A STUDY OF THE HEAVY MINERALS OF THE MODELO FORMATION IN THE EASTERN PORTION OF THE SANTA MONICA MOUNTAINS

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CONTENTS

Page

ILLUSTRATIONS

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Introduction

Within recent years there has been a renewed interest among geologists in the field of sedimentary petrography. This interest has been rewarded by the accumulation of much new and interesting data. Careful studies of the textures and mineral compositions of formations have yielded important clues regarding climatic and geographic conditions during ancient times. These studies have made it possible in some cases to correlate unfossiliferous sediments.

Purpose

In this paper the writer is chiefly concerned with the heavy minerals of the Modelo sediments with the view to learning what lateral and vertical variations may occur in the mineral composition of a formation over a small area - a matter which is of great significance if the minerals are to be used as criteria for correlation - and to learn something of the paleogeography during the deposition of the sediments in question.

Although heavy minerals have served as the key to many perplexing problems, they have not been universally used with success. Many of the failures however, are directly attributable to unreasonable expectations on the part of investigators.

Theory of Correlation

It is appropriate at this point, in order better to understand the purpose of this problem, to indicate briefly the general theory on which correlations of sediments by means of their mineral compositions is based. The general premise is that within any basin of deposition, sediments of contemporaneous age will have approximately the same composition. Complications often arise and occasionally upset this very simply hypothesis. If highlands of uniform composition are shedding sediments into the basin, it is to be expected that perhaps with minor exceptions there will be uniformity in the composition of the sediments. If however two or more land masses are each shedding a different kind of material into the basin, the problem becomes more complex. Under these conditions, it is highly probably that in the shallow water close to shore, the mineral composition of the sediments will change sharply at various points along a line parallel to the beach. Gradually out from shore, where a mingling of material can take place, these sharp boundaries of composition will be replaced by transitional zones which will become broader and broader and ultimately coalesce, resulting in a sediment, well out from the land, which will have a homogeneous composition. If the basin is very large and the land masses that are shedding material into it are far apart, it is unlikely that the sediments over the entire basin will have a common composition, but it is very probable that broad transitional zones will lie between the areas occupied by sediments which have been derived from different rock types.

Currents, which may be present, are also powerful agents affecting sedimentation. They may disturb the bottom and agitate the water sufficiently to cause a thorough mingling of material derived from various sources and consequently produce a sediment having a homogeneous composition. More often, they produce concentrations of the heavy minerals in patterns which may be very confusing and difficult to decipher; or they serve to restrict various mineral species to distinct areas, thus making for an inhomogeneity in the mineral composition of the sediments occupying a given basin.

Considerations of this nature indicate the need for careful sampling and point to the unreasonableness of declaring heavy minerals useless as correlation criteria when the samples that were compared have been taken many miles apart.

A survey of the literature concerning heavy mineral studies has impressed the writer with the fact that although many attempts have been made to use heavy minerals in correlation and as guides for the differentiation of various unfossiliferous formations, little has been published[1] regarding lateral variations in the mineral composition of a stratum. Since the practicability of correlation and differentiation of formations rests on the hypothesis that the mineral composition remains more or less constant for a given formation, it appeared to the writer that an investigation of lateral variations in the composition of a stratum was of fundamental importance.

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[1] Reed, R.D., Role of Heavy Minerals in the Coalinga Tertiary Formations, Econ. Geol., vol. 19, 1924, pp. 730-740.

Acknowledgments

The observations and opinions recorded here are the results of studies made during the years 1931, 1932, and 1933. The writer wishes to express his deep appreciation for the encouragement and helpful suggestions given to him by Dr. Ian Campbell during the course of the investigation.

Field Requirements

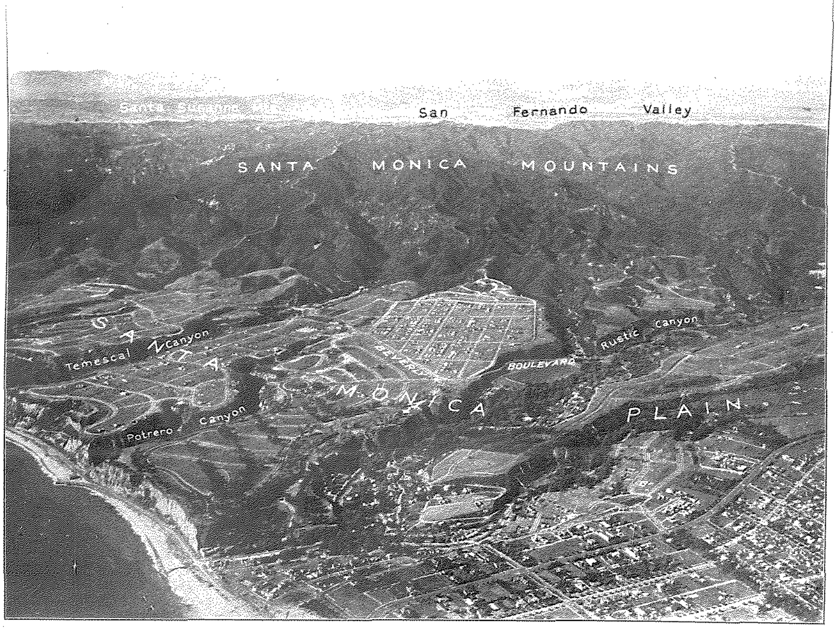
For this study a sandstone stratum, not too highly indurated, of a few feet in thickness, and traceable on the surface of the ground for several miles, was sought. Such a stratum would have provided samples of approximately contemporaneous age and easy workability. Nature, however, was not favorably inclined and the writer failed to find a stratum fulfilling all of the requirements. In the Modelo formation of the Santa Monica Mountains there occur several sandstone members, much thicker than desired, but otherwise favorable, and these were selected for the investigation.

Location of Area

The sediments which were studied lie on the north flank of the eastern portion of the Santa Monica Mountains, immediately north of the city of Beverly Hills, a suburb to the west of Los Angeles. The region is readily accessible, being traversed by a network of fine roads and lying within an hour's drive from Los Angeles. The walls of the road-cuts offer excellent opportunities for the collection of samples and on their cleanly scraped surfaces the geologic structure is beautifully exposed.

General Geology

It will suffice here to give only a brief statement regarding the geology of the area, since a very complete report has already



AIRPLANE VIEW TAKEN ABOVE THE CITY OF SANTA MONICA LOOKING NORTH AT SANTA MONICA MOUNTAINS, CALIF.
Photograph by Spence Airplane Photos.

Plate 2 - From U. S. G. S. Prof. Pap. 165-C.

been published by H. W. Hoots.[1] It is an area "which presents a section of varied rock types including coarsely crystalline plutonic rocks, basic and acidic intrusive and pyroclastic rocks, metamorphic slate and schist, and a wide assortment of sedimentary rocks . . . .

"Structurally the eastern part of the Santa Monica Mountains is a broad anticline whose axis lies in the extensive central area of the Santa Monica slate (Triassic?) and plunges westward. . . . . ."[2]

It was in the Modelo formation (Upper Miocene), on the north limb of the major anticline that this study was undertaken. The work was greatly facilitated by an excellent geologic map[3] on which the sandstone members of the Modelo formation had been carefully differentiated from the shale. These sandstone members, as mapped, may be seen to extend uninterruptedly for distances of three to four miles. Their thicknesses vary and offer an obstacle toward procuring samples of exactly contemporaneous age, but this difficulty was largely overcome by carefully locating the samples stratigraphically.

Procedure of Investigation

Field Work

The general method of attack on the problem consisted in selecting a sandstone member and sampling it from top to bottom at intervals of about a half mile along the strike. In detail the field collecting

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1. Hoots,H.W., Geology of the Eastern Part of the Santa Monica Mountains, Los Angeles County, California; U. S. G. S. Prof. Pap. 165-C, 1930, pp. 83-134.

2. Hoots,H.W., loc. cit., p.83.

3. Hoots,H.W., loc. cit., pl. 16.

was carried on as follows: The surface of the sand was scraped away exposing fresh unweathered material. Generally this was a very simple procedure because sampling was nearly always done on the walls of road-cuts which were barren of any soil. By means of a sharp pointed moil and a five pound hammer, samples weighing about one kilogram each were collected from points near the top, middle, and bottom of the stratum, placed in strong paper bags, labelled and carefully located. The sandstone sometimes exhibited strong cross-bedding with coarse streaks of sand occasionally interspersed between finer material. Care was taken, however, to secure specimens which appeared to be representative of the entire member.

Laboratory Procedure

Preliminary Preparation of Samples.- In the laboratory the samples were crushed between wooden blocks, allowed to air dry for a day, and reduced to a suitable size with the aid of a Jones sample splitter. After reduction, the material was weighed and placed in beakers of 250 cc. capacity. Owing to the paucity of heavy minerals in the Modelo formation, it was found suitable to employ samples weighing between 150 and 200 grams. Samples of this weight generally yielded from 25 to 50 grams of sand lying in the 1/4-1/8 mm. grade-size, which was the fraction that had been selected for investigation in this study. From this amount of sand a heavy mineral crop of less than half a gram was secured for examination.

As a means of disintegrating the sandstone a solution of approximately 1 normal, cold hydrochloric acid was poured into each beaker and the sandstone was allowed to soak for a day. In general this method yielded satisfactory results, especially if the aggregates of particles had been crushed by the wooden blocks to the size of peas or smaller. At the end of the soaking period, the acid was decanted and the residue well washed with water.

In order to secure good screening results in the steps to follow, it was found necessary to remove the excessively fine material from the sand. Experiment showed that particles smaller than 1/16 mm. tended to clog the openings in the screens and to form surface coatings on the larger grains thus preventing accurate size classifications. Removal of the fine material was accomplished by washing the sample in a large beaker where it could be well stirred and completely brought into suspension for a few moments. In conformance with Stokes' law[1] the larger grains settled sooner than the smaller, and after a calculated time interval of seventy-one seconds, material less than 1/16 mm. in diameter, which still remained in suspension, was decanted. This is the length of time required for particles with a diameter of .016 mm. and a specific gravity of 2.63 to settle through a column of water five inches high. In practice a small additional allowance of time was made in order to preclude any loss of grains greater than 1/16 mm.

Following the removal of the fine silt and clay by decantation, the samples were placed on sheets of absorbent paper and allowed to dry. When completely dry each sample was divided into its constituent grade-sizes by means of a set of Tyler screens which were shaken for fifteen minutes by a mechanical shaking machine. Six screens with

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[1] $d = \sqrt{\frac{v}{700}}$ where d = diameter in mm. of settling particle and v velocity of particle in mm. per second. This is the equation of Stokes' law reduced for particles averaging 2.63 specific gravity and settling in water.- From Tickell, F.G., The Examination of Fragmental Rocks, Stanford Univ. Press, 1931, p.11.

mesh sizes approximating the series[1] 1/16, 1/8, 1/4, 1/2, 1, 2 mm. constituted the set. Each grade-size of sand was weighed to the nearest tenth of a gram, then poured into a glass cylinder and saved for future study. The weight loss suffered by the original sample, as a result of solution and decantation, was arbitrarily added to the weight of the fraction containing material smaller than 1/16 mm.[2] These results were then converted into percentages and plotted as shown on plate I.

It was at first planned to study the heavy minerals in each grade-size. However time did not permit and only a single grade was investigated. For this purpose the size lying between 1/4 and 1/8 mm. was chosen. The examination of larger grains was often impracticable because of their opacity to transmitted light. They had to be crushed to smaller sizes before they could be identified. This procedure resulted in an increase of the number of grains on the slide and consequently interfered with determinations of their normal abundance. This remained a real deterrent to the use of the larger grain sizes as long as the petrographic microscope was being employed as the tool with which to carry out the grain counts and identifications. As will be described below, it was learned that the various species of minerals could be recognized and differentiated under the binocular microscope, after one had acquired some familiarity with them. However, since grains between 1/4 and 1/8 mm. in size were more suitable for making permanent reference mounts in Canada Balsam, they were chosen for investigation.

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[1] Actual size openings as stamped on the screens by the manufacturer are .061, .124, .246, .495, .991, 1.981 mm.

[2] This is not a precise method for determining the weight of particles smaller than 1/16 mm. because a part of the weight difference is caused by solution of cementing agents.

Heavy Mineral Separation.- The procedure which was followed for the heavy mineral separation was that suggested by H. B. Milner.[1] Two funnels were set up as shown in figure 1. Bromoform with a density of 2.85 was poured into the upper funnel. A known weight of sand was dropped into the bromoform and gently stirred for two minutes. Continuous and gentle stirring for this length of time was found to be sufficient to allow for a complete separation of the heavy minerals from as much as twenty-five grams of sand. The mixture was then allowed to remain undisturbed for three minutes, giving the heavy minerals sufficient time to settle, after which the pinch cock was carefully released and the heavy grains which had been deposited at the bottom of the stem in the upper funnel were drained onto the filter paper in the funnel below. The occluded bromoform was thoroughly removed from the heavy minerals by washing them with alcohol. They were allowed to dry, and then given a preliminary examination under the binocular microscope in order to determine whether a treatment with acid was necessary. Nearly all of the heavy mineral concentrates were given a treatment which consisted of boiling them for thirty minutes in 1 normal hydrochloric acid. This generally removed alteration coatings and facilitated identification of the minerals. Apparently none was dissolved by the acid, for in no case were minerals which had been observed prior to the acid treatment, absent afterwards. Following the acid bath, the minerals were washed with water and dried. The fraction of light minerals remaining from the bromoform separation was also drained onto a filter paper, washed thoroughly with alcohol, and allowed to dry.

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[1] Milner, H.B., Sedimentary Petrography, D. Van Nostrand Co., New York, 1929.

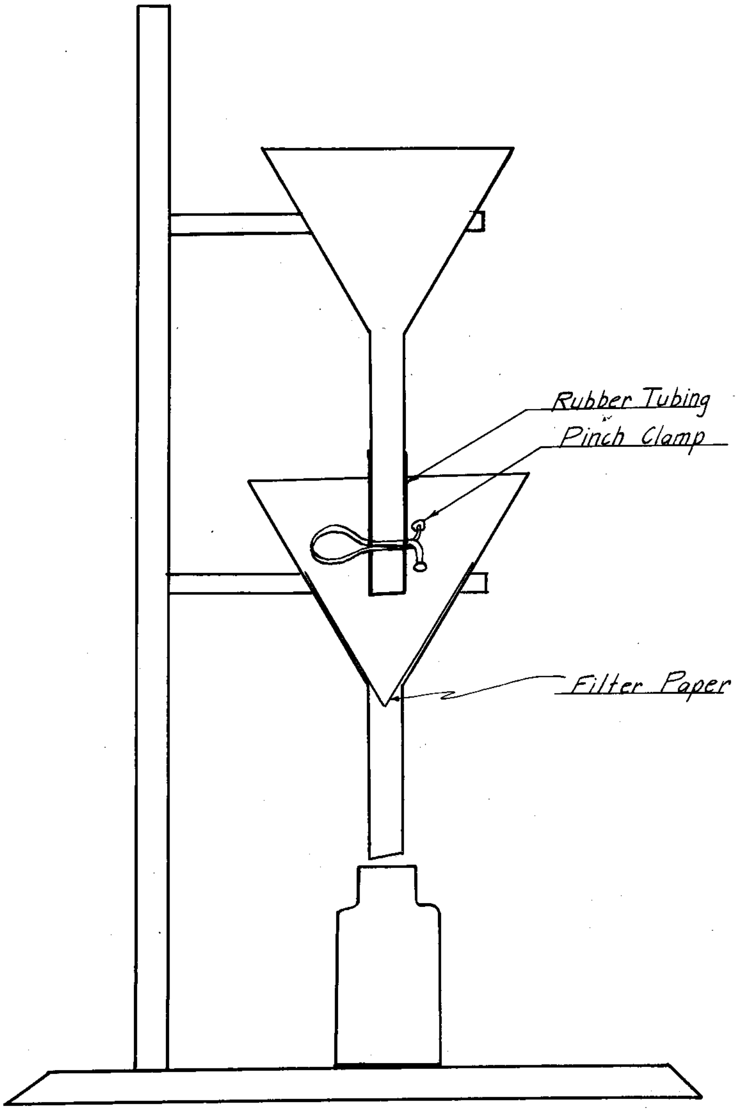

Fig. 1. Funnel arrangement for heavy mineral separation.

Method of Mineral Observation.- A number of trials were then made in order to determine the most convenient method of making grain counts and identifications. The heavy minerals were prepared for observation by splitting off a representative fraction (300 to 1000 grains) of the total heavy crop. This was accomplished with the aid of a miniature sampling device[1] patterned after the Jones sample splitter. Grains were mounted on glass slides, in Canada Balsam and in piperine (refractive index 1.69).

These mounts were examined under the petrographic microscope and did not afford complete satisfaction. Many of the grains could not be identified because they were badly fractured or still retained alteration coatings and hence transmitted light poorly. The advantage of the piperine mounts lay in the fact that the refractive index of that medium serves to divide the heavy minerals into two nearly equal divisions, those having indices below 1.69 and those with indices above. This property of piperine facilitates identification of minerals since it makes it possible to limit the number of species very quickly on the basis of their refractive indices. Its chief disadvantage is a consequence of the property of strong dispersion which it possesses. Because of this quality, minerals mounted in piperine and observed in transmitted light display colors that are distinctly different from those exhibited by the same minerals in air and in reflected light. This is troublesome because many identifications of unknown minerals mounted in piperine have to be made by using analagous grains taken from the unmounted fraction of

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1. Otto, G.H., Device For Sampling Heavy Minerals, Bull. Geol. Soc. Amer., vol. 44, 1933, p. 159.

the heavy crop and examining them in various index liquids. Owing to the fact that the color of a mineral species in air is different from what it is in piperine, the selection of analagous grains from among the unmounted minerals is often made with difficulty.

Canada Balsam mounts were unsatisfactory largely because of the low index of the mounting medium (1.53) compared to the high refractive indices of most of the heavy minerals. This caused the mounted grains to exhibit extremely high relief, adding difficulty to their identification.

Trial observations were made with the binocular microscope and it soon became apparent that when one was familiar with the color, luster, cleavage, and shape of the various minerals, it was a comparatively easy matter to tell them apart. Whenever the identity of a mineral was in doubt, it was removed to a slide and studied in various index liquids under the petrographic microscope. Delicate color differences were readily distinguishable and color proved to be a remarkably good criterion for recognizing mineral species.

This method of observation was adopted. It was greatly facilitated by the use of an electro-magnet with which it was possible to split the heavy minerals roughly into three groups magnetic, moderately magnetic, and non-magnetic. The first group was composed almost entirely of ilmenite, the second of hornblende, garnet, epidote, and tourmaline, and the third of titanite, rutile, barite, and leucoxene. The grains were spread on grid paper to facilitate counting. Throughout the entire suite of approximately fifty samples which were examined, the colors for the various mineral species remained distinctive. The titanite was always yellow, the hornblende dark green to black, the tourmaline smoky or reddish black, the epidote yellowish green, the garnet pink and orange (except in one sample where much colorless garnet was present).

Methods of Computing Mineral Abundance.- It was of interest in this problem to study the relative and absolute abundance of the heavy minerals. For this purpose 300 to 1000 mineral grains were usually counted for each sample. Percentages of the various species were calculated in two different ways. According to one method they were calculated as functions of the total number of grains counted, according to the other they were computed as functions of arbitrarily assumed numbers. In the first procedure, which is the one in common usage among sedimentary petrographers, barite and leucoxene were not counted. Barite, although a heavy mineral and very abundant in some samples, is of dubious origin and may only be a cementing agent. Leucoxene is distinctly an alteration product of titaniferous minerals and in the suite of samples examined by the writer, it had been derived almost exclusively from ilmenite or titaniferous magnetite. Occasionally leucoxene grains were observed as octahedral pseudomorphs after magnetite. Since alteration of minerals often occurs after deposition in the sediment, the writer felt that the relative abundance of leucoxene offered no clue to the source of the material nor was it an important characteristic mineral of a formation. The results of these calculations are plotted in the form of histograms on plate I.

In order to secure information regarding variations in the absolute abundance of the heavy minerals the following method was employed: It was arbitrarily assumed thqt for each of the minerals, ilmenite, garnet, titanite, hornblende and epidote, 1000 grains per 20 grams of sand of grade-size between 1/4 and 1/8 mm. were equivalent to 100 percent; for tourmaline and zircon, 500 and 200 grains constituted respectively 100 percent. Using the formula $\frac{20\,n}{w\,f\,d} \cdot 100 =$ absolute percent[1], it was an easy matter to calculate the mineral percentages for any sample.

A brief comparison of the two methods employed here for calculating percentages, indicates that the latter procedure not only affords a means for determining absolute abundance of the heavy minerals, but it also serves to show relative abundance of mineral species; whereas the first method is only useful for determinations of relative abundance of minerals in each sample. A more complete discussion of the desirability of using absolute percentages is to be found in an earlier paper by the writer.[2]

Conclusions

Textural Analysis and Inferences

As described earlier in the paper, each of the samples was graded by means of screening. No effort was made to grade accurately material smaller than 1/16 mm. in diameter, but all such material was lumped together under the grade-size defined as less than 1/16 mm. The results

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[1] $\frac{20\,n}{w\,f\,d} \cdot 100 =$ absolute percent

where n = the number of grains of the mineral species which were counted,
w = the weight of sand from which the minerals were separated,
f = the fraction, of the total heavy crop, which was counted,
d = the number of grains which has been arbitrarily assumed to equal 100 percent.

[2] Cogen, Wm. M., Some Suggestions For Heavy Mineral Investigations, Presented at the meeting of the Amer. Ass. of Petrol. Geol. in Houston, Texas on March 25, 1933.

have been plotted and are shown diagramatically on plate I. The histograms reveal the existence of a maximum, in nearly all of the samples, for the particles lying between 1/2 and 1/4 mm. or between 1/4 and 1/8 mm. Maxima in several of the samples for material smaller than 1/16 mm. are unreliable and would undoubtedly be eliminated by grading the sand down into finer divisions. No distinctions can be made between the textures of the various sandstone members of the formation. The basal member shows no coarser texture than the uppermost, nor are any distinct and regular changes to be observed laterally in any of the sandstone members. In short, the entire lower unit of the Modelo formation of this region may be said to be characterized by a texture having a single maximum which lies between the sizes 1/2 to 1/4 or 1/4 to 1/8 mm. It is impossible, at this time, for the writer to make any definite statement regarding the possibility of distinguishing the Modelo formation from the underlying Topanga and Chico formations on the basis of texture alone. It should be remembered that the Modelo samples (with the exception of sample SR_1-c-2)[1] whose textures are figured in plate I were carefully selected as being representative of the sandstone members from which they were taken. There is no doubt in the writer's mind that samples collected indiscriminately from the Modelo would be found to give wide variations in texture and this probability is founded on the evidence furnished by sample SR_1-c-2.

Little could be learned from the texture regarding paleogeographic conditions. Proximity of land masses and degree of surface relief were

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[1] Sample SR_1-c-2 was purposely selected from a coarse streak of cross-bedded material in order to learn what effect texture had on the heavy mineral content of a sediment.

indeterminable. The absence of a conglomerate at the base or elsewhere in the section does not necessarily negate the possibility that the sediments have been derived from a region of moderate relief. In the Santa Monica Bay, off the coast of southern California, the writer failed to find evidence of conglomeratic material or even gravel although the Santa Monica Mountains, which have a relief of two to three thousand feet, border the bay for a distance of nearly fifteen miles. Apparently the conditions governing the deposition of a conglomerate are more than just high relief. "Too great a relation must not be assumed to exist between the sediments which may be deposited and the elevation of the surface from which they come. Streams entering the sea from areas of relatively low relief may contribute either coarse or fine material, depending on the length of transportation and the effectiveness of the vegetable cover. Streams from regions of high elevation may contribute either gravel or silt for the same reasons."[1]

Texture is equally poor as a criterion for indicating the position or proximity of shore. Trask has shown that the mechanical composition of sediments is dependent on the configuration of the sea bottom, the finer sediments tending to accumulate in the basins and the coarser on the high parts between basins; and that submarine topography is of far greater importance in determining the texture of sediments than depth of water or distance from shore.[2]

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1. Twenhofel,W.H., Treatise on Sedimentation, Williams and Wilkins Co., Baltimore, Md., 1932, p. 123.

2. Trask, P.D., Sedimentation in the Channel Islands Region, California, Econ. Geol., vol. 26, 1931, pp. 24-43.

The sand grains, even up to sizes of 1 and 2 mm., were extremely angular in all of the samples, which suggests that they have been transported comparatively short distances. This does not necessarily exclude the possibility of their having been reworked from older sediments.

Heavy Mineral Analysis and Inferences

Minerals Present in the Modelo Formation:- The heavy minerals served as a much more fruitful source of information than did the study of texture. The following suite was found to occur in the Modelo formation:

Yellow titanite, angular and often fractured, rarely exhibiting any crystal faces, occurs quite commonly.

Pink and orange garnets, glassy and angular in appearance, occasionally with crystal faces, are abundant. Colorless garnets were found in large quantity in only one sample.

Ilmenite occurs as black angular fragments.

Titaniferous magnetite in the shape of perfect octahedrons is sparsely present.

Zircon, nearly always present although not in abundance, always exhibits many crystal faces. Prismatic forms seem to be most abundantly developed. Their color is pale violet, appearing almost colorless.

Epidote occurs as yellowish-green to colorless crystal fragments, always angular and never exhibiting crystal faces. White alteration borders are often present.

Hornblende, present abundantly in the intermediate zone, occurs as angular, elongated fragments which exhibit shiny cleavage surfaces and are dark green to black in color.

Tourmaline, black in reflected light, is abundant in the lowest zone. In transmitted light it is generally smoky gray. A few blue grains were also observed. The absence of cleavage surfaces served to distinguish the tourmaline from hornblende, under the binocular microscope.

White opaque leucoxene was abundant in many samples and occasionally occurred as octahedral pseudomorphs after titaniferous magnetite; more often it was in the form of shapeless grains.

Barite was found in many of the samples. It was generally angular, shapeless, and rarely exhibited cleavage surfaces. Usually it was colorless. Sometimes it had a faint pink tinge.

Rutile was a rare mineral. It was deep red in color, angular in shape and never exhibited any crystal faces.

Sillimanite, (two grains) having the form of basal plates, was observed in only one sample.

Mineral Zones of the Modelo Formation:- Using the heavy minerals as horizon markers, it is possible to divide the lower unit of the Modelo formation into three distinct divisions. Either of two methods is employed by sedimentary petrographers for such purposes. One procedure is qualitative in nature; the other is quantitative. In the first, the presence or absence of one or more mineral species serves as the characteristic feature of the zone. When the same minerals are present throughout a formation this scheme is useless and the quantitative method has to be resorted to. The relative abundance of the various mineral species in each sample is determined by grain counts of representative fractions of their heavy mineral crops. A definite proportional relationship between several minerals may serve as the criterion for the recognition of a particular zone.

Table I – Heavy Mineral Analysis of Modelo Formation In The Eastern Portion of the Santa Monica Mountains
(Percent by number of grains calculated as a function of the number of heavy minerals counted in each sample)

Sample No.	Ilmenite	Garnet	Titanite	Epidote	Zircon	Hornblende	Tourmaline	Rutile	Leucoxene	Barite
MR-a-2	12	7	78	—	2	—	—	1	R	A
MR-a-3	32	19	47	—	2	—	—	—	R	R
MR-a-8	43	23	26	—	7	—	—	1	A	R
MR-a-9	30	37	27	—	7	—	—	—	A	—
MR-b'-1	57	32	6	—	5	—	T	—	A	A
MR-b'-3	48	33	14	T	4	T	—	—	A	A
MR-b-1	32	17	40	1	4	5	—	—	A	A
MR-b-2	41	39	3	1	15	1	—	T	A	A
MR-b-4	21	55	12	1	10	2	—	—	R	A
MR-c-1	44	36	12	—	8	—	—	—	A	A
MR-c-2	29	60	1	2	7	1	1	—	A	A
MR-c-3	31	51	3	1	13	—	—	2	A	R
MR-d	29	8	59	1	1	—	1	—	A	—
NR-a	58	20	11	1	5	3	1	T	A	A
R-34	12	1	38	47	—	2	T	—	R	R
SR$_1$-a-1	19	7	74	—	1	—	—	—	R	R
SR$_1$-a-2	26	11	63	—	T	—	—	—		
SR$_1$-b-1	18	4	64	2	T	12	—	—	R	R
SR$_1$-b-2	26	9	57	6	1	1	T	—	R	R
SR$_1$-b-3	16	9	74	—	—	—	1	1	R	A
SR$_1$-c-1	46	34	1	—	17	—	—	2	A	A
SR$_1$-c-2	69	23	4	—	4	T	—	—	A	R
SR$_1$-c-3	56	32	8	—	3	—	—	1	A	A
SR$_1$-c'-1	31	8	45	12	1	3	1	1	R	—
SR$_1$-c'-2	6	44	45	2	1	1	1	1	A	R
SR$_1$-d-1	6	3	17	9	—	65	—	—	R	R
SR$_2$-a-1	25	14	59	—	2	—	—	—	R	R
SR$_2$-a-3	25	13	61	—	1	—	—	T	R	
SR$_2$-b-1	3	2	27	4	T	63	—	—	R	R
SR$_2$-b-2	3	3	28	6	—	61	—	—	R	R
SR$_2$-b-3	3	6	30	3	T	58	—	T	R	R
SR$_2$-c-1	10	2	41	12	1	35	—	—	R	R
SR$_2$-c-2	3	6	52	8	T	30	—	—	R	
SR$_2$-c-3	16	7	45	6	1	25	—	—	R	R
SR$_2$-d-1	27	7	26	22	T	17	1	—	R	—
SR$_2$-d-2	7	2	7	43	T	40	—	T	R	—
SR$_3$-a	6	2	9	24	—	59	—	—	—	R
SR$_3$-c	11	4	25	10	T	50	—	—	R	R
SR$_4$-a	10	3	23	19	—	45	—	—	R	—
B-1	1	62	—	—	—	—	38	—	—	A
B-2	25	70	1	—	3	1	—	—	R	A
B-3	4	22	34	1	1	1	37	1	A	A
B-4	—	15	2	—	—	—	83	—	A	R
B-5	6	66	T	—	3	—	25	—	R	R

A = abundant ; R = rare ; T = trace (< 0.5 %)

Note:- Leucoxene and barite were not included in the mineral count-see p. 14 for explanation.

A study of the histograms on plate 1, which show the mineral proportions, clearly indicates that here the quantitative relations among the minerals would be useless as zone markers. There is far too much variation among the proportions of the minerals in any one sandstone member. Three divisions may be made however, on the basis of the presence or absence of characteristic minerals. The basal zone of the Modelo, which includes only one sandstone member, is characterized by the presence of an abundance of tourmaline crystals, except where it overlies the Topanga formation. The intermediate zone is marked by an abundance of hornblende and epidote and the notable absence of tourmaline. It includes several sandstone members. The upper division is distinguished on the basis of negative evidence, namely an absence of tourmaline, hornblende, and epidote in significant amounts.

The absence of tourmaline in the lower zone of the Modelo, where it overlies the Topanga formation, may be explained in two ways. It will be observed that on the geologic map the lowest sandstone member of the Modelo formation is separated from the underlying Topanga rocks by a wedge of shale. It appears quite probable , judging from the localities at which tourmaline is present in the Modelo formation, that the Santa Monica slate and perhaps the Cretaceous Chico sediments are the sources of the tourmaline. One line of reasoning therefore suggests that the absence of tourmaline from the eastern extremity of the lowest sandstone member is the normal result of its higher stratigraphic position in the geologic column; and that in the interval prior to its deposition, the slate and Cretaceous rocks had become completely submerged and protectively blanketed by the sea. The wedge of shale underlying the sandstone in this locality tends to confirm the idea that this portion of the basal sandstone is slightly younger in age than the rest of the member.

A second explanation for the absence of tourmaline may lie in the action of currents. A current sweeping toward the west could have prevented tourmaline, which was being furnished by the slate areas, from being carried toward the east onto the Topanga rocks.

The writer believes that the former explanation is the more probable one and that the process was one of progressive overlap by the sea from the central portion of the basin toward Topanga rocks to the east.

Although the three zones are well marked within the region studied, the writer is very skeptical regarding their extension into the Modelo of the Santa Clara Valley and western Santa Monica Mountains unless precautions are taken to recognize variations in the mineral composition of the sediments along their strike. The writer believes that the minerals which serve as zone markers in the region here described were derived from local rocks (Topanga and Santa Monica slate) and that therefore it will be necessary to discover new markers in the region to the west and northwest. The reasons for this will be clearer after the paleogeography during lower Modelo time has been discussed.

Paleogeographic Conditions During Modelo Time:- It will be observed from an inspection of the geologic map that the Modelo, with which the writer worked, apparently lay almost entirely within a small basin flanked on the east and west by rocks of Topanga age.

This basin is mentioned by Hoots[1] in his report on the geology of the eastern part of the Santa Monica Mountains. The geologic columns[2] on plate I. also indicate its presence by changes in the thickness of the sediments. It is obvious that the central part of the basin which had the Santa Monica slate for its floor was in existance from earliest Modelo time. It is questionable however, whether the Topanga rocks on the east and west flanks of the basin were not uplifted during Modelo time.

The heavy minerals serve as an excellent key for deciphering the geological events of this bygone age. In early Modelo time the sea encroached upon the land, reworking the material over which it passed. Apparently it spread rapidly and covered a large portion of the Santa Monica Mountains in a relatively short period. This is attested to by the comparatively limited thickness of the basal graywacke. The graywacke, so called by Hoots, "is commonly 20 to 30 feet thick"[3] and is composed almost entirely of angular fragments of slate which give it a dark gray to black appearance. Judging from the absence of slate fragments in the sandstone members above the basal graywacke, it appears that the sea covered all of the Santa Monica slate and protected it from the agents of erosion very early in Modelo time.

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[1] Hoots, H.W., loc. cit., p. 104.

[2] The geologic columns were constructed from measurements taken from the geologic map in conjunction with auxiliary data on the on the attitudes of the beds which the writer had gathered.

[3] Hoots,H.W., loc. cit., p. 104.

The absence of hornblende in the basal sandstone also points to a surface of low relief which was rapidly inundated by the Modelo sea. The Topanga formation is known to contain large quantities of hornblende[1] and although it must have been exposed during early Modelo time, for Topanga rocks lie directly beneath the Modelo formation, it yielded no sediments. Apparently the relief of the Topanga surface was so low that the sea spread over it rapidly without any tendency to cut. In brief, the evidence, as presented by the limited thickness of the graywacke and the absence of hornblende in the lowest sandstone member of the Modelo formation leads to the conclusion that the topography of the region in early Modelo time was probably in a late stage of the cycle of erosion.

An examination of the heavy minerals from the second sandstone member above the base of the Modelo leads to some very interesting conclusions. Samples taken in it from east to west at localities SR_3-a, SR_4-a, and SR_2-d-2 show an abundance of hornblende and epidote, and in addition a striking lateral variation in the absolute abundance of the heavy minerals. See figure 2. Clearly there is a greater abundance of the heavy minerals at the extremities of the sandstone reef, where it lies close to the Topanga rocks, than in its middle portion. The Topanga formation is known to contain hornblende and epidote; this, coupled with the singular lateral variations in the abundance of the heavy minerals, suggests a basin of deposition with Topanga rocks on its eastern and western shores.

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[1] Hoots, H.W., loc. cit., p. 95.
A sample collected by the writer in the Topanga formation at the head of Beverly Glen Canyon yielded a large crop of heavy minerals containing 99% hornblende.

Figure 2.- Illustrating lateral variations in the absolute abundance of several minerals from the lowest sandstone member of the intermediate zone. Localities are plotted along the abscissa approximately proportional to the intervening distances. Note the diminution in the abundance of the minerals toward the central portion of the sandstone reef.

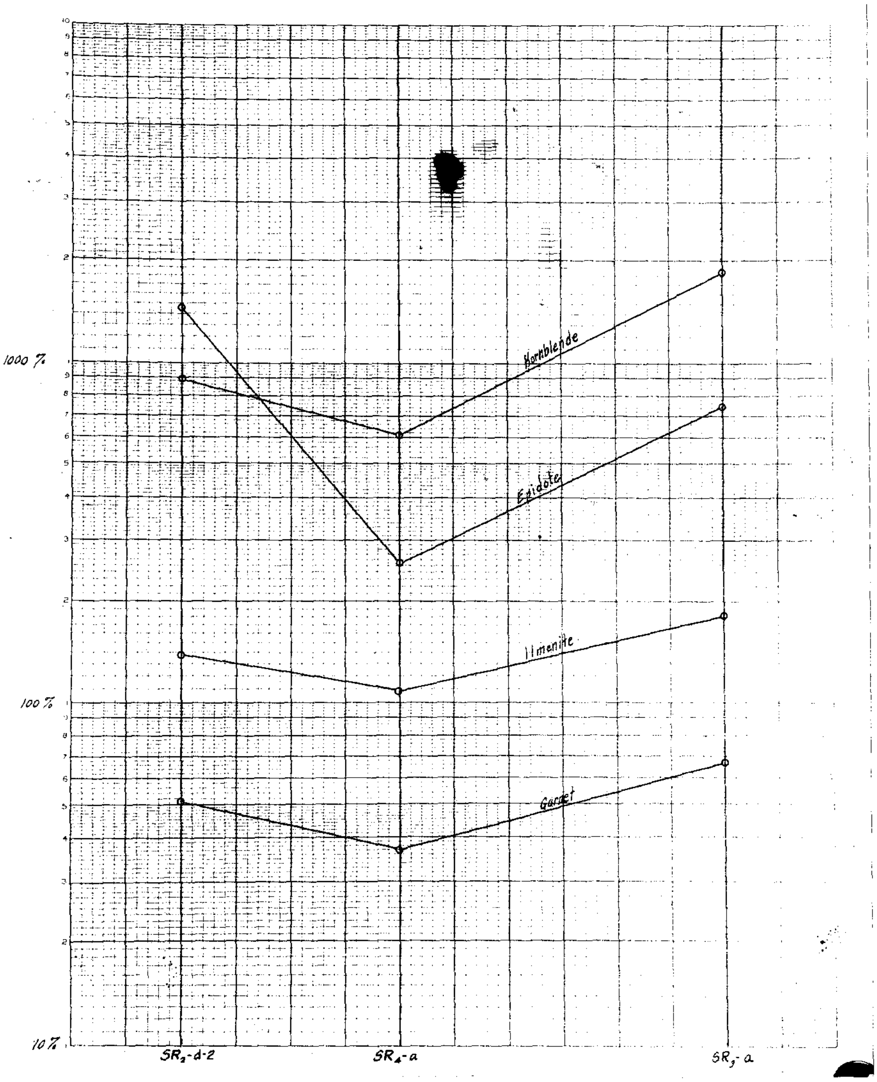
1000 %
100 %
10 %
Hornblende
Epidote
Ilmenite
Garnet
SR_2-d-2
SR_4-a
SR_3-a

Figure 2.

It might be suggested that the large granitic rock mass directly to the east could have furnished the hornblende and epidote to the Modelo sandstone. This is a possibility worthy of consideration. Optically, it is impossible to distinguish the hornblende which occurs in the granite from that found in the Topanga and Modelo rocks. Assuming however that the granite mass is responsible for the hornblende and epidote that occur in the intermediate zone of the Modelo formation, it is difficult to rationally explain the increase in absolute abundance of these minerals from the central portion of the zone toward its western extremity. It seems therefore that although the granite may have stood high on the east side of the basin, on the west side, Topanga rocks had been elevated. The evidence exhibited on the geologic map such as the thinning of the Modelo formation and the terminating of the sandstone members toward the eastern contact between the Modelo and Topanga formations supports the belief that the eastern shore of the Modelo basin was also composed of Topanga rocks. This does not negate the possibility that the granite mass was also elevated and shed material into the basin.

If then, rocks of Topanga age and/or the granite mass furnished the hornblende and epidote, it means that they must have been elevated above the sea during the interval between the deposition of the basal graywacke and the sandstone member immediately above it. This elevation was very probably a consequence of diastrophic movements which occurred along the Benedict Canyon fault and the fault which cuts across the head of Mandeville Canyon.

There is a gradual diminution in the absolute abundance of the hornblende toward the top of the section, until in the upper zone it is absent or present in only insignificant amounts. See figure 3. This may be rationally interpreted as evidence for the gradual erosion and lowering of the Topanga rocks and their final submergence beneath the sea by upper Modelo time. A decrease in mineral abundance toward the top of the section is not confined to hornblende, but is common to all of the other heavy minerals with the possible exception of titanite, and suggests a sea spreading outward in all directions from the basin or a land surface passing into the old age stage of the cycle of erosion.

If the data have been interpreted correctly and the shorelines which have been proposed were in existance during lower Modelo time, then the sediments of the lower unit of the Modelo formation in the Santa Monica Mountains may safely be considered as having been deposited in the waters of a shallow sea.

Significance of Variations in Absolute Abundance of Heavy Minerals.- Some very significant and interesting information has been secured as a result of studying the variations of the absolute abundance of the heavy minerals. From the data, it appears that there is a distinct and noticeable increase in the abundance of the minerals toward their source. The significance of this is that it appears to be possible, from studies of the heavy minerals, to establish with a considerable degree of certainty the positions of ancient shorelines. This is especially interesting in view of the fact that in this investigation no clues to the position of shorelines could be secured from textural studies.

Mackie in an article discussing the distribution of particles of heavy minerals in sediments pointed out the tendency for peripheral

Figure 3.- Illustrating the vertical variation in absolute abundance of hornblende in the Modelo formation. The percentage of hornblende has dropped to zero at locality SR_1-b-3. Localities are plotted along the abscissa schematically and not to scale.

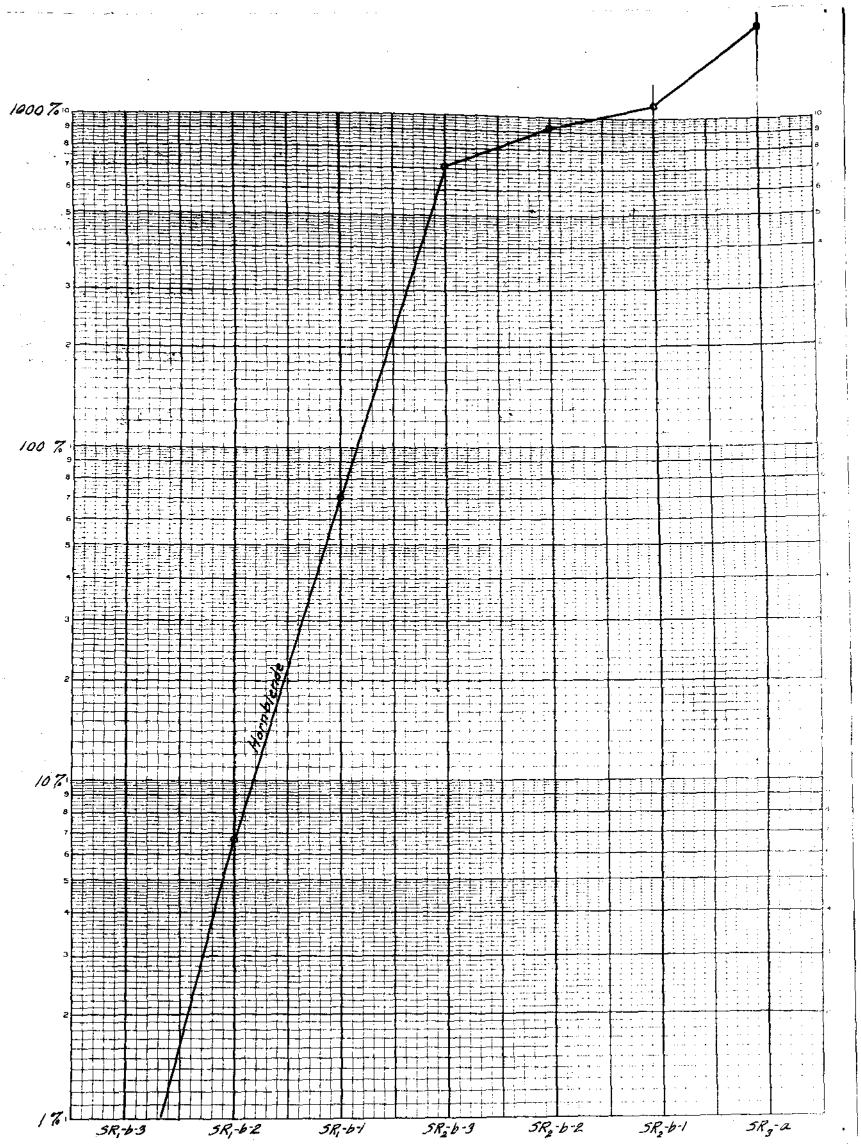
1000 %
100 %
10 %
1 %
Hornblende
SR₁-b-3
SR₁-b-2
SR₁-b-1
SR₂-b-3
SR₂-b-2
SR₂-b-1
SR₃-a

Figure 3.

deposition of large and heavy grains of minerals thus: "Heavy minerals of high specific gravities, or that are prone to persist as large grains, show a tendency to occur in relative abundance in peripheral positions in the various areas of deposit, and to be scanty or altogether absent from beds occupying a more central position."[1] Despite this published statement, little use has been made of this apparently significant feature of mineral distribution in studies of paleogeography.

It has been tacitly assumed by many geologists that the texture of material which is being deposited in a body of water gradually becomes finer as the distance from the shore increases. Observations of sediments now being deposited on the continental shelves have proved the erroneousness of this assumption.[2] It is not at all unusual for muds and silts to be deposited close to shore in regions where sands occur farther out. It seems that currents are more important agents in determining the texture of sediments than is proximity of land. Since textures are unreliable as indicators of shorelines, it was of much interest to learn that heavy minerals could be used for this purpose, apparently with reliability. The writer believes that this is a point worthy of further investigation.

Summary

In summary, it may be stated that the sandstone members of the Modelo formation on the northern flank of the eastern portion of the Santa Monica Mountains are characterized by a uniform texture having

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[1] Mackie, Wm., The Principles That Regulate the Distribution of Particles of Heavy Minerals in Sedimentary Rocks, Trans. Edin. Geol. Soc., vol. 11, 1923, p. 151.

[2] Shepard, F.P., Sediments of the Continental Shelves, Bull. Geol. Soc. Amer., vol. 43, 1932, pp. 1017-1040.

Figure 4.- Illustrating lateral variations in the absolute abundance of the heavy minerals in a sandstone member of the upper zone. Observe the variations in the relative proportions among the minerals from one locality to another. Observe also the general increase in the abundance of the minerals toward the eastern and western extremities of the reef.

Localities are plotted along the abscissa roughly proportional to the intervening distances.

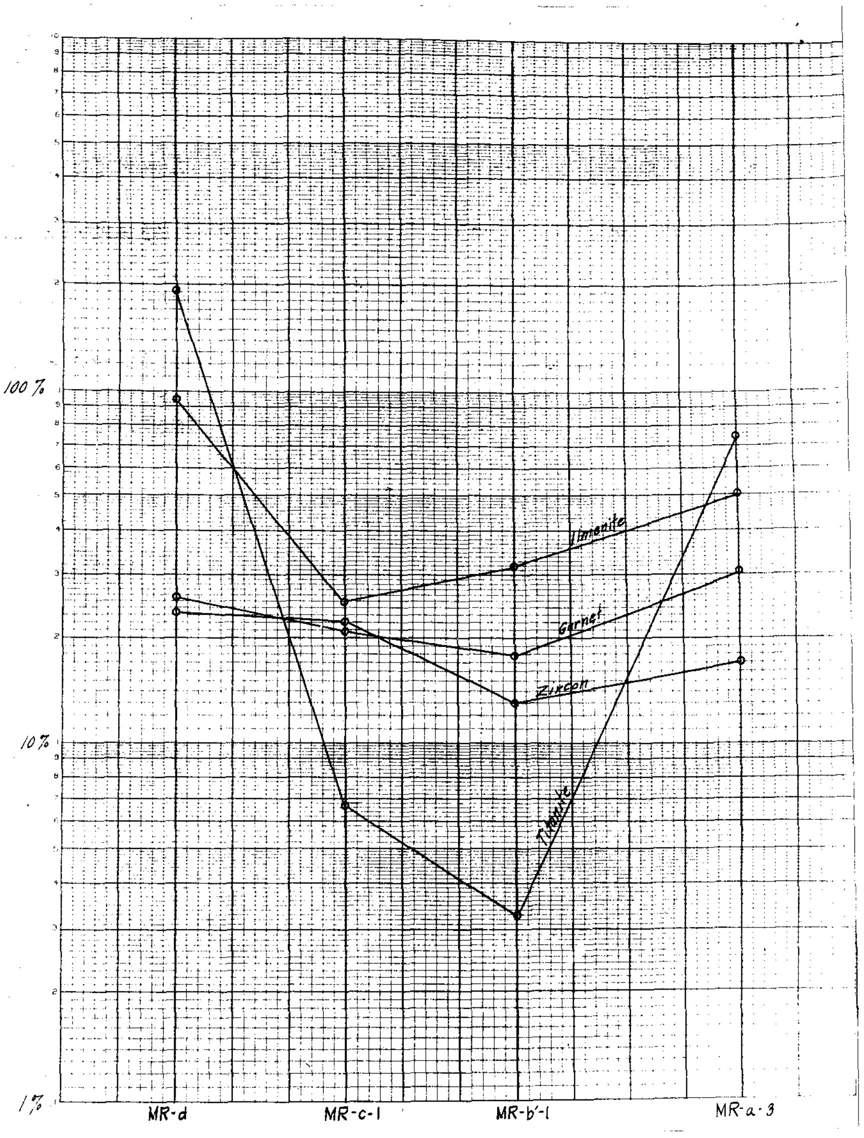
100 %
10 %
1 %
MR-d
MR-c-1
MR-b'-1
MR-a-3
Ilmenite
Garnet
Zircon
Tourmaline

Figure 4.

Figure 5.- Illustrating lateral variations in the absolute abundance of the heavy minerals in the basal sandstone of the Modelo formation. Where the curves are broken at the 1% ordinate, the abundance has dropped below .5%. Observe the increase in the abundance of garnet, zircon, and ilmenite, toward the eastern and western extremities of the reef and the variations of the relative proportions among the minerals from one locality to another. Observe also the rough parallelism between the curves for tourmaline and titanite which suggests that they may have a common source different from that of the other three minerals.

The distances between the localities plotted along the abscissa are not to scale.

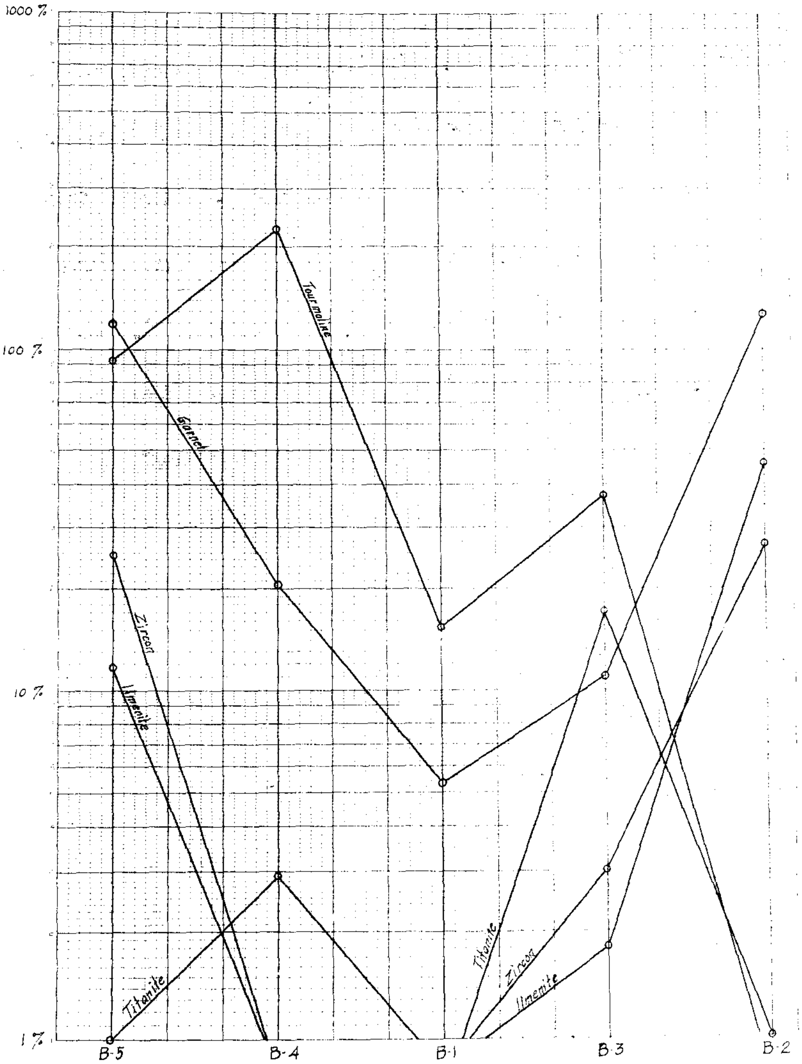
1000 %
100 %
10 %
1 %
B-5
B-4
B-1
B-3
B-2
Tourmaline
Garnet
Zircon
Ilmenite
Titanite
Titanite
Zircon
Ilmenite

Figure 5.

a maximum which falls either between the sizes 1/2 to 1/4 or 1/4 to 1/8 mm., and that the lower unit of the Modelo in this region is divisible into three zones on the basis of heavy minerals. Rapid and wide fluctuations in the proportions among the heavy minerals were found to occur within single sandstone members indicating the futility of attempting correlations in this region on the basis of mineral proportions. The absence or presence of distinctive minerals were therefore used as criteria with which to distinguish the various zones. The basal division was characterized by the presence of tourmaline; the intermediate one by the presence of hornblende and epidote; and the upper zone by the absence of tourmaline, hornblende, and epidote. A new method for indicating absolute abundance of heavy mineral species was employed here for the first time. Distinct and systematic variations in the abundance of minerals along the strike of the beds were disclosed. These variations were strongly suggestive of former shorelines and sources of sediment and have led the writer to believe that studies of the absolute abundance of heavy minerals may be found to yield far more information regarding the proximity of shorelines than can be secured from textural studies.

Considerations of the heavy minerals with regard to paleogeography point to a surface of low relief, during the opening of the Modelo epoch, which was rapidly submerged by an encroaching sea. Subsequently, diastrophic movements occurred which elevated the margins of an already nascent submarine trough in which an imposing thickness of Modelo sediments was later deposited. By upper Modelo time the land masses bordering the basin had been worn down and once more the sea had transgressed over the land.