

have the shorter wave-lengths). The individual shells, with few exceptions, range through a graduated series of tints. In many of the shells the upper whorls start with a middle tint (d), and grade off through a paler tint (f); in other shells, however, the upper whorls start with the deepest tint (b), of a full color, and gradually fade through the lighter tints (d) and (f). Still other shells show a distinct color band which follows whorl-indentations or extends through the middle of the whorl. Shells of more or less uniform color are invariably represented by a pale tint (f), which may or may not fade to almost white. None of the shell colors is represented in the shades of a hue shown in the vertical Color Guide scale which runs downward from the middle horizontal line of full colors. There are many cases of a gradual fading from a deeper tone to almost pure white.

DIATOMS AS A SOURCE FOR CALIFORNIA PETROLEUM: A SUMMARY REVIEW

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Abstract

The diatom has been variously regarded as the major source, as an accessory source, and as a doubtful source for California petroleum. The two main lines of evidence cited by upholders of the first view are: (1) the intimate association of diatomaceous deposits with the majority of oil producing areas in the state, and (2) the observed ability of living diatoms to manufacture oil, which under favorable conditions could be stored in contemporaneous sediments. Opposed to this view are the facts that (1) some petroliferous areas in the state produce from horizons high above the postulated diatomaceous source beds, (2) some diatomaceous formations have shown no indication of being oil producers, (3) diatomite generally contains little or no hydrocarbons or fixed carbon, and (4) certain organic, siliceous shales, generally admitted to be source beds, contain relatively small amounts of recognizable diatom remains. An intermediate viewpoint holds that California petroleum is polygenetic, asphaltic oils having been derived from vegetable remains, including diatoms, paraffin oils having been derived from marine animals, such as foraminifera.

It has been known since early days of geological exploration in California that diatomaceous deposits are extensively developed within the state. Strata rich in diatom remains range in age from Cretaceous to late Tertiary, although by far the greatest volume of diatomaceous "shales" occurs in

the so-called Monterey group, of Miocene age. Organic, siliceous shales of the Monterey type attain thicknesses up to 5,000 feet, in many sections consisting of some hundreds of feet of hard, thin-bedded opal or chalcedony, overlain by soft diatomaceous shale. Layers of volcanic ash, siltstone, limestone, and sandstone are commonly interbedded with the shale (29, pp. 163, 188; 18; 24)¹. The diatomaceous deposits are extensively developed on the west side of the San Joaquin Valley from the extreme southern portion to Mount Diablo on the north. On the west side of the Coast Ranges they are extensive from the Los Angeles Basin northward to Point Arena.

The facts that diatomaceous deposits are locally impregnated with bituminous substances, and are associated with a great many Californian oil fields, have led some geologists to believe that diatoms have been a major source for much of the state's oil and gas. Occasionally it has been maintained that wherever diatomaceous beds are lacking, chances for discovering petroleum are small. On this matter, however, there has been some diversity of opinion.

It is the purpose of this paper to set forth, insofar as is possible from a survey of the literature, the salient arguments for and against the theory that the diatom has been a source for much of California's petroleum. The manuscript was originally written by the senior author for a course in Petroleum Geology offered at Harvard University by Professor K. F. Mather, who suggested certain changes. Circumstances preventing the immediate recasting of the manuscript by the original author, the paper was entrusted to the junior author for rewriting. The writers wish to express their appreciation to Professor Mather for his criticism of the paper.

Evidence Favoring Diatomaceous Source of California Petroleum

(1) *Close Relationship of Diatomaceous Deposits with Many Oil Fields.* It has been estimated (34, p. 462) that approximately 75% of the source rocks of California are of

¹Numbers in parentheses refer to articles listed in the bibliography at the end of this paper.

Miocene age. The fact that the Miocene is further notable for its abundant diatomaceous deposits provides strong circumstantial evidence for a genetic relationship between diatoms and petroleum.

This view has been clearly but cautiously stated by Ralph Arnold and Robert Anderson in their report on the Santa Maria district.

The general conclusion is that in the Santa Maria district the organic material in the Monterey shale which may have acted as the source of the oil was without doubt adequate in amount for the production of the vast quantity of petroleum now present, and that the forms included in greatest abundance, the diatoms, were the chief source, although animals and perhaps plants, contributed largely. (6, p. 113).

Arnold and Anderson have upheld the diatom theory to account for the oil of the Summerland and Coalinga fields (3, p. 51; 7, p. 188). Pack (28, p. 10) believes that the oil of the Sunset-Midway field "originated in the diatomaceous shale, chiefly from the alteration of organic matter contained in diatoms and foraminifera." Writing of the Huntington Beach field, Gester (16, p. 45) states that "the Puente in this district is an organic shale largely made up of diatoms which could likely be the source of all the oils in the field". Cunningham (12, p. 711) has pointed out the close association of oil bearing zones with diatomaceous deposits in parts of the Hovey Hills, Kern County, in the Torrance, and in the Puente fields. However, he believes that the importance of the diatoms as a source remains to be proved.

(2) *Biogenesis of Oil by Living Diatoms.* The diatom theory finds one of its strongest supporting arguments in the fact that living diatoms are known to manufacture oil when their chlorophyll bodies are activated by sunlight. Mann (26) has reported that living diatom plants always contain from two to ten shining oil globules, which constitute from 5 to 50% of the volume of the diatom.

Study of diatom "epidemics" as Copalis Beach, Washington, has cast considerable light on problems of accumulation of diatomaceous deposits and the storing of biogenetically produced oil in these deposits. Under certain favorable weather conditions, which seem to have the net result of decreasing the salinity of the water, prodigious

quantities of diatom culture are washed up on Copalis Beach. During the epidemic of 1925, a ridge of diatom culture some twenty miles long and from four to six inches deep was heaped upon the beach by the waves. Becking, Tolman, and others have made a painstaking study of these epidemics.

The fresh diatom material collected May 3, 1926, contained one or two droplets of oil associated with each of the chlorophyll bodies of the diatom. At the time the material was collected there had been no direct sunlight, and the chlorophyll bodies had not been intensely activated. Under more favorable conditions larger amounts of oil may be secreted. . . . (9, p. 364).

The material collected in 1925 was kept in storage six months before it was studied. Examination of the material showed no oil droplets. This suggests that the organism may consume its store of oil and die, and also suggests why certain types of diatomaceous deposits may appear barren in oil. (9, p. 365).

Judging from this last observation, oil droplets produced by diatoms must in some way escape from the enclosing siliceous shell in order to be preserved for potential petroleum supply. How the rupturing of the shell may come about was revealed when some of the diatoms were placed in fresh water. The brittle shells broke, the plastids swelled to twice their original volumes, and the oil globules began to ooze out (9, pp. 365-368).

The observation that the living diatom explodes when immersed in fresh water is of great importance. The osmotic pressure of the cell sap is sufficient, when the diatom is immersed in fresh water, to break the brittle shell and drive out the oil into the adjacent colloidal material of whatever type it may be. A sufficient change in salinity in estuaries and bays at times of floods might produce this phenomenon. . . . In any case, we have actually seen the process under action, whereby the hydrocarbons formed directly by the diatoms can be driven out into the surrounding medium (34, p. 472).

Apparently no diatomaceous material is being preserved in the sands of Copalis Beach. This, however, is to be expected, since the unstable conditions of the strand make it a poor place for the preservation of organic material. On the other hand, diatomaceous materials might be buried and their petroleum derivatives preserved in deposits laid down in lagoons, estuaries, and shallow bays. Tolman has cited several independent lines of evidence, paleontological and lithological, to support the contention that the Miocene siliceous shales were deposited in relatively shallow

basins, the diatomaceous deposits themselves often extending up to the shore line of these basins (34, pp. 460-461).

Evidence Against Diatomaceous Origin of California Petroleum

(1) *Lack of Diatomaceous Deposits in Producing Zones of Some Fields.* Although the Miocene diatomaceous deposits are closely, possibly genetically, associated with the majority of producing areas in California, there are fields in which this association is not so intimate. In the Santa Fe Springs field the base of the Pliocene is more than 2200 feet below the deepest producing zone. In the Inglewood field, the base of the Pliocene is at least 4600 feet below the top of the producing horizon. In these and similar cases Cunningham (12, p. 716) believes that the Pliocene beds, which are relatively free from diatoms, should be regarded as the source of the petroleum.

If we are confined to the Miocene shales as the possible source of the oil, how has the oil reached its present position? It seems unreasonable to expect oil to migrate transversely to the bedding through this thickness of sediments in view of the high percentage of impervious shale contained in the section. If such were the path of the migration, we should expect the oil zones to be most extensive in and confined to the beds closest to, the top of the Miocene. Such is not the condition.

(2) *Failure of Some Diatomaceous Deposits to Produce Oil.* The Truckee formation, described by Robert Anderson (2, p. 489) is reported to be exactly like the white, softer variety of the Monterey. Despite this close resemblance, the Truckee contains no oil. Anderson does not believe that these beds are barren simply because the diatoms therein are fresh-water rather than marine forms. He suggests that the strata were deposited in marshes and shallow bodies of water in which conditions favored decomposition and escape of organic matter present in the diatoms.

(3) *Absence of Indigenous Hydrocarbons and Fixed Carbons in Much Diatomite.*² Although the Miocene diatomaceous shales are often found to be discolored by petroleum believed by some to be indigenous (34, p. 462), in many places the purer varieties of diatomite are bleached and

²A commercial term adopted by Tolman (34, p. 467) for massive, pulverulent, porous, opal sediments composed largely of diatom tests.

notably devoid of bituminous substances. Takahashi (32, p. 154) has noted that only one per cent of oil (by weight) in diatomaceous earth is sufficient to color it black, provided the oil is homogeneously soaked into the earth. It is argued, therefore, that if diatomaceous beds in the Monterey have been source beds, they should everywhere retain enough residual hydrocarbons or fixed carbon to attest the fact.

(4) *Scarcity of Recognizable Diatom Tests in Organic Siliceous Shales.* Miocene opal shales are often conspicuously impregnated with hydrocarbons, but conspicuously lacking in recognizable diatom remains. This argument would be of less concern to the diatomists could it be shown that the organic siliceous shales have been derived from diatomite by secondary alteration. Davis (13, pp. 278-290; 353-408), however, has presented strong arguments against this explanation, maintaining that the opal shales are deposits of submarine, siliceous springs. The problem of origin remains unsettled at present. Reed (29, p. 197) believes that while Davis's arguments against secondary alteration appear to be valid, "the hypothesis of diagenetic alteration is less thoroughly considered, and might be made to account for all the conditions he described."

The Intermediate Viewpoint

Between the extremes of diatomist and non-diatomist viewpoints is one which recognizes the importance of the diatom, but which also appeals to other organic sources for California oil.

F. M. Anderson (1), from a study of the composition of various California oils, has shown that there are two major types of petroleum in the state. One has an asphaltic base; the other resembles typical paraffin oil in that it contains naphthalenes, olefines, and related hydrocarbon members. Anderson believes that these major types reflect differences in organic sources. The asphaltic oils, mostly confined to the Miocene formations, are believed to have been derived from vegetable organisms, diatoms included. The other type is believed to have originated from marine animals, such as foraminifera, remains of which abound in the older Tertiary formations.

Under this conception, oils that contain both asphaltic and paraffin members or equivalents may be regarded as resulting from the mingling of diverse organisms, either within the same bed or the mingling of oils that emanate from different, sometimes alternating layers, . . . (1, p. 599).

Tolman (34, p. 474) fully recognizes the importance of other organisms, and suggests that biogenesis by colonial algae, *Eleophyton*, "may be the dominant process of oil generation in other types of 'mother rock' ". Thiessen (33, p. 130) has observed that the cell walls of living *Eleophyton* are composed largely of oil or oily substances. Here again is an instance of production of oil biogenetically.

The conservative viewpoint with respect to petroleum origin has been well summarized by Clarke (11, p. 757).

Wherever sediments are laid down, enclosing either animal or vegetable matter, there bitumens may be produced. . . . Seaweeds mollusks, crustaceans, fishes, and even microscopic organisms of many kinds may contribute material for the change.

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