ORIGIN OF SOME OF THE SILICEOUS MIOCENE ROCKS OF CALIFORNIA

A Thesis

by

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Chapter I

INTRODUCTION

The upper Miocene marine section in California is characterized in many places by the presence of unusually large amounts of highly siliceous rocks. These can be roughly divided into two classes: the lithified chert-like beds which are characteristic of, and generally largely confined to, the lower part of the section, and the unconsolidated diatomites and diatomaceous and radiolarian silts which are commonly found overlying them. The chert-like beds have been referred to in California geological literature by a variety of names, including cherty shales, platy shales, siliceous shales and cherts. The merits of these, and some other designations are discussed in the section on nomenclature and it will suffice to say here that the writer has decided to use only the terms chert and cherty shale. In addition to the siliceous rocks the lower part of the Upper Miocene or the immediately underlying part of the section frequently contains considerable amounts of volcanic material, both extrusive and intrusive in nature.

Considerable petrologic work has been done on the siliceous rocks and several different theories have been advanced to account for their origin. Some of these consider the contemporaneous or immediately preceeding volcanism to have been an important factor in their development. These theories will be discussed in detail farther on, and it will suffice to say here that there is little agreement among them and that most of them do not explain all the observable facts quite satisfactorily. Most of these theories were formulated as the result of reconnaissance studies covering the rocks of a very considerable area, and although it is possible that before the origin of all the varieties of these siliceous deposits can be satisfactorily explained, state wide studies will have to be made, it nevertheless seemed likely that an intensive study of a limited area might lead to some fairly definite conclusions regarding the origin of some of them. With this idea in mind, the writer undertook to study one particular area in fairly great detail.

The area chosen forthis study lies in the south western part of the present Los Angeles Basin and includes the Palos Verdes or San Pedro Hills. This region seemed particularly suitable because, although structural complications added some difficulties to the problem, these were more than offset by the fact that both types of siliceous rocks are more abundant and more diversified than in many other localities.

Some less complete investigations were also carried out in other parts of the state, especially in the Santa Barbara district and in the region in Ventura County drained by Piru Creek and its tributaries. The relevant data obtained in these areas havealso been incorporated in this paper.

Maps and reports covering the general geology of these last two regions have been published.[1] However, no comprehensive report on the geology of the Palos Verdes Hills has been published at this date, (January, 1934) and for that reason a short resume of the general structure and stratigraphy and a geologic map will be included here.

The writer wishes to express his thanks to the members of the geological divisions of the California Institute of Technology and of the Texas Company of California for many helpful suggestions during the course of this study. Acknowledgment is especially due to Dr. Ian Campbell of the California Institute and Dr. R. D. Reed of the Texas Company for their criticisms and advice, and to Mr. Boris Laiming and Mr. Frank Bell for their assistance in foraminiferal work, and in the identification of diatoms and radiolaria. Dr. W. P. Woodring of the United States Geological Survey assisted greatly in establishing the stratigraphic sequence in the San Pedro Hills, especially in the differentiation of the Pleistocene units there. Mr. M. N. Bramlette of the United States Geological Survey also made several helpful suggestions. To these and many others the writer is deeply indebted.

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[1] Kew, W. S. W., Geology and Oil Resources of a Portion of Los Angeles and Ventura Counties, California. U.S. G. S. Bull. 753:
Arnold and Anderson, U. S. G. S. Bull. #317
Arnold, Ralph, Geology and Oil Resources of Summerland Dist. U. S. G. S. Bull. 321, 1907.

Chapter II

GENERAL GEOLOGY OF THE PALOS VERDES HILLS

The index map, Fig. I, shows the location of the Palos Verdes Hills with respect to better known parts of the Los Angeles Basin. Plate I is a geologic map of this area, modified from a map made by Dr. E. K. Soper and the writer for the Texas Company in 1931. The work was done in a more detailed manner than is shown on Plate I and many of the structural complications are omitted from this plate, whose purpose is merely to show the distribution of the larger stratigraphic units and the major structural features.

Stratigraphy

JURASSIC?

The oldest rocks in this region are a series of metamorphics commonly referred to the Jurassic and correlated with the Franciscan formation of central California. They have been described in some detail by Woodford[2] and consist of quartzites and quartz-albite-sericite schists, both of which nearly always contain important amounts of either glaucophane, crossite, or actinolite. The exposed area of these old rocks is quite small, about one third of a square mile nearthe center of the hills, but the structure is such that a fairly good section of them is visible.

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[2] Woodford, A. O., The San Onofre Breccia, its nature and origin. Univ. Calif. Pub. Nol 7, 1925.

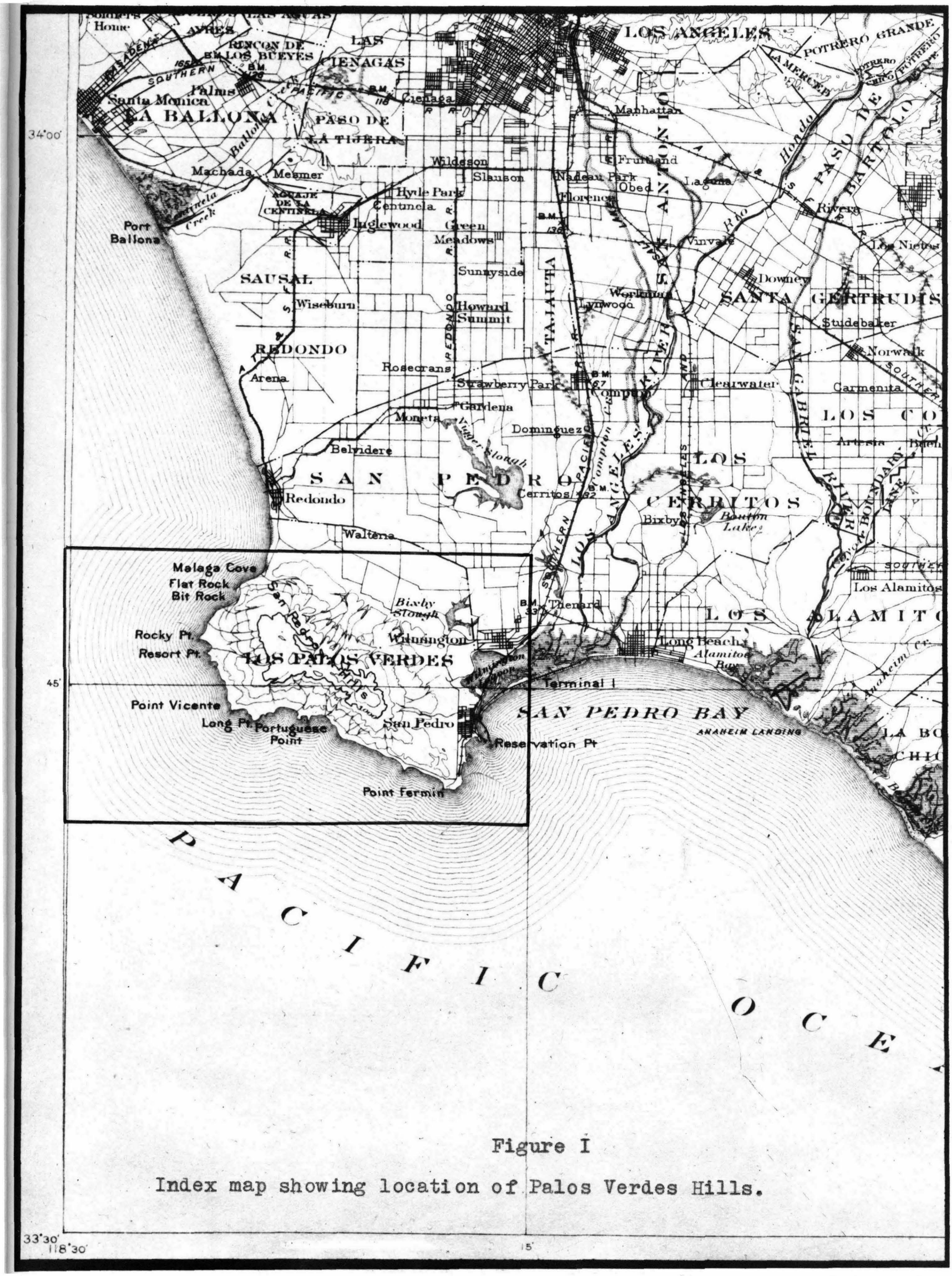

Figure I

Index map showing location of Palos Verdes Hills.

MIOCENE:

Wherever the contact is visible the Franciscan is unconformably overlain by a series of Miocene sediments and volcanics, part of which are the subject of the detailed study to be presented later. On the basis of lithology, the sediments can be divided into three distinct members: the lowest of these is quite variable in thickness, contains several types of rocks, including sandstone, tuff, limestone, silt and cherty beds, and shows considerable lateral variation; the middle member consists largely of diatomite and diatomaceous silts with minor amounts of limestone and chert and shows relatively little lateral variation; the upper member consists almost entirely of radiolarian-diatomaceous silts. There is considerable controversy among geologists who have worked in this area as to the stratigraphic value of these lithologic units, and the writer does not care to enter into the argument at this time. It should be emphasized, however, that whether or not the above mentioned members have a strict stratigraphic significance, they always have the same <u>general</u> stratigraphic relation to one another. That is, the diatomite member always overlies the chert-sandstone-tuff member, and the radiolarian silts always <u>overly</u> the diatomite. Foraminifera from these members indicate that they all belong in the upper half of the Miocene. (See Plate III)

Intercalated with the sediments of the lowest member of this series are some bodies of basaltic rock. These are generally nearly concordant with the bedding, but are believed to be largely intrusive in

PLATE V

GENERALIZED STRATIGRAPHY OF THE SAN PEDRO HILLS

Sedimentary Rocks

PLEISTOCENE	Palos Verdes Formation Q.p.v.	Palos Verdes Formation			50'±
	Sepulveda Group Q.s.	Lower San Pedro Formation -		sand	100'±
		Timm's Point "		silt	100'±
		Lomita "		calcarenyte cgl.	-100'±
LOWER PLIOCENE	Repetto Formation (Tr.)	Foraminiferal Siltstones			100'±
UPPER MIOCENE	Monterey Formation	Upper Member Tum	Radiolarian Silts Bolivina seminuda		500'±
		Middle Member Tmm	Diatomite Bolivina hughesi		1000'±
		Lower Member Tlm	Cherty shale Division	cherty shales, tuffs, limestones, silts Valvulineria Californica	500'±
			Bentonite Division	Tuffs-bentonite silts "Gould shale" fauna	300'±
			Sandstone Division	Sandstone	500'±
JURASSIC	Franciscan Formation Jf.	Quartz-albite-glaucophane schists and quartzites			

Igneous Rocks

UPPER MIOCENE	Tb.	Basalt and diabase, probably mostly intrusive

nature. Further details of the stratigraphy of this epoch will be given later.

PLIOCENE:

The uppermost Miocene member is overlain with no visible unconformity by a series of foraminiferal siltstones of lower Pliocene age. These siltstones are superficially quite similar to the underlying Miocene sediments, but differ markedly on closer inspection: for, whereas the Miocene silts are very fine grained, slightly micaceous, and contain abundant siliceous organisms and very few foraminifera, the Pliocene silts are coarse-grained, quite micaceous, and contain very few siliceous organisms and abundant foraminifera. Moreover, the lower part of the Pliocene silts always containsabundant glauconite grains, which are rare or absent in the underlying Miocene. These features enable one to distinguish the two formations without difficulty in the field. The maximum thickness of Pliocene which can be observed is only 100 feet, but well data indicates that a great deal of the upper part of the section is concealed by the overlap of the Pleistocene.

Foraminifera from these rocks indicate that they are of lower Pliocene age and can be correlated with the Repetto formation of the Los Angeles Basin. The lowest Pliocene faunule discovered, however, which is 50' or less above the base of the formation, correlates with a faunule 2000 feet or more above the base of this formation a few miles to the north in the Dominguez oil field. Whether this is due to thinning or overlap is uncertain, but the abundant glauconite grains and the sharp change in lithology lead the writer to believe that the latter is more probably the case.

PLEISTOCENE:

The Pleistocene formations of this area have been made classic by the work of Ralph Arnold[3], C. N. Crickmay,[4] Alex Clark[5], and others, and although they are extremely interesting both petrologically and paleontologically, no attempt will be made to describe them in detail here. Plate IV shows the lithologic nature and thickness of the different units. Neither of these characters is uniform throughout the area and it is even possible that a considerable part of the Lomita and Timm's Point formations are equivalent in age and merely represent ecologic facies. The Lower San Pedro is generally a sand deposit and relatively poor in fossils, so that its recognition in isolated outcrops is also liable to certain inaccuracies.

The three lower formations have all suffered considerable folding and dips in them may amount to 70°, although this is only locally true and 20°-30° is a more common figure. Since their differentiation is not significant from the standpoint of this paper they have been grouped on the map as one unit and called the Sepulveda group. They are exposed as a nearly continuous band along the east and north flanks of the hills.

In contrast to the disturbed condition of the lower Pleistocene beds the Palos Verdes formation is generally a nearly flat lying terrace deposit. Occasionally, however,

PLATE IV

GENERALIZED PLEISTOCENE STRATIGRAPHY OF THE SAN PEDRO HILLS

UPPER PLEISTOCENE		Palos Verdes Formation (Upper San Pedro)	Non marine earthy silts Marine fossiliferous sands and gravels 50'	Terrace Deposits
LOWER PLEISTOCENE	Sepulveda Group	Lower San Pedro Formation	clean, cross bedded sands. Some silt near base. A few molluscs and ostracods 50-200'	dips up t to 45°
		Timms Point Formation	Silts abundant molluscs and foraminifera 0-200'	dips up to 70°
		Lomita Formation	Calcarenite, marls, sands, some cgl. very abundant foraminifera 100-300'	

it is gently folded. The lower part of these terrace deposits generally contains autochthonous marine molluscs, but the upper part is generally an earthy non-marine sandy silt. The terraces on which these deposits lie are very extensive, although discontinuous. In many cases thin veneers of the Palos Verdes formation have been ignored when making the geologic map.

Structure

As mentioned above, the structure of this region is quite complicated, and a discussion of its intricacies does not seem pertinent to this paper. Plate I contains enough details to show the distribution of the major stratigraphic units, and to enable one to anticipate to a certain extent the types of rock that may be studied in a given area. This is sufficient for the purpose of this paper.

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[3] Arnold, Ralph, The Paleontology and Stratigraphy of the Marine Pliocene and Pleistocene of San Pedro, Calif. Calif. Acad. Sci. Mem. 3 1903.

[4] Crickmay, C. N., Anomalous Stratigraphy of Deadman's Island, Jour. Geol. vol. 27, 1929.

[5] Clark, Alex, The Cool Water Timm's Point Pleistocene Horizon at San Pedro, Calif. Trans. San Diego Soc. Nat. Hist. vol. 4, 1931, p. 25-42.

PLATE III

CORRELATION OF MIOCENE OF PALOS VERDES HILLS AND SANTA BARBARA

Palos Verdes Hills	Santa Barbara	Zone	Characteristic Foraminifera
Upper Member Radiolarian Silt 500'	Diatomaceous and Radiolarian Silts 1600'	1	Bolvina seminuda, B. aff.spissa, B. sinuata Bulmina (Globobulimina)crushed Uvigerina fractocostata, U. aff. canariensis Pulvinulinella bradyina Arenaceous foraminifera - chiefly Haplophragmoides
Middle Member Diatomite 800'	Diatomite 500'	2	Bolivina hughesi, B. brevior, B. beyrichi, B. dilitata, B. plicata Buliminella brevior Uvigerina aff. flintii Virgulina californiensis Cassidulina crassa
Missing?	Silt and limestone 300'	3 and 4	Bulimina (Uvigerinella) sp. Bolivina californica Baggina californica Bulimina affinis Cassidulina crassa Valvulineria cancriformis
Cherty Shale Division 500'	Cherty Shale and bentonite 550'	5	Anomalina ammonoides Bolivina advena var. striatella Pullenia miocenica Siphogenerina collomi Valvulineria californica
Bentonite and Sandstone (?) division of Lower Member 800'	Siltstone 350'	6 and 7	Bolivina advena (sinuate var.) Buliminella subfusiformis Nodosaria koina Nonion costifera Robulus sp.(large umbonate) Siphogenerina branneri, S. hugesi Valvulineria miocenica, V. ornata

Chapter III

MIOCENE STRATIGRAPHY

In the preceding chapter it was noted that the Miocene of the Palos Verdes Hills is divisible into four major stratigraphic units. In this chapter these units will be described in more detail and their stratigraphic position with respect to some other Miocene sections will be given. Plate III gives the microfaunal zones of the upper Miocene in the Santa Barbara districtand their correlations with the Palos Verdes section. This zoning is based on foraminifera, and is the work of Mr. Boris Laiming.* It will be noted that the term "Monterey" is used to include all of the Palos Verdes section. The merits of this designation of the upper part of the Miocene have been discussed by R. D. Reed in his "Geology of California"[6] and will not be repeated here. Whether or not the term is justifiable, the foraminiferal zones shown in Plate III are nearly always present in complete sections throughout the state, and are generally believed to represent stratigraphic and not ecologic units. They serve, therefore, as an excellent means of correlating this section with some others which are more generally known. Whether or not the lowermost part of the column should be called Temblor and the uppermost part Santa Margarita is not important to this discussion.

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*Micropaleontologist for The Texas Company, Los Angeles, Calif.

[6] Ralph D. Reed-Geology of California, 1933, publication of the American Association of Petroleum Geologists.

LOWER MEMBER: (Sandstones, Tuffs, and Cherty Shales)

This member shows a great deal of lithologic variation both vertically and laterally, as well as great differences in thickness, so that a generalized section is of little use for the purpose of stratigraphic correlation, unless it is used very cautiously. There are, however, certain rock types which are almost or entirely confined to this member, and a certain general sequence in the order of their occurrence, which should be emphasized. The rock types characteristic of this member are sandstones, bentonites, tuffs, and the so-called cherty or platy shales. The order of their appearance in the column will be discussed presently, but first it seems advisable to describe one nearly complete and very thick section, after which it will be pointed out how this section compares with other equivalent strata.

Section A: (Exposed along and adjacent to the line A-A') (Plates II and V).

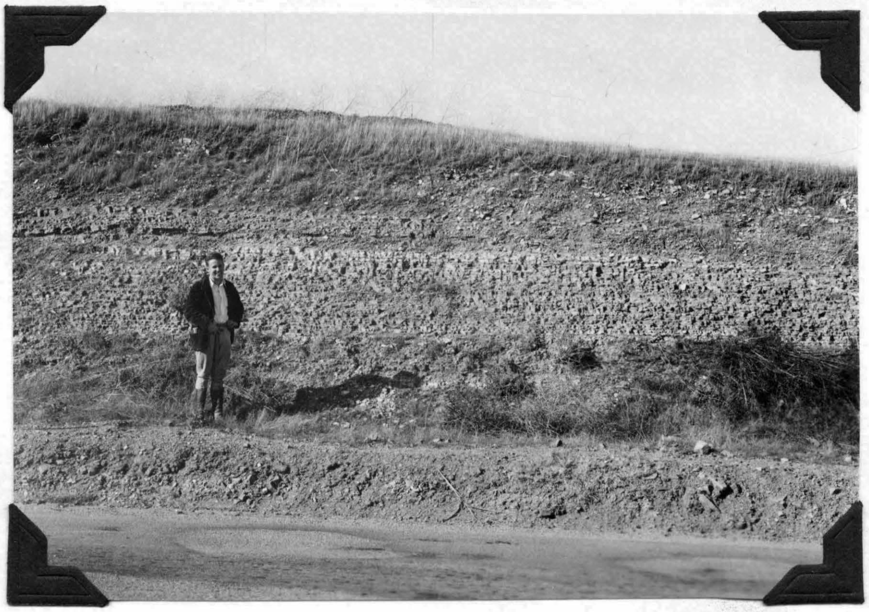
A large part of this section is exposed along the coast highway between San Pedro and Redondo in S15, T5S, R14W, in the southeast quarter of the San Pedro Hills Quadrangle. The remainder is exposed in adjacent road cuts and ravines.

Due to the fact that good exposures are not sufficiently continuous along any one line to permit the rocks to be described along such a line, it was necessary to make several offsets in the traverse when examining this section. Fortunately, it was possible to tie in most of the offsets to each other by tracing beds between them, and in other cases to correlate them with little probable error by dips and strikes. Due to the necessity of making offsets, it did not seem advisable to draw an actual cross section along some mean traverse line, and so only a columnar section is given. However, most of the locality numbers are given on both the columnar section and on the map so that correlations can be made between the two if desired. It was found that this particular section could be divided into three lithologic units which are shown in Plate V and in more detail on Plate II. On the basis of their most characteristic rock types they are called the sandstone division, the bentonite division, and the cherty shale division.

Sandstone Division

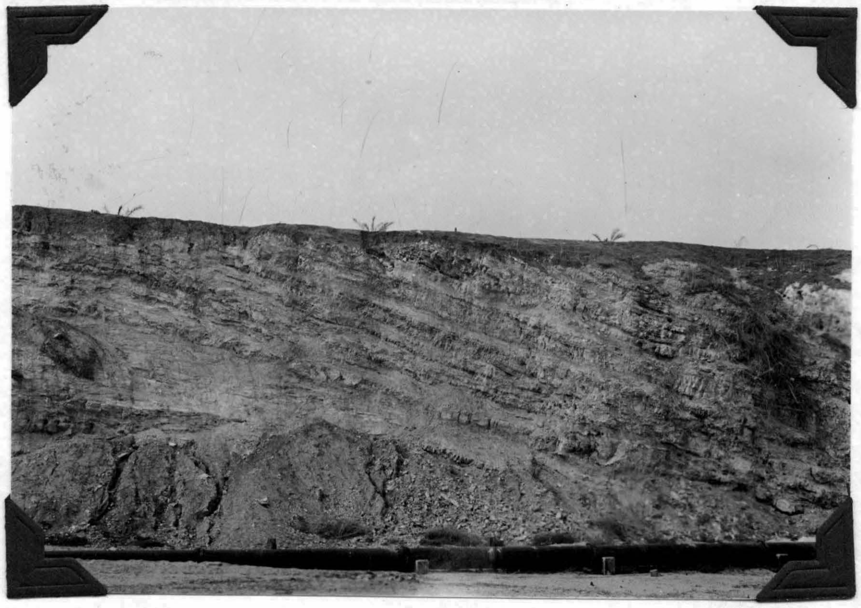
The lowest 400 feet of this section is rather poorly exposed, but certainly consists largely of coarse to medium grained sandstones containing a high percentage of Franciscan schist fragments. Some of these sandstones are highly cemented with calcium carbonate, some are unconsolidated. In addition, this part of this division also contains some thin beds of arenaceous limestone, and a few thin beds of tuff. Near its base it contains a body of basalt which may be extrusive in nature, but is not certainly so. The contact with the Franciscan is unconformable and is

Fig. 2



Rhythmically interbedded tuffaceous silts and sandstone near top of sandstone division of lower member.

Fig. 3



Middle part of diatomite member at Cabrillo Beach showing rather unusual concentration of limestone and chert. See page 26.

marked by a thin limestone bed containing abundant schist fragments. The thickness of this part of the section is based on dips and strikes available and cannot be measured directly, but is probably correct within ten to fifteen percent.

The 120 foot section overlying the 400 feet just described is well-exposed and consists of about 85 percent soft, gray, well bedded, medium grained sand, very rich in glaucophane; about 10 percent tuff; and about 5 percent limestone and silt. There are four beds of nearly pure bentonite. The lowermost three are in the lowest 30 feet of the section and are each one inch thick. The upper bed is one foot thick and is at the top of this division. This 120 foot section can well be included with the lowest 400 feet in the sandstone division. It is described separately because of the difference in the quality of the exposures and the consequent difference in the value of the description.

Bentonite Division

Overlying the lower sandstone division is a section 575 feet in thickness consisting of approximately 38 percent basalt, 30 percent silt and tuffaceous silt, 19 percent bentonite, 10 percent sandstone, and minor amounts of cherty shale and diatomite. The thickness given is almost certainly a minimum, since small normal faults have probably cut out part of the section.

Basalt.

Exposures of the contacts of the basalt bodies in this particular section are too limited to permit a definite statement concerning their nature. However, where they are exposed the contacts are parallel to the bedding and no apophyses or xenoliths were noted, so there is some suggestion that the igneous rocks are extrusive. On the other hand, at the upper contact of the thickest basalt body the overlying sediments are considerably silicified and apparently baked. This suggests an intrusive origin, although the phenomena might be explained otherwise. At any rate the basalt bodies are not very extensive and it is necessary to subtract their thickness from this part of the section when comparing it with other equivalent strata. All three bodies of igneous rock are too badly weathered to permit a reliable classification, but comparison with other igneous masses in the area suggests that they are either basalts or diabases. See page 29.

Silt.

The silt is a compact, tan colored, fairly well laminated rock containing abundant fish scales, and a few diatoms, radiolaria,sponge spicules, and silico-flagellates. It is often quite tuffaceous, and in fact some of it might be called silty tuff rather than tuffaceous silt. In places it contains abundant casts of globigerina tests, but the actual shells of these organisms were never found.

Bentonite.

Bentonite occurs in three beds: one 45 foot bed 50 feet above the base of this division; one 9 foot bed 20 feet higher; and one 55 foot bed at the top of the division. The lower two bentonites are very similar, and disintegrated samples have approximately the following physical composition:

Clay mineral (montmorillonite) (N_p=1.485±.005; N_g=1.510±.005)	80%
Quartz (feldspar ?) angular grains	10%
Volcanic glass (N 1.497)	5%
Siliceous organisms (sponge spicules, diatoms, silico-flagellates)	5%

A chemical analysis* of a sample from the top of the lower bentonite which had the mechanical composition given above, gave the following results:

SiO_2	57.82
Al_2O_3	17.37
CaO	2.65
Na_2O K_2O	1.04
M_gO	3.46
FeO	2.01
Fe_2O_3	.90
SO_3	.32
Cl	.05
P_2O_5	.16
Ignition	14.27
TOTAL	100.05

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* The analysis was performed by Mr. Ed Eisenhauer, Jr. Assayer and Chemist, So. Spring St. Los Angeles.

Assuming that the volcanic glass is a rhyolitic glass, to which category its index would assign it according to Tilley[7], and assuming that such a glass consists of 65% alkali feldspar, 55% of the total alkalies in the above analysis can be assigned to volcanic glass. Whether the remainder would be combined with SiO_2 to form some of the doubtful feldspar grains or combined in the clay mineral cannot be stated definitely. At any rate its assignment is a matter of little importance considering its amount, and the possible errors in the physical analysis. Assuming that it is present in the form of alkali feldspar grains and deducting the silica present in these, plus that present as quartz and siliceous organisms from the total SiO_2 in the above chemical analysis, the clay can be calculated to have approximately the following formula:

$$CaO.2MgO.4Al_2O_3.16SiO_2.20H_2O$$

The indices of refraction of the clay mineral places it in the beidellite-montmorillonite group of Ross[8] and Kerr[9] and the composition also agrees with what can be expected in this series. The above authors give:

$H_2O+H_2O . Al_2O_3 - 3SiO_2$ Aq for beidellite

$H_2O+H_2O . Fe_2O_3 . 3SiO_2$ Aq for nontronite

$H_2O+H_2O . (MgO . CaO$ etc.$) Al_2O_3.5SiO_2$ for montmorillonite

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[7] Tilley, C. E., Density, Refractivity, and composition Relations of some Natural Glasses. Mineralogical Magazine, Vol. XIX, No. 96, 1922.

[8] and [9] Ross and Kerr, Paul, Jour. Sed. Pet. Vol. I, #1, 1931.

and consider that there is a continuous isomorphous series between these minerals and that the indices vary with the composition between 1.480 and 1.60.

The occurrence of siliceous organisms is perhaps noteworthy, since they are a common constituent of most of the bentonite beds of this area, and moreover are common above them, but are very rare in the underlying section. This is interesting in view of the fact that several authors[9,10] have considered that the abundant occurrence of diatoms is directly connected with volcanic outbursts.

The upper bentonite differs from the two lower ones only in containing a higher percentage of volcanic glass and clastic quartz.

Sandstone.

The sandstone of this division is generally coarse grained, brown, well cemented by calcium carbonate, sometimes tuffaceous and characteristically contains much less amounts of the Franciscan amphiboles than do the rocks of the underlying sandstone division.

Cherty Shales.

The petrologic characters of these rocks will be discussed later, but it is desirable here to emphasize the location of their lowest occurrence in the section, which is in the middle of the lowest bentonite of this division. They also occur just above this bentonite, and in the diatomite near the center of the division. (See Plate II)

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[9] Taliaferro, N. L., Relation of Volcanism to Diatomaceous and Associated Siliceous Sediments. Univ. Cal. Publ. vol. 23, 1933.

[10] Whitney, J. D., On the Fresh Water Infusorial Deposits of the Pacific Coast, etc. Proc. Calif. Acad. Sci. pp. 319-24.

Diatomite.

A 10 foot bed of highly diatomaceous silt or diatomite occurs about 380 feet above the base of this division. Opaline frustules are perfectly preserved in a matrix of slightly compacted tuffaceous silt.

A few diatoms were noted in some of the silts below this bed and they are fairly common in some beds above it, but this is the only abundant occurrence of these organisms in the lower member. The position of this bed is believed to be important because some workers have contended that the cherty shales to be discussed later represent metamorphosed diatomites and that the chief agent of metamorphism was the pressure of super incumbent strata. The presence of this diatomite bed well below the main body of cherty shales suggests that this explanation is very unlikely.

Limestone.

A few beds of quite pure limestone occur throughout the section, but are of very minor importance. Several of them contain considerable numbers of opaline diatom frustules.

Cherty Shale Division

The thickness of this division is believed to be about 975 feet, of which the lower 300 feet is excellently exposed, the middle 250 feet is poorly exposed and the upper 405 feet is fairly well exposed. Better exposures in the upper part might lead to a different estimate of the thickness, and to variations in the estimated percentages of the different rock types, but could scarcely change either very radically. The division is estimated to consist of 35% tuff, 25% tuffaceous silt, 20% cherty shale and 20% limestone and tuffaceous limestone.

Tuffs and Tuffaceous Silts.

Most of the tuffs are light gray to pale bluish white beds with irregular limonitic stainings. They are very soft and generally appear unlaminated to the naked eye, although when allowed to thoroughly dry a certain amount of lamination is apparent. They almost always have a weak, waxy luster and with a hand lens appear to consist of an aggregate of minute spheres. This texture is especially characteristic, though hard to explain. On soaking in water the rocks break down into particles much smaller than the apparent sphere size. Microscopically, they can be seen to consist of 10-25% of very angular quartz grains, plus 25-30% of an altered appearing isotropic material of very low index (N=1.480±.005) which is believed to be somewhat altered volcanic glass. The remainder of these rocks consists of a bentonitic clay mineral similar to that mentioned in the discussion of the bentonites of the bentonite-division and of shards of fresh volcanic glass. A few grains of glaucophane or crossite are generally also present.

Tests of foraminifera are sometimes abundant in the silts and are frequently very well preserved. In the tuffs, on the other hand, the only indication of the former existence of these organisms is the presence of moulds and casts. Diatoms and sponge spicules are never abundant, but are quite frequently present in small numbers.

Cherty Shales.

These rocks are much more abundant in this division than in any other part of the entire Miocene section. They are particularly common in the lowest 175' where they make up 30-35% of the section. They will be more fully described later, but it might be mentioned here that they are commonly light gray or tan in color, generally, but not always banded, the bands averaging 1/10 inch in thickness, and that they always occur in regular beds of uniform thickness, not in nodules or irregular masses, as do some of the siliceous rocks which will be described later. Individual beds vary from ½ inch to 10 inches in thickness and average about four inches. Their hardness* varies considerably, there being a complete gradation from slightly indurated cherty shales which are only a little harder than a finger nail, to very well indurated cherty shales which are nearly as hard as quartz. Most of them, however, are just inferior to a knife in hardness. (About 5).

Limestones.

Limestones are of much greater importance in this part of the section than in the underlying divisions. They can be divided into three types: (a) rather soft, often crumbly, tuffaceous limestones containing 30-60% calcium carbonate; and seldom if ever containing any organic remains; (b) laminated limestones generally containing abundant diatoms and often quite well silicified by blebs of chalcedony;

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*Except in the softer varieties of these rocks it is believed that the quality measured is really hardness and not merely the state of aggregation of the constituent parts. In the softest rocks it is likely that the quality measured is a function of the state of aggregation.

(Fig. 4) and (c) cream to dark buff limestones generally showing no lamination and no silicification. These last rocks sometimes contain diatom casts and foraminifera.

As far as the writer knows the laminated limestones and tuffaceous limestones are confined to this part of the section. They have never been noticed in either of the overlying members, nor in the underlying divisions of this member, although the presence of tuffaceous limestones in the latter would not be surprising.

Summary of Lithology of Section "A" of the Lower Member

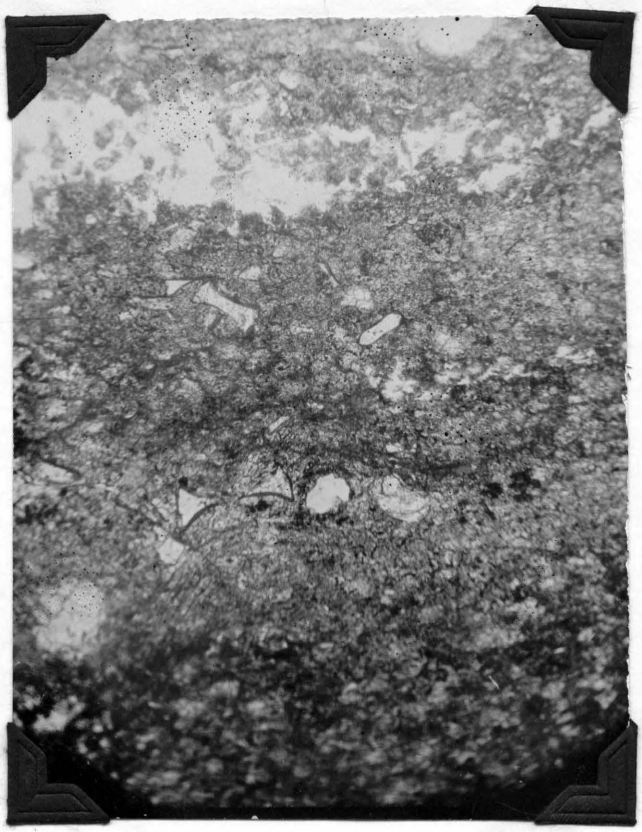
This member can be divided into three divisions. The lowest division, 520 feet thick, consists chiefly of sandstones derived from Franciscan schists with very minor amounts of tuffaceous and bentonitic material. The middle division, 575 feet thick, consists largely of tuffaceous and bentonitic material, silt and basalt, with very minor amounts of cherty shales. The upper division, 975 feet thick, consists largely of tuffaceous material and cherty shales and, in addition, contains considerable amounts of limestone.

It may be significant that diatoms start to be fairly common as soon as tuffaceous material becomes abundant, and also that minor amounts of fairly incoherent diatomite exist so low in the section. It may also be significant that cherty shales first appear in the section at the same place where tuffaceous material starts to be abundant.

Age of Section A of Lower Member:

The lowest foraminiferal faunule discovered in

Fig. 4.



Siliceous Limestone Upper-division of Lower member.

The irregular white area in the upper part of the picture is chalcedony.

The dark areas are calcite. Note diatoms filled with chalcedony in center of picture.

Spl. 590 X from S.W. $\frac{1}{4}$ of S15, T5S, R14W.

Fig. 5 (See also Figs. 48 and 49)

General View of intraformational conglomerate in upper division of member. NW$\frac{1}{4}$, S21, T5S, R14W.
The matrix of the conglomerate is very soft fine grained silt, cobbles and cherty shale limestone and silt. Note also cherty shale cobble in overlying limestone bed.

this section was not collected by the writer but was found by Dr. Robert Kleinpell.* It occurs 100 feet below the top of the sandstone division and contains forms which he correlated with the "Gould-shale" fauna of Chico-Martinez Creek west of Bakersfield. According to Mr. Laiming and Dr. Kleinpell the Gould shale fauna correlates with zones 6-17 of the Miocene column shown in Plate III.

A foraminiferal faunule from a point about 300 feet below the top of the upper division contained the following species:

Valvulineria californica
Baggina californica
Siphogenerina branneri
Uvigerinella californica
Bulimina ovata (odula)

These forms are characteristic of Zone 5 of the same column.

It appears then that most of the lower member can be correlated with the lower part of the Monterey stage of the Miocene. Whether or not the sandstones underlying the first mentioned faunule belong in the Temblor stage of the Miocene cannot be stated at the present time.

It should be noted that the top of the section just described is not marked by the base of the diatomite member. This may be because the stratigraphic equivalent of the latter is represented by a portion of the upper part of the lower member and the diatomite lithologic facies is missing. Such is not believed to be the case, however, because the highest foraminiferal faunule of this section, although 300 feet below its top, is considerably

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* Consulting geologistand micropaleontologist, Bakersfield, California.

older than any known faunule in the diatomite.

Other Sections Through the Lower Member

Strata Corresponding to Upper Division of Section A.

Unfortunately most other sections through the lower member are either less well exposed than the one just described or else structural complications make it difficult to be certain that the entire section is present. For this reason no complete section from the diatomite member to the basal sandstone was described. In many cases, however, several hundred feet of strata immediately underlying a well-exposed diatomite-lower member contact could be readily examined. This is true of the beds below the diatomite in the Rocky Point Syncline, and along the north flank of the hills. In both cases these strata are lithologically comparable to the upper division of the lower member, that is they contain cherty shales, limestones, tuffs and silts and all gradations between them. The percentages of these rocks in the section vary and as a general rule there seems to be less tuff and more silt and limestone than were present in Section A. Whether this is due to the fact that these strata are really somewhat higher in the section, or to lateral variation is not known for certain, but the latter is believed to be the case, and the top of the cherty shale division of section A is believed to be nearly as high as the base of the diatomite member.

There is one locality at which the rocks of the upper division differ markedly from the general constituents of this part of the section. This is at Point Fermin. The strata exposed on the beach at the axis of the Point Fermin Anticline contain abundant foraminifera which seem to be the equivalent of those collected 300 feet below the top of the lower member. (Section A) The rocks in which they occur are siltstones containing a few cherty shale beds. They are overlain by 50 feet of coarse sandy tuffs and cherty shales and then by 100 feet of very coarse glaucophane schist-sandstone breccia. This is the only known important occurrence of coarse sandstone so high in the section. Moreover, the contact as exposed on the west side of Point Fermin looks like an unconformity, and on the south end of the point there are certainly some irregularities along the contact. This possible unconformity and sudden change in lithology is mentioned here because it may help to explain the apparent hiatus, which, judging from the foraminifera, seems to exist somewhere in this part of the column.

Before leaving this discussion, the presence of an intra-formational conglomerate containing cobbles of very hard cherty shale, limestone, and siltstone should be mentioned. This conglomerate is well exposed at low tide at the station marked 615-A, which is about three quarters of a mile east and one quarter of a mile south of Inspiration Point. (Plate I). Its stratigraphic position compared to Section A is given in Section B, Plate II, the correlation being made on the upper-bentonite bed of the bentonite division. The conglomerate bed is about two feet thick and consists of about 25% cobbles in a matrix of soft silt. (Figs. 5 and 48). Some of the cobbles are quite soft shale and are well rounded, but all of the cherty shale and limestone cobbles are subangular. This conglomerate is believed to be significant when considering the origin of the cherty shales. The softness of the silt matrix and the fact that there is no cemented transition zone between the cherty shale cobbles and the surrounding silt seems to preclude the possibility of the cobbles having been silicified subsequent to their deposition in the conglomerate. Since their angularity,considered in conjunction with their size,seems to indicate that they could not have been transported very far, and since they are petrographically identical with some cherty shales in the immediately underlying 200 feet of section, and since finally,cherty shales are not known to occur in any adjoining area at a point more than 380 feet below the conglomerate, it seems likely that they were derived from an uplifted part of the underlying 200-400 feet of section.

Since the intraformational conglomerate is a very local feature and since according to the foraminiferal evidence there is no hiatus in this part of the section, it seems necessary to conclude that the cherty shales of the section underlying the conglomerate attained their present indurated state before more than 400 feet of sediments were deposited upon them.

Strata Corresponding to the Lower Two Divisions of Section A

Field work throughout the San Pedro Hills indicates that the lithologic types described as typical of the lower part of section A are fairly persistent. In some cases there seem to be great variations in thickness. For example, just north of the Franciscan area the total apparent thickness of the lower member is 300 feet or less, but here, as often elsewhere, one cannot be certain that this apparent thinning is not largely due to faulting. At any rate, the lower part of the lower member nearly always consists of coarse sandstone derived from Franciscan schist and is overlain by sediments rich in tuffaceous material. Moreover, as far as is known cherty shales do not exist below the point in the section where tuff is abundant.

Summary

It is believed that although section A shown on Plate II is probably somewhat thicker than its stratigraphic equivalents elsewhere in the area, it nevertheless contains the lithologic types typical of this member in approximately the same percentages that exist elsewhere, and in the same stratigraphic sequence. In other words, the lower member, with some local exceptions, consists of a basal division consisting largely of sandstone, a middle division consisting largely of bentonite, tuff and silt, and an upper division consisting largely of tuffs, cherty shales, limestones and silts. Scattered foraminiferal samples indicate that the lithologic divisions of this member correspond approximately to stratigraphic divisions, but these samples are too few in number to permit this to be considered a proven fact.

MIDDLE MEMBER OR DIATOMITE MEMBER

In contrast to the lower member, the middle member is remarkably uniform in lithologic character and is fairly uniform in thickness. There are, to be sure, several exceptions to its uniformity which will be mentioned later, but by far the greater number of the sections which were examined consists of the following types of rocks:

Diatomite, or very highly diatomaceous silts -	70-95%
Limestone	5-20%
Black chert	2-10%
Vitric tuffs	1%

In addition to these rocks, this member exceptionally contains diatomaceous glaucophane sands and breccias, slightly diatomaceous silts, and cherty shales, these last being similar to the cherty shales described in the lower member, and quite different from the black chert mentioned above.

Diatomite and Highly Diatomaceous Silts

These rocks are dead white to buff colored when dry and considerably darker when wet. They are composed of from 50-85% or more of siliceous organisms, and from 15-50% of clay or silt. Diatoms are the most common siliceous organisms, but radiolaria, sponge spicules, and silico flagellates are nearly always present and occasionally make up 20-30% of the rock by weight. In numbers they are, however, always of much less importance. (Fig. 6)

A microscopic examination of a disintegrated sample of diatomite from the Decolite quarry south of Harbor City showed that it consisted of:

+240 mesh (0.65 mm.)		2%
	Radiolaria	
-240 mesh		
	Diatoms	75%
	Radiolaria	1%
	Sponge spicules	7-8%
	Silico-flagellates	1%
	Bentonitic clay	15%
	Detrital quartz	- less than 1%
	Volcanic glass	less than 1%

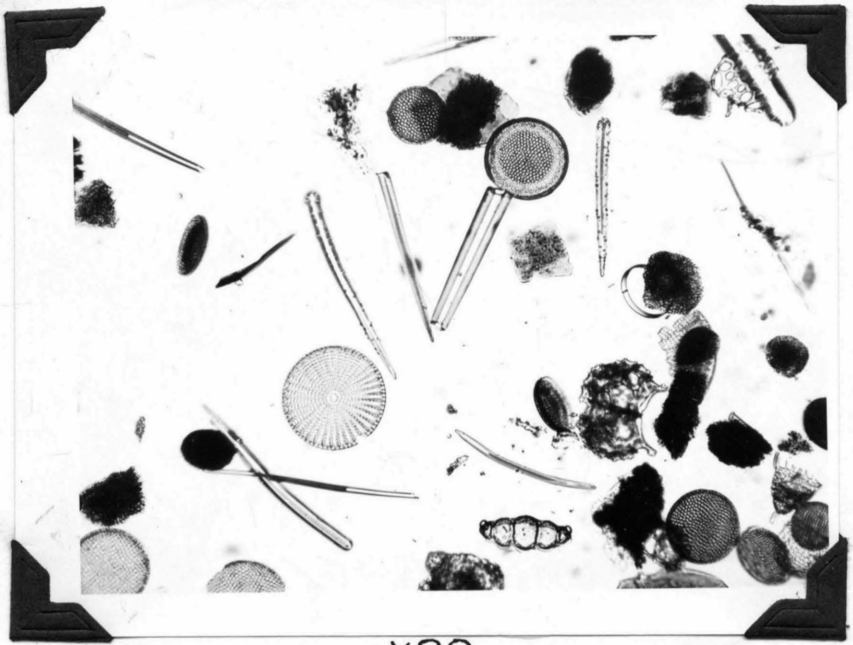
The density of this rock was 0.43

Another sample of buff colored diatomaceous silt from Malaga Cove had the following composition:

+240 mesh (.065 mm.)		- 15%	
	Diatoms		3%
	Radiolaria		4%
	Sponge spicules		5%
	Quartz		3%
-240 mesh		- 85%	
	Yellow isotropic material (clay or altered volcanic glass)		25%
	Diatoms		35%
	Radiolaria		5%
	Sponge spicules		5%
	Silico-flagellates		5%
	Quartz and feldspar (very angular)		10%
	Volcanic glass (N 1.480 - 1.525) - present		

The latter specimen probably has about the average clastic constituent, organic constituent ratio. The ratio of the amounts of different types of siliceous organisms varies a great deal but diatoms are always the most important. It should be noted that most of the siliceous organisms are quite small, and in fact of those below .065 mm. in diameter, prob-

Fig. 6



X90

Diatoms, sponge spicules and radiolaria from coarse concentrate of silty diatomite (+240 mesh)

Fig. 7

The banding is nearly horizontal, note dark colored transition band between diatomite on left and chert on right.

(X5)

Secondary chert from diatomite - Cabrillo Beach.

ably 60% by weight are below .02 mm.

The volcanic glass content is very characteristic. Of several dozen specimens examined not one was devoid of this constituent. The bentonitic clay content may be more variable, although all the specimens which did not contain typical birefringent shreds of this mineral did contain some nearly isotropic material of approximately the same indices which may be a clay mineral.

Limestone.

A few thin beds of limestone (4-18 inches thick) are found in nearly every section of diatomite, and in some exceptional cases, they are so abundant that they make up 30-40% of a 50 foot section through the member. Such occurrences are not usually persistent, however, for more than a few hundred yards along the strike.

Most of these limestones are compact, cream to buff colored rocks with few signs of lamination, and are generally devoid of fossils of any sort. Foraminifera are sometimes present, but strangely enough diatoms are seldom present in appreciable numbers. A CO_2 determination of a specimen from Malaga Cove showed 82% $CaCO_3$.*

Black Chert.

Black glassy cherts with a conchoidal fracture and a hardness of 6-7, occur in the diatomite member in three ways:

1. As beds, generally about 3 inches thick and sometimes continuous for several hundred feet with no great variations in thickness or stratigraphic position, but showing, nevertheless, slight nodular swellings at irregular intervals.

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*A qualitative analysis showed only a trace of magnesium, so all the CO_2 was calculated as $CaCO_3$

2. As nodules of irregular shape, but generally more or less ellipsoidal, varying in long diameter from a few inches to a foot or more and in short diameter from .25 inches to about 6 inches.

3. As veins cutting across several feet of strata.

All of these cherts are discontinuous, although some of those occurring as beds are fairly persistent and unless exposures are good their discontinuous nature might be overlooked. When they end they always do so in the same way, very sharply and suddenly. (See fig. 7) The petrology and origin of these cherts will be discussed later, but their distinction from the cherty shales in mode of occurrence should be emphasized here and it should be remembered that the cherty shales occur as regular stratigraphically limited beds, whereas these cherts occur in more or less irregular bodies.

Vitric Tuffs

Beds one half inch or less in thickness and consisting almost entirely of fresh shards of volcanic glass occur at intervals throughout the diatomite member. The index of refraction of the glass varies from 1.480 to 1.525. Some of these beds contain abundant foraminifera.

Vertical Variation.

The following observations on the stratigraphic position of the above described rock types may be important: (a) Vitric tuffs and limestones seem to be particularly abundant in the lower part of most sections. (b) The percentage of admixed silt is greater in the upper part of most sections. (c) Black cherts do not occur in the uppermost part of most sections.

Lateral Variation.

It was mentioned above that, exceptionally, some types of rock, other than those just described, occur in the diatomite member. This variation occurs chiefly at two places: in the southwestern part of the town of San Pedro, and along the northern flank of the hills south and a little east of the town of Waltheria.

Variation in San Pedro Area

A glance at the geologic map, Plate I, shows an uncolored area in the southern part of the town of San Pedro. This area is partially bounded by known faults, but to the northwest the rocks included in it, (sandstones, cherty shales and tuffaceous silts) seem to grade along the strike into quite pure diatomite. Unfortunately, exposures are not good enough to preclude the possibility of this apparent lateral gradation being due to faulting, and for this reason no such gradation has been assumed in the consideration of the genesis of any of the rocks. This discussion is merely inserted here to explain the geologic map.

There are two types of rocks in the San Pedro area, however, which are unusual for this member. These are:

1. Diatomaceous glaucophane sands and silts, which occur just east of the Cabrillo Beach fault between 10th Street and 21st Street. These rocks vary from glaucophane sandstones and silts with 10-15% of siliceous organisms to diatomites with 10-15% of fairly coarse glaucophane schist detritus.

2. Cherty shales. These rocks closely resemble the cherty shales of the lower member, and differ from them only in the fact that they contain sufficient detrital glaucophane to give them a bluish green tint. They differ from the black cherts characteristic of the diatomite in that their boundaries are strictly stratigraphic and their hardness is generally somewhat inferior to the latter.

Variation in the Waltheria Area

In this area a lens 50-75 feet thick composed largely of cherty shales and tuffaceous silts is interbedded with the diatomite. These rocks are in all respects similar to the cherty shales and tuffs of the lower member,and the cherty shales show no similarities in mode of occurrence with the black cherts of the diatomite.

Thickness of the Middle Member

Unfortunately, minor faulting makes an accurate measurement of the thickness of this member difficult or impossible in many cases.

A section measured on the northwest side of the hills in a small canyon which runs slightly east of north, just west of the line between S33 and S34, T5N, R14W, gave a thickness of 825 feet for this member. No faults were observed in this section, but exposures are not sufficiently continuous to preclude the possibility of their existence.

Another section measured just west of Hilltop Quarry, S11, T4N, R14W was 900 feet thick. The top of the section is not exposed, due to overlap of the Lower Pleistocene and the bottom is cut out by faulting, so the true thickness probably exceeds this figure.

A section measured from the Cabrillo Beach fault along and adjacent to the line L-M in the town of San Pedro had a thickness of 1200 feet, but there is certainly considerable minor faulting across this line. It is believed, however, that the section in this area is at least 1200 feet thick because most of the faults seem to be normal and would decrease rather than increase the apparent thickness.

It appears, therefore, that the thickness of the diatomite member may vary from 1200 feet or more to 800 feet, the thickness becoming less along the northern face of the hills. This variation is not surprising considering the greater amount of clastic material mixed in with the diatoms in the San Pedro town area.

Nature of the Diatomite Lower Member Contact

In all localities where the contact is well exposed between these two members, it is very sharp and apparently perfectly conformable. It has already been noted that in some places certain rock types, more characteristic of the lower member than the diatomite member, do occur in the latter. It was also noted that diatomite occurs sparingly in the lower member. For this reason, it would not be surprising if the contact between these two lithologic units were not always a strictly stratigraphic one. However, the writer wishes to emphasize the fact that while the rocks typical of the lower member are more compact and more dense than the diatomites, there is no gradual increase in compactness or denisty as one goes downward in the diatomite section. Wherever the contact between the typical lower member rocks and diatomite is visible, this contact is a very sharp one, whether the cherty shales and tuffs are interbedded with the diatomite (north side of the hills) or underlying it, as they much more generally are. This sharpness of the contact is beautifully seen along the sea cliff just south of Rocky Point and on the southeastward plunging nose of a small anticline near the west end of 7th Street, San Pedro. The nature of this contact is emphasized here because, as was mentioned before, several investigators have advanced the theory that the cherty shales are essentially highly compacted diatomites. Considering the sharpness of the contact between punky diatomites and cherty shales and the absence of any transitional types near the contact, this hypothesis seems untenable.

Age of the Diatomite Member.

It often happens in California that foraminifera are only locally abundant in highly diatomaceous beds and the diatomites of this area are no exception. For this reason the age of the diatomite throughout its entire extent cannot be stated with certainty.

Foraminifera from the member just north of the breakwater at Cabrillo Beach indicate a definite Zone 2 age. Conformably underlying cherty shales are also of the same age, but it is not certain that these cherty shales are not a lens in the diatomite member.

Around the nose of the anticline near 7th Street, mentioned above, the foraminifera from 50 feet above the base of the diatomite indicate a Zone 2 age. Those from the underlying cherty shales indicate a Zone 5 age. The contact here is almost certainly a depositional one. Whether the apparent hiatus is due to an unconformity, to non-deposition of Zones 3 and 4, or to the fact that ecologic conditions were unfavorable to the growth of foraminifera, cannot be said with certainty; but since the contact between the diatomite and the lower member always appears perfectly conformable, and since Zones 3 and 4 were not discovered anywhere in this area, the writer believes that one of the last two alternatives is the more likely, and probably the last one. In all cases the foraminiferal faunules collected from the top of the diatomite are characteristic of the top of Zone 2.

Summary of Description of Diatomite.
(Middle Member)

1. This member is essentially a deposit of siliceous organisms, containing varying amounts of silt, bentonitic clay, and vitric tuff.

2. The black cherts of this member are discontinuous bodies occurring as irregular masses not confined by bedding planes, and differ sharply in this respect from the cherty shales characteristic of the lower member.

3. Lenses of cherty shales and other rock types typical of the lower member sometimes occur within the diatomite member. When this occurs, their contacts with diatomite both above and below are sharp.

UPPER MEMBER (Radiolarian Siltstone).

This member consists almost entirely of one type of sediment, a siltstone very rich in radiolarian tests, and containing in addition, considerable numbers of diatoms and sponge spicules and a few silico-flagellates. In addition to the siltstone there are a few rather silty limestones, generally in discontinuous lenses, and some thin beds of vitric tuff.

Siltstone.

This rock is generally grayish tan to pinkish tan in color, very poorly stratified or not stratified at all, and possesses a characteristic conchoidal fracture.

A microscopic examination of a sample from 3rd Street, San Pedro, showed the following constituents:

Diatoms	4%
Radiolaria	8%
Sponge spicules	8%
Quartz (.01-.07 mm.)	5%
Chlorite	10%
Clay mineral isotropic	65%

Foraminifera - very rare
Volcanic ash - present

Mechanical analyses of several specimens by means of a continuous weighing apparatus indicate that the rock is nearly always a fine silt rather than a clay or a coarse silt.[*]

The ratio of the constituents shown in the above microscopical analysis undoubtedly varies between rather

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[*] The divisions between clay, silt, and sand used were recommended by Wm. Rubey, U. S. G. S. Proff. Paper 165-A

wide limits, but most of them are always present except foraminifera which are extremely rare throughout the member and often totally lacking.

Vitric Tuff.

A few thin beds of vitric tuff very similar to those which were described in the diatomite occur in this member. The index of the glass from these beds varies from 1.480 to 1.54.

Limestones.

These were not examined microscopically. Their mode of occurrence suggests that they are either diagenetic or secondary.[11]

Relation of Radiolarian Silt Member to Diatomite Member.

It was mentioned above that the upper portion of the diatomite member is considerably siltier than its base, and it might be assumed that the radiolarian silt is merely a still siltier phase, and that the contact is entirely gradational. This is probably true to some extent, but the transition zone is always very thin and it is not difficult to map the contact between the two members. This is due to the fact that the degree of siltiness is not the only difference between the two members; for although radiolaria and diatoms exist in both units, the latter are much more important in the diatomite member and the former in the upper member. Whether or not this change in organic dominance was

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[11] Reed, R. D. A siliceous shale formation from So. Cal. Jour. Geol. Vol. 36, 1928.

conditioned by the increased silt in the water or by some other cause cannot be determined at present.

Age.

Foraminifera from this member are extremely rare: a faunule collected 50 feet above its base and one collected near its top (Timm's Point) both indicate a Zone 1 age for the unit.

Thickness.

Due to the fact that the top of the siltstone is nearly always obscured by the overlap of the Pleistocene, no maximum thickness could be determined for this member. A minimum thickness measured in the town of San Pedro is 500 feet.

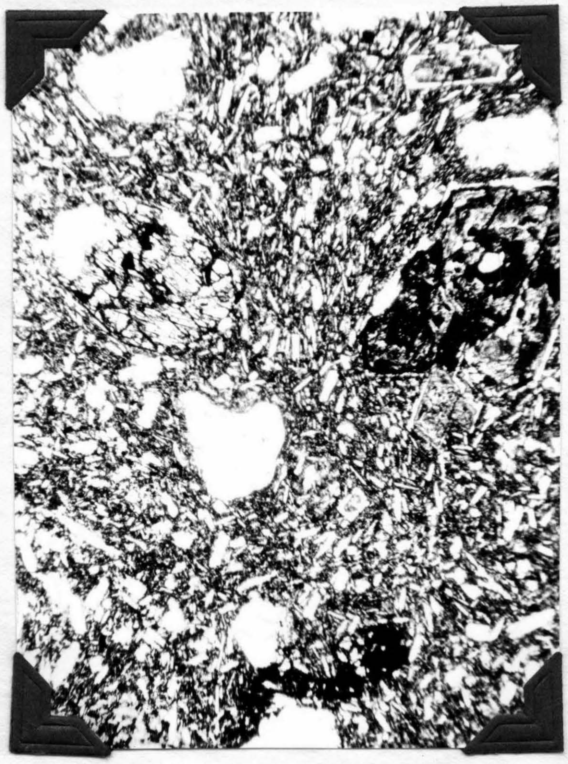
IGNEOUS MEMBER

Outcrops of basic igneous rock are common throughout the southwestern half of the Palos Verdes Hills. In many cases the contacts of the igneous bodies were so poorly exposed that it was impossible to tell whether they were intrusive or extrusive in nature. In several cases, however, the igneous rock can be seen to be definitely intrusive, the body having the form of a sill and being for the most part quite conformable to the bedding, but showing nevertheless such indisputable evidences of its intrusive nature as the presence of xenoliths of the overlying rock, and apophyses running into the overlying strata. (See Fig. 8) Whether

Fig. 8.

Top of basaltic sill - Coast Highway S25, T4E, R15W. Note steeply dipping xenolith below hat.

Fig. 9.



Basaltic rock from S22, T52, R14W.

The large feldspar crystals are $Ab_{22}An_{78}$. The small feldspar crystals are $Ab_{32}An_{68}$.

Note large hypersthene crystal (left center). The inclusions in the feldspar seem to be volcanic glass. (cp. upper rt. hand corner).

or not all of the igneous rock masses are intrusive cannot be stated definitely, but the writer is inclined to think that most of them are.

In nearly every case the igneous rock is so severly altered that an accurate classification is impossible. The feldspars, however, are sometimes sufficiently fresh to be recognized; when so, those of the ground mass consist of $Ab_{32} An_{68}$, and the phenocrysts consist of $Ab_{22}An_{78}$. Most of the ferromagnesian minerals are altered beyond recognition, either to chlorite or to calcite. Sometimes, however, a few crystals of hypersthene remain fresh enough to be determined. The texture varies between that of a basalt and that of a diabase, but is probably more often diabasic. Fig. 9

Age of the Igneous Member.

In no case is the igneous rock interbedded with or intruded into sediments as high in the section as the diatomite member. Moreover, pebbles of diabase very similar in composition to the sills of the middle member were found in the basal part of the radiolarian silts. These two facts suggest that the intrusions were all pre-diatomite age.

Contact Metamorphism.

In several cases where the igneous rock is definitely intrusive, the overlying sediments have suffered changes in composition and texture.

Figs. 10 and 11 show a recrystallized and somewhat silicified limestone or dolomite which probably owes its texture to the fact that it is immediately adjacent to a basaltic intrusion.

More important from the standpoint of this paper are the secondarily silicified beds associated with the intrusions. In several cases beds adjacent to the intrusions have been silicified, the silicification being definitely related to the intrusion, and for any particular bed not parallel to the contact, dying out as one proceeds away from the igneous rock.

The beds which were silicified include tuffs, silts and sandstones. In all cases observed the silicified beds are black and the silicifying material is opal. There are many examples of irregular silicification and in the field it is not difficult to recognize these rocks as being of secondary origin and definitely related to igneous rock bodies. Even in hand specimens it is generally not difficult to differentiate these rocks from the cherts of the diatomite and from the cherty shales. (Fig. 12)

SUMMARY OF MIOCENE STRATIGRAPHY

Sediments

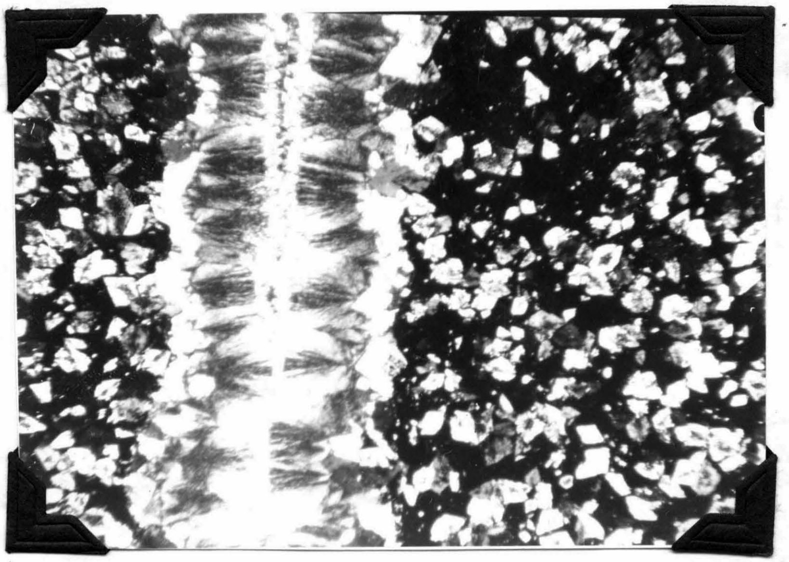
1. The Miocene sediments in this area can be divided on the basis of lithology into three major units: (a) a lower member containing typically a basal sandstone division, an intermediate tuff-bentonite-silt division, and an upper cherty shale tuff-limestone division, (b) a middle member consisting almost entirely of highly diatomaceous silt and diatomite and (c) an upper member consisting almost entirely of radiolarian silt.

2. The cherty shales of the lower member differ

Fig. 10.

Silicified limestone (center S25, T4S, R15W) Light crystals calcite (dolomite?) Dark areas opal silt cement. White band-chalcedony vein. (Spl-549-B)

Fig. 11.



Same as Fig. 10
Crossed nicols

from the black cherts of the middle member in that the former occur as continuous stratigraphically limited bands, generally of light color, whereas the latter occur as nodules, cross-cutting veins and nodular beds, which are nearly always black.

3. Lenses of cherty shales are occasionally found well up in the diatomite member, and soft diatomite is occasionally found well down in the lower member.

4. An intra-formational conglomerate containing cobbles of hard cherty shale in a soft silt matrix was found well down in the lower member.

5. Pyroclastics of various types are found throughout the upper three fourths of the section.

Igneous Rocks.

Bodies of basic igneous rock are associated with the sediments of the lower member. Some of these are definitely intrusive, but some of them may be extrusive lavas.

Fig. 12.

Secondary chert including some unsilicified tuffaceous silt in center. (Spl 549A - NE 1/4, S25, T4S, R15W)

Chapter IV

THE NOMENCLATURE AND HISTORY OF THEORIES CONCERNING THE DEVELOPMENT OF THE SILICEOUS MIOCENE ROCKS OF CALIFORNIA.

From as early as 1855 the siliceous Miocene sediments of California have attracted considerable attention. In that year Blake[12] wrote an article describing the diatomaceous and cherty sediments of what is now considered to be the type "Monterey" at Monterey Bay. Trask,[13] Whitney,[14] and other early workers also described these rocks at various places throughout the state, and some of them made suggestions regarding their origin.

Oneof the earliest papers on these rocks is due to Professor Lawson.[15] At Carmelo Bay he divides the rocks into soft white shales, and opal beds. Both rocks, according to Lawson, consist of finely divided acid tuff somewhat cemented by opal. Concerning the origin of this opal he says, "Such silica can, farther it seems to us, only be regarded as of the nature of an original chemical deposit. The question is whether the silica was derived from organic remains or from volcanic glass. Whichever form the silica had originally, there seems no escape from the conclusion that the sea water has affected it on a wholesale scale as a chemical reagent, dissolving it and reprecipitating it as pulverent or gelatinous silica. The chalky formations probably represent the pulverent deposit and the opaline beds the gelatinous." He argues

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[12] Balke, W.P., Notice of Remarkable Strata Containing the Remains of Infusoria and Polythalomia in the Tertiary Formation of Monterey, Cal. Proc. Acad. Sci. vol. 7, pp. 328-331, 1855.

[13] Trask, Report on the Geology of the Coast Mountains, Assem. Jour. 1856.

[14] Whitney, Calif. Geol. Surv., Geol., vol. 1, 1865

[15] Lawson, A. C., Geology of Carmelo Bay, Univ. Cal. Pub. vol. 1, pp. 22-27

further that the absence of diatoms associated with these beds suggests that the opal was probably derived from volcanic ash.

After Lawson's work the"Monterey type" sediments were investigated by many workers, but generally only while in the process of working on some other problem. The siliceous rocks were divided into several types, different workers using different names. The soft beds were referred to as diatomite, diatomaceous shale, "chalk rock", diatomaceous earth, white shale and opal shale. The indurated rocks were referred to as cherts, flints, flinty cherts, cherty and flinty shales and a variety of other names. Some early workers considered that the indurated rocks had developed from the softer sediments by secondary silicification.

One of the first to advance this idea was Fairbanks[16]. Referring to the soft shale in the San Luis Folio he says, in part: "Over large areas it has undergone silicification, which has so changed its appearance, that, were it not for numerous transition phases, the origin of the silicified beds would often be difficult to recognize. The different degrees of change can be traced from the dark bituminous shale through the light porcelain-like varieties to the flinty forms. The metamorphism has affected the rock so irregularly that often considerable variation can be seen in the same hand specimen." He believed that the silicification occurred before the upper Miocene because he found boulders of Monterey chert in the overlying San Pablo Formation.

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[16] Fairbanks, H. W., San Luis Folio, U. S. G. S. Folio #101, 1904.

A similar suggestion was made by Arnold and Anderson.[17] Describing the rocks of the Santa Maria District, they say in part: "...the best explanation of the origin of the harder rocks appears to be that they are products of metamorphism of the soft variety. It is believed that the soft white and chocolate-colored organic shale represents the original state of the beds of the whole formation, and that a process of silicification and crystallization has caused the changes, this process having been aided possibly by structural disturbances and pressure. ...The chief agent in causing the change was probably infiltrating water carrying silica in solution."

In contrast to these views Davis[18] advanced the hypothesis that the Monterey cherts were primary deposits, the silica being derived from volcanic springs. He argued that the inclusion between chert beds of laminae of unsilicified shale was not explicable under the hypothesis of secondary silicification and that the interbedding of soft sandstone and chert would not be possible if the cherts were secondary products.

Speculation regarding the origin of the siliceous rocks seems to have died down for some time after Davis' work, but was somewhat revived by a symposium "On the Siliceous Shales and the Origin of Oil in California", called by Tolman[19] at a meeting of the Geological Society of America in 1926.

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[17] Arnold and Anderson, Geology and Oil Resources of the Santa Maria Oil District, U. S. Geol. Surv. Bull. 322, 1907.

[18] Davis, E. F. The Radiolarian Cherts of the Franciscan Group Univ. Cal. Publ. vol 11, 1918.

[19] Tolman, C. F., Biogenesis of Hydrocarbons by Diatoms, Economic Geology, vol. 22, pp. 454-475, 1927.

On the basis of the results of this symposium he divides the siliceous rocks into the following types:

1. Diatomite and diatomaceous shale (soft beds containing a high percentage of diatoms)
2. Uncemented opal silt and opal shale (soft beds containing a high percentage of diatoms and diatom flour)
3. Cemented opal shales - diatom debris cemented by opal, (porcellaneous and slabby shales.
4. Vitreous opal - flints, occurring as "secretions, lenticular beds and laminae."
5. Chalcedonic and dolomitic shales.

He concludes that most of these rocks represent altered or unaltered diatom debris, but that the vitreous opal is in part a sedimentary gel. Of the chalcedonic and dolomite shales he writes:"Induration and diagenesis result in the development of a series of chalcedonic and dolomitic shales, and massive beds of dense chalcedonic material. This process of induration is due to compacting, cementation by opal, and recrystallization. The fine diatom flour packs harder with the increase in the original opal cement. Partial solution and recrystallization of the opal to chalcedony produces the contorted flints usually accompanied by dolomitic layers. This process consists of the recrystallization first, of the opal cement into chalcedony, and later of diatom flour and diatom tests to chalcedony."

Since Tolman's paper the most extensive studies of the Miocene sediments are due to Taliaferro[20] and Reed[21]. Taliaferro discusses at length the relationship of siliceous

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[20] Taliaferro, N. L., Volcanism in Tertiary Formations, Univ. Cl. Publ. vol. 23, p. 16, 1933.

[21] Reed, R. D., op. cit.

rocks in general, and diatomite in particular, to volcanism. He concludes that there is a direct relationship between volcanism and the extensive development of diatoms and that these organisms derive their silica from the products of volcanic eruptions. In discussing the indurated rocks he says, "It is concluded that the vast majority of the opaline sediments of the Miocene are not the result of silicification nor is the opal in them derived from the solution of the tests of siliceous organisms. The opaline shales and cherts are not dependent on these organisms for their formation, but have an independent origin. The diatomaceous shales and diatomite are chemical deposits resulting from the coagulation or precipitation of silica by inorganic agencies. Although these types differ greatly in character and mode of formation their very intimate relation and sudden and simultaneous appearance indicate a common source of silica."

Reed reviews the petrographic work already accomplished and discusses the paleographic conditions essential to the formation of these peculiar sediments.

The latest study of the siliceous rocks is being carried out by Mr. M. N. Bramlette for the United States Geological Survey. At present none of his results have been published.

From the foregoing it is apparent that there is little agreement among workers on the siliceous Miocene rocks either as to their origin, or as to their nomenclature. It is probable that some of the disagreement concerning their genesis is only apparent, and is due to the confusion in the nomenclature.

However, it is also possible that all of the rocks of a given general type do not have the same origin. Whether the rocks investigated by the writer have the same origin as some superficially similar rocks investigated by other workers cannot be stated definitely. There are some statements made by other workers which are certainly not true of the rocks studied, but since specimens used by them were not available to the writer, it seemed futile to point out all of the inconsistencies.

As far as nomenclature is concerned, it seems to the writer that the present terminology is very unsatisfactory. Chert and flint have been indiscriminately used for chalcedonic and opaline rocks, and "opal shale" is used for both indurated rocks and diatomites. However, in view of the fact that a comprehensive work on all of the siliceous rocks in the state will probably appear within a short time*, and in view of the fact that the writer is not personally familiar with all of the types, no suggestions will be made here concerning this matter.

Chert as defined by Van Hise[22] and as it is commonly, although probably erroneously understood,[23] includes practically all siliceous indurated non-clastic sedimentary rocks. It will be used here for unbanded highly indurated and highly siliceous rocks such as those frequently associated with the diatomite. For the banded siliceous rocks of variable, but appreciable hardness, the term cherty shale will be used.

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* See M. N. Bramlette, p. 45.

[22] Van Hise, A treatise on Metamorphism, U. S. Geol. Surv. Monograph 47, 1904.

[23] Hinde, Cayeux, Jukes-Browne, and many other workers on siliceous rocks consider chert to be a predominantly chalcedonic rock.

Chapter V

DESCRIPTION AND ORIGIN OF THE BLACK CHERTS OF THE DIATOMITE MEMBER AND SOME OTHER SECONDARY CHERTS

The following chapters will be devoted to petrographic descriptions of the cherty rock types and to a discussion of their possible modes of origin. The discussion of the black cherts of the diatomite member will be taken up first, because it is believed that their mode of occurrence gives almost conclusive proof concerning their mode of genesis, and it seems possible that the information derived from the examination of such rocks may be useful in considering the genesis of some rocks of more obscure origin.

BLACK CHERTS OF THE DIATOMITE

It has already been mentioned that these rocks occur as nodules, veins and beds. This variety of occurrence is itself suggestive of secondary origin. Further examination, however, yields even more suggestive, if not indeed conclusive proof of such an origin. There are three points which are considered to be diagnostic:

1. The nature of the terminations of the chert beds.
2. The relations of these beds to underlying and overlying strata.
3. The relations of chert beds to cross cutting veins and faults.

In addition there are several other peculiarities which, though not necessarily diagnostic, are very suggestive.

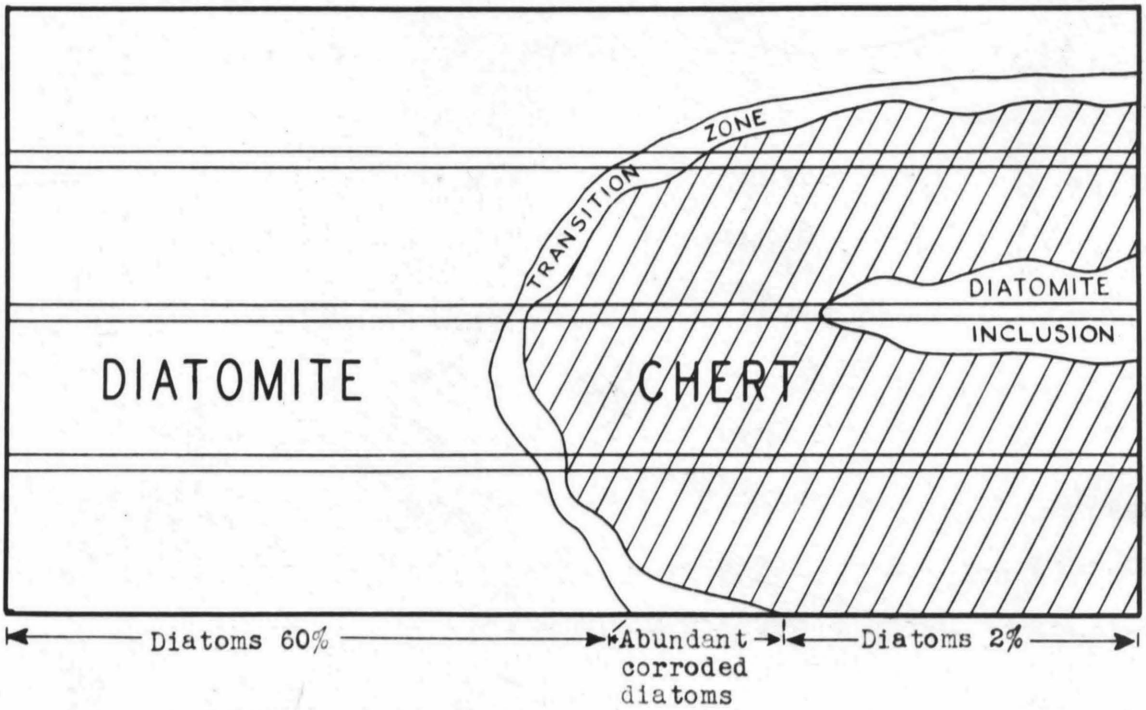
The Nature of the Lateral Terminations of the Cherts, Beds, and Nodules and their Relations to Enclosing Strata.

Figures 7, 13 and 14 show the termination of some beds of chert against diatomite. It will be noted that the diatomite is finely laminated and that the laminations continue without interruption or disturbance into the black chert. In some cases a given lamina contains a higher percentage of detrital quartz or more abundant fish scales than adjacent laminae, showing that it is a primary depositional feature and has not been induced by secondary action. Even when such evidences of the primary nature of these structures are lacking, it is inconceivable to the writer that identical and continuous laminations could be developed in chert and diatomite by any secondary processes. It also seems inconceivable that such laminations could develop in such different types of rocks if they were both primary deposits. The conclusion, therefore, seems reasonable that both chert and diatomite were once a continuous bed of the same sediment. Do the diatomites then represent altered cherts, or were the cherts derived from diatomite? A microscopic examination of a thin section cut across the contact zone leaves no doubt as to which is the correct hypothesis. Proceeding along any given lamina from diatomite through a thin transition zone into chert, the following phenomena can be observed:

In the diatomite nearly all of the field is covered

Fig. 13

SKETCH SHOWING THE NATURE OF THE LATERAL TERMINATIONS OF SECONDARY BLACK CHERTS IN DIATOMITE



The horizontal lines represent recognizable laminae which continue without interruption from chert into diatomite.

Fig. 14

In the photograph is is difficult to see the actual continuation of laminations from chert into diatomite, but it can be seen that overlying and underlying beds do not change their spacing with a change in the thickness of the chert. Cabrillo Beach, directly under Ft. McArthur.

with diatoms, radiolaria and sponge spicules. In the transition zone, which is generally not more than one-eighth inch thick, none of the smallest types of these organisms are visible and most of the larger forms show distinct evidences of corrosion. This can be particularly well observed on rod like types and on sponge spicules, but even on the networks of the other types it can often be noted and clearly distinguished from breakage. In the cherty itself, only the largest and coarsest textured forms are preserved, and these do not make up more than 2 percent of the rock. It therefore appears certain that these cherts were derived from diatomites and that the diatomites can not represent leached cherts.[24]

It will be noted in fig. 14 that the laminations not only continue from the chert into the diatomite, but that there is no change in their spacing. This continuity of individual laminations without convergence or divergence, considered in conjunction with the fact that the specific gravity of the diatomite is 0.43 and that of the chert is 2.0, indicates that *silica must have been added* to the particular stratum which was transformed into chert, and precludes the possibility of the cherts being endo-

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[24] E. F. Davis considered that certain white shales represented leached cherts. He also suggested that the absence of siliceous organisms from some cherts might only be apparent, and due to the fact that the cement of the rock had the same refringence as the organisms. This is not so in the cherts described: The index of the cement is always distinctly higher than that of the siliceous tests.
Davis, The Radiolarian Cherts of the Franciscan Group. Univ. of Cal. Publ. vol. 11, No. 3, 1918, pp. 296and 299.

genetically derived from diatomite beds. This possibility is further precluded by an examination of the spacing of underlying and overlying marker beds (Figure 14). Such beds have frequently been observed, where laminations could not be clearly distinguished in the chert, and in all cases they had exactly the same spacing in the section which included the chert bed, or nodule, as in the adjacent section where it had ceased to exist.

In summary, then, it seems that:

1. The continuation of primary laminations from chert into diatomite indicates that both of these rocks were once a continuous bed of the same sediment.

2. The fact that siliceous organisms are at least thirty times as abundant in the diatomite as in the chert indicates that the chert must have once been a diatomite and not visa-versa.

3. The fact that there is no divergence of laminations when they pass from chert into diatomite, nor any divergence of overlying and underlying marker beds on passing from a section containing chert to an adjacent one not containing it, considered in conjunction with the fact that the density of the chert is about five times that of the diatomite, indicates that the chert could not have been endogenetically derived from a diatomite bed, but must have experienced the addition of silica.

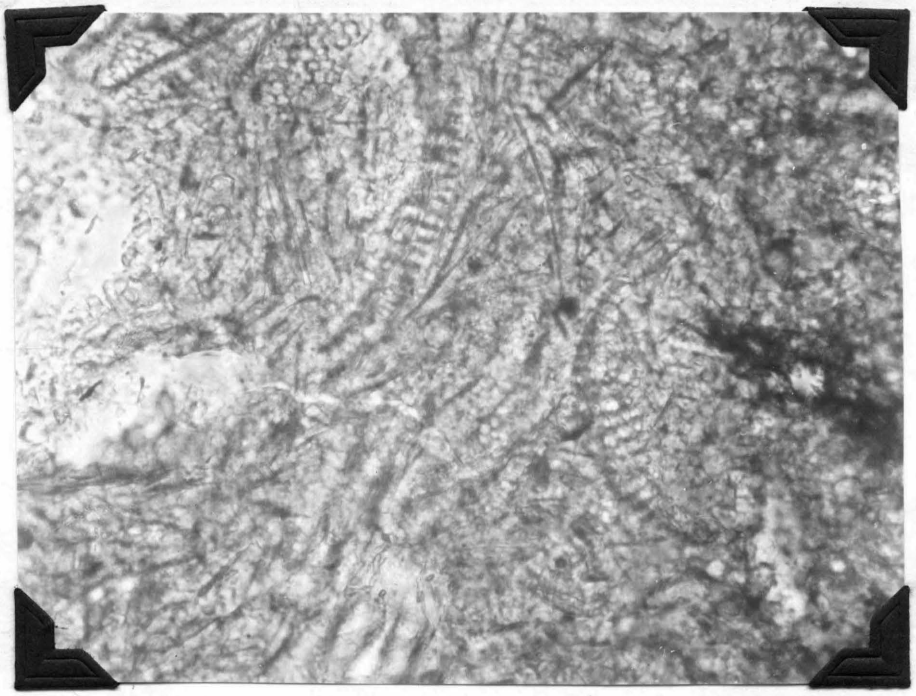
4. The relative paucity of siliceous organisms in the chert compared to the diatomite into which it grades indicates that the silica bearing solutions were capable of dissolving siliceous organisms.

Time of Silicification.

The features just described give few clues as to the time of silicification of the diatomites. There is one group of phenomena, however, which are believed to indicate clearly the time of silicification of some of the black cherts and may be diagnostic of the period at which most of them were formed. These phenomena concern the relations of cross cutting veins to chert beds and to faults. Fig. 19 shows a chert bed in diatomite and its behavior on intersecting a small fault. It will be noted that in addition to being offset along the fault, the chert bed swells greatly near the fault and actually runs in the fault plane as a cross cutting vein. The junction of a cross curring vein running along a fault plane with a chert bed was discovered in nearly every case where a bed could be traced along the strike for a few hundred feet.

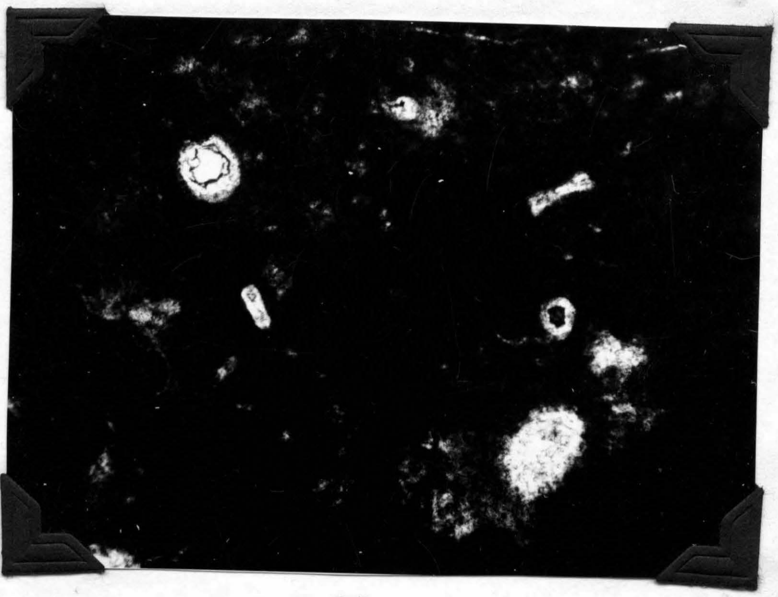
These relationships are considered to indicate that the time of formation of the chert veins was post-faulting and they may indicate also that the chert beds are post-faulting. However, in all cases where the relationships were perfectly clear it was noted that the chert bed always exists in the <u>same</u> stratigraphic horizon on both side of the fault. Considering the extremely high permeability of the diatomite enclosing the chert bed, and the local crumpling associated with some of the faults it seems very remarkable that such selective silicification should take place if the process was all post-faulting. The writer therefore

Fig. 15



X 520
Photo micrograph of diatomite from Cabrillo Beach.
(Spl- 510)

Fig. 16.

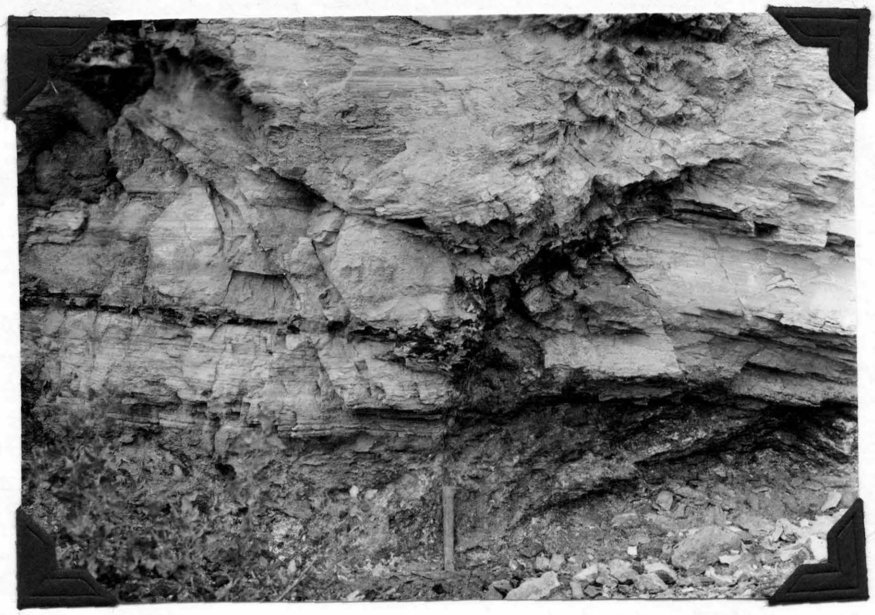


X 90

Photo micrograph of black chert into which the diatomite of Fig. 15 grades. Note corrosion of diatoms. Fillings are non-fibrous chalcedony.

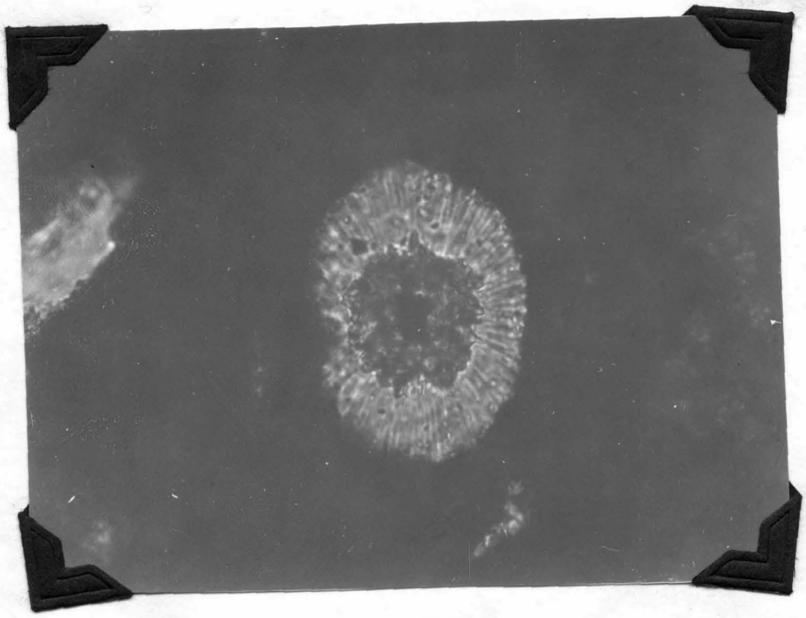
Spl. 510.

Fig. 17



Chert bed in diatomite swelling near fault, running in fault as a vein, and continuing on other side again as a bed. Cabrillo Beach, NW$\frac{1}{4}$, S30, T5S, R13W

Fig. 18



X 520
Uncorroded radiolaria in secondary black chert from diatomites.

wishes to advance an alternative explanation for the association of cross cutting veins with faults and chert beds and before stating his convictions in this matter.

The only explanation which seems tenable is similar to one used by Bowerbank,[25] Dolomieu,[26] Cayeux[27] and others to explain the localization of cherts in the "Chalk" of England. These workers considered the cherts to be secondary and to have been localized by previously existing concentrations of sponge spicules. The silica of these spicules was believed to have exerted an attraction on the silica of migrating solutions and to have caused its precipitation in and around beds where spicules were unusually abundant. In explaining the association of chert veins with chert beds it seems possible that already existing chert might have a tendency to precipitate the silica of solutions migrating along faults. If this is so, a few broken pieces of a preexisting chert bed scattered in the fault zone and the truncated ends of the faulted bed might cause sufficient precipitation of silica to produce the vein chert. The fact that chert veins never extend any appreciable distance in the fault plane beyond the ends of the truncated chert beds would fit in with this hypothesis, although it could also be explained in the assumption that both veins and bed were contemporaneous and post-faulting.

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[25] Bowerbank, J. S., On the Siliceous Bodies of the Chalk, Greensands, and OOlites (Trans. Geol. Soc. London, vol. 6, 1841.

[26] Dolomieu, Deodat, Memoire sur les pierres composees et les roches (Jour. Phys. t. XL, 1792.

[27] Cayeux, Lucien, Les Roches Sedimentaires de France, Memoires de la Carte Geologique de France, 1929.

Although the fact that the chert bed always seems to occupy the same stratigraphic position on both sides of the fault seems very remarkable to the writer, he is inclined to consider that the chert beds and veins are contemporaneous and post faulting. This preference is due largely to the fact that it was impossible to sharply differentiate the chert veins from the chert beds, and to the fact that the general limitation of chert beds to stratigraphic horizons indicates that very selective silicification can take place even in apparently homogeneous rocks.

On the assumption that the silicification of the chert beds was post-faulting in age, these rocks must be considered as of fairly late origin, because some of the faults cut fifty feet or more of strata above the cherts.

There is no direct evidence bearing upon the age of the irregular chert nodules but it seems likely that they were formed at the same time as the beds and veins.

Split Chert Beds

In addition to the above features there is one other which is probably developed only in secondary or diagenetic cherts and may be diagnostic of such origin. This is the "splitting" which can frequently be observed in these rocks. A chert band will be continuous for some distance and will then split into two branches, including a bed of diatomite, and later on these branches will anastomose. In such cases the laminations in the included diatomite continue into the chert as they do when a chert bed ends. The included lense of diatomite is often partially silicified or partly leached, and the siliceous organisms in it are badly corroded.

Description of Black Cherts in Diatomite

As implied in the title these rocks are almost always black or very dark brown in color. The brownish ones generally grade laterally and sometimes vertically into brown, quite silty diatomites. The black ones, which are far more common, generally grade laterally into quite pure, white, punky diatomites.

The hardness of the black rocks is quite constantly about 6½, that of the brownish ones may be as low as 4. The specific gravity of the black cherts varies from 1.94 to 2.00*

Microscopically these cherts can be seen to consist almost entirely of dirty yellowish isotropic opal. The cause of this yellow color, which is frequently quite dark, is not clearly understood. Sometimes it disappears on heating and is then believed to be due to organic matter. In other cases it does not disappear and may be due to some other cause, possibly to the inclusion of a certain amount of clay. The only chalcedonic portions of the rock are fillings of diatoms, radiolaria, or foraminifera. A few angular grains of quartz and some shreds of bentonitic clay are generally present, and sometimes there are a few grains of glaucophane and crossite.

Siliceous organisms are very rare, but a few specimens of <u>large</u> diatoms, radiolaria and sponge spicules are

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* This statement is based on only three determinations.

nearly always present. Such specimens frequently show no signs of corrosion, although in many cases this phenomenon can be clearly seen. (Figs. 18) The corroded forms may be of the same size and species as the uncorroded ones. In most cases the diatoms are filled with clear, colorless opal, or non-fibrous chalcedony. The colorless nature of these fillings is in distinct contrast to the dirty yellowish opal of the cement, possibly because the organic matter and clay of the exterior never penetrated into these tests and the silica deposited therein was never contaminated with these ingredients.

Foraminifera are frequently present and in nearly all cases the tests are preserved as aragonite and the chambers are filled with chalcedony, frequently fibrous.

Summary and Conclusions

The problem of the origin of these cherts is a relatively simple one, but they have fortunately served to permit the discarding of some criteria which have been used as indications of various processes in the discussion of the origin of indurated siliceous rocks. After considering the phenomena discussed above, the following facts seem evident:

1. The existence of apparently uncorroded siliceous organisms in a rock cannot be considered evidence that the silica of the cement of that rock was not derived from the solution and reprecipitation of similar tests. This is especially true if the preserved tests are large and coarse textured, and many have been associated with finer and more

delicate varieties.

2. Calcareous organisms can remain unaffected by solutions which are capable of dissolving siliceous ones.

These two facts are believed to be of noteworthy significance, because several authors[28,29] have considered that the presence of siliceous organic remains in an indurated siliceous rock precludes the possibility of the cement of that rock having been derived from similar organisms. In some cases even the presence of small circular or ellipsoidal areas of chalcedony, which were supposed to mark the former presence of radiolaria have been used in the same argument. In view of the common occurrence of well preserved siliceous tests, and the abundant occurrence of chalcedonic fillings of very distinctive shape, in the secondary cherts just described the latter criterion seems entirely fallacious and the former very apt to be so unless <u>all</u> of the tests are definitely uncorroded and there is some assurance that no smaller types of siliceous organisms existed with those whose remains are preserved. Some of the above authors and several others, have also used the presence of calcareous organic remains as evidence that siliceous organisms could not have once been present in a rock and subsequently dissolved to produce cement. They maintained that any naturally occurring solutions capable of dissolving opaline tests would also necessarily be capable of dissolving calcareous ones.

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[28] Davis, E. F., op. cit. pp. 353-376.

[29] Tarr, W. A., The Origin of Chert and Flint, Univ. of Mo. Studies, vol. 1, #2, 1926

OTHER SECONDARY CHERTS

Silicification Related to Intrusion

It has already been mentioned that silicification has frequently taken place around intrusive masses of basaltic rock. The nature of the rocks which were silicified varies from tuff to fine sandstone, and the silicifying material is always opal. The same phenomena in regard to the preservation of siliceous and calcareous organisms were noted in these rocks as were noted in the black cherts of the diatomite. In many cases the outlines of the silicified rock are quite irregular and cross-cutting veins and split chert beds, with unsilicified rock in the split, are quite common. (See Fig. 12). When the igneous mass is conformable with the bedding of the adjacent sediments, the maximum thickness, perpendicular to the contact through which silicification was found to take place, is about 10 feet. This, however, is very unusual and a few inches is a more common figure.

Secondary Silicification of Unknown Origin.

In a few places in the lower member cross cutting chert veins were discovered which were not related to any visible intrusion. The cross cutting veins were always associated with chert beds of a somewhat different character than the cherty shales. The chief point of difference is that the cherts associated with the cross cutting veins, although superficially fairly well confined to a particular stratum, could be seen on closer inspection to pinch and swell and cut across the bedding to a much greater extent than ever takes place in typical cherty shales. Fig. 19

Fig. 19

S21,T5S,R14W

Cross cutting chert vein in uppermost part of lower member. (Vein crosses picture at bottom of pick handle)

Chapter VI

THE CHERTY SHALES

Before starting the description of these rocks it may be well to remind the reader that in the San Pedro Hills column they occur most abundantly in the thousand feet of section immediately underlying the diatomite member. They constitute 20-25 percent of this part of the section and are therefore quantitatively very much more important than the secondary cherts discussed in the preceding chapter, which probably have an average aggregate thickness of only 25 to 50 feet.

The cherty shales are banded rocks which occur in beds and possess a considerable, though varying, degree of induration. They are generally light colored, but are sometimes darker, some varieties even being jet black. Chemically and mineralogically their composition is quite variable, but they always contain a high percentage of siliceous cement. The density varies from about 2.0 to 2.6. In spite of the rather high variability of the properties mentioned above, it seems justifiable to describe all of these rocks as cherty shales, because they always occur as banded beds and because there are no sharp breaks in the variations of the other characteristics.

General Characteristics

Mode of Occurrence.

In their mode of occurrence the cherty shales are remarkably uniform. With extremely few exceptions they occur as beds of uniform thickness having strictly stratigraphic boundaries. The average thickness of a cherty shale bed is about four inches, but some beds are only one-half inch thick and some may be as thick as ten inches. Out of hundreds of beds examined only two showed clear cut divergence from strictly stratigraphic boundaries, and in these only the uppermost few laminations changed from cherty shale to soft tuff along the bedding planes. (Fig. 20) Considering the extreme rareness of this phenomenon it seems that these two exceptions will not vitiate whatever deductions may be drawn from the general conformity to stratigraphic limits which the cherty shales exhibit. In fact it seems more probable that these two rocks were formed differently than the majority of cherty shales and should not be considered when discussing the latter's origin.

Although they are strictly stratigraphic units, the cherty shales nearly always have a thin transition zone between their borders and the surrounding sediments whenever these latter are soft, fine-grained rocks. This transition zone is always very thin, seldom more than one-tenth inch in thickness, and is only slightly more indurated than the adjacent soft sediments. It is easily recognized, however, by the fact that when a piece of

Fig. 20

X 5

Very Hard cherty shale.

Showing transition along the bedding from cherty shale to soft tuff. (Upper right hand corner)

Whether this rock represents a secondarily or diagenetically silicified tuff it illustrates the fact that silicification can bring out banding in an apparently homogeneous rock. (Spl-500-φ)

center-S-15, T5S, R 14W

cherty shale is removed from its matrix the break always occurs a short distance within the limits of the adjacent soft rock. It should be emphasized, however, that this transition zone is itself of uniform thickness and does not penetrate irregularly into the adjacent strata.

The stratigraphic limitation of cherty shale beds and the uniform thickness of the transition zone are believed to suggest that these rocks are not secondary silicificates. More evidence will be presented relative to this point later, but the contrast between the regularity of these beds and the slight but persistent nodular character of the secondary cherts previously described is *believed to be significant*.

Physical Composition and Banding

Microscopically cherty shales can be seen to consist essentially of cement of three types, plus certain clastic and organic constituents. Of the clastic constituents a clay mineral near montmorillonite and small grains of quartz are the most important. Organic tests include those of foraminifera, diatoms, radiolaria, silicoflagellates and sponges. In addition, bituminous matter and marcasite are sometimes present in appreciable amounts. The cement is either chalcedony, quartzine, dirty white opal or a clear yellow isotropic material which is believed to be a dehydrated alumina-silica hydrogel. All of these types of cement are generally not present in any one rock, and the presence of quartzine is extremely unusual.

The banding which is so characteristic of these sediments is conditioned primarily by differences in the cement:clastic constituent ratio and by differences in the type of cement. Occasionally it is conditioned by variations in the amount of bituminous material present in adjacent laminae, but this is a relatively rare cause of this structure. With the naked eye a particular band generally appears to be continuous and fairly uniform in thickness. In thin sections, however, it can be seen that most bands vary considerably in thickness, that some are discontinuous, and that some branch and anastamose.

VARIATIONS IN INDURATION

As might be expected, the hardest types of cherty shale are those which contain the highest percentage of cement, and this largely chalcedonic. From these extremely hard rocks, there is practically a continuous gradation to slightly indurated tuffs. (See Figs. 21-30 Whether the members of this gradational series are genetically interrelated, or whether they merely represent the results of primary depositional differences, will be discussed after they have been more fully described. It is desirable, however, to note here that although all gradations have been found between tuff and chalcedonic cherty shale, the softer members of this series are relatively rare.

Figs. 21-30 are slightly enlarged photographs of some members of the tuff-cherty shale series. Most of the tuffs have a peculiar texture which makes them appear to be aggregates of minute spheres. The magnification of the photographs is not sufficiently great to permit the actual recognition of this texture, but they do show clearly the persistence of the same texture from soft tuffs to certain bands in quite hard cherty shale. They also show that the distribution of more and less silicified portions of the rocks is generally fairly well limited to stratigraphic units. In many cases, however, it can be noted that bands of cement split and include portions of material which retain their typical tuffaceous texture. Figures 24 and 26 show this feature in some of the softer rocks, and even in figure 30 which is a photograph of a very hard cherty shale, the splitting of bands can be noted. This phenomenon is believed to be important; because although the general conformity of silicifying cement to bedding planes suggests that the development or introduction of cement was regulated by original differences between laminae, or was primary; the occasional irregularities in the cement bands are believed to indicate that some of this material was either secondarily introduced or was derived by diagenesis.[30]

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*Diagenesis is used in this paper in the sense defined by Walther who considered that it includes all of the physical and chemical modifications experienced by a sediment from the time of its deposition to the time of lithification, except such changes as depend upon orogenic pressure, volcanic activity and the emergence of the sediment into the zone of ground water circulation.

[30] Walther, Einleitung in die Geologie als historische, Wissen schaft, 1893-94, pp. 693-712.

Fig. 21

X 5
Soft White Tuff
(S15, T5S, R14W)

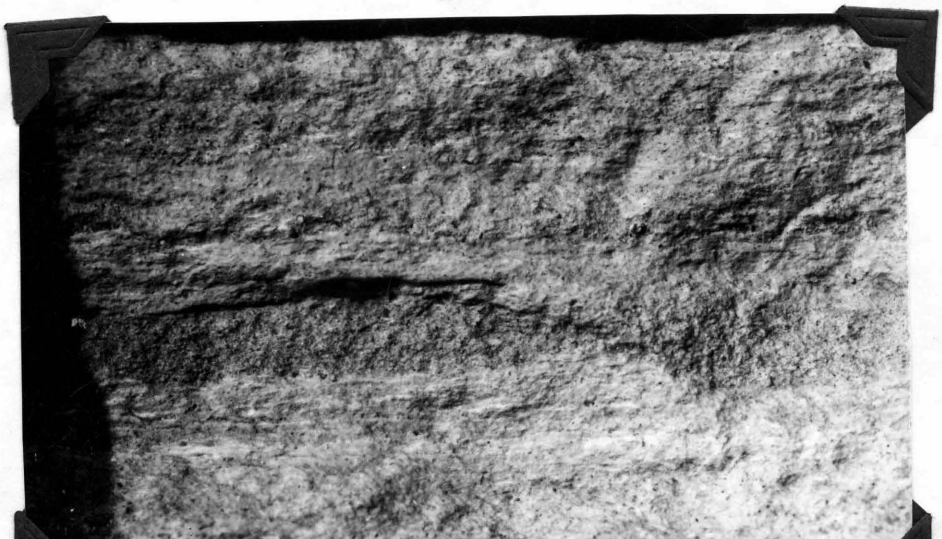
Fig. 22

X 5
Slightly Silicified Tuff.
The whole specimen is slightly silicified. One Smooth band across the center is fairly well silicified. S15, T5S, R14W.

Fig. 23

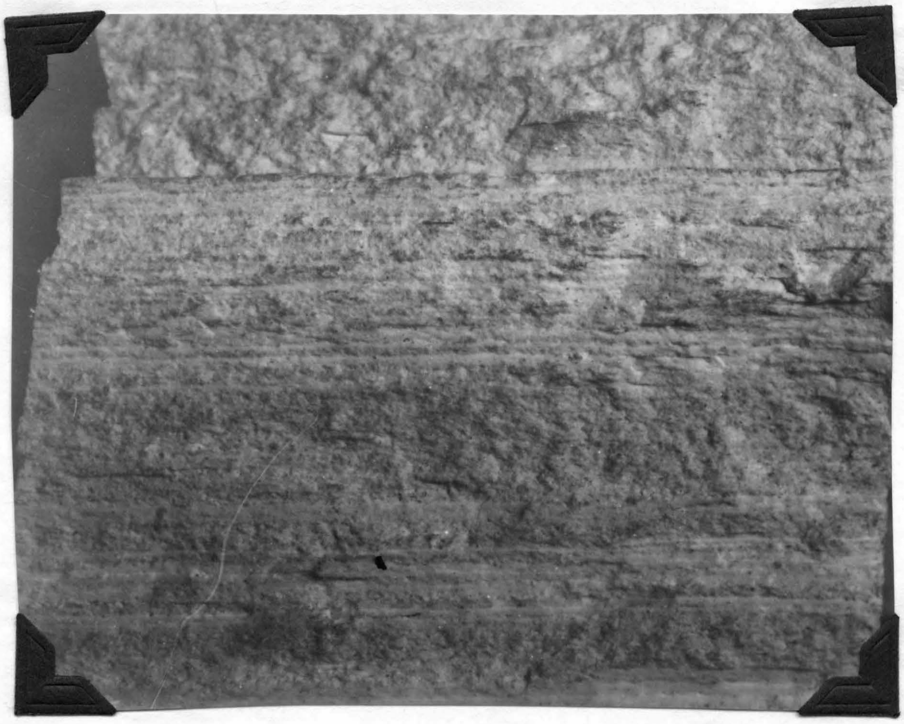
X 5
Slightly Silicified Tuff (somewhat more indurated than Fig. 22. S15, T5S, R14W

Fig. 24



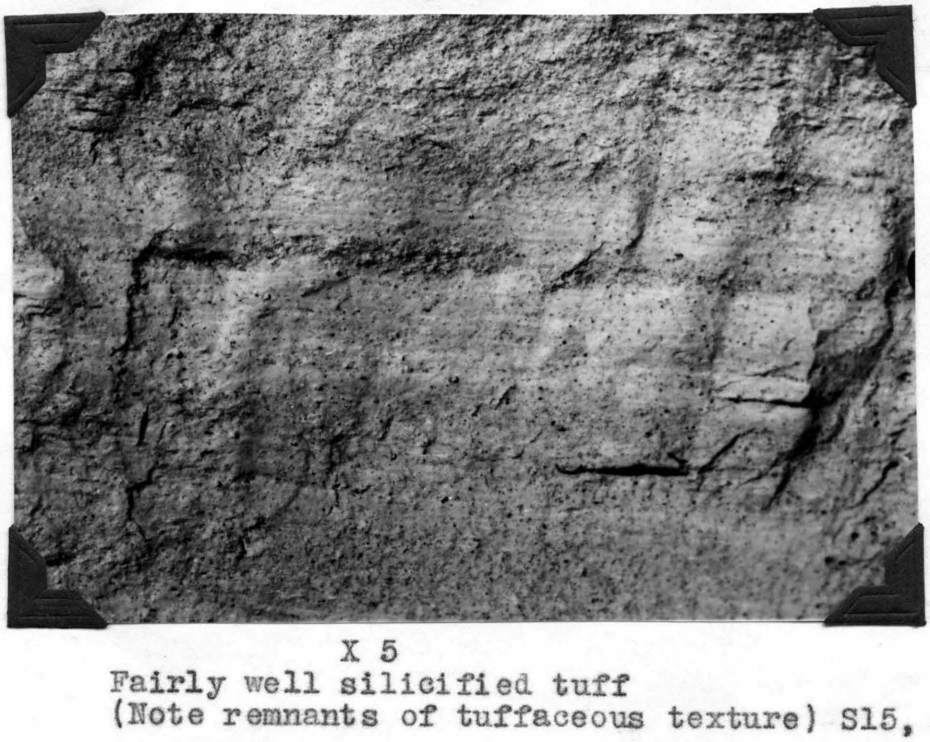
X 5
Moderately Silicified Tuff
Note remnants of tuffaceous texture. S15, T5S, R14W.

fig. 25



X 5
Moderately Silicified Tuff.
(Somewhat harder than Fig. 24) S15, T5S, R14W.

Fig. 26



X 5
Fairly well silicified tuff
(Note remnants of tuffaceous texture) S15, T5S, R14W.

Fig. 29

X 5

Well silicified tuff (typical cherty shale)
S15, T5S, R14W

Fig. 30

X 5

Very hard cherty shale. Note irregularities in thin white bands. S15, T5S, R14W.

Admitting the correctness of this argument does not of course preclude the possibility of some, or even most of the cement being a primary deposit. Before discussing this possibility further detailed descriptions of some members of the tuff-cherty shale series will be given.

THE TUFF CHERTY SHALE SERIES

Examinations of disintegrated samples and thin sections of unsilicified tuffs show that they are largely composed of a fibrous clay mineral having the optical properties and composition of a member of the beidellite-montmorillonite group and probably approaching montmorillonite.* In a few cases this mineral is the only important constituent of these rocks, but generally clastic quartz in small very angular grains makes up 5-25% of the rock. Sometimes fresh or altered shards of volcanic glass are present and occasionally make up 5-10 percent of the rock. Large and small diatoms and other siliceous organisms are frequently, but not always, present and are never abundant. In addition to the constituents mentioned, the tuffs sometimes contain an appreciable quantity of apparently isotropic material of about the same index as the lower index of the clay mineral (1.485). Similar material has been noted by most workers on bentonites.

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*In this connection see page 14.

Ross and Shannon[31] consider that it is a finely divided clay mineral. Weiser[31] on the other hand considers that some of it may be an alumina-silica gel. The same lack of agreement about soil colloids exists among reputable workers on this subject. Probably with the present methods of investigation of such substances, it is not possible to decide which theory is correct.

Without a microscope the tuffs seem in most cases to be unlaminated, although in a few instances fine laminations are very apparent. Frequently thin sections show that these rocks are banded, the bands owing their identity to differences in the amount of quartz and to differences in the size of the clay shreds. It should be noted in this connection that in two instances apparently unlaminated tuff grades laterally into hard banded cherty shale. Fig.20 shows one of these beds, the other is very similar. Whether or not these particular beds of cherty shale represent secondary or diagenetic silicificates this gradation shows clearly that an apparently unbanded rock can by silicification be transformed into a well banded one.

Slightly Silicified Tuffs and Soft Cherty Shales

These rocks are always more distinctly banded than the soft tuffs. They also differ from the latter in

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[31] Ross, C. S. and Shannon, E. V., The minerals of bentonite and related clays and their physical properties. Journ. Amer. Ceram. Soc. IX, pp. 77-96, 1926.

[31] Weiser, H. B. - The Hydrous Oxides - McGraw Hill - 1926

containing a considerable proportion of cement. This cement is of two kinds: (1) a clear yellow isotropic material, with an index of refraction which varies from 1.471 to 1.463 and which for the sake of convenience will hereafter be called Type A cement, (2) dirty white opal with a considerably lower index than the above and characteristically having a very fine but distinct honeycomb structure. The index of the Type A cement seems to vary with its hardness, decreasing as the latter increases. A partial chemical analysis of one gram sample of this cement having an index of 1.464 and a hardness of about 4.7 showed the following constituents:*

SiO_2	84.96%
Al_2O_3	6.95%
Ignition	5.60%

A thin section of the bands from which this sample was taken when examined under 1000 magnifications showed less than .5 percent of foreign ingredients. Whether the alumina present is due to the inclusion of submicroscopic clay particles or is due to the fact that this cement is an alumina-silica gel probably cannot be decided without an X-ray analysis, and perhaps not then. For reasons which will be brought out later, however, the writer is inclined to consider that it really represents a partially dehydrated alumina-silica hydrogel. The dis-

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*Analysis by Mr. Ed Eisenhauer, Jr., Assayer and Chemist, South Spring Street, Los Angeles.

The distribution of the two varieties of cement is probably significant. Type A cement occurs in two different manners: (a) in distinct stratigraphically limited bands, which will be called Type A bands, (Figs. 27 and 28) in which all of the cement is Type A cement and the cement clastic constituent ratio is very high, (95:5) or greater, and in which the only clastic constituent is clay in very fine shreds $(01 \times .001 \times ?)_{mm}$ or less, and (b) distributed more or less uniformly throughout the rest of the rock. The dirty white opal,on the other hand, occurs typically as irregular islands and in branching bands which have only approximate stratigraphic limits. The distribution of the white opal suggests that it has either been secondarily introduced or diagenetically derived. On the other hand, distribution of Type A cement, especially in Type A bands, suggests that it is not of secondary origin, but is either diagenetic or primary.

The clastic constituents of these rocks consist almost entirely of clay and quartz. The quartz occurs as small angular grains, averaging about .04 mm. in diameter. The clay occurs in two forms: (a) as discrete, somewhat twisted shreds up to (.1 X .02 X ?)mm. in size, with positive elongation, a maximum birefringence of about .02 and a maximum index of refraction of about 1.535, and (b) as indefinitely limited smear areas of variable but distinctly lower indices and birefringence,which often include a few shreds of the more birefringent clay, and seem to grade outward from these into the cement.

On the basis of their optical properties, the clay shreds are believed to be montmorillonite fairly high in Fe_2O_3. Whether the smear areas represent a related clay mineral, an alteration of the montmorillonite shreds, or a mixture of submicroscopic montmorillonite shreds and opal is rather difficult to determine. The smear areas seem to definitely grade outward into Type A cement, which of course would be possible if they were a definite clay mineral and thinner on the edges than in the center, but also suggests that they are altering into Type A cement. The smear areas frequently include a shred of more highly refringent and birefringent clay, which might be due to the fact that they represent an alteration of this shred, but could be merely a matter of chance. Finally, the birefringence of uniform smear areas varies from nearly that of the clay shreds to practically zero. This might also be due to differences in the thickness of different areas, or to the fact that they represent transitional stages from clay shreds to cement. With no more data than these, it would therefore appear futile to speculate as to the nature of these smear areas. Fortunately, however, the following facts also seem relevant to this problem:

With the exception of the smallest ones, (.005 X .0005 X ?)mm. practically all of the clay shreds in these rocks are oriented so that their long axes are parallel to the stratification. This is of course quite natural when one considers that the ratio of the long dimension to the short one is generally about 10:1. The lack of such uniform orientation among the smallest shreds is also not surprizing, considering their minuteness and the consequent slight effect that gravity would have on their orientation. The clay smear areas are also generally elongated parallel to the stratification, although this is not always true. In nearly all cases, however, the slow ray in such areas vibrates parallel to the stratification. Now, since the smallest visible clay shreds described above are not uniformly oriented, it seems unlikely to the writer that submicroscopic ones would be. Therefore, considering the uniform optical orientation of smear clay areas, it seems unlikely that these could represent a mixture of submicroscopic clay shreds and opal. Consequently, it seems more probable that these areas either represent a different clay mineral than montmorillonite, or an alteration of the latter. To decide conclusively, on the correctness of one of these two alternatives is difficult. As far as the writer knows, there are no clay minerals with such low indices as the smear areas which also have low birefringence, but considering the incomplete state of our knowledge about clays, this probably is not an important objection to considering these smear areas as a definite mineral. Ross and Kerr[32] describe smear-like clay areas in some shales, but do not mention any

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[32] Ross and Kerr, op. cit. pp. 58.

more variations in the properties of these areas than occur in clay shreds or crystals. Considering then the lack of uniformity of these clay areas, and the gradation in their optical properties from those of the clay shreds to those of the cement; the frequent inclusion of clay shreds in clay smear areas; and the fact that Type A cement is known to contain an appreciable percentage of alumina, the writer is inclined to believe that the smear clay areas represent alterations of the clay shreds and that at least some of Type A cement is derived from this decomposition.[33] A slight extension of this line of reasoning also suggests that Type A cement is an alumina:silica gel rather than a mixture of clay and opal.

The disposal of the Al_2O_3 resulting from the decomposition postulated is problematical, but if the process was a diagenetic one and took place soon after deposition, this disposal of this matter would not necessarily involve difficulties.

The organic constituents of these rocks include diatoms, radiolaria, sponge spicules, silico-flagellates and foraminifera. The tests of the siliceous organisms are always preserved as opal and those of the foraminifera as calcite or aragonite.

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[33] Cayeux and Belliere considered that some of the opaline cement of certain "gaizes" was derived from the decomposition of clay. Their reasons for believing this seem to have been mainly that certain irregular areas in these rocks contained a high cement:clay ratio than surrounding areas.
Cayeux, L., op. cit. pp. 304.
Belliere, M., Contribution a l'etude lithologique de l'assise de Chokier (C. R. XIII Congres geol. int. Bruxelles, 1922.

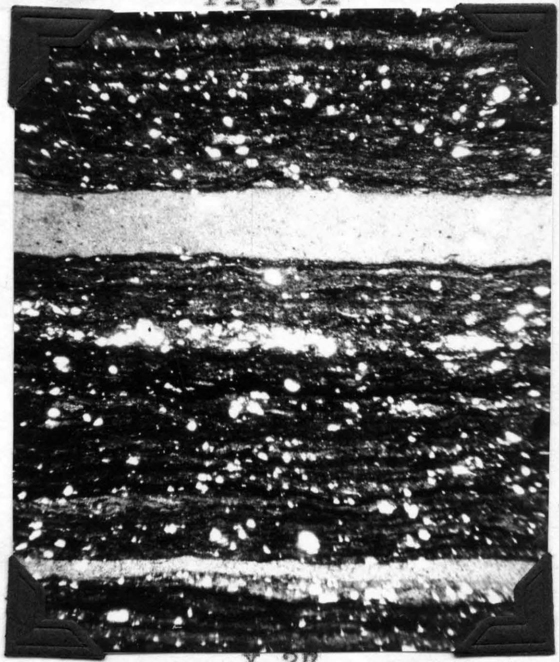
It is interesting to note that neither the abundance nor the mode of preservation of these organic tests is uniform throughout the rock. In this regard, the contrast between the Type A bands and the remainder of the rock is striking.

In Type A bands, whose clastic constituents generally consists of one percent of very fine clay shreds, very delicate diatoms and silico-flagellates are frequently abundant and in the softest varieties of these bands generally show no signs of corrosion. (Fig. 31,32) They are nearly always filled with Type A cement, but are sometimes filled with clear colorless opal or chalcedony. Large siliceous organisms and foraminifera, on the other hand, are very rare in these bands.

In the remainder of the rock, the only siliceous forms present are large coarse textured diatoms, radiolaria and sponge spicules. These are nearly always filled with clear colorless opal or non-fibrous chalcedony.

In short, then, the slightly silicified tuffs and soft cherty shales consist of a matrix of clear yellow isotropic cement (Type A cement) which contain a considerable percentage of alumina and is believed to be an alumina-silica gel. In this cement are imbedded variable amounts of clay, quartz grains, well preserved siliceous organisms and foraminifera; and also irregular, but roughly stratigraphic areas of dirty white opal. The clay occurs as discrete shreds and as smear areas of lower refringence

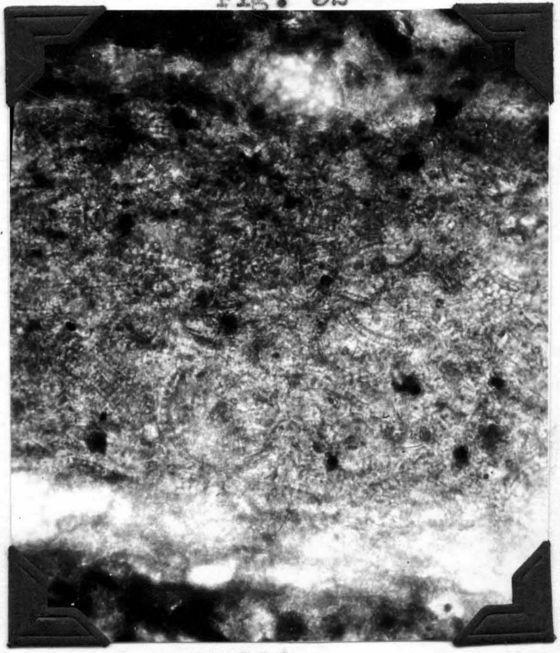
Fig. 31



X 27
Sp1565-B. Point Fermin

Fairly hard cherty shale showing two Type A bands. (white bands) The lower contains abundant well-preserved diatoms (Fig. 32) the upper contains only a few corroded ones. Hardness of upper band-6; lower band-3½.

Fig. 32



X 520
Lower band of Fig. 32 Note very abundant diatoms.

and birefringence. These smear areas include some shreds and seem to grade outward into Type A cement. They are believed to be alterations of the clay shreds and eventually to decompose into Type A cement. The banding in these rocks is largely conditioned by variations in the cement: clastic constituent ratio and by the distribution of the dirty white opal areas. One type of band is unique in that it consists almost entirely of Type A cement and delicate siliceous organisms and contains not more than one to two percent of clay, and this in very finely divided shreds. Delicate siliceous organisms are present only in these Type A bands. Large, coarse textured forms, on the other hand, are present throughout the rest of the rock, but are very rare in Type A bands.

Fairly Hard Cherty Shales

These rocks are frequently, though not always, somewhat more distinctly banded than the soft cherty shales. They consist of cement of three types, in which are imbedded shreds and smear areas of clay, diatoms, radiolaria, sponge spicules, silico-flagellates and foraminifera.

The most abundant cement is a clear yellowish isotropic material very similar to the Type A cement of the softer cherty shales, but differing therefrom in that its indices of refraction are appreciably lower, (1.462 - 1.440) as compared to (1.471 - 1.462); its hardness is somewhat greater, (4.5 - 6.5) as compared to (3 - 4.5);

and its color is generally somewhat paler. This cement is also similar to Type A cement of the softer rocks in that it constitutes the general matrix for all of the rock, and in addition sometimes occurs as discrete stratigraphically limited bands uncontaminated by any clastic constituents except a few very fine shreds of montmorillonite. These bands will be called hard varieties of Type A bands. Aside from the slight differences in the properties of their cement, they differ from the softer varieties in one important particular: diatoms and other siliceous organisms are quite rare in them, and those present, generally delicate types, always show distinct evidences of corrosion. Clay shreds are generally somewhat less abundant in the hard varieties than in the soft varieties of these bands, but this is not always true.

The fact that soft varieties of Type A bands nearly always contain abundant diatoms and that these become progressively less abundant, and at the same time show distinct evidences of corrosion as the bands become harder, suggests that the hard and soft bands are genetically related, and that the hard bands once contained abundant diatoms which have now been largely dissolved. From these facts alone, it would probably be impossible, however, to prove that the dissolved silica had been redeposited in situ, although this would seem to be very likely. Fortunately, the relationship which exists between the hardness and the index of refraction of the cement of Type A bands gives a good indication of the disposal of the dissolved silica. Spilchal investigated the properties of alumina:silica hydro-gels and found that the index of refraction of ignited gels varies with the $SiO_2:Al_2O_3$ ratio and decreases as the percentage of silica increases. He also found that the indices of these gels increased on ignition. Fig. 33 shows Spilchal's results and figure 34 shows the results of some determinations made by the author on the relationship between refringence and hardness in Type A bands. Due to the difficulty of obtaining bands of sufficient width to measure the hardness, the total number of observations is somewhat limited, but those obtained seem to show a definite decrease of index with increasing hardness.[34] Since it is known, then, that Type A cement consists essentially of SiO_2, Al_2O_3 and H_2O, and since the indices of silica-alumina gels decrease with an increase in the $SiO_2:Al_2O_3$ ratio, and also with an increase in the percentage of H_2O; it would seem reasonable to attribute the observed decrease in the index of Type A cement to either an increase in the $SiO_2:Al_2O_3$ ratio or to an increase in the percentage of water, or to both. Since further, diatoms are abundant in soft typeA

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[34] J.Spilchal:Agric. Arch. Prague, 1919, vol. 10, pp. 413-431.

*It should be emphasized here that none of the bands used for the determination of hardness or refringence contained any visible white opal cement.

Fig. 33

Graph showing the relationship of the $SiO_2:Al_2O_3$ ratio to the index of refraction of some ignited artificial $SiO_2.Al_2O_3$ hydrogels. Data from J. Spilchal - Agric. Arch. Prague, 1919. Vol. 10, pp. 413-431. in Min. Abst. Vol. 19, 1922, pp. 288

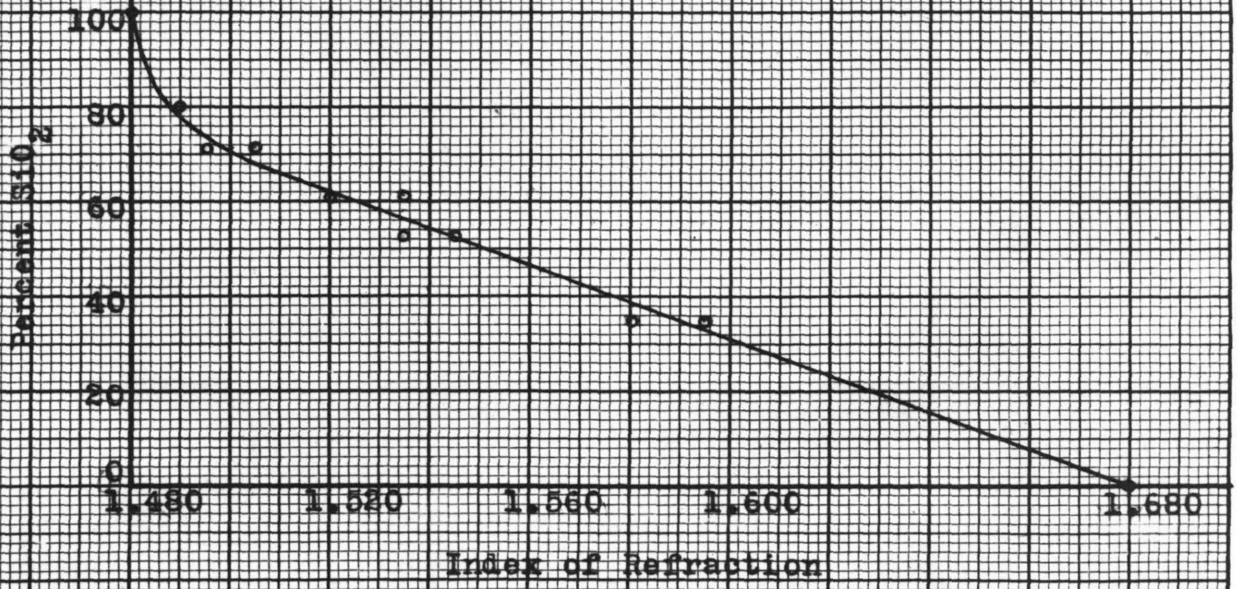


Fig. 34

Graph showing the relationship of the hardness to the index of refraction in the "Type A cement" of the cherty shales. Hardness determined with standard hardness minerals.

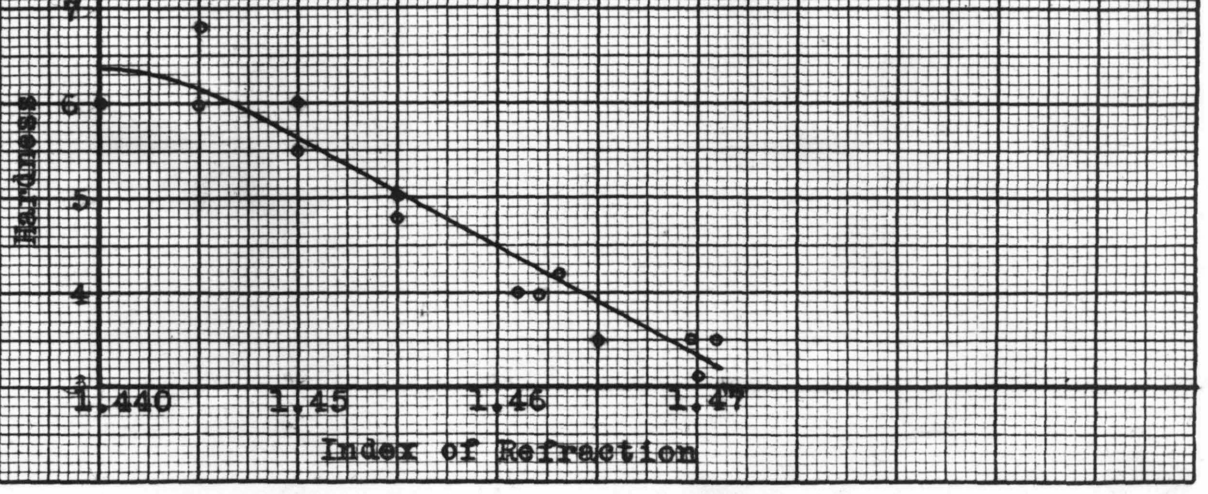
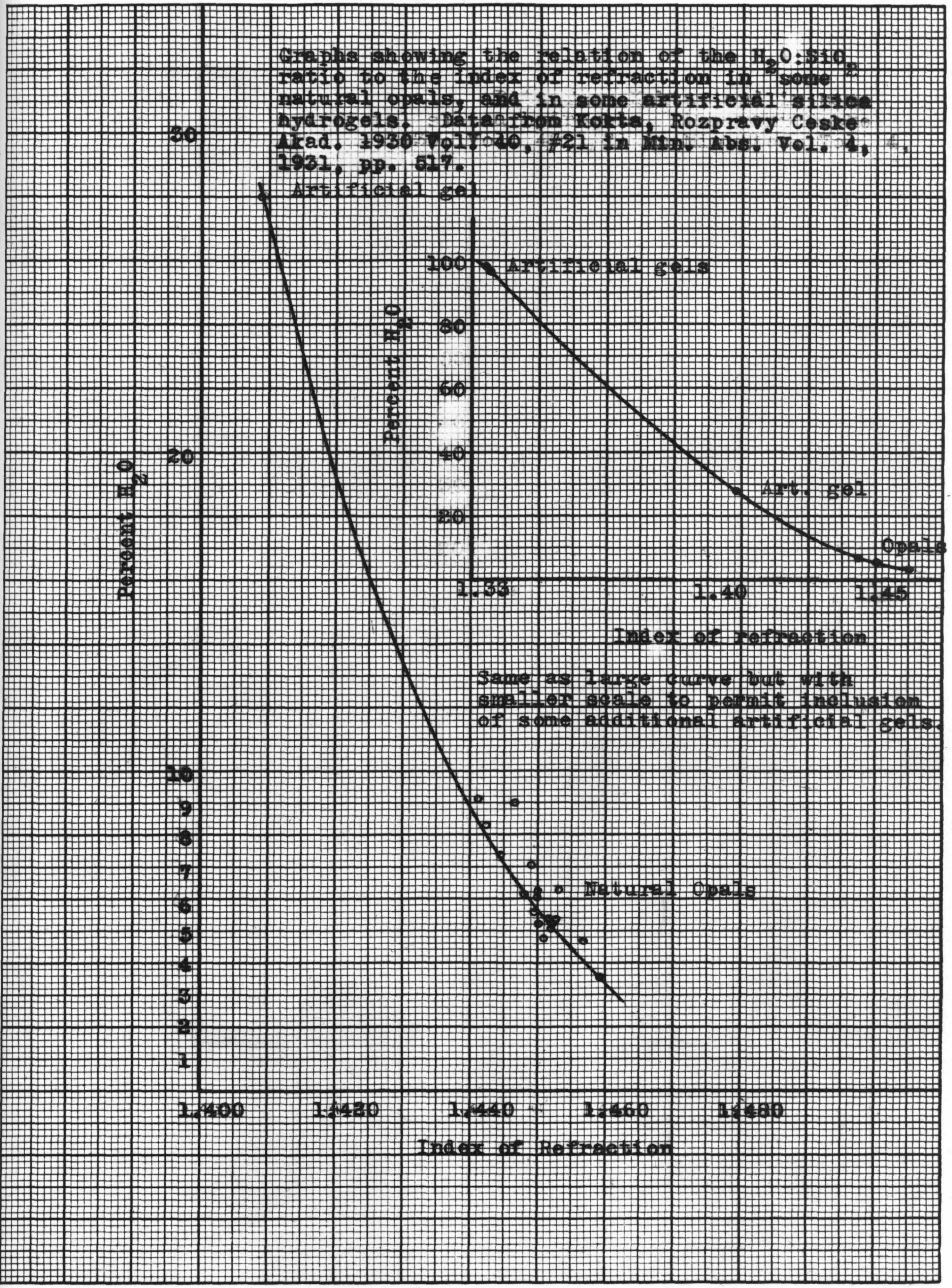


Fig. 35



Graphs showing the relation of the $H_2O:SiO_2$ ratio to the index of refraction in some natural opals, and in some artificial silica hydrogels. Data from Kokta, Rozpravy Ceske Akad. 1930 Vol. 40, #21 in Min. Abs. Vol. 4, 1931, pp. 517.

Same as large curve but with smaller scale to permit inclusion of some additional artificial gels.

bands with relatively high indices, and rare and corroded in hard bands with lower indices, it also seems reasonable to attribute the decrease in refringence to the assimilation by the soft cement of the silica, or the water, or both, of dissolved diatoms. The fact that the harder cherty shales always contain less water than do the softer ones indicates that it is probably a change in the $SiO_2:Al_2O_3$ ratio which is responsible for the decreased indices of the harder Type A bands.* It seems likely then, that hard Type A cement actually contains a higher percentage of silica than soft Type A cement, , and that this was derived from the solution and reprecipitation of the silica of organic tests once present in the hard bands.#

It is true that the indices obtained by the writer are all lower than those obtained by Spilchal, but considering the fact that the gels used by him were ignited and the cement used by the author was not, this difference is understandable. In fact, the relationship of indices to hardness is believed to confirm, to a certain extent, the presence of alumina in other bands of cement than the one which was analyzed. According to Kokta,[35] the index of opal decreases with increasing H_2O content (Fig. 35) and it seems very probable that the hardness also decreases

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[35] Kokta, Rospravy Ceske Akad. 1930 vol. 40 #21, in Min. Abs. vol. 4.

*For a comparison of the chemical composition of the members of the tuff-cherty shale series see Table I.

This discussion may seem unnecessary in view of the fact that hard cherty shales are more silicious than soft ones, but that fact might be due to the presence of silica in other forms than assimilated in Type A cement.

with increasing H_2O content. Consequently, the index should increase as hardness increases if the cement were opal, and the fact that it does the opposite confirms the idea that it is not pure opal, but is either an alumina-silica gel, or a mixture of opal and submicroscopic clay particles. Unfortunately, in either an $Al_2O_3:SiO_2$ gel, or a mixture of opal and a clay of higher index, the index of the cement would rise with the alumina content, so these relationships throw no light on the actual physical state of the cement.

In addition to the Type A cement just described, dirty white opal with a fine honeycomb texture occurs in these rocks as irregular but roughly stratigraphic bodies. As far as could be determined, this opal has the same index of refraction as the white opal of the soft cherty shales. It generally differs therefrom, however, in having a finer honeycomb texture and in appearing less dirty. Possibly the "dirtyness" is an optical effect dependent upon the texture and decreases with the latter's increasing fineness. This opal is more abundant in these rocks than in the softer types. It frequently makes up a considerable portion of a band, the remainder of which will consist of very small lenses of Type A cement. The boundaries of white opal areas, however, are typically not stratigraphic, and "islands" and branching bands of this material can be found in every thin section. There is one important respect inwhich the occurrence of white opal in soft cherty shales differs from its occurrence in hard cherty shales: in the latter it sometimes occurs as thin interlacing filaments in hard Type A bands. The writer believes that these interlacing filaments could not possibly have been produced by primary deposition and must either represent secondarily introduced or diagenetically derived silica. It is important to note that clay shreds are seldom found in areas of white opal, whether these occur in Type A bands or in other parts of the rock. This fact, combined with the fact that the mode of occurrence of the white opal suggests that it is diagenetic or secondary, and that these white opal areas never show any indication of having disturbed the original banding by being forced into the rock, seems to show that the white opal either replaced some clay shreds, or else was formed in areas which never contained them. The general distribution of clay and white opal makes the latter possibility seem rather unlikely. It does seem possible, however, that the white opal is developed from Type Acement which had previously been formed from the clay.

The third type of cement present in fairly hard cherty shales is chalcedony. This occurs in two ways:

1. As lense shaped areas surrounding and continuous with the chalcedonic fillings of organic tests.

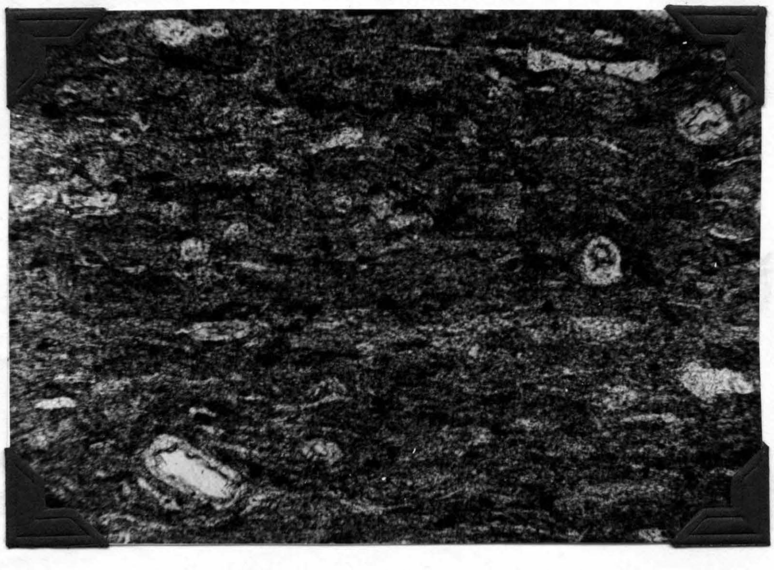
2. As small points and circular areas (.01 mm.

Fig. 36

X 27

Fairly hard cherty shale (533-C) Cabrillo Beach. This rock is largely composed of yellow isotropic cement, and clay shreds and diatoms.

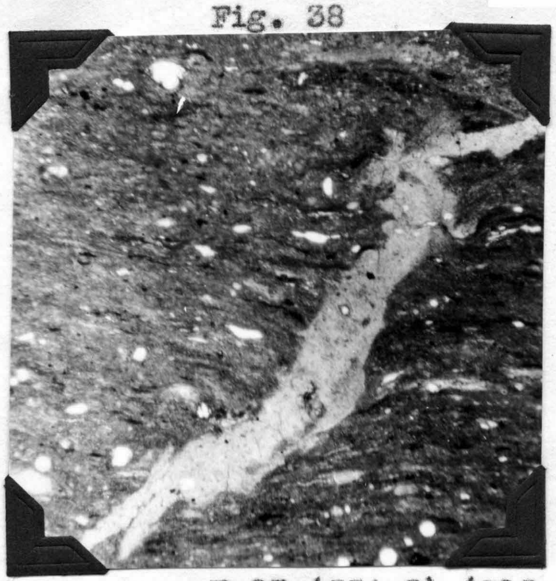
Fig. 37



X 90

Same as Fig. 36. Note somewhat corroded diatoms filled with chalcedony.

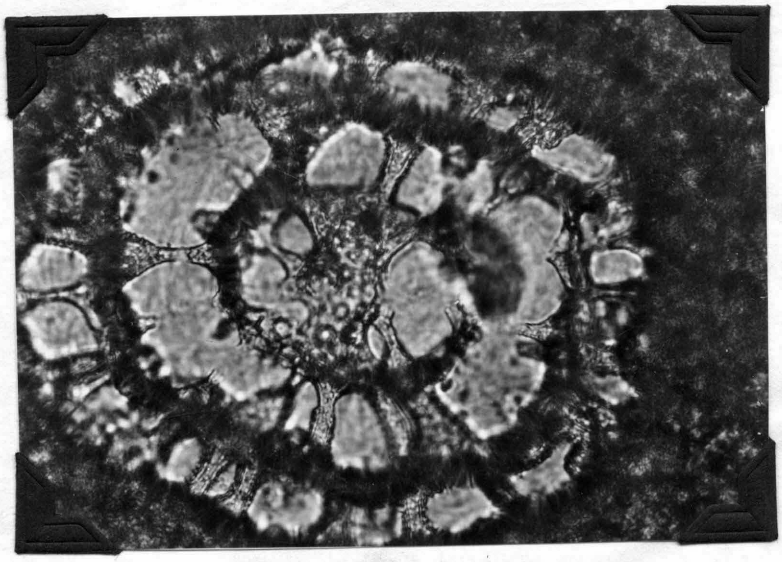
Fig. 38



X 27 (554-C) (S15, T5S, R14W)

Dike in fairly hard cherty shales. The stratification is horizontal. Delicate siliceous organisms are very abundant in the dike but are entirely absent from the rest of the rock.

Fig. 39



X 520 From same rock as above

Opaline radiolarian test filled with chalcedony. Note corrosion of original test.

in diameter) included in areas of dirty white opal.

The chalcedony occurring in lenses is occasionally fibrous, that occurring in the white opal areas is never so. Chalcedony never occurs in areas of Type A cement, except where it fills an organic test. In many cases where chalcedony surrounds a chalcedony filled opaline test, the latter will be partly dissolved.

As in the soft cherty shales, the clastic constituent of fairly hard cherty shales consist chiefly of clay shreds, clay smear areas, and small angular quartz grains. These last have approximately the same abundance as in the soft rocks, but both types of clay are considerably less abundant. Moreover, the smear clay area:clay shred ratio is generally greater in the harder rocks, and there are many smear areas whose properties approach those of the cement. In fact, in some rocks there are practically no clay shreds, and most of the smear areas have extremely low birefringence and a refringence nearly identical with that of the cement.

It has already been mentioned that in the Type A bands of fairly hard cherty shales fewer delicate siliceous organisms are present than in the soft varieties of these same bands, and that those present generally show distinct signs of corrosion. Apart from these differences, however, the organic constituents of fairly hard cherty shales are not appreciably different than those of the softer varieties of the same rocks. Large diatoms, radio-

TABLE I

Chemical analyses of some rocks in the tuff-cherty shale series.
Analyses by Mr. Ed Eisenhauer Jr. - S. Spring Street, Los Angeles.

All samples from S15 T5S R14W

(Black) - Original analyses.
(Red) - Analyses recalculated to 100% after deducting H_2O at 100°C.

	602 - C_1	600 - B	602 - C_3	600 - U	600 - O_2	602 - D_1
	Very Hard Cherty Shale	Hard Cherty Shale	Fairly Hard Cherty Shale	Fairly Soft Cherty Shale	Soft Tuff	Soft Laminated Tuff
SiO_2	88.90 91.74	86.75 91.27	86.23 90.67	82.55 87.38	71.15 78.62	67.97 77.90
Al_2O_3	2.28 2.35	1.96 2.43	4.11 4.32	4.82 5.10	10.54 11.65	9.45 10.83
Ca0	1.05 1.08	1.25 1.31	.90 .95	1.30 1.38	1.51 1.67	1.65 1.89
Na20	.49	.42	.24	1.09	.88	.62
K_2O	.51	.44	.25	1.15	.97	.71
FeO	.20 .21	.52 .55	.31 .33	.13 .14	.44 .49	.42 .48
Fe_2O_3	.87 .90	1.96 2.06	1.28 1.35	.90 .95	1.42 1.57	1.53 1.75
Cl_2	.27 .28	Trace	.11 .12	.81 .86	.26 .29	.77 .88
Loss on Ignition	2.80 2.89	1.79 1.88	1.93 2.04	2.90 3.07	4.26 4.71	4.88 5.59
Loss at 100°C	3.10	4.95	4.90	5.53	9.50	12.57
Total	100.06 99.96	99.95 99.94	100.61 100.03	100.03 100.03	99.46 99.97	100.04 100.03

laria, sponge spicules and foraminifera are present and the siliceous forms show few, if any more, signs of corrosion than do similar types in the softer rocks. In the harder rocks, however, they are generally filled with chalcedony, whereas in the softer rocks they are usually filled with opal. The foraminifera have practically the same abundance in both hard and soft rocks, but in the latter some of the originally calcareous tests have been replaced by either opal or chalcedony. Whether the calcareous tests have been preserved or replaced, they are nearly always filled with fibrous chalcedony.

In spite of the fact that delicate siliceous organisms are rare in fairly hard Type A bands, and are entirely absent from other bands in fairly hard cherty shales, they sometimes occur in these rocks in crack fillings or dikes. These features extend across several inches of strata and frequently branch. They are filled with Type A cement, which contains abundant well preserved delicate diatoms, silico-flagellates and foraminifera. (Fig.) It was impossible to tell from the examinations of these features whether they were filled from above by normal processes of sedimentation or were filled by injected material. If it could be shown that these cracks were filled from above by the normal processes of sedimentation, it seems to the writer that the presence in them of delicate siliceous tests, and the absence of such tests in the surrounding rock, would indicate that any solution of diatoms which took place in the cracked rock probably did so very soon after its deposition. Unfortunately, however, it is difficult to preclude the possibility of these features having been formed by injection at some fairly late stage.

Summary and Preliminary Conclusions

The fairly hard cherty shales are similar to the soft cherty shales in consisting largely of yellow isotropic cement in which are imbedded shreds and smear areas of clay, grains of quartz, siliceous organisms and calcareous foraminifera. Similarly to the softer rocks, these rocks also contain irregular areas of dirty white opal. They differ from the softer rocks, however, in containing chalcedony as a third type of cement, and in the relative proportions and characteristics of some of the above constituents. The important differences are as follows:

1. The total percentage of cement is higher in the harder rocks.
2. The percentage of clay is lower in the harder rocks.
3. The clay smear area:clay shred ratio area is greater in the harder rocks.
4. The hardness of Type A cement, as determined in Type A bands, is greater in the harder rocks.
5. The index of refraction of this cement is lower in the harder rocks.
6. Delicate siliceous organisms are much rarer in the harder Type A bands.
7. Those delicate forms present in these bands show

much more corrosion than the forms present in soft Type A bands.

8. The dirty opal:Type A cement ratio is higher in the harder rocks.
9. The fillings of organic tests are largely chalcedonic in the harder rocks as compared to opaline in the softer ones.

The following preliminary conclusions were reached:

1. The clay smear areas are formed by the partial decomposition of the montmorillonite shreds.
2. Some of the Type A cement is formed by the decomposition of the clay smear areas.
3. The harder type A bands owe their greater hardness to a higher silica content, and this is derived from the solution and reprecipitation in situ of the silica of once present delicate diatoms.
4. The distribution of dirty white opal areas indicates that they are either of secondary or diagenetic origin, and the absence of clay shreds in these areas suggests that the opal either replaced clay,or Type A cement derived from clay.

As might be inferred from the above statements, the writer believes that hard Type A bands are produced directly from soft Type A bands, by the solution and assimilation of the silica of the delicate siliceous organisms which once existed therein. Whether or not the rest of a hard cherty shale bed is genetically related to a soft cherty shale bed is a different matter.

The fact that Type A cement is believed to be derived, to some extent at least, from the decomposition of clay, combined with the fact that the cement:clay ratio is higher in the harder than the softer rocks, suggests that the soft cherty shales may be genetically related to the hard cherty shales. This conception is somewhat strengthened by the fact that, except in Type A bands, the organic constituents, and the clastic constituents other than clay, are practically identical in both varieties of these rocks. It may also somewhat be strengthened by the fact that in the harder rocks, the percentage of the clay-cement transitional stage, clay in smear areas, is more abundant. It is not considered, however, that the above features necessarily indicate that hard cherty shales and soft cherty shales had an identical "mother sediment." The fact that some of the Type A cement was derived from the decomposition of clay does not necessarily indicate that it all came from this source. It is possible that an original, or introduced, cement was capable of decomposing the clay mineral. It is also possible that the cement was produced largely from clay, but that in the harder rocks some of this was more finely divided, or even had a different composition than in the softer rocks. The possibility of its having been more finely divided derives some support from the fact that in Type A bands, which are largely cement, the clay present occurs in much smaller shreds than in the rest of the rock. These possibilities and some others will be more fully discussed later, but it seemed desirable to point out some of the evidence for and against considering the soft and hard rocks so far described as members of a genetic series.

Very Hard Cherty Shales

These rocks are similar to those just described, but differ therefrom in several particulars. They generally have a somewhat higher specific gravity, a more vitreous lustre, and are sometimes transparent on thin edges. Moreover, the hardest varieties are often quite dark colored. The cause of these differences is largely to be found in the amount and character of the cement. Like the fairly hard cherty shales, the very hard cherty shales generally have three types of cement: pale yellow isotropic material, white to colorless opal, and chalcedony. The relative proportions of these materials vary a good deal, but the total percentage of cement in these rocks is always appreciably higher than in the softer rocks. In fact, the total amount of clastics in these rocks probably never exceeds 5 or 6 percent, most of which is quartz.

In some instances it is not possible to differentiate the isotropic cement into white opal and yellow Type A cement, but it is frequently true that there are two varieties of isotropic material present with slightly different indices. The difficulty in differentiating these two isotropic cements is due to the fact that the yellow cement is generally a good deal paler in the hard rocks than its counterpart in the soft rocks, and, because in many cases, the white opal no longer has a dirty appearance or honeycomb texture. It is important to note in this regard, however, that there is good reason to believe that some of the cement of the hard rocks still contains an appreciable amount of alumina. A chemical analysis of a sample of very hard cherty shale by Mr. Eisenhauer showed:

SiO_2	91.74 %
Al_2O_3	2.35
CaO	1.08
Na_2O K_2O	.51
FeO	.21
Fe_2O_3	.90
Cl_2	.28
Loss on Ignition	2.89
TOTAL	99.96

A very careful microscopical analysis of a thin section showed that the maximum amount of clay was 1.7 percent.* Assuming the clay to be montmorillonite, the total Al_2O_3 attributable to the clay in the rock would be about 0.4 percent. The only other clastic constituent was believed to be quartz, and since the Cl_2 present is sufficient to combine with practically all of the alkalies to form NaCl, it seems likely that the identification of this mineral was correct and that there is no feldspar present. If such is the case, a total of about 2 percent Al_2O_3 must

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*This maximum was obtained by assuming that all clay shreds were as thick as the thin section. Considering that the measurable dimensions were often .01 mm. X.001 mm. this seems unlikely, and the total clay should probably be less.

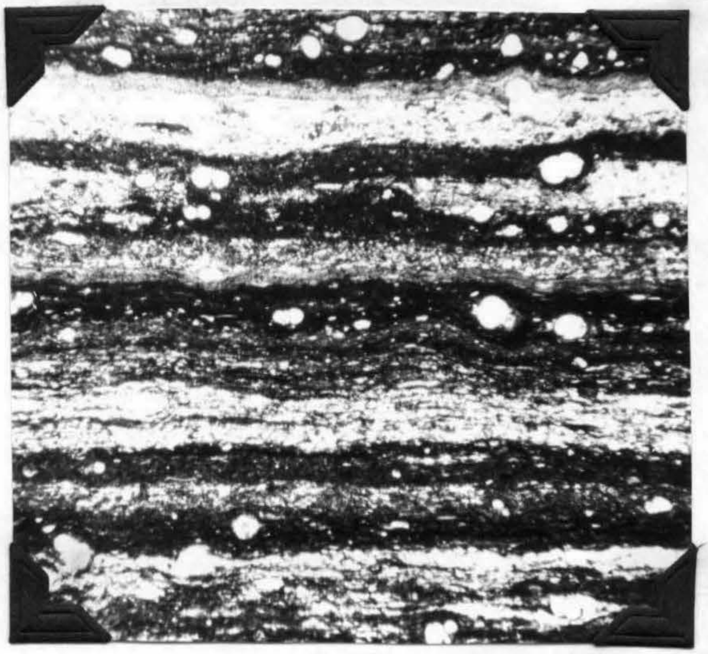
be assigned to the cement, which in this case was nearly all isotropic. Probably 50 percent of this cement was white opal, and if this is assumed to contain no Al_2O_3, the yellow cement would contain 4 percent of this substance.

Where two types of isotropic cement can be recognized, it is generally true that the colorless or white opal occurs as islands and irregular bodies in a matrix of pale yellow material. Sometimes, however, opal occurs as quite regular bands.

The yellow cement occurs as discrete bands containing no clastic or organic remains and also irregularly distributed throughout the rest of the rock. The discrete bands, however, almost always contain some filaments or areas of white opal.

Chalcedony is generally much more important in these rocks than in any of the softer types, although it is sometimes only present in small amounts. It occurs as fairly regular bands, as irregular lenses, and as cross cutting veins. (Figs 40, 42) Many bands of chalcedony contain irregular bodies of opal, and small chalcedonic areas appear in bands of honeycomb white opal. In some cases the opal has a distinct globular structure and occurs as small spheres from .010 mm. to .014 mm. in diameter. (Fig. 43) The distribution of opal and chalcedony suggest that one was derived from the other. In many cases it is probably impossible to say whether the opal was derived from chalcedony or visa versa. However, in some rocks which contain a large amount of chalcedony, opaline diatom frus-

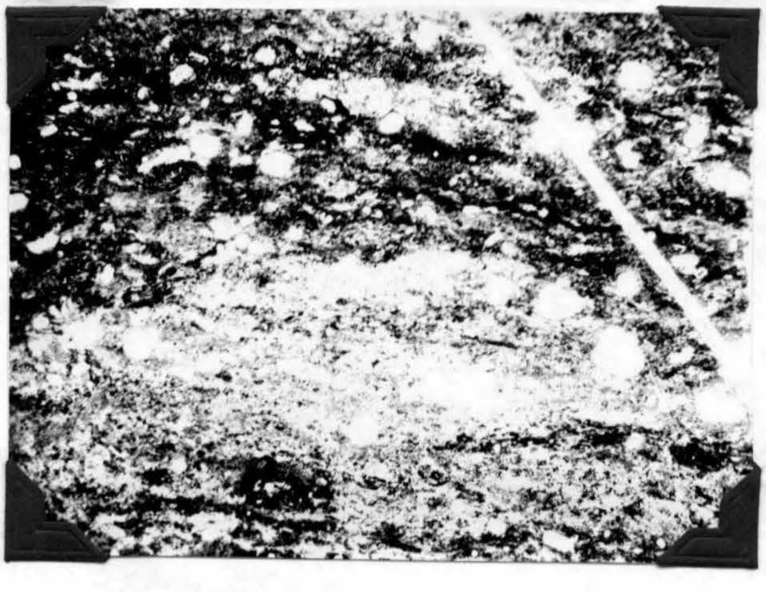
Fig.40



X 27 (567) (S21, T5S, R14W)

Very hard cherty shale, white chalcedony, gray and black - opal and type A cement. Circular white areas are fillings of foraminifera.

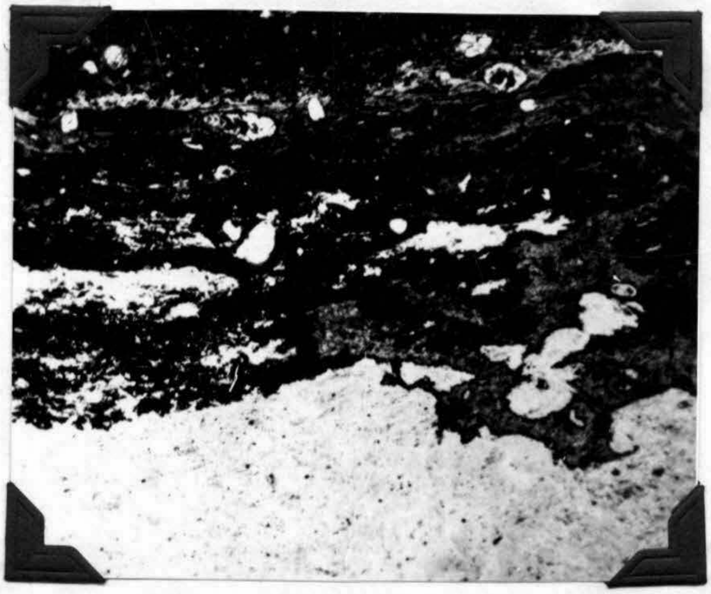
Fig. 41



X 27 (537) (S12, T5S, R15W)

Very hard cherty shale showing irregular development of chalcedony, (white) and cross-cutting vein. Dark areas are opal - white circular areas are chalcedonic fillings of foraminifera.

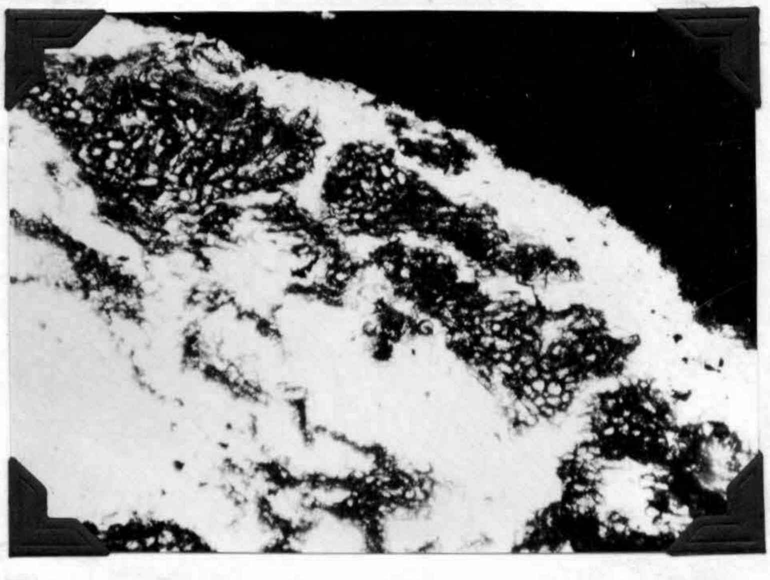
Fig. 42



X 90 (545) (S15, T5N, R14W)

Very hard cherty shale showing the irregular development of chalcedony, white, in opal, gray and black. Note chalcedonic filling of foraminifera. (Upper center)

Fig. 43



X 90 (532) Point Fermin
Globular opal in chalcedonic band.

tules are preserved, but only in areas of opal or Type A cement. Moreover, diatoms or calcareous foraminifera are frequently abundant in the opaline part of a band, but where this band changes laterally into chalcedony the diatoms disappear and the calcareous shells are replaced. Such features leave no doubt in the author's mind that the chalcedony in these cases was derived from the opal and not visa versa. Even in those cases where relationships do not indicate the direction of the genetic relation, it seems likely that the chalcedony crystallized from the opal. Storz[36] and Cayeux[37] have noted opal globules surrounded by chalcedony and believe that chalcedony was formed by the crystallization of the opal. Many other workers on cherts have also suggested such a change.

Chalcedony veins are common in very hard cherty shales, especially in those which contain abundant chalcedony. The origin of these veins is not certain, but it seems possible that they represent fillings of cracks which were produced by volume changes associated with the lithification of these sediments. For, if it is true as suggested above, that chalcedony is derived from the crystallization of opal, this change of state would necessarily produce considerable shrinkage, and might well produce cracks. The fact that many chalcedonic cherty shales show considerable disturbance of the original banding which is

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[37] Cayeux, op. cit., pp. 264-318.

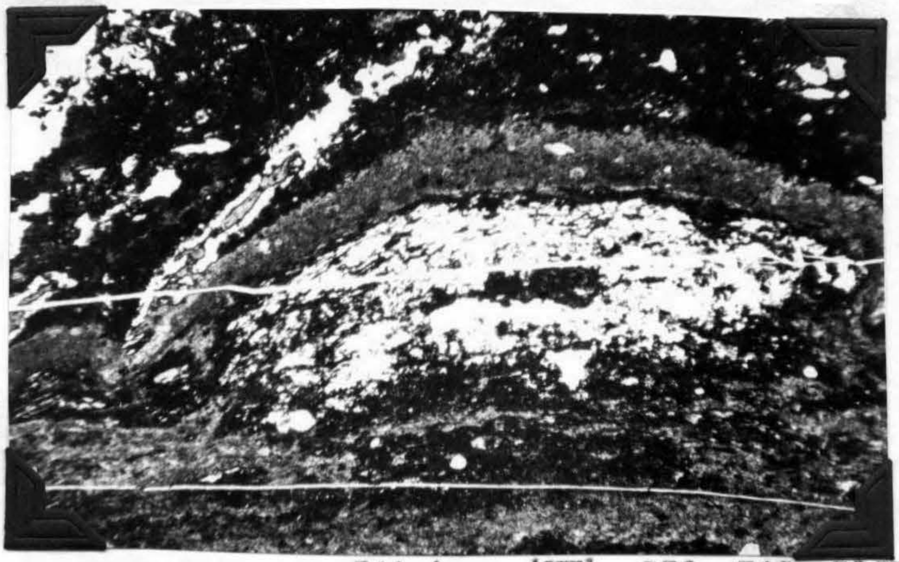
[36] Storz, Max von, Die sekundare authigne Kieselsaure in ihrer petrogenetisch-geologischen Bedeutung, Monographien zur Geologic und Paleontologie, 1928. p. 8.

not shared by adjacent strata also suggests that they have undergone considerable internal rearrangement, and fits in with the idea that the cracks mentioned above were caused by crystallization of chalcedony from opal. (Figs. 44, 45)

It has already been mentioned that the clastic constituents of these rocks are relatively unimportant. Quartz grains sometimes make up 3 to 4 percent of a rock, but the total amount of clay probably never exceeds 2 percent and is generally much less. The clay generally occurs as very fine shreds, although a few small smear areas of very low birefringence are sometimes present. Clay is never present in chalcedonic areas.

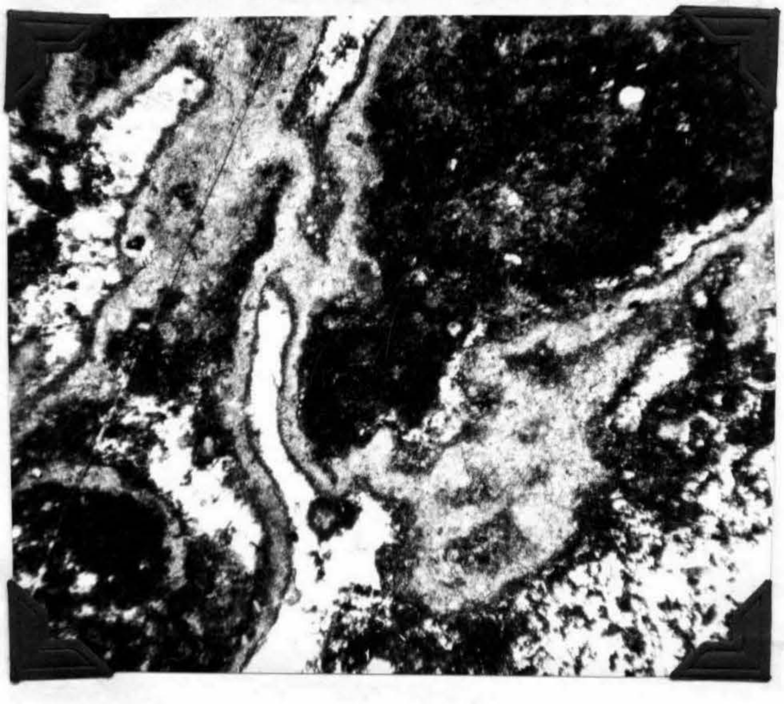
The organic constituents consist of large diatoms and radiolaria and some foraminifera. Delicate siliceous organisms are never present. The foraminifera are sometimes calcareous and filled with chalcedony, and sometimes replaced by one type of chalcedony and filled with another. Frequently, in chalcedonic bands, a thin line representing the trace of the original test is the only evidence of the former presence of foraminifera and even the crystallization of the chalcedony has not been affected. The large siliceous organisms found in these rocks, frequently show little evidences of corrosion. (Fig. 47) The tests are opal and are generally filled with chalcedony. They are entirely confined to non-chalcedonic areas and are approximately as abundant there as in the softer rocks.

Fig. 44



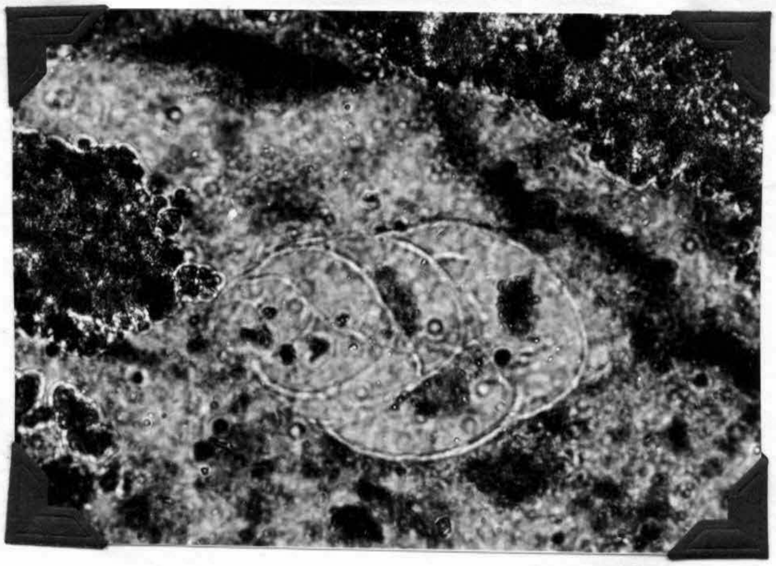
544-A (NW¼, S36, T4S, R15W)
Chalcedonic cherty shale, showing contorted beddings. White areas chalcedony, gray areas opal, black areas impure opal. Note opal inclusion in chalcedony, left center.

Fig. 45



544-A
Same as Fig. 44, but cut parallel to bedding.

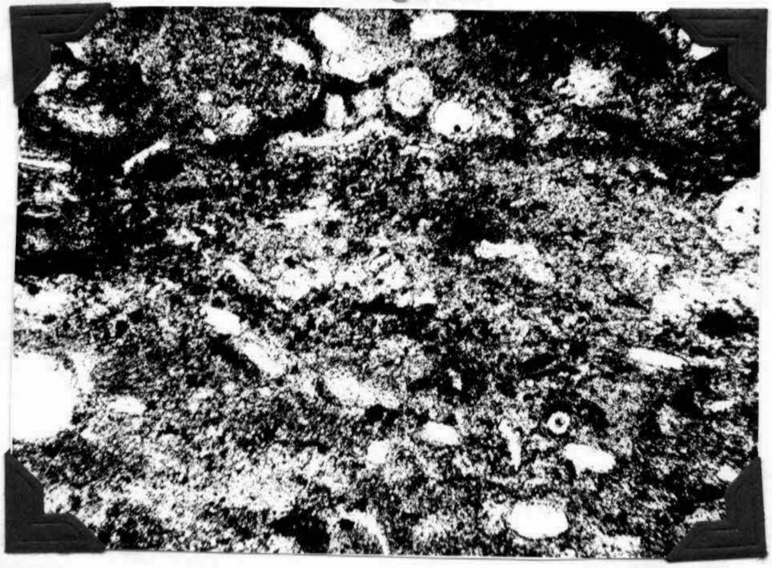
Fig. 46



X 520 - Spl- 567-A ; S21, T5S, R14W.

Trace of test of foraminifera in chalcedony. There are no actual calcareous remains, nor is the crystallization of the chalcedony affected by the test.

Fig. 47



X 90 (537) S12, T5S R15W.

Very hard cherty shale containing some well preserved diatoms. Tests opal and filled with chalcedony. Light areas chalcedony. Dark areas impure opal.

Comparison of Very Hard Cherty Shales and Fairly Hard Cherty Shales

The very hard cherty shales are similar to fairly hard cherty shales in consisting essentially of three types of siliceous cement in which are imbedded clay, clastic quartz, siliceous organisms and foraminifera. They differ from the softer rocks in the following characteristics

1. The total percentage of cement is much higher in the harder rocks.
2. The total percentage of clay is much smaller in the harder rocks and it only occurs as minute shreds and minute smear areas.
3. The chalcedony:isotropic cement ratio is generally much higher in the harder rocks.
4. Delicate siliceous organisms are never present in the harder rocks.

Preliminary Conclusions

1. From the mode of occurrence of chalcedonic areas and their relationships to organic remains, it was concluded that the chalcedony of these rocks was formed by the crystallization of opal.

2. A comparison of a chemical analysis with a microscopic analysis indicates that some of the isotropic cement of the hardest rocks contains an appreciable amount of alumina.

SUMMARY OF TUFF CHERTY SHALE SERIES

Except for the soft tuffs, which may not contain any cement, all of the members of this series consist essentially of cement of two or three types, in which are imbedded:

1. Clay, in discrete shreds and smear areas of lower refringence and birefringence.
2. Quartz in small angular grains.
3. Large diatoms, radiolaria and sponge spicules.
4. Delicate diatoms and silico-flagellates.
5. Foraminifera.

The cement consists of: (a) chalcedony; (b) white and dirty white opal which generally has a fine honeycomb texture; and (c) a clear yellow isotropic substance of somewhat variable index and hardness, which contains appreciable amounts of alumina and is called Type A cement.

The changes which take place in connection with the increasing induration of the members of this series can best be divided into two groups: those associated with the tuff:fairly hard cherty shale series, and those associated with the fairly hard:very hard cherty shale series.

The changes associated with increasing induration in the tuff:fairly hard cherty shale series are as follows:

1. The percentage of Type A cement increases greatly.
2. The percentage of white opal cement increases slightly.
3. Small amounts of chalcedony appear in the white opal cement areas.

4. The percentage of clay decreases greatly.
5. The clay smear area:clay shred ratio increases considerably.
6. Delicate siliceous organisms gradually disappear.
7. Large siliceous organisms are unchanged in abundance, but show a small amount of corrosion.

The changes associated with increasing induration in the fairly hard:very hard cherty shale series are as follows:

1. The percentage of total cement increases.
2. The ratio of white opal to Type A cement increases.
3. The ratio of chalcedony to Type A cement increases.
4. The percentage of clay decreases.
5. The average size of clay shreds decreases greatly.
6. All delicate siliceous organisms disappear.
7. Large siliceous organisms decrease slightly in abundance in the final stages of induration.
8. Calcareous foraminifera are frequently replaced by silica.

The following preliminary conclusions have been reached:

1. The clay smear areas represent decomposition products of the clay shreds.
2. The decomposition of clay smear areas contributes to the formation of Type A cement.
3. The solution and reprecipitation in situ of the silica of delicate siliceous organisms contributes to the harder varieties of Type A cement.

4. The white opal cement is either of secondary of diagenetic origin.
5. Chalcedonic cement is derived from the recrystallization of opal.

GENETIC RELATIONSHIPS OF THE TUFF-CHERTY SHALE SERIES

Relationships of Chalcedonic Rocks and Opaline Rocks.

Since it has been shown that the distribution of some chalcedonic areas in the harder rocks indicates that they were derived from the crystallization of opaline cement, and since the distribution of small points of chalcedony in dirty white opal areas in rocks of intermediate hardness also suggests that they are the result of the crystallization of this material, and since further, many of the chalcedonic rocks show evidences of contraction and internal readjustment, it appears to the writer that it is reasonable to assume that all of the chalcedonic cement of the hardest rocks was derived from the crystallization of opal. Therefore, it is believed that the chalcedonic cherty shales may be considered to be the descendants of rocks containing equivalent amounts of opaline cement.

The cause of this crystallization is not clearly understood, although its occurrence, or a crystallization of quartz from opal, has been supposed by many workers [37,38]

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[37] Lawson, A. C., San Francisco Folio, U. S. G. S. Folio, No. 193, 1914, pp. 5.

[38] Davis, E.F., op. cit., pp. 253-259, and many others.

on siliceous rocks. Mr. M. N. Bramlette# who has been working on the origin of the siliceous Miocene rocks of California reported to the writer that in many areas in the state chalcedonic cherty shales seem to be particularly abundant in the lower parts of the column. If this is so the crystallization might be due to pressure or to age. In this connection the following facts seem pertinent: In the intraformational conglomerate containing chert cobbles which was described on page 23, it was observed that the cobbles of chalcedonic cherty shale were less rounded than the cobbles of softer cherty shale, in spite of the fact that they were generally larger. In view of the fact that this conglomerate is a very local feature, and all of the cobbles in it except soft silt cobbles are poorly rounded, it seems that the rounding was probably conditioned more by the hardness of the cobbles than by the distance which they travelled. Granting this, the greater angularity of the chalcedonic cherty shale cobbles indicates that they were harder than the associated softer cherty shale cobbles <u>before they became cobbles</u>. This seems to make it rather unlikely that they recrystallized after their deposition in the conglomerate. Since, as has been shown previously* they were probably derived from the underlying 400 feet of section, and since there is no important unconformity in this part of the column, it appears that the formation of chalcedony cannot be due entirely to

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* Page 23

Fig. 48

(615-A (S21, T5S, R14W)

Close up of intraformational conglomerate of Fig.5 Cherty shale cobble under knife.

Fig. 49

Same conglomerate as Fig. 48

age. It might be of course due to pressure related to the uplift of the land which produced the cobbles.

Relationships of Opaline Rocks to Type A Cement Rocks.

If it is granted that the chalcedonic cherty shales, are genetically related to the opaline cherty shales, it is still necessary to explain the origin of the opal. In all rocks containing this material its distribution in islands, interlacing filaments, and irregular bands indicates that it is not a primary deposit, but represents either a diagenetic or secondary product. It is difficult to preclude the possibility of its being secondary, but the fact that [illegible] cherty shales are strictly confined to stratigraphic boundaries and have a transition zone of uniform thickness between them and adjacent soft sediments seems to indicate that their siliceous cement was not secondarily introduced.

It is also important in this connection to remember that the cherty shale cobbles found in the intraformational conglomerate described on page 23, indicate that the underlying cherty shales were lithified before more than 400 feet of section were deposited. It is of course still possible that the silicification was secondary, but the time available for its occurrence is more limited.

Another point in connection with possible secondary silicification concerns the origin of the silicifying solutions. The abundant pyroclastics and intrusions of the San Pedro Hills area indicate that volcanic activity might have furnished silicifying solutions, but in many other parts of the state, as in the Piru Creek district, identical types of cherty shale are at least 20 miles removed from any known volcanic activity of Miocene or later age. This of course does not remove the possibility of silicification being due to non-volcanic waters, but it removes one reasonable source for the abundant silica which would be needed.

It seems to the writer therefore that although it is impossible to preclude the possibility of the opaline cement of the cherty shales being secondarily introduced, this mode of origin is less likely than a diagenetic one.

If it is assumed that the opal is a product of diagenesis, its presence might be considered to be due to one or all of the following processes:

(a) The solution and reprecipitation of the silica of siliceous organisms.

(b) The decomposition of clay.

(c) The decomposition of Type A cement.

(d) The decomposition of some other material, such as volcanic ash.

It is believed to have been shown that diatoms present in soft Type A bands have been dissolved and their silica assimilated by the surrounding cement. It might therefore seem likely that some of the opal cement of the cherty shales is a product of similar action. The only objections to this hypothesis seem to be that white opal cement only appears in <u>soft</u> cherty shales in areas other than Type A bands, and that the only siliceous organisms present, outside of Type A bands, are large uncorroded forms. This might be due to the fact that all small forms had been dissolved or to the fact that they were never present. Since, however, delicate forms have never been found in the softest cherty shales outside of Type A bands and are always abundant in the latter, the writer is inclined to think that they were never abundant except in these bands.

It must be admitted, however, that the fine grained type A bands are probably less permeable and porous than the adjacent rock and on that account may be better suited to preserve organic tests. Still, it seems to the writer that these delicate forms were never abundant outside of Type A bands and on that account could not have furnished sufficient silica to account for all of the white opal areas.

Considering the fact that clay shreds seldom exist in opal areas, it seems possible that some opal was derived directly from the decomposition of clay. However, since there is evidence that clay alters directly to Type A cement, the writer is somewhat reluctant to suggest that it also alters to opal. It seems somewhat more likely that the opal is derived from Type A cement by a loss of alumina. This last suggestion receives some support from the fact that opal appears as discrete areas in the hardest varieties of Type A bands. These bands are harder than any which contain siliceous organisms, and although it is possible that the opaline filaments and islands are introduced from outside the band, or result from a "supersaturation" by organically derived silica, it also seems possible that they were derived directly from the Type A cement.

It should be emphasized here that whether opal is derived directly from clay, or from it through an intermediate Type A cement stage, the occurrence of large areas of opal in clay rich bands, and the absence of clay in these opal areas seems to necessitate the existence of one of these processes, or else the complete removal of the constituents of the clay.

The only objection that can be raised to the assumption that opal was derived from some substance other than those mentioned, is that there is no evidence for the existence of such a substance. Such materials as finely divided volcanic glass might, however, have been present without having been recognized.

In conclusion then, it seems that as far as the opaline cement is concerned, some of it may have been derived from siliceous organisms or some finely divided unstable substance such as volcanic glass; but a considerable portion of it was probably derived from clay or Type A cement. Such an assumption of course requires the disposal of considerable alumina, and the writer has no evidence bearing on the disposal of this substance. However, if, as is believed to be the case, the process of lithification took place soon after the sediments were deposited, the lack of any evidence of the final resting place of the Al_2O_3 does not seem to be a fatal objection to the correctness of this hypothesis.

Origin of Type A Cement

It is believed to have been shown that chalcedony results from the crystallization of opal and that therefore those cherty shales rich in chalcedony may be the direct descendants of rocks containing an equivalent amount of opal. The origin of this opal has also been considered and it appears that a considerable part of it may come from the removal of alumina from Type A cement or from clay. There still remains to be discussed, however, the origin of the most important of the cements, namely Type A cement.

In this regard it has already been shown that part of this cement is probably derived from the decomposition of clay and that in some instances, at least, it is enriched by the assimilation of organically derived silica. Granting these two sources of the ingredients of Type A cement, and considering the fact that the chief difference between the soft and fairly hard members of the tuff cherty shales series lies in the Type A cement:clay ratio, and to a lesser extent in the amount of delicate siliceous organisms present, it might appear that the tuff-cherty shales series is truly a genetic one. However, this explanation has several alternatives:

1. It might be contended that Type A cement is chiefly composed of a primary, chemically precipitated gel, and that its enrichment by the decomposition of clay and diatoms is purely incidental and of minor quantitative importance.
2. It might also be contended that although the chief sources of this cement are clay and organic silica, these constituents were finer in those sediments which developed into cement in the harder rocks and that for this reason the tuff-cherty shale series is not a truly genetic one. Under this hypothesis will also be included the assumption that the cement was largely derived from the fine isotropic material of bentonites, whether this is truly a gel or very finely divided clay.
3. It might also be contended that Type A cement was largely derived from some easily decomposed substance other than clay such as volcanic ash, or from a clay of different composition than that which remains.
4. Finally, it might be contended that the cement is largely secondary, and that the evidences of decomposition shown by the clay and diatoms were due to corrosion by these secondary solutions.

Secondary Silicification

The hypothesis of secondary silicification probably cannot be disproved on strictly petrographic evidence. The absence of abundant diatoms in the secondary cherts of the diatomite showed that silicifying solutions can be capable of dissolving silica as well as being silica bearing; and it also seems possible that such solutions might be competent to decompose clay. However, it has already been shown in connection with the discussion of the white opal cement that the mode of occurrence of cherty shale beds suggests strongly that they do not represent secondarily silicified beds. Therefore, although, the possibility of secondary action cannot be entirely ruled out, the writer feels that its intervention in the formation of these rocks is extremely unlikely.

Gel Hypothesis

The hypothesis that some of Type A cement represents a chemically precipitated gel is hard to definitely disprove and there is some evidence that might be considered favorable to it:

In the soft varieties of Type A bands very delicate diatoms are abundant, and the only clay present occurs as minute discrete shreds, not as smear areas. The abundance of delicate uncorroded diatoms suggests that the cement was not even partially derived from organic silica. It is true that there are diatoms more delicate than those preserved, which might possibly have been dissolved without the remaining forms showing any evidences of corrosion, but considering the size, abundance, and perfect state of preservation of the forms present, the writer is inclined to think that none of the cement of the softer varieties of Type A bands was derived from siliceous organisms.

It does not seem necessary, however, that the discrete nature of the clay shreds present in Type A bands is any indication that the cement was not derived from clay; either from shreds of the same size or from more finely divided material. The absence of smear areas may be only apparent. The average size of clay shreds in Type A bands is not greater than .01 mm. X .001 Mm. X ? mm. and smear areas of comparable size might be very difficult to recognize. This argument is, of course, not direct evidence against the gel hypothesis. There is, however, some evidence which suggests that Type A cement was not largely deposited as a gel.

In 1922 Henri Coupin[39] published the results of some experiments performed on some diatom cultures. Several cultures were kept alive for a period of two months in Knop gelatin. To different cultures were added different ingredients, including powdered orthoclase, quartz, kaolin, other clays, potassium silicate, sodium silicate, and gelatinous silica. In those cultures to which orthoclase, kaolin and certain clays were added the diatoms multiplied rapidly. In those to which the silicates were added they either died or remained un-

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[39] Coupin, Henri. Sur l'origin de le carapace siliceux de diatomees Accad- des Sciences - Compte Rendu #175-1922 pp. 1226-1229

changed, depending upon the amount of material added. In those cultures to which gelatinous silica was added the diatoms did not develop. Now, in all of the cherty shales diatoms are common, and in those soft bands which contain the greatest amount of Type A cement they are extremely abundant. It seems probably, therefore, that the material composing these bands was favorable to the development of these organisms.

Since, therefore, the presence of clay is very favorable to the development of diatoms, and silica in the form of a gel is not, it appears that the abundance of diatoms in soft type A bands constitutes some proof that the original medium in which they were deposited was not a gel. Since it is known that Type A cement contains alumina, this suggestion is of course dependent upon the assumption that diatoms would not thrive on an alumina-silica gel, and it is true that there is no direct evidence of this fact. However, since the state of silica in an alumina-silica gel is not considered to be different than the state of silica in a silica gel,* but is fundamentally different than its state in an aluminium silicate, this assumption seems fairly reasonable.

In short, then, while there is no conclusive proof that the soft varieties of Type A cement were not deposited as primary alumina-silica gels, there is some organic suggestion that they were not, and no very good evidence for considering that they were.

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*Oral Communication - Dr. Linus Pauling.

Clay and Siliceous Organisms

Let us now consider the hypothesis that all of Type A cement was derived from the decomposition of clay and siliceous organisms, but that the clay shreds and ditaoms which decomposed were smaller than those which remain, and that therefore the variations in induration of the numbers of the tuff-cherty shale series were conditioned by primary differences in the sediments. There are some facts which seem to support and some which seem to militate against this hypothesis.

The fact that in the hardest cherty shales and in Type A bands, both of which are largely cement, all of the clay present is very finely divided, suggests that these rocks and bands may owe their high cement:clay ratio to the fine state of once present clay shreds.

Against such an argument, however, one might point out that some of the softest tuffs are largely composed of shreds of equal fineness and sometimes even contain an appreciable amount of sub-microscopic material. It might also be mentioned that clastic quartz, and all organic constituents other than small diatoms, are present in practically the same abundance in all members of the tuff-cherty shale series. These last facts might be considered to indicate that the hard rocks were once very similar to the soft ones.

The writer is inclined to think that the fineness of the clay shreds originally present in the sediments may have been a factor in determining whether they were decomposed to cement or not. The fact that soft tuffs exist which consist of equally fine clay shreds is not proof that this is not so. Other factors may have intervened. Variations in temperature, salinity and decomposable organic matter may have affected the diagenesis.

Against the suggestion that Type A cement was derived from a clay of different composition than that which now exists in these rocks or from some such material as volcanic ash nothing can be said. The absence of known occurrences in this region of a different clay mineral is of little significance, but in the absence of such occurrences it would seem to be introducing unnecessary complications to assume its existence. As far as assuming that Type A cement is derived from volcanic glass is concerned, there are no important objections. Glass is present in many of the tuffs and is known to be a relatively unstable substance. It may well have decomposed along with clay mineral or minerals, but in the absence of any direct proof of this process it can hardly be assumed to be a fact.

In summary, then, it seems to the writer that the assumption that Type A cement was secondarily introduced is extremely unlikely. It also appears that there is no evidence that any of this material represents a primary gel. There is no evidence that some of this cement was not derived from volcanic ash, but since there is good evidence that some of Type A cement was derived from clay and some if it from siliceous organisms, it seems reasonable to assume that all of it was derived from these sources. This assumption does not of course mean that those rocks having a high Type A cement:clay ratio are direct descendants of similar rocks having a lower ratio. Original differences in the state of division of the clay and perhaps differences in its composition, combined with differences in the size and relative amount of siliceous organisms may have been the factors which determined whether or not the clay:cement ratio was to be high or low. The writer is convinced, however, that Type A cement was largely derived from the decomposition of clay and siliceous organisms.

Concerning the processes by which these changes were brought about, the writer has little to offer. Murray and Irvine[40] showed that the putrefaction of the soft parts of siliceous organisms produces solutions capable of decomposing clay and Cayeux[41] has considered that such solutions were probably responsible for the decomposition of the clay in certain sediments. Taliaferro[42] and some others maintain, however, that the acids set up by such putrefaction would also dissolve the foraminifera present. Whether or not this is so would depend upon the exact

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[40] Murray, J. and Irvine, R., On Silica and the siliceous remains of organisms in modern seas. Proc. Roy. Soc. of Edinburgh, vol. 18, 1889, p. 229-250.

[41] Cayeux, op. cit.

[42] Taliaferro, op. cit. p. 14.

nature of the solutions produced, the general bottom conditions, and to some extent upon the size of the foraminifera compared to the clay shreds. As far as the last factor is concerned it can be said that the largest clay shreds are about the same size as the smallest foraminifera, but that the majority of them are very much smaller. The other two factors are undoubtedly interrelated and about them the writer can only speculate; but it seems quite possible that under proper conditions of temperature and salinity the putrefaction products of organic matter might suffice to produce the alterations postulated. A discussion of these factors seems, however, to be more properly in the realm of an oceanographer, than of a geologist.

CONCLUSION

In conclusion it may be said that the writer believes that the cherty shales studied in this area are endogenetically silicified diatomaceous tuffs and that the major portion of the cement was derived from the decomposition of bentonitic clay. It is believed that most important processes in the silicification took place very soon after the sediment reached the sea bottom, and that the entire process of lithification was completed before many hundreds of feet of sediment were deposited on top of a given bed.

The black cherts of the diatomite, on the other hand, are believed to be definitely the products of secondary silicification.

In the San Pedro Hills the cherty shales are much more important quantitatively than the secondary cherts, but it seems possible that in other areas the reverse would be true.

The Stratigraphic Position of Some of the Diatomite Horizons in the Los Angeles Basin

by

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May 25, 1934

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The Stratigraphic Position of Some of the Diatomite Horizons in the Los Angeles Basin

In most places in the Los Angeles Basin where a complete section of upper Miocene rocks is exposed there exists a mappable unit which is composed largely of soft, white, highly diatomaceous silt. This unit is commonly referred to as the diatomite. It varies considerably in thickness and in its relationship to other rock types, but the constancy of its lithologic characteristics considered in conjunction with their unusualness suggests that the unit has stratigraphic significance. Since, however, structural and physiographic conditions make it impossible to trace the diatomaceous deposits continuously around the Los Angeles Basin, the only method of determining the age relationships of various isolated areas of these rocks is the paleontological one.

At the present time few paleontological observations have been published which are relevant to this problem, except the report by W. D. Rankin[1] on the foraminifera from the Modelo formation of the Santa Monica Mountains. The correlation of the diatomaceous part of that formation with the diatomites examined by the writer will be given later, but it is first necessary to explain the paleontological section which will be used for a standard.

Unfortunately, there seems to be no complete upper Miocene section in the Los Angeles Basin which contains sufficiently abundant foraminifera throughout, to justify its being used as a standard of comparison. Probably the best section for this purpose is exposed east of Capitan Point in Santa Barbara County. This section is upper Miocene in age and is richly foraminiferal. Its foraminifera have been examined by Mr. Boris Laiming,[2] who divid-

[1] W. D. Rankin - U.S.G.S. Prof. Paper 165-C.

[2] Micropaleontologist for the Texas Company, Los Angeles

ed the section at this locality into nine microfaunal zones. Subsequent work by Mr. Laiming and many other economic micropaleontologists has shown that these zones are present in the same order in practically all of the complete upper Miocene sections in central and southern California which are foraminiferal.

The foraminifera which are common in, and characteristic of, the uppermost five of these zones are given in Table 1. Those whose presence in considerable numbers are considered to be especially diagnostic of a given zone are underlined in red.

The localities at which foraminifera were collected by the writer are shown in Figure 1. Several other localities were examined without success for these organisims which were found to be relatively rare in diatomaceous beds. However, several good samples were collected from the diatomite horizons at San Pedro, South Pasadena, and Burrell Point.

Table 2 gives the faunal lists at the localities examined, the approximate thickness of the diatomaceous deposits, and the stratigraphic position of the samples in these sections. An examination of this table shows that the lower part of the diatomite in the San Pedro Hills section is characterized by the abundance of Bolivina hughesi, Bolivina beyrichi and other forms typical of Zone 2. The faunule from the top of this unit suggests a Zone 1 age. The sediments underlying the diatomite at Cabrillo Beach have a Zone 2 age (spl 553-B) but at other places in this area they have a Zone 5 age. Zones3 and 4 were never found in the San Pedro Hills and it is possible, therefore, that some of the diatomite in this region is of that age.

Only two good samples were found in the South Pasadena area, but since one of them (116) is near the base of the diatomite and the other (108) is near its top the age of the entire unit can be fairly well established. The abundance of Bulimina uvigerinaformis in sample 116 indicates that this part of the section is of Zone 3 age. The faunule in sample 108 is not quite so

TABLE - 1

Characteristic and Common Foraminifera from the Miocene Exposed East of Capitan Point, Santa Barbara County, California

	Thickness	Characteristic and Common Foraminifera
Zone 1	1600'	Bolivina sinuata Bolivina advena var. spissa Bolivina seminuda Pulvinulinella bradyina Uvigerina hootsi Uvigerina subperigrina
Zone 2	500'	Bolivina beyrichi Bolivina brevior Bolivina californica Bolivina dilatata Bolivina hughesi Buliminella brevior Cassidulina crassa Uvigerina flintii Virgulina californiensis
Zone 3	100'	Bolivina californica Bulimina ovula Bulimina uvigerinaformis Pullenia capitanensis
Zone 4	200'	Baggina californica Bulimina affinis Pullenia capitanensis Valvulineria villardeboana
Zone 5	450'	Anomalina ammonoides Bolivina advena var. striatella Pullenia miocenica var. rotunda Siphogenerina collomi Valvulineria californica

TABLE - 2

Foraminifera from Diatomaceous Beds of the Los Angeles Basin

	San Pedro Hills						So. Pasadena			Burrell Point		
	Total thicknes varies from 600'-1200'						Total thickness-200'			Total Thickness-1200'		
Sample	553-B 50' below base at Cabrillo Bch	590-A Approx equivalent to 553-B. 600' below Top	248 150' above base C.B.	249 200' above base C.B.	246 Top Equiv. to 557	557 Top = to 500-800' above base Cabrillo Bch	116 Top	115 20' below Top	108 base	172 Base = 1200' below Top.	171 Approx. equivalent to 172	Reference
Anomalina sp.		vr	c			c			c			
Bolivina cf. argentea Cushman	r			vc								Cont.Cush.Lab.vol.2, Pt.2,Pl.6,fig.5
Bolivina beyrichi Reuss	vc		c	vr								
Bolivina brevior Cushman									c			Cont.Cush.Lab.vol.1, Pt.2,Pl.5,fig.8
Bolivina california Cushman										c		Cont.Cush.Lab.vol.1, Pt.2,Pl.5,fig.10
Bolivina decurtata Cushman			c						vc			Cont.Cush.Lab.vol.2, Pt.2,Pl.6,fig.7-a
Bolivina hughesi Cushman	c	c	vc	vc								Cont.Cush.Lab.vol.2, Pt.2,Pl.6,fig.4
Bolivina modeloensis Cush.& Kleinpell	abt	r	r			vc	c					Cont.Cush.Lab.vol.10,Pt.2
Bolivina seminuda Cushman			c	r		c						
Bolivina sinuata Cushman				vr	r		vc	r	r			
Bolivina subadvena Cushman							c		abt	vc		Cont.Cush.Lab.vol.2, Pt.2,Pl.6,fig.8
Bolivina sp. (ribbed)							vr		r	r		
Bolivina tumida Cushman									r	r		Cont.Cush.Lab.vol.1, Pt.2,Pl.2,fig.9
Bulimina ovula (d'Orb)		r	vr	c	r					vc	r	Bull.Scripps vol.1, Pl.2,fig.10
Bulimina inflata Seguenza					c	r						
Bulimina uvigerinaformis Cush.&Kleinpell							vc	r		vc	r	Cont.Cush.Lab.vol10,Pt.2
Bulimina sp.		r	r									
Buliminella curta Cushman	r	r										Cont.Cush.Lab.vol.1, Pt.2,Pl.5,fig.13
Buliminella subfusiformis Cushman	vc		c	c		vc	r		vc	r		Jour.Paleo.vol.5,No.12, Pl.11,fig.14
Cassidulina off barbarana Cush.& Kleinpell							vr					Cont.Cush.Lab.vol.10, Pt.1,Pl.3,fig.5
Cassidulina crassa d'Orb		r		c								
Cassidulina cresentastoma			c			c						
Cassidulina off laevigata (d'Orb.)				c								
Cassidulina sp.			r									
Dentalina barnsei Rankin									vr			Cont.Cush.Lab.vol.10 Pt.1,Pl.3, fig.6
Elphidium sp.	r											
Globigerina bulloides (d'Orb)					vc	vc			abt	c		
Gyroidina off soldanii (d'Orb)									c			
Gyroidina sp.			vc	c	r	c						
Nodogenerina (nodosaria)sp.					vr		r					
Orbulina universa d'Orb			vr		r			vr	vr			
Planulina sp.	c		r	c			c	r	r	vr		
Pullenia off quinculoba		r										
Pulvinulinella capitaneusis Cush.& Kleinpell		r	c									Cont.Cush.Lab.vol.10 Pt.2,Pl.3,fig.3
Pulvinulinella subperuviana Cush.				r					r	r		Cont.Cush.Lab.vol.2 Pt.3,Pl.9,fig.9
Pulvinulinella sp.			r									
Siphogenerina sp.									vr			
Uvigerina carmeloensis Cush.& Kleinpell									c			Cont.Cush.Lab.vol.10,Pt.
Uvigerina hootsi Cush.&Kleinpell			c		vr	c						Cont.Cush.Lab.vol.10,Pt.
Uvigerina modeloeusis Cush.&Kleinpell	vc	c		c	c		r			c		Cont.Cush.Lab.vol.10, Pt.1,Pl.2,fig.8
Uvigerina senticosa Cushman							vr					Bull.Scripps Inst. Vol.1,Pl.3,fig.14
Uvigerina subperigrina Cush. & Kleinpell	c		c	c			c	r	c			Cont.Cush.Lab.vol.10, Pt.1,Pl.2,fig.9-11
Valvulineria auracana d'Orb	vr						r		r			
Valvulineria villardeboana (d'Orb)										vc		Cont.Cush.Lab.vol.2, Pt.2,Pl.7,fig.6
Virgulina californiensis Cushman	abt	r		vr								Cont.Cush.Lab.vol.1, Pt.2,Pl.5,fig.11

characteristic and this part of the section might be either Zone 3 or Zone 2 in age.

Sample 172 from Burrell Point indicates a Zone 3 age for these rocks, but it is unfortunately at the very base of a thick section of diatomite which is apparently barren of foraminifera. This section is unconformably overlain by upper Pliocene silts, so the exact age of the diatomaceous beds cannot be definitely stated. They must, however, be Zone 3 or younger in age.

The faunal list given by Rankin for the diatomaceous beds in the Santa Monica Mountains indicates that they are of Zone 1 age.

Conclusions

Foraminifera from highly diatomaceous silts in the San Pedro Hills, the Santa Monica Mountains, South Pasadena, and Burrell Point indicate that all of these beds are younger than the Vavulinera californica horizon. The diatomite in South Pasadena is probably confined to Zone 3; that at San Pedro is largely of Zone 2 age but may include Zones 3 and 4 and range up into Zone 1. The diatomite at Burrell Point may include Zones 1, 2, and 3; that in the Santa Monica Mountains is all of Zone 1 age.