures, and leaching to lighter-colored and more porous rocks by surface weathering. Only the thicker beds and masses of silica rocks, and especially those that have been changed to chalcedony and microgranular quartz rocks, can be classed as highly stable; for these the designation of "roches mortes," suggested by Cayeux[77] in his comprehensive volume on the silica rocks, may be appropriate. Cayeux believed that almost all the changes in the silica rocks occurred at an early stage, and that the rocks were thereafter little affected by subsequent events, through he expressly excepted any changes involving dynamic metamorphism.

COMPARISON WITH OTHER BEDDED CHERT DEPOSITS

The conclusion that most of the porcelaneous and cherty rocks of the Monterey formation were formed through an alteration that consisted largely of a rearrangement of the silica of originally diatomaceous deposits is based almost entirely on direct evidence derived from examination of these rocks. No principles of phyical chemistry, or theories derived from them, that might be of general application to other siliceous deposits have been recognized. It seems worth considering, however, whether certain older siliceous rocks, resembling those of the Monterey in many respects, may not be similarly interpreted, inasmuch as the evidence for such an origin becomes increasingly obscure with age and alteration. Direct evidence on the original nature of some of these older and more highly altered formations would almost necessarily be scanty, even as the evidence becomes more obscure in the lower part of the Monterey siliceous rocks, especially wherever a great thickness of overlying strata and great structural disturbances have obliterated most of the transitional stages of their alteration.

Davis[78] has pointed out the many similarities between the cherts of the Franciscan formation and those of the Monterey formation, and has suggested that the study of the Monterey might offer the best clues to an interpretation of the origin of the older formation. He presented some objections to various hypotheses of origin, including evidence that the thin-bedded cherts were not formed by an epigenetic alteration of deposits of siliceous organisms. These objections, however, were largely confined to alteration effected at the present surface or near it, and do not exclude the possibility of an early alteration within the strata. Intermediate stages of alteration would not be expected in these older rocks, and therefore no method of testing this hypothesis is apparent. Judging from alteration evident in the Monterey formation, however, it seems possible, and even probable, that the Radiolaria preserved in the cherts of the Franciscan formation represent only the heavier-shelled forms of the Radiolaria or other siliceous organisms originally present. The difficulty, if not impossibility, of determining the original character of some of the more ancient and altered deposits of bedded chert is thus emphasized.

[77] Cayeux, L., Les roches sedimentaires de France—Roches Siliceuses, p. 696, Imprimerie Nationale, Paris, 1929.

[78] Davis, E. F., The Radiolarian cherts of the Franciscan group: Univ. California Pub., Dept. Geol. Sci. Bull., vol. 11, no. 3, pp. 235-432, 1918.

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☆ U. S. GOVERNMENT PRINTING OFFICE, 1947—696489