THE GEOLOGY OF THE EAST COACHELLA TUNNEL

OF THE

METROPOLITAN WATER DISTRICT OF SOUTHERN CALIFORNIA.

by

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ABSTRACT.

The following paper describes the geology of the East Coachella Tunnel of the Metropolitan Water District of Southern California. This tunnel extends along the southern flank of the Little San Bernardino Mountains, in Riverside county, California,

Four rock types were encountered in the excavation of the tunnel: a regionally metamorphosed series of schists and gneisses of sedimentary origin, here called the Berdoo series; granitoid rocks resulting from replacement, called the Thermal Canyon series; a granitic intrusive called the Fargo granite; and bench gravels.

The Berdoo series is divisible on the basis of lithology into three facies: a dark thin-bedded feldspathic and biotitic schist, a light gray feldspathic gneiss, and a medium gray coarse grained schist which is transitional between the first two.

The Thermal Canyon series consist of massive granitoid rocks which are of the mineralogical composition and general aspect of quartz-diorites.

Between these two rock series occurs a transition zone of from 1000 to 6000 feet in width within which, as examined in the field, the sedimentary textures and structures which characterize the Berdoo series appear to gradually give way to the massive granitoid textures of the Thermal Canyon series. Petrographic studies reveal the existence of a zone of mineralogical gradation between the two series within which the assemblage which constitutes the Berdoo series gradually becomes replaced through recrystallization by that which constitutes the Thermal Canyon series. The minerals of the recrystallized assemblage are not conformable to definite surfaces such as bedding, but instead show the fortuitous orientation of an igneous rock. Also, the plagioclase feldspars of the recrystallized assemblage are slightly more calcic than those of the Berdoo series.

Chemical analyses show that the composition of the two rock series is very nearly the same, excepting for a progressive increase in lime, and corresponding decreases in ferric iron and potassa with advancing recrystallization.

The results of field, petrographic, and chemical methods of investigation thus indicate that the Thermal Canyon series rocks resulted through recrystallization of a portion of the Berdoo series rocks. Ascending hot solutions and gases of magmatic origin are postulated as the actuating agencies in the recrystallization.

The Fargo granite occurs as an intrusive stock in the east central portion of the area, and consists of a pinkish gray coarsely crystalline rock of about the mineralogical composition of a quartz-monzonite.

The chief structural feature of the area is faulting, of which two systems are recognizable, one which trends easterly, and one which trends northerly. Two successive periods of domical uplift in the south-eastern portion of the area are postulated as causes for the faulting.

The geological aspects of tunnel excavation, with especial reference to the influence of structure, are discussed briefly.

Fig. 1. Outline Map of California

Showing location of East Coachella Tunnel Area

Scale, 1 inch = 80 miles.

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INTRODUCTION

In the year 1929 the Metropolitan Water District of Southern California began operations on the construction of an aqueduct the purpose of which is to bring water from the Colorado river to various cities in the southern California coast region. As the route of this aqueduct traverses the entire width of the state of California several mountain ranges were encountered, many of which had to be pierced by tunnels. The longest of these tunnels is the East Coachella, which extends along the southern flank of the Little San Bernardino mountains. (See Fig. 1.) Acting on a suggestion by the faculty of the Division of Geology and Paleontology of the California Institute, a study of the geology of the region traversed by the East Coachella tunnel was made by the writer, a report on the findings of which is hereby presented. The report includes detailed descriptions of the rock formations occurring in the area, together with explanations of the various geologic processes by which these rocks were modified since their emplacement. The surface manifestations of certain unfavorable conditions encountered during the process of excavation of the tunnel are described, in the hope that similar manifestations encountered elsewhere may be more easily recognized, and their significance more fully appreciated.

Location and Size of Area. The East Coachella Tunnel extends along the southern flank of the Little San Bernardino mountains from Thermal Canyon to Fan Hill Canyon, in Riverside county, California. (See Fig. 1 and Pl. 1.) It has a length of almost nineteen miles and a cross-section sixteen by sixteen feet.

The study on which this report is based included examinations of all rocks exposed in the tunnel and on the overlying surface, a topographic map made by the engineering department of the Metropolitan Water District being used as a base map on which to plot the surface geology. The area examined includes the entire slope of the Little San Bernardino mountains from Thermal Canyon to Fan Hill Canyon, the tract thus delimited being about twenty miles long and three to three-and-one-half miles wide.

Routes of Access. The most important community in the vicinity of the East Coachella Tunnel area is the city of Indio, which is about fifteen miles south of the east portal of the tunnel. This city can be approached over either the Southern Pacific Railway or the United States' Highway No. 99. From Indio a system of well paved motor roads constructed and maintained by the Metropolitan Water District extends along the base of the mountains and connects with the various operating camps which are located near the line of the tunnel, such as Fargo, Berdoo, and Pushawalla. No roads or trails have been made over the mountains.

Field Work. Altogether about eight months were spent in the field, including three months during the summer of 1934, four months during the summer of 1935 and numerous trips of only a few days' durati Slightly less than half of this time was spent in examination of exposures in the tunnel, the remainder being devoted to the surface.

Acknowledgments. The writer acknowledges his indebtedness to the executive staff of the Metropolitan Water District, who permitted him free access to their tunnels during the field investigations. Especial appreciation is expressed for courtesies extended by the field personnel of that organization, especially Mr. R. B. Diemer, Chief Engineer, and Mr. Weller, Superintendent of Berdoo camp, and Mr. Neil O'Donnell, Superintendent of Fargo camp.

The entire study was carried on under the guidance of Professor Ian Campbell of the California Institute, to whom the writer is indebted to an extent that the mere mentioning of the fact can scarcely requite. Thanks are also due to Professor John P. Buwalda for advice pertaining to structural problems, and to Drs. George H. Anderson and Horace J. Fraser for helpful suggestions.

<u>Earlier Investigations</u>. Although it is known that some previous geological studies have been made in the region of the Little San Bernardino mountains, there apparently has never been any general statement published regarding the geology of the area described in this rep The Cahuilla Valley, of which the Coachella Val forms a part, was described by W. P. Blake (1)*, who in 1853 made a reconnaissance survey of the southern portion of the State of California in conjunction with a party of engineers of the Pacific Railway Survey.

In 1909, W. C. Mendenhall (2) in giving a sketch of the geography of the Colorado Desert briefly

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*Throughout this report numbers enclosed by parentheses refer to works similarly designated in the bibliography.

but aptly described the physiography, climate, and vegetation of the mountains east of the Coachella Valley, within which lie the East Coachella Tunnel area.

In 1930 Professor F. L. Ransome made a reconnaissance survey of the entire route of the aqueduct for the Metropolitan Water District, to the executive department of which he submitted his findings in the form of a private report; this report, however, has not been made public.

Geological investigations have been made in territory adjacent to the East Coachella Tunnel area in which some conditions were encountered which apparently did not differ greatly from those described in this report.

In 1932 Vaughan (3) published a comprehensive report on the geology of the San Bernardino mountains, the western edge of the area described by him being about fifteen miles east of the easternmost limit of the East Coachella Tunnel area.

In 1931 Fraser (4) described the geology of the San Jacinto quadrangle which is some twenty miles south of the East Coachella Tunnel area, and on the opposite side of the Coachella valley.

Physiography. The Little San Bernardino mountains constitute an exceedingly rugged range of relatively moderate elevation forming a portion of the chain of mountains which constitutes the east wall of the Coachella Valley. When viewed from Indio, which lies near the center of the Coachella Valley, the Little San Bernardino mountains, there about twelve miles distant, appear as a comparatively straight mountain chain of even summit which rises about 2000 feet above the valley floor. They constitute a typical arid range, and appear to be almost completely devoid of vegetation or of soil. The lower portions of the slopes are quite commonly incised by steep-walled dry ravines, which, however, usually terminate a considerable distance below the ridge-line, so that the upper slopes tend to be more gently rounded.

From the deeper canyons, such as Yellow Spots, Fargo, Indio, and Berdoo, alluvial fans of remarkably symmetry extend outward into the valley for eight or ten miles.

Although presenting to the observer in the valley the appearance of a single continuous mountain chain the Little San Bernardino mountains actually consist of a number of short, more or less irregularly-aligned mountain masses which vary considerably in altitude, these being separated from one another by precipitous canyons and high passes. The crest-line of the range varies in elevation from 2500 to 3000 feet, with individual masses attaining elevations of 3500 feet or more. The floor of the Coachella valley here ranges in elevation from twenty feet below sea level at Indio to about 200 feet above sea level at a point opposite Fan Hill. Owing to the concavity of the transverse profile of the valley, the "toe" of the mountain passes under valley alluvium at elevations which range from 400 to 800 feet.

Across the southern slopes of this range occur a number of wide benches, which if joined would form a single continuous surface the elevation of which would range from 1500 to 2000 feet. These benches are more distinct towards the eastern end of the range, where they occasionally attain widths of 1000 or more feet. Other less distinct and less definitely correlatable benches occur at various higher elevations throughout the range. As shall be explained more fully later, these represent surfaces of denudation cut during pauses in the uplift of the range.

Climate and Vegetation. Owing to the relatively low elevation of even the highest ridges, the entire area described in this report is subjected to an unusually arid climate, and is considered as forming a part of the Colorado Desert, one of the most truly arid parts of western North America. According to observations made by engineers of the Metropolitan

Water District, who maintain a rain-guage at Camp Berdoo, the yearly rainfall since the establishment of the camp in June 1931 was as follows:

June to December,	1931	2.31 inches
Jan. 1 to Dec. 31,	1932	5.11 "
Jan. 1 to Dec. 31,	1933	5.78 "
Jan. 1 to Dec. 31,	1934	5.08 "

During the same period the average daily temperature range for the mid-summer and mid-winter seasons averaged as follows:

June 20 to August 30	117 F to 74 F
December 15 to March 1	70 F to 44 F

(Courtesy of the Metropolitan Water District of Southern California.)

Most of the precipitation occurring in this region is in the form of local but intense downpours of the cloud-burst type. There are no permanent springs or streams, so that, excepting for a few hours following the heavier showers, no water is obtainable on the surface at all; even in the East Coachella tunnel only one or two seeps were found, and of these none was sufficiently pronounced to form continuous drippers. Under such conditions no soil, in the ordinarily accepted sense of the term, can form at all, the greater part of the products of erosion being removed almost as quickly as formed either by run-off during the periods of rain-fall or by wind during the long intervening periods of dessication. However, none of the mountain slopes is completely devoid of vegetation, the distorted and spinous growths characteristic of semi-tropical deserts such as the barrel cactus, the ocatilla, the cholla, the greasewood, the iron-wood, and palo verde being found sparingly distributed throughout the entire area.

Excepting for the more or less temporary occupancy by the employees of the Metropolitan Water District, the area is entirely uninhabited.

GEOLOGY

The portion of the Little San Bernardino mountains here considered is composed almost entirely of crystalline rocks, of which three distinct types are recognizable: a metamorphic rock series largely of sedimentary origin, a granitoid rock probably due to a replacement process, and a granitic intrusive rock. Owing to the absence of any reliable means of correlating these with other previously described rocks local names are here given them, each one being named after some locality at or near which it is typically exposed. Accordingly, the metamorphic rocks will be referred to as the Berdoo Series, the granitoid replacement rocks as the Thermal Canyon Series, and the granitic intrusive as the Fargo granite.

The nomenclature thus developed embraces all the rock formations exposed within the area excepting local bench gravels, which, on account of their geomorphological significance are deemed worthy of consideration as a separate rock formation. The absence in this area of other rocks with which they might be confused obviates the necessity of giving them a name.

The Berdoo Series

The Berdoo Series, named after Berdoo Canyon (Plate II), is the most widely distributed rock group in the area, and includes all surface rocks from Indio Canyon westward to beyond Fan Hill Canyon. Members of this series form the surface rocks throughout the greater part of the Little San Bernardino mountains.

Stratigraphy. The Berdoo Series constitute the metamorphic derivatives of a great thickness of clastic sediments in which shales predominated, but in which shaly sandstones, probably with lenses of arkose and graywacke, were fairly common. These have all been intensely metamorphosed, so that none of the original minerals remains; the smaller scale original structures likewise have been completely obliterated, and others, more in keeping with the later history of the rock, imposed in their stead.

The grade of metamorphism within a given lithologic unit is always uniform throughout the entire area, excepting where affected by local recrystallization. The metamorphism is thus seen to be regional rather than local in its nature.

A certain measure of stratification is discernible everywhere throughout the Berdoo Series; this is occasionally shown as in a sedimentary series by superposition of individual beds, but more commonly by superposition of members of formations of contrasting color and lithology, which on account of their greater thickness, and consequent wider range of visibility give to the group a characteristic banded appearance.

Three facies generally are recognizable: a dark gray to black, somewhat fissile schist; a massive, light gray gneiss; and a medium gray coarse-grained schist which is transitional between the two first mentioned. These occur as distinct lithologic units of from 50 to 200 feet in thickness, which by their contrasting colors and more or less conformable superposition indicate the stratification, as noted above.

The Dark Schist. The dark schist members are usually the most persistent and uniform in the series. Where typically developed they are thin-bedded, and frequently show alternating beds of light and dark minerals, each about one inch in thickness. The lighter-colored beds often consist of conformably aligned lens-shaped masses a few tens of feet in length, composed of coarse-grained light gray minerals, individual lenses being separated from one another by thin folia of dark minerals. These lenses often overlap sufficiently to give the impression of continuous beds of uniform thickness.

The dark-colored beds are usually somewhat thinner than the aggregate thickness of a typical light-colored bed, around the lenses of which they tend to sweep; they always show foliation, and are often intricately contorted.

The average hand specimen of the dark schist shows bands about one inch in thickness which consist of coarse-grained interlocking minerals in which pinkish-white and ice gray feldspars predominate; these are separated by bands of similar width composed of dark ferromagnesian minerals among which biotite greatly predominates, but which show varying amounts of amphiboles.

With increasing thickness and closer spacing of the lighter colored bands, the dark schist gradually merges laterally into the gray schist, and finally into the massive gneiss mentioned above.

The Gneiss. The gneissic facies of the Berdoo series is somewhat less uniform than the dark schist facies, and therefore less conformable to any one readily described standard. Several varieties or types which in their most widely divergent forms show but little resemblance to one another can be distinguished; the general field relationships, however, are such as to leave scarcely any doubt regarding their derivation from a common origin.

A frequently occurring variety bears a strong resemblance to the dark schist just described, excepting that the proportion of dark minerals to light minerals is different: this variety consists essentially of bands six to ten feet in thickness, composed largely of coarsely crystalline light gray minerals, mostly plagioclase feldspars, and hence analogous to the light bands in the schist, which are separated from one another either by single bands of biotite a fraction of an inch in thickness, or by beds a few feet in thickness composed of alternating layers of light and dark minerals as in the dark schist. Bedding in this variety is shown only by the attitude of the biotite bands, the lighter colored beds usually being massive and devoid of any internal structure.

In a second variety the mineralogical composition is about the same as that of the variety just described, but the relationship between the minerals differs in that the dark minerals no longer occur in distinct beds but rather in fairly continuous streaks which do not constitute parting planes and which blend laterally into the masses of lighter colored minerals. Hand specimens exactly similar to those which seem to have been used for illustrations of "banded gneiss" in elementary text-books of geology can be collected at will from outcrops of this rock.

In the two varieties described the amount of light colored minerals greatly exceeds that of the dark colored ones; in a third variety which occurs somewhat sparingly throughout the Berdoo series the amount of dark colored minerals is about equal to that of the light colored ones. As typically developed this variety is medium to dark gray in color, very fine-grained and even-textured; in the hand specimen it may closely resemble andesite. It commonly shows a faint banding parallel to the bedding of the enclosing members, but very few parting planes.

The Gray Schist. As already mentioned, the gray schist can be considered as constituting a facies which is transitional between the dark schist and the gneiss. It resembles the variety of gneiss which was first described above, excepting that the beds of light colored minerals are usually only about one foot in thickness, and that the beds of dark colored minerals are thicker, as in the dark schist.

General Field Relations. The Berdoo series is composed of the three rock types described above, these being superposed on one another as strata in a sedimentary formation. In the section as exposed, each type is repeated a number of times as individual members of formations. There seems to be no very definite order of superposition, although there is a noticeable tendency towards concentration of dark schist members towards the lower portion of the exposed column. Nothing which could be interpreted as either a base or a top for the Berdoo series has been observed anywhere in these mountains, either during the detailed examination of the East Coachella tunnel area itself, or during a general survey of the surrounding region. For this reason the thickness of the Berdoo series is still unknown; even statements regarding the thickness of the exposed portion can at best be but reasonable estimates, since in the absence of distinctive beds which would serve as horizon markers, changes in the apparent thickness through deformation, such as repetition of beds by faulting or isoclinal folding cannot be detected. However, in the mountains immediately west of Berdoo Canyon (Plates II and III), which constitute a relatively slightly deformed block, 2500 feet of these rocks are exposed without a trace of either an upper or lower surface. From this point westward to the limits of the area the beds are intensely deformed and folded, but the most commonly occurring dip appears to be towards the southeast; in its progress westward, therefore, the tunnel penetrates lower and lower strata, but here likewise, no base has been exposed. The only safe statement that can be made at the present time regarding the thickness of the Berdoo series is that it exceeds 2500 feet.

Within the limits of the area investigated in connection with this study the Berdoo series was found to come into contact with two rock types, the Thermal Canyon series and the bench gravels. As the relationship between the Berdoo and the Thermal Canyon series furnished one of the more interesting problems of the entire study, a discussion of it is reserved for a later section. The relationship with the bench gravels is always one of simple unconformable contact.

The petrography of the Berdoo series will be discussed in a later section.

Age. No definite information could be obtained regarding the age of the Berdoo series. On account of its advanced state of metamorphism no internal evidence of age such as the occurrence of fossils could be expected, had such ever existed. Indirect methods of age determination by establishment of relationships with other rocks of known or determinable age are of but little value in the case of the Berdoo series as the only sediments found in contact with it are bench gravels of possibly late Pleistocene age, and present day alluvium.

The metamorphism which affected the Berdoo series was of the regional rather than the thermal type. This presumably involved deep burial of the original sediments, and hence, a prolonged period of sedimentation after their deposition. This must have been followed, after a period of unknown duration, by uplift and profound erosion. Since erosion of a given thickness of rock, especially if these be highly metamorphosed, might require as much time as would the deposition of an equal thickness of sediments, the time involved by the three periods thus postulated could quite conceivably include the whole of the post-Proterozoic. The general appearance of the Berdoo series suggests a pre-Cambrian age; it is definitely more highly metamorphosed than the undifferentiated schists of the San Bernardino mountains, which are described by Vaughan (3), and classified by him as being possibly pre-Cambrian.

In the absence of a more satisfactory method of determining its age, the Berdoo series, on the basis of this relationship, is also classified as possibly of pre-Cambrian age.

The Thermal Canyon Series

The Thermal Canyon series, named after Thermal Canyon (Plate II), forms the surface rock in the greater portion of the area between Thermal and Indio canyons. The continuation of the mountain range for ten or twelve miles southeasterly beyond Thermal Canyon exposes similar rocks along its southern flanks; these appear as detached outcrops, separated from one another by wide gravel-filled canyons, but they doubtlessly represent one continuous rock mass, through which the various canyons have been cut.

Lithology. The freshest material found at the type locality, the west bank of Thermal Canyon, is of a medium gray color, and has in many respects the general aspect of a quartz-monzonite. The range in grain size, however, is unusual in quartz-monzonites as it extends from near the lower limits of unaided vision to occasional individuals ten to fifteen millimeters in length. The megascopic minerals are wax-gray feldspars, in more or less automorphic crystals five to fifteen millimeters in length, and commonly showing twinning according to the Carlsbad law; light gray to almost white feldspars, xenomorphic to automorphic in form, and one to three millimeters in length; biotite, locally in distinct flakes one to two millimeters wide, but sometimes in obscure specks; water-clear quartz, in xenomorphic grains one to three millimeters wide; a dark green to black ferromagnesian mineral occurring in elongate prisms and showing a splintery cleavage suggestive of hornblende; and rarely, yellowish gray sericite flakes on the cleavage faces of the larger feldspar grains.

Excepting in the contact zone which separates this series from the Berdoo series, and which is discussed at some length below, the texture of this series is comparatively uniform: the xenomorphic material forms a ground mass of more or less granitoid texture which encloses the automorphic grains. The large feldspar grains occur as separate individuals which show no system or regularity either in alignment or in spacing, being scattered at two to five centimeter intervals as plums in a pudding. Throughout the greater part of the exposure the ferromagnesian minerals tend toward a more or less distinct arrangement in space: the biotite grains quite frequently show a tendency toward concentration into narrow bands, within which the individual grains approach to within ten or fifteen degrees of actual parallelism; the prismatic ferromagnesian minerals likewise show concentration within the bands determined by the biotite grains, where, however, they show no noticeable tendency toward alignment of grains. Usually, the larger the grain of either mineral the more definite the arrangement into bands.

The petrography of this series will be discussed later, in conjunction with that of the Berdoo series.

Relationship Between the Berdoo Series and the Thermal Canyon Series. As explained above, the Berdoo series where typically developed consists of a number of beds which are superposed more or less conformably upon one another, and which clearly reveal by their structure a sedimentary origin. The Thermal Canyon series, on the other hand, shows none of the common physical attributes of a sediment, but instead more nearly resembles an igneous rock of peculiar texture.

Between these two contrasting rock series occurs a zone of very indefinite boundary, within which the properties of the one rock give way to those of the next. This zone varies in width from a few feet to two or three miles, the average width being about one mile. Here, typical beds of the Berdoo series, if followed in a direction towards the Thermal Canyon series, can be observed to more or less gradually lose the properties which suggested a sedimentary origin and acquire those of the Thermal Canyon series as described above.

The first noticeable change in the Berdoo series is the appearance of a pink feldspar which in the hand specimen resembles ordinary orthoclase. In the very outer limits of the transition zone where this mineral first attracts attention it is in the form of small rounded reddish pink to creamy white grains two to three millimeters in diameter which occur diffusely scattered throughout the schist, but with a noticeable tendency toward concentration along the contacts between light and dark beds. Grains which form along these contacts, and also those which form entirely within beds of high ferromagnesian content, often show more red coloration than do those which form in beds of high feldspar content.

Within a very few tens of feet (the observer in every instance being supposed to be moving from the Berdoo series towards the Thermal Canyon series) these grains become idioblastic individuals, usually of prismatic outline, and of dimensions which approximate one to two centimeters in length, and five to eight millimeters in width. With increase in grain size the tendency toward concentration into definite bands becomes less noticeable, so that, although they occur more commonly in the lighter colored beds, these grains can be found in all members of the Berdoo series.

Chloritization of the ferromagnesian minerals almost invariably accompanies the first appearance of the pink feldspar and becomes more pronounced with approach toward the Thermal Canyon series. It does not, however, eventually become universal: indeed, the tongues of dark schist which penetrate farthest into the Thermal Canyon are those which show the least chloritization, and also the least pink feldspar content.

The degree of transformation varies greatly with the different facies of the Berdoo series; beds of dark schist, for example, may persist more or less unchanged for several thousand feet into definitely recognizable Thermal Canyon, whereas in the case of the gray gneiss the transgression is always by the Thermal Canyon into the Berdoo, the inference being that the schist gives way to recrystallization less readily than does the gneiss. Also, inclusions are fairly common in the Thermal Canyon series, especially toward the borders; these almost invariably consist of masses of dark schist. A point worthy of note regarding these inclusions is that they still preserve the prevailing attitude of the Berdoo series in the alignment of bedding or schistosity, even when separated from these rocks by several thousand feet of Thermal Canyon series rocks.

The next noticeable stage in this process of transformation is characterized by a general induration of all rock types in the series, with a definite tendency toward obliteration of sharp contacts. In members composed of alternating beds of contrasting material, such as the dark schist, the contacts between beds no longer are definite surfaces but zones of a few centimeters in width within which blending of the one bed into the other has taken place.

Further progress in the process of transformation is marked by a tendency toward obliteration of all contrasting features within the rock: mutual diffusion brings about a blending of light and dark colored beds, so that the general aspect approaches that of a granitoid rock.

When the last vestiges of the light and dark bedding which characterizes the Berdoo series will have vanished, the rock will be here considered as no longer a part of the Berdoo series but instead a border phase of the Thermal Canyon series. Accordingly, the line which joins the various points of westernmost extension of continuous bedding is shown on the map (Plate II) as the contact between the Berdoo series and the Thermal Canyon series.

The transition, however, cannot be considered as completed at this line, since, for some tens to hundreds of feet beyond, there still persist some features of the Berdoo series which are not found in typical Thermal Canyon. The large porphyroblasts still retain traces of the pink coloration which characterize them throughout the Berdoo series, as contrasted with the waxy gray color which they show in the Thermal Canyon series. The texture of the finer grained material is less even than in the typical Thermal Canyon, where the range in grain size for this material is relatively narrow. Also, the ferromagnesian minerals show some traces of chloritization, a feature which is quite common in the transition zone, but very rare in the typical Thermal Canyon. The subordination or passage of these features, with the more or less complete dominance of the characteristics of the Thermal Canyon series, usually takes place within two hundred to five hundred feet of the line here chosen as the contact of the Thermal Canyon series with the Berdoo series.

Petrology of the Berdoo and Thermal Canyon Series. In the preceding pages in which the general field aspect of the Berdoo and of the Thermal Canyon series are described the two are treated separately, and are considered as separate rock groups. On account of the great dissimilarity in appearance which they show they cannot be considered as constituting a unit for purposes of description; in any case they differ so greatly in structural characteristics and in genesis that they would be classified as separate rock groups according to any of the accepted systems of rock classification. However, in the petrologic study now to be presented the two series, together with the intervening transitional zone, will be considered more or less together, in order that the similarity in mineralogical composition and the contrast in genesis can be more clearly brought out.

During the course of the field investigations some two hundred and fifty rock specimens were collected and taken to the California Institute for further study. These were so chosen as to be illustrative of every rock facies and type found within either group. In most cases the attitude of the rock mass from which the specimen was taken was indicated on each one by means of suitable symbols placed on it at the time of collection. From these specimens thin sections of chosen orientation were then cut, in order that the features observed during petrographic examination could be definitely correlated with the larger scale features of the rock mass as a whole.

A notable feature which immediately attracts attention during a petrographic study of these rocks is the similarity in mineralogical composition which all members of these series show, irrespective of the contrast in appearance which they may show in the field. Species of the same mineral groups constitute ninety-eight per cent of the component minerals in all the varieties of rocks found in either series, the differences which are so evident in the field being due largely to differences in the relative proportions of minerals and to structure and texture. Within the Berdoo series itself changes in facies are usually brought about solely by changes in the relative proportions of identical minerals; between typical Berdoo series rocks and those of the transitional zone, or between the transition zone rocks and those of the Thermal Canyon, changes in facies are invariably accompanied by changes in the mineralogical composition also, these being usually in the nature of substitution of one mineral for another closely related one, such as oligoclase for albite, or hornblende for biotite.

Below is listed (Table I) the results of Rosiwal analyses of four thin sections, each one of which was chosen as being typical of the particular facies from which it was taken. Number 1 represents the dark schist of the Berdoo series; number 2, the gray gneiss in the transition zone of the Berdoo series; number 3, the transition zone of the Thermal Canyon; and number 4, the typical Thermal Canyon.

Table I

Rosiwal Analyses of Berdoo and

Thermal Canyon Series Rocks

	1*	2*	3*	4*
Total feldspars	62%	82%	63%	66%
Biotite	26	6	22	22
Cordierite	-	9	6	7
Total white mica	10	-	-	-
Hornblende	-	1	5	2
Quartz	1	1	2	1
Opaques, chlorite, myrmekite, epidote, clinozoisite, sphene, carbonates, zircon, allanite, and unidentified	1	1	2	1

*No. 1. Field specimen 7679 - 75 Dark schist, Berdoo series.

No. 2. Field specimen 7616 - 60 Gray gneiss, transition zone, Berdoo series.

No. 3. Field specimen 7505 - 40 Transition zone Thermal Canyon series.

No. 4. Field specimen 7484 - 00 Thermal Canyon series.

(Specimens collected from exposures in the tunnel were in every case given numbers which corresponded with the survey station number of the point of collection; these in turn corresponded with distances in feet from the Colorado River.)

Description of Minerals. Plagioclase feldspar is usually the most common mineral constituent, and is present in two or more varieties or types in practically every thin section. Of these, one occurs as grains which may attain dimensions of one to five millimeters in length, and one-half to one millimeter in width, and which almost invariably shows polysynthetic twinning, and not infrequently Carlsbad twinning as well. The composition of this type according to determinations made by zone method of Rittman, which were occasionally checked by the more exact but more tedious Berek method, ranges in the case of different individual grains from $Ab_{92}An_{8}$ to $Ab_{80}An_{20}$. Sericitization is always evident, and sometimes is quite advanced. The borders of the grains of this type quite commonly show local corrosion and invasion by small grains of other minerals. This type is usually quite distinctive because of its advanced stage of seritization and its polysynthetic twinning.

A second type, which perhaps constitutes the most common mineral in the Berdoo series, resembles the type just described excepting that the grains are usually quite fresh and less uniform in size, ranging from one to two millimeters down to individuals barely recognizable at magnifications of fifty diameters. Extinction angles on albite twinning normal to the 010 face indicate that the composition ranges from $Ab_{80}An_{20}$ to $Ab_{68}An_{32}$. Twinning according to the albite law is observable in almost all grains of this variety; pericline and Carlsbad are also fairly common. Another rather unusual type of twinning can be seen in some of the larger grains of this type of feldspar; it appears as polysynthetic twinning lamellae which cut the albite twinning lamellae at angles of from forty-five degrees to fifty degrees.

The larger grains of this variety of feldspar usually show undulatory extinction of the type commonly referred to as "strain shadows"; these are sometimes accompanied by actual deformation of the grain, which is shown by curvature of the twin lamellae. In such cases the twinning is always more clearly developed in the strained portions: not infrequently the twinning dies out entirely in the unstrained portions.

A peculiar zoning is also noticeable in the arrangement of the strain shadows; these do not sweep uniformly across the entire grain as they so commonly do in the case of quartz, but instead show a certain geometric pattern which occasionally seems to bear a relationship to the outline of the grain. Inclusions in this variety are rare, although in some of the larger grains minute specks of biotite can be seen.

The mineral which usually is next in importance to plagioclase in these rocks is biotite. In the typical Berdoo series it occurs as irregularly shaped flakes the greater portion of which is approximately conformable to the bedding. No euhedral crystals were observed. Basal sections are virtually uniaxial.

Pleochroism is noticeable in all grains, and is quite pronounced in the typical Berdoo series and in the Thermal Canyon. Haloes of intense pleochroism develop around grains of zircon, allanite, and epidote; the reverse phenomenon, "anti-pleochroism", in which complete bleaching to the transparency and optical properites of muscovite take place, was observed in one or two instances as haloes of about .01 millimeter in width around grains of pyrite.

Ordinarily the biotite occurs either as fairly continuous roughly parallel bands of irregular width, usually one to two millimeters, which are separated by much wider bands of feldspathic material; or, as interstitial filling between individual grains of feldspar or other minerals. Large numbers of individual flakes, however, always occur fortuitously scattered throughout all sections of these rocks.

Near the outer edges of the transition zone, and in various local areas throughout the Berdoo series a white mica appears in place of biotite. It is usually quite colorless and non-pleochroic, although faint yellowish and greenish tinges are not unknown. An extinction angle, Y to a, of from two degrees to three degrees can often be seen, although usually the extinction is parallel. This mineral is quite probably muscovite; it occurs both as bands and as interstitial filling analogous to the biotite.

In intimate association with the muscovite occurs a second variety of white mica, sericite, which appears as fine-grained felted masses within feldspar grains from which it has been derived.

Orthoclase occurs as ice-gray grains which usually vary in size from one-half to three millimeters. It occasionally shows Carlsbad twinning and almost invariably sericitization.

Cordierite occurs fairly commonly throughout all members of this series, but is decidedly more abundant in the Thermal Canyon than in the typical Berdoo series. It usually occurs as relatively small anhedral grains, the largest of which rarely exceed two millimeters in width. It is colorless in thin section, and, excepting for some occurrences in the Thermal Canyon, is always fresh and free from inclusions. In the Berdoo series the grains are always small and untwinned; in certain parts of the Thermal Canyon where larger grains occur, they show both polysynthetic twinning and sericitization. One of the indices of refraction of the mineral is about equal to that of the O ray of quartz, while the other is considerably higher. It usually shows pale straw yellow interference colors in sections in which quartz appears gray. It is biaxial, negative, with the angle

2V ranging from forty-two degrees to eighty-three degrees.

Hornblende was found in almost every thin section. It is usually quite pleochroic, directions parallel to both X and Y showing a greenish yellow, while directions parallel to Z show dark green to bluish green. Maximum values for the angle Z to c as measured on the microscope stage ranges from nine degrees to thirteen degrees. Occasional grains cut approximately normal to the c axis show simple twinning, in which the composition plane is parallel to 100. A few grains of a blue amphibole, probably glaucophane, were found. Hornblende is always intimately associated with the biotite, and is more common in the Berdoo series than in the Thermal Canyon.

Quartz was found in thin sections from every rock type examined excepting some of the dense, more highly biotitic beds of the dark schist. The most frequent occurrence is as distinct anhedral grains, although some is found as a fine-grained interstitial filling. It usually shows undulatory extinction, and is quite commonly noticeably biaxial. Individual detached grains are often composed of two or three interlocking anhedral crystals of different optical orientation.

Opaque minerals consist largely of black iron oxide, although a few grains of pyrite were found. The opaques are almost invariably associated with the ferromagnesian minerals, and are fairly common in all members of the rock series under discussion.

Chlorite occurs as pseudomorphs of biotite; it is usually yellowish green in color, and often shows purplish interference colors.

Sphene occurs either as very minute specks along the borders of the biotite flakes, or as larger, more or less euhedral wedge-shaped to rhombic grains, which may attain .75 millimeters in width. The larger grains occur either in association with biotite, the lamellae of which they seem to crowd aside, or in euhedral crystals throughout the areas occupied by the feldspars. The smaller, anhedral grains are almost always intimately associated with biotite, the grain borders of which they corrode. The concentration of titanite grains is noticeably less in the western portion of the Thermal Canyon, although there is a tendency there toward larger, more nearly euhedral grains.

Zoisite occurs sparingly in all portions of the Berdoo series, a few sections being found in which it constituted about one per cent of the minerals present; it is less common in the Thermal Canyon series. It occurs as very small rounded grains which show a high index of refraction but quite low birefringence. Some grains are practically isotropic. Anomalous deep blue interference colors are rather common.

Clinozoisite, epidote, and, very rarely, allanite also occur in the Berdoo series, where they are almost invariably associated with biotite. Epidote and allanite commonly produce haloes of intense pleochroism in the biotite. Some epidote occurs in the Thermal Canyon series also, but not nearly as sommonly as in the Berdoo series.

Zircon is widely but diffusely distributed throughout the Berdoo series, but is rare in the Thermal Canyon series. It occurs as small but definitely recognizable grains of very high relief, which show bright interference colors. It is usually associated with biotite in which it almost always produces pleochroic haloes.

Small anhedral grains of carbonate, probably calcite, occur sparingly throughout both the Berdoo and Thermal Canyon series; they are more common in areas affected by sericitization. Carbonates also occur as filling of microscopic cracks in both series.

Textures. Besides the textures which are manifest to the unaided vision, and which have been described above, others, possibly of equal significance in the history of the rocks, are of such scale as to be visible only in the field of the microscope. One of the most important of these is that which George H. Anderson (5) has described, and to which he has applied the term "pseudo-cataclastic." According to Dr. Anderson, pseudo-cataclastic texture typically consists of a mosaic of fine-grained minerals which occupies the interstitial spaces between larger grains of the essential rock-forming minerals, the same as the products of mechanical granulation do in the case of mortar structure, but with the following inherent differences:

First: that the fine-grained material did not result through attrition of previously existing grains, but instead, the minerals of which it is composed were precipitated from solution by a process analogous to replacement.

Second: that the constituent minerals all interlock, instead of occurring as discrete particles embedded in a matrix; and

Third: that the mineralogical composition of the fine-grained material does not depend upon that of the larger grains which enclose it, but may include mineral species which do not occur as primary constituents of the rock mass at all.

This texture is very common in both the Berdoo and the Thermal Canyon series, but is more noticeable in the Berdoo. As developed in these rocks it consists essentially of an aggregate of unevenly sized, interlocking grains of feldspars, biotite, zoisite, clinozoisite, and epidote which occur as interstitial filling between the grains of the essential minerals of the rock mass. The range in grain size in this material is usually very great, extending from near the lower limit of microscopic visibility to about .1 millimeter.

In both series the mineralogical composition of the pseudo-cataclastic material is very nearly the same as that of the enclosing rock, but the physical relationships between the grains of interstitial material themselves, and between these and the grains of the enclosing rock, are such as to indicate that the process by which this texture was brought about was of a chemical rather than a mechanical nature. In case of mechanically comminuted material formed in place, the finer-grained material would be expected to be found in the more constricted areas between the larger grains, that is, in those areas where the supposed grinding agents approached one another more closely. This relationship does not hold in case of pseudo-clasis: a not unusual condition is to have detached, relatively large individual grains of pseudo-cataclastic material spaced at irregular intervals along the mutual boundary of two large grains, both of which they invade, while much finer-grained material occupies relatively wider interspaces nearby. The more common condition is to have the grains of the essential minerals partly or completely separated from each other by an irregularly shaped band or zone of about .01 millimeter to .5 millimeter in width which is crowded with fine-grained, variously oriented minerals which mutually interlock, and which invade the boundaries of the adjoining grains of the essential minerals. The relationship is exactly that which would obtain were the original grain boundary a mineralizing fissure, along the walls of which solution and deposition, that is, replacement, had taken place.

In these rocks pseudo-cataclasis seems to have been a selective process: the most typical developments always occur between large feldspar grains of contrasting composition, such as potash and soda-lime feldspar, in which case the pseudo-cataclastic material occupies a relatively wide zone, and consists of grains which appear to be potash and soda feldspars. Between two soda feldspars, on the other hand, this texture is developed only sparingly. An important exception to this rule, however, is afforded by the cases in which the pseudo-cataclastic material consists of biotite and quartz, which develop extensively between grains of like mineralogical composition.

Pseudo-cataclasis can be seen in these rocks in various stages of development, and seems to be but the initiation of a general process or recrystallization, which, were conditions to persist for a sufficient length of time, would eventually affect the entire rock mass.

Another morphological feature which is very wide-spread throughout both of these series, but which is more nearly a microstructure than a texture, is myrmekite. This is an intergrowth of plagioclase and vermicular quartz, which occurs as a replacement of the borders of feldspar grains. According to J. J. Sederholm (6) the host mineral is almost invariably a potash feldspar; in the rocks being discussed here myrmekite has been found occasionally invading grains of plagioclase also, but never as extensively as in case of potash feldspars. It is very commonly associated with pseudo-cataclasis in cases where the product of that process is feldspathic; the quartz vermiculae can then be seen traversing pseudo-cataclastic grains of plagioclase in dense concentration.

In agreement with the findings of Sederholm, myrmekitization here, too, seems to be confined to the earlier stages of metamorphism, since in the more completely recrystallized portions of the rocks it is comparatively rare.

Origin of the Thermal Canyon Series. It has already been shown how in the field when following the Befdoo series westward from its more typical development a transition zone is met with within which the features which indicate a sedimentary origin for these rocks gradually become obliterated, and other features more nearly like those which would be expectable in an igneous rock gradually develop in their stead. The same transition manifests itself in the microscopic features of these rocks, where it is seen to include a very much wider area than is evident in the field.

About the first change noticeable in this process of transition is the practically simultaneous appearance of quantities of dark green chlorite and of two varieties of white mica. The chlorite was formed directly from the biotite, and is always pseudomorphous after the biotite flakes, shreds of which quite frequently still remain within the chlorite flakes. In the formation of chlorite from biotite more or less iron is discarded; here, this usually crystallizes out as magnetite, which appears as small grains in the chlorite.

Not infrequently some sphene also forms at this stage of the process; it appears as small grains aligned along the cleavages of the wasting biotite flakes. The association of titanite with biotite is quite noticeable throughout these rocks; it very often invades the borders of the biotite flakes in such a manner as to suggest its having formed through decomposition of the biotite. The only constituent of sphene which biotite would not normally be expected to yield, titanium dioxide, could be present in solution during many of the various stages of metamorphism, as sphene grains are rather common throughout the Berdoo series; it could also quite conceivably have been present as an ingredient of the original biotite itself.

White mica, as mentioned, appears in two varieties at about the same time as the chlorite, and apparently these are derived from different sources. Large quantities of medium to coarse-grained muscovite develop at the expense of biotite, the place of which it fells in the interstices between the feldspar grains. It is noticeably finer-grained than the biotite which it invades and replaces.

The finer-grained variety of mica commonly referred to as sericite appears simultaneously with the phlogopite. It first appears as minute flakes, visible only at high magnification, which occur as disseminations throughout feldspar grains. With advance of the process of metamorphism these specks very quickly increase in area, and may, occasionally, replace the entire grain. Some thin sections, notably those from the outer limits of the transition zone, show all of the older feldspars as having been converted to sericite. The grain size always remains small, even in the most advanced stages of sericitization, so that identification usually has to depend on physical appearance and on the more easily determined optical properties.

A certain amount of exceedingly fine-grained carbonate usually appears among the sericite. On account of the smallness of the grains it gives lower interference colors in polarized light than does the more massive carbonates of the average thin section, so that it could easily be mistaken for sericite. It probably represents calcium discarded during sericitization of lime-soda feldspars.

The initiation of a process of general recrystallization by the alteration of high temperature minerals such as biotite and feldspar to comparatively low temperature minerals such as chlorite and sericite might as first sight seem anomalous. As described, the typical Berdoo series can be considered the product of a somewhat advanced grade of metamorphism; it is composed of a mineral assemblage which, strictly speaking, would not be stable at temperature conditions which differed greatly from those under which it formed. Its continued preservation is due to the vanishingly slow rate of change imposed on it by the low temperature to which it is subjected. Any increase in temperature which would affect a mineral assemblage of this kind would tend to accelerate the rate of chemical reaction; as long as the temperature remained below the stability range of the given mineral assemblage all chemical reactions would be in the direction of substitution of lower temperature minerals for high temperature ones. Hence any temperature which fell short of the temperature of formation of its component minerals would tend to cause retrograde metamorphism in the Berdoo series; also, the results of metamorphism of this kind would tend to be preserved around the edges of an aureole of metamorphism such as the outer limits of the transition zone, where the obliterating effects of further rises in temperature would be less expectable.

The changes involved in this step, which, it must be remembered, is carried to completion only in the case of biotite and its derivatives, can be summarized as follows:

orthoclase - plagioclase - biotite - muscovite (?)

↓

sericite - chlorite - muscovite - magnetite - sphene

The next step in the process of recrystallization is the formation of pseudo-cataclastic texture. This involves the formation of feldspars, biotite, and occasionally such minerals as hornblende, zoisite, and epidote; in short, a mineral assemblage very similar to that which constitutes the Thermal Canyon series begins to appear. At this stage the amount of sericite present sharply decreases; it never entirely vanishes, however, as more or less of it can be found within the grains of potash feldspar and cordierite even in the most completely recrystallized portions of these rocks.

Very shortly after the first appearance of the pseudo-cataclastic texture myrmekite begins to appear. It soon becomes very common, but individual masses never become large, .1 millimeter being about the upper limit of width for this material.

Its range of stability is apparently narrow, since, with advancing metamorphism it soon vanishes, probably through absorbtion of its constituent minerals by adjoining grains.

The changes involved in this step can be summarized thus:

orthoclase - sodic oligoclase - sericite - chlorite - muscovite - magnetite - calcite

↓

calcic oligoclase - biotite - zoisite - clinozite - epidote

Further advances in the process of recrystallization are marked by increases in the widths of the interstitial areas and by increases in the size of the grains which form the pseudo-cataclastic material, rather than by the formation of new minerals. This is accompanied by a relative decrease in the number of grains in these areas, since the larger grains here tend to develop by replacing not only portions of the older primary minerals, but the smaller grains of the interstitial areas as well. The resemblance to cataclastic texture gradually decreases, and finally vanishes completely, since, with increase in grain size the interlocking relationship between grains becomes increasingly obvious.

The newly forming biotite is less conformable to definite planes than was the biotite of the typical Berdoo series, which by its attitude imparted to the entire series an appearance of stratification. In thin section no evidence of conformity between individual flakes of this mineral can be seen at all, although in the field the attitude of the early and now almost entirely obliterated bedding can often be seen, even in the most thoroughly recrystallized portions of the Thermal Canyon series.

One step, the position of which in this sequence has not as yet been very clearly established, is that marked by the appearance of the mineral cordierite. The conditions favorable for the formation of this mineral seem to cover a wider range than did those of the features which have been here used as indicators of the progress of the metamorphic processes. Its first appearance sometimes slightly precedes, sometimes follows the first appearance of myrmekite. The smaller grains of cordierite are always fresh, untwinned, and free from inclusions. Later, however, after the grains have attained dimensions comparable to those of the feldspars, they may show polysynthetic twinning and sericitization.

The final stage in this process of recrystallization is represented by the typical Thermal Canyon series rocks. These, as has been seen, have attained a texture which is comparable to that of the Berdoo series, although the range in grain size is somewhat greater. There are also some mineralogical differences between the two series:

The plagioclase feldspars are slightly more calcic in the Thermal Canyon; although the prevailing composition in both is within the limits conventionally set for oligoclase, the anorthite content, as determined by measurements of extinction angles, is prevailingly higher in the Thermal Canyon.

Quartz and cordierite are both more common in the Thermal Canyon than in the Berdoo. Cordierite seems not to have been an original constituent of the Berdoo series at all, but probably resulted entirely from the later recrystallization to which the Thermal Canyon series is due. The increase in quartz doubtless represents silica discarded during the formation of oligoclase and of cordierite from such minerals as potash feldspars, albite, and sericite.

To supplement the field and laboratory studies chemical analyses were made of four rock specimens which had been chosen so as to typify as nearly as possible the more significant stages of the process of recrystallization. The percentage composition of these samples is shown in the following table.

Table II

Chemical Analysis

of Indio and Thermal Canyon Series Rocks

	1*	2	3	4
SiO_2	64.73	64.40	64.07	67.63
TiO_2	.08	.05	.07	.07
Al_2O_3	14.03	14.52	14.95	14.46
Fe_2O_3 . . .	1.70	1.81	2.92	2.27
FeO	6.80	4.06	4.61	4.30
CaO	2.31	4.33	4.72	3.03
MgO	2.19	1.95	1.96	2.25
Na_2O	2.21	3.95	2.65	2.30
K_2O	3.29	2.96	2.88	3.01
H_2O at 105 C . .	.87	.46	.38	.17
H_2O above 105 C .	1.84	1.55	.72	.26
P_2O_5	none	none	none	tr.
Cl	.05	.03	.03	.04
SO_3	none	tr.	none	.13

(Ed Eisenhauer, Jr., analyst)

*No. 1. Field specimen No. 7679.75. Dark schist, Berdoo series.

No. 2. Field specimen No. 7616.60. Transition zone, near Thermal Canyon contact.

No. 3. Field specimen No. 7484.00. Typical Thermal Canyon series rock.

No. 4. Field specimen No. 7751.55. Lobe of Thermal Canyon series, near transition zone.

These samples were all taken from exposures in the East Coachella tunnel; numbers 1, 2, and 3 constitute a progressive series which show a continuous and comparatively uniform gradation from slightly recrystallized Berdoo to typical Thermal Canyon, while number 4 is, in effect, a special sample which was intended to compare the chemical composition of a somewhat local intensely recrystallized portion of the Berdoo with the typical Thermal Canyon, as represented by number 3.

Number 1 was chosen to represent typical Berdoo series rock, unaffected by the later recrystallization; in the microscope, however, it does show considerable sericitization and pseudo-cataclasis, because, as has been mentioned above, the actual aureole, here referred to as the transition zone, extends farther into the Berdoo series than is discernible to the unaided vision. Number 2 was taken from a point about one mile farther to the southeast, that is, nearer to the Thermal Canyon, and definitely within the transition zone. Number 3, chosen to represent the typical Thermal Canyon, was taken from a point some four miles southeast of that from which Number 2 was taken.

As has been indicated (Plate I), the contact between the transition zone and the Thermal

Canyon as shown by its trace on the surface, is very irregular; its trace on a vertical plane normal to its strike would, it appears, be even more irregular. Exposures in the tunnel, when referred to the surface above, show that the aureole not only widens greatly with depth, but has several "cupolas" of intense recrystallization invasive into the Berdoo series, within which the rock is exactly similar to that of the Thermal Canyon. Sample number 4 was taken from one of these at a point some 7200 feet northeast of that from which number 1 was taken.

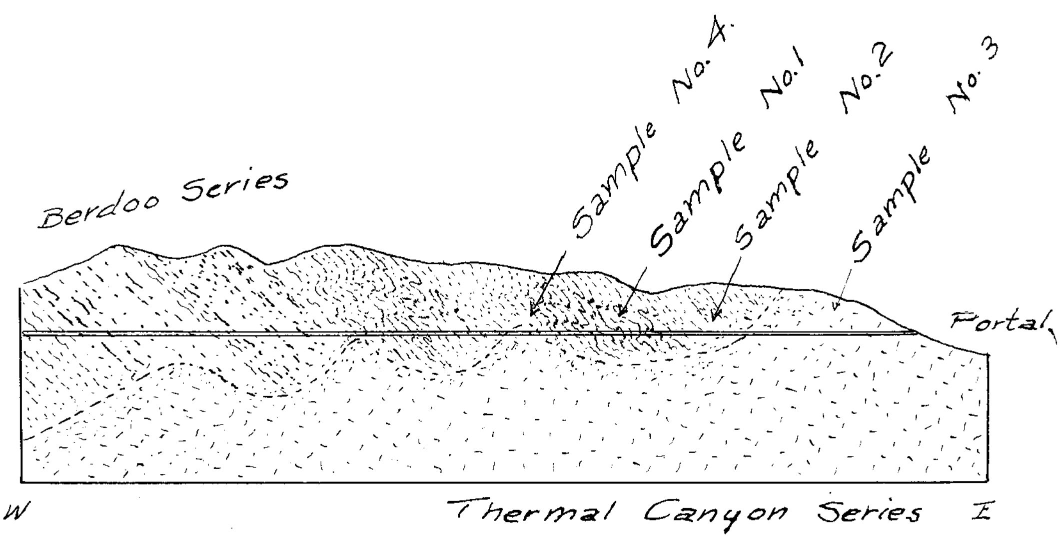
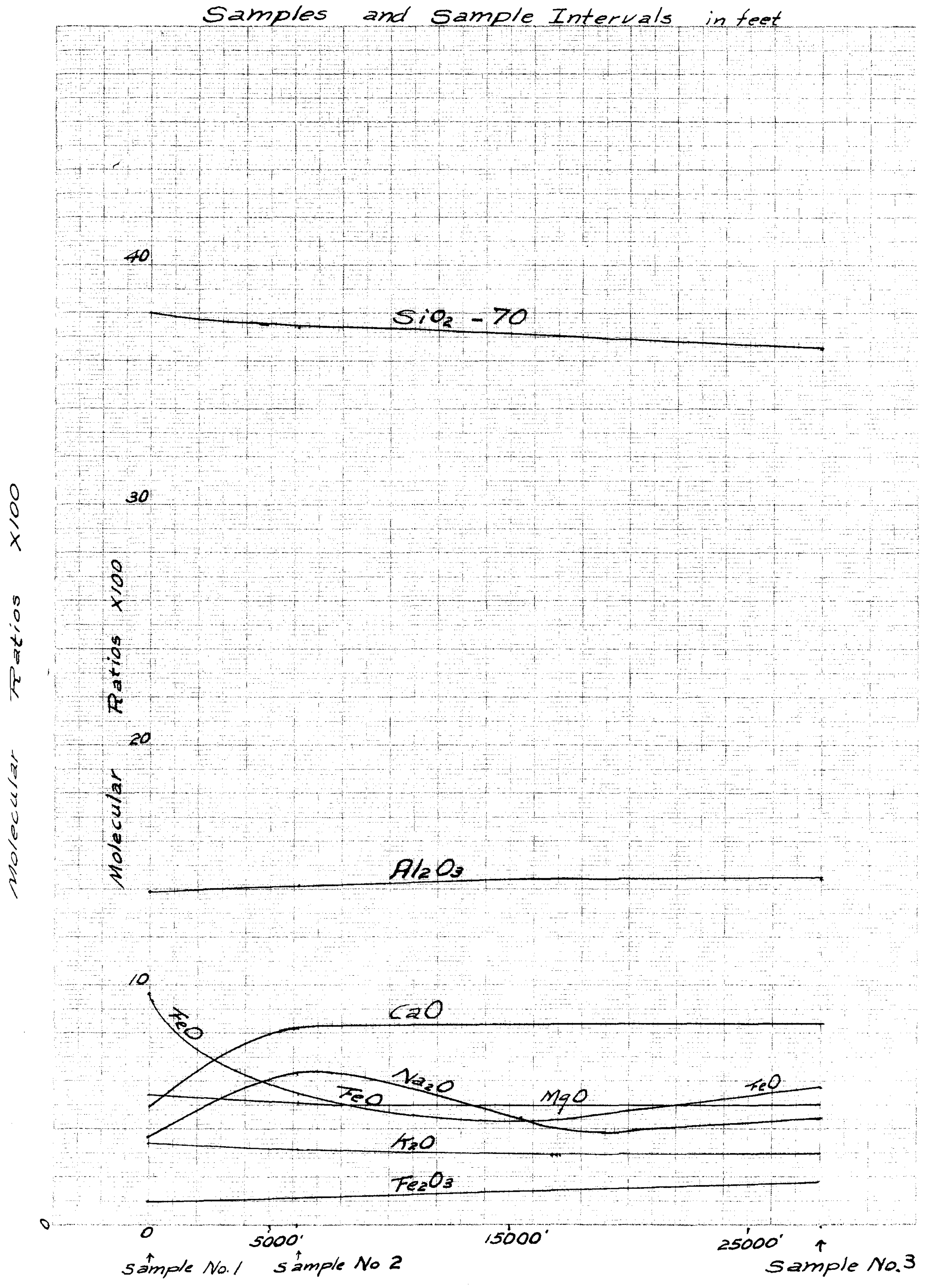


Fig. 3. Vertical Section, East Portal, East Coachella Tunnel, showing locations of samples analyzed.

Scale- 1" = ± 10,000'



Samples and Sample Intervals in feet
Molecular Ratios X100
Molecular Ratios X100
40
30
20
10
0
SiO_2 - 70
Al_2O_3
CaO
FeO
Na_2O
FeO
MgO
FeO
K_2O
Fe_2O_3
0
5000'
15000'
25000'
Sample No. 1
Sample No 2
Sample No. 3

The chemical changes which took place in the rock during recrystallization are shown graphically in the diagram (Plate I) which is similar to that used by Pirsson to illustrate magmatic differentiation. (Pirsson, L. V., 20th Ann. Rept. U. S. Geol. Surv., pt. 3, p. 571, 1900.) The abscissas here used are distances in feet along the tunnel, which in this part of the area crosses the contact very nearly at right angles; the ordinates are the molecular proportions of the oxides, as shown in Table II. In order to condense the diagram the curve for silica has been plotted seventy ordinate divisions below its true position.

Since sample number 4 does not constitute a member of the same series as numbers 1, 2, and 3, the results obtained from it are omitted from the diagram, but will be discussed later.

Significance of Analyses. In the following remarks, numbers 1, 2, and 3 will be considered first; number 4, the status of which is slightly different, will be discussed later.

These analyses show a definite and fairly progressive subtraction of iron. In view of the results of the petrographic study, this was to be expected. In the earlier stages of recrystallization a certain amount of iron was liberated through the alteration of biotite to chlorite and to white mica; a large part of this iron, to be sure, remained in the rock as magnetite, but in a system in which a certain amount of circulation was taking place, some material would be bound to be carried off during any process of adjustment which included solution. Also, somewhat later, shortly after the first appearance of pseudo-cataclasis, iron-bearing minerals such as epidote and allanite appeared in quantity, but with advancing recrystallization they disappear almost entirely. Much of the iron liberated during the destruction of the epidote and allanite went into the formation of biotite from chlorite and white mica, but at this time also a considerable proportion could quite conceivably be carried off in solution.

During the later stages of recrystallization there appears to have been some introduction of iron: in the diagram the curve which indicates the molecular proportions of the ferrous oxide descends sharply between numbers 1 and 2, that is, within the zone of supposed greatest abstraction of iron. When readjustment progressed beyond the stage of destruction of existing iron-bearing minerals and into that of formation of new ones, removal by solution greatly decreased. During the further progress of recrystallization the iron content of the rock increased slightly, as shown by slight rises in these two curves from number 2 to number 3.

In case of the ferric oxide, on the other hand, there seems to have been a progressive and uniform increase throughout recrystallization. This may be due to the comparative stability of the mineral magnetite, which appears in more or less similarly sized grains in both series.

The alumina content, which when compared with that of iron and magnesia, and especially with that of lime, is quite low, remained practically constant throughout. The low ratio of alumina to calcium, iron, and magnesium probably had an important bearing on the course which the metamorphism took, and on the minerals which resulted from the recrystallization. The absence of garnet in these rocks was a source of wonder during the field examination, and later during the petrographic study; in the examination of over two hundred and fifty thin sections only one grain of garnet was seen, and none at all was seen in the field. A possible explanation may be found in the low alumina ratio, together with the recognized instability of chlorite and sericite in the presence of calcite. Turner (7) found, while studying the recrystallization of a green schist which was somewhat similar in composition to the Berdoo series, that garnet formed only in those portions which contained alumina in excess of the amount required to form biotite, hornblende, and oligoclase from chlorite, sericite, and albite. In the case of the Berdoo series all the available alumina would have probably been used up in the formation of biotite and in the conversion of potash and soda feldspars to oligoclase before attainment of the grade of formation of garnet.

The analyses show an increase in Na_2O and a decrease in K_2O; this also is in line with the results expected from the petrographic study, in which the replacement of orthoclase by oligoclase was noticed. The increment in sodium doubtless represents introduction by solutions during recrystallization. During the earlier stages of recrystallization the potash feldspars were apparently being replaced by sodic plagioclases; with rising temperatures the percentage of anorthite which albite is capable of holding tends to increase, so that in the higher grades of metamorphism sodium may gradually give way to calcium [Harker (10), p. 93.] Hence, in the initial stages of recrystallization of feldspathic rocks there may take place a considerable and relatively sudden increment in sodium, which in part tends to displace potassium; with advancing metamorphism, however, the sodium tends to be displaced in part by calcium. The operation of these tendencies is indicated in the diagram (Plate II) which shows the curve for Na_2O rising sharply from sample number 1 to sample number 2, but falling somewhat from sample number 2 to sample number 3.

In the petrographic study it was found that very early in the period of recrystallization such calcium-bearing minerals as zoisite, clinozoisite, and epidote begin to appear, but with advancing metamorphism are seen to give way to hornblende and biotite. With advanding metamorphism likewise appeared a progressive anorthitization of the plagioclase. The effects of these diverse processes on the calcium content of the rocks are reflected in the analyses, which show a considerable increment in calcium between samples number 1 and number 2, and a relatively slight increment between numbers 2 and 3.

Silica shows a very slight although progressive decrease with advancing metamorphism; this decrease is proportional to the increase in alumina, by which it is very nearly offset, so that it seems reasonable to correlate part of the variation in these compounds also with the anorthitization of the feldspars.

The rock from which sample number 4 was taken could be said, in regard to degree of metamorphism, to lie between numbers 2 and 3. Having come from a localized cupola where, due to the impounding action of the enclosing rocks, the effects of mineralizers would be more noticeable, its composition varies somewhat from that of numbers 2 and 3. Nevertheless, in such constituents as alumina, lime, soda, and potassium oxide, it shows a fairly uniform gradation between numbers 2 and 3.

Summary and Conclusions

From the foregoing study it is evident that the northwest portion of the East Coachella Tunnel area is formed of regionally metamorphosed rocks which are of sedimentary origin; also, that in following these rocks southeastward a zone of gradual transition is encountered within which all structures reminiscent of a sedimentary origin give way to those which usually characterize an igneous rock; and finally, that these latter structures once established prevail to beyond the limits of the area under discussion here.

In the petrographic study of these rocks a gradual process of recrystallization was noted, the progress of which was followed from the first noticeable change in the metamorphosed sediments which constitute the Berdoo series through the various intervening stages to the end-product, the Thermal Canyon series.

Chemical analyses, too, show the existence of a close relationship between the Berdoo series and the Thermal Canyon, such slight changes as were noted being gradual, and always in accord with the conditions observed in the field and in the petrographic laboratory.

Thus, the results of field, petrographic, and chemical methods of investigation were such as to render inevitable the conclusion that the massive rock in the southeast portion was derived by recrystallization from sediments which once constituted the entire area. There remains now but to show, by reviewing the available evidence, how such recrystallization could be brought about.

With this object in view, certain peculiar featureswhich characterize the recrystallization of the Berdoo series will now be considered, together with such inferences and conclusions as seem to follow logically from the facts as ascertained.

It is quite apparent that the process by which recrystallization was effected was local rather than regional in its nature; it is also clear that during the process the rock never lost its rigidity, since inclusions and traces of bedding still maintain their conformability with the regional attitude of the Berdoo series.

Recrystallization seems to have been initiated as an incomplete process of retrograde metamorphism, which resulted in the formation of an unstable mixture of high temperature and low temperature minerals. This was followed by a process of general recrystallization, which apparently was initiated as replacement along grain boundaries of the older minerals. From these loci it developed until it replaced practically all of the previously existing minerals, thus bringing about the formation of a new rock. The newly formed mineral assemblage was of very nearly the same chemical composition as that from which it was derived, although the new feldspars were prevailingly more calcic than those of the parent rock. Throughout the recrystallization the chief motivating agency seems to have been heat, with but little substitution of materials.

Whatever the source of the heat may have been, a copious supply is indicated, judging by the volume of material affected. The local topography exposes a vertical section of about 2000 feet of Thermal Canyon series rocks, within which interval there exists no discernible variation in degree of recrystallization. In the case of a rock as dense and apparently impervious as the Berdoo series, this condition is scarcely compatible with the idea of a limited supply of heat.

The feldspars of the Thermal Canyon series are prevailingly more calcic than those of the Berdoo series; this, according to the results of recent investigations, indicates a higher grade of metamorphism for the Thermal Canyon series as compared with the Berdoo series. Phillips in studying green schists of various grades of metamorphism found that with increasing temperature the plagioclase feldspars became more calcic, the composition ranging from $Ab_{97}An_3$ in the chlorite zone to $Ab_{63}An_{37}$ near the boundary of the kyanite-sillimanite zone. Vogt (9), Turner (7), and Harker (10) record similar observations.

Considering the localized nature of the recrystallization it would appear reasonable to postulate a subjacent intrusive as the source of heat. The possibility that a large intrusive underlies the Thermal Canyon series is suggested by the existence in this region of several outcrops of igneous rocks, all having approximately the same composition, namely the Fargo stock, with its many outliers. (See Pl. I.)

However, many authorities, among whom are Larsen (11), Billingsley and Locke (12), and especially

Bowen (13) seriously doubt the existence of much superheat in intrusives in the upper part of the earth's crust. In this connection it is worthy of note that the less highly recrystallized portions of the Thermal Canyon are to be found in immediate contact with the Fargo stock.

Even if intrusives in themselves were to be found inadequate as sources of heat, conditions connected with their emplacement might quite conceivably result in large scale tranference of heat from the earth's interior.

Gilluly (14) in describing a granite of replacement origin discusses four possible sources for the heated solutions which brought about granitization: 1) nearby portions of the solid diorite (intrusive); 2) the intruded greenstones; 3) rest-magma solutions of local source; 4) hydrothermal solutions of deep-seated origin.

Of these, the fourth was found to be the most probable source, breccia zones which occur within the intrusive being supposed to have served as channels of access.

Gustafson (15) in discussing the genesis of the Homestake ore-body postulates hot ascending waters, probably of connate but possibly of magmatic origin, as distributors of heat, these in turn deriving their heat from deep-seated igneous intrusions.

In the case of the recrystallization of the Berdoo series the only source of heat which seems to be accordant with the observed conditions is that afforded by ascending emanations of magmatic origin. In this area no large scale sturctures were found which could have served as passage-ways for such emanations; however, a deep-seated igneous intrusive could furnish a passage-way during the interval between the time of its emplacement and that of its final consolidation.

The influence of circulating fluids is manifest in all phases of the recrystallization. Sericitization and chloritization are usually regarded as hydrothermal processes even in mineral assemblages where no transfer of material is involved; in the case of the Berdoo series, it will be recalled, some ferrous oxide was removed and some soda and lime introduced during the lower temperature phases of the recrystallization.

In the later phases more striking evidence of the instrumentality of circulating fluids was furnished by the close association of the newly forming minerals with local passage-ways such as grain boundaries and interstitial spaces. Besides the introduction of new material there took place considerable transfer of material which existed within the rock mass itself. The biotite of the Berdoo series, it will be recalled, usually occurs as fairly definite bands, while that of the Thermal Canyon characteristically occurs as fortuitous disseminations throughout the rock mass.

Although the medium which carried the heat must have had relatively free access to the original rock, judging by its widespread thermal effects, its progress through it, as far as available evidence shows, was not along fissures but along openings of such minute order of magnitude as grain boundaries. This is shown by the fact that the final recrystallization always began as interstitial replacement, and that the Thermal Canyon itself shows no evidence of the existence of open passage-ways for mineralizers, such as veins or fissures. Permeation was effected probably in a manner analogous to that by which certain media produce extensive alteration in rocks enclosing ore-bodies, as in the case of the Boulder batholith in the neighborhood of Butte.

Regarding the nature of the fluids which were instrumental in bringing about these changes little can be said; their own direct effects on the rock were less than those of the heat which they brought. The completeness with which they permeated the rock suggests that they must have included gases, while their transportation of chemical compounds indicates that they also included liquids. Chemically, they appear to have been relatively inert; as solutions they were probably of very lean concentration. During the earlier stages of recrystallization some ferrous iron, lime, and soda were removed, while in the later stages all of these compounds appear to have been added. This does not necessarily mean any change in the concentration of the solutions; under temperature conditions which would induce katamorphic action in the existing mineral assemblage a solution of very lean concentration might dissolve additional quantities of compounds which it already carried in solution, while later, when the country rock would have become more highly heated, conditions favoring the formation of minerals rich in these compounds might bring about their precipitation.

No direct evidence could be obtained regarding the time in which this recrystallization took place, so that the age of the Thermal Canyon was not found to be definitely determinable. The close of the Jurassic was marked by intense igneous activity along the Sierra Nevada, to which epoch the emplacement of granitoid rocks in the San Bernardino and San Jacinto mountains have been referred (references 3 and 4). In the absence of more definite information the recrystallization which resulted in the formation of the Thermal Canyon series will likewise be correlated with the late Jurassic epoch of igneous activity.

The Fargo Granite

The Fargo Granite occurs chiefly as a stock which intrudes the Thermal Canyon series near the head of the west branch of Little Fargo Canyon. (See Plate I.) The outcrop here is about one and one-half miles long and one mile wide, the total area exposed being about two square miles. It is a very homogeneous rock, and is slightly more resistant to erosion than the enclosing Thermal Canyon, so that it forms rounded hills which contrast sufficiently in color with the surrounding rocks to constitute a prominent feature of the landscape.

Other outcrops of this rock, each of a few hundred square feet in area, occur at various localities throughout the area in which the Thermal Canyon series is exposed, the largest of these being that on the ridge between Front Hill and Thermal canyons near the southeastern limits of the area.

It is prevailingly of a reddish color, and in the field appears to be quite fresh. As will be seen from the following description, this rock to which the general field term "granite" has been applied approaches a quartz monzonite in composition.

A typical hand specimen (F 16) shows the following mineral assemblage: pinkish gray orthoclase, in grains two to five millimeters in length, which seem to constitute about sixty per cent of the specimen; ice gray plagioclase, difficultly distinguishable from quartz, in grains one millimeter to four millimeters long, and constituting about thirty per cent of the specimen; light gray quartz, in grains one millimeter to two millimeters long, and constituting six to eight per cent of the specimen, and dark minerals which appear to consist of altered biotite, two to four per cent. These minerals occur as interlocking, allotriomorphic grains which usually show no structural arrangement, although occasionally indefinite banding is discernible.

A border zone of from two to ten feet wide toward the margin of the intrusive is finer grained, darker colored, and less fresh looking. The orthoclase in this zone appears to have been replaced by a darker colored plagioclase.

Petrography. In thin section the Fargo granite appears to be of very uneven texture, the grain size ranging from five millimeters down to .05 millimeter. Rosiwal analysis of a thin section made from a typical specimen showed the following composition:

Table III.

Rosiwal Analysis of Fargo Granite

Orthoclase	54%
Plagioclase	35%
Quartz	10%
Chlorite, biotite, etc. .	1%

Specimen FG6, Fargo stock
250 feet from margin

Under the microscope this rock is seen to be profoundly altered, many of the grains being surrounded by reaction rims. The degree of alteration of individual minerals varies greatly in different parts of the same thin section, the contrast being such as to suggest that some minerals are much older than others. On the basis of degree of alteration the mineral grains of the Fargo granite could be divided into two sub-equal groups, one consisting of highly altered individuals, another of quite fresh ones.

The group of highly altered mineral grains includes over eighty per cent of the orthoclase and about thirty per cent of the plagioclase of the rock. These minerals occur as large, highly sericitized, and nearly opaque grains, the boundaries of which are invariebly corroded by narrow fringes of fresh looking feldspars and quartz. Both orthoclase and plagioclase show beautiful examples of the structure Colony (16) has described as "injection perthite", the intercalated material usually being quartz. The orthaclase occurs in grains three to five millimeters wide which have reaction rims .1 to .5 millimeter wide consisting of quartz and untwinned plagioclase.

The altered plagioclase grains are usually somewhat smaller than those of the orthoclase, and invariably show polysynthetic twinning. The composition, as determined by extinctions on albite twinning, ranges from Ab_6An_4 to Ab_8An_2. The reaction rims which surround the plagioclase grains are also twinned, the bands of the new material in every instance being perfectly aligned continuations of the bands of the older portion.

This group of highly altered grains includes all of the biotite in the rock. Actually very little biotite remains in this rock, its place being taken by yellowish green chlorite, magnetite, and very minor amounts of limonite. Such biotite as does remain occurs as narrow shreds, the optical properties of which are difficult to determine.

In contrast to the sericitized and altered grains just described stand other groups which consist of plagioclase, quartz, and probably orthoclase, all of which are quite fresh. These occupy broad zones between clumps of interlocking grains of the sericitized material, the grain borders of which they invade and corrode. The plagioclase is almost invariably untwinned, but the index of refraction is that of oligoclase. The range in grain size is from two millimeters to less than .1 millimeter. Quartz carries trains of dust-like inclusions and is often noticeably biaxial; the grain size varies from four millimeters to the lowest limits of visibility under the microscope. A few grains which are probably orthoclase also occur in this material; they are usually too small to determine accurately.

Myrmekite occasionally occurs as a constituent of reaction rims throughout the intrusive, and is quite common toward the borders. In this rock it seems to affect only the potash feldspars.

Pseudo-cataclasis is not common, and where seen is not characteristically developed: in this rock the newer recrystallization which occurs along grain boundaries typically consists of but a few units of continuous optical orientation, rather than a number of individually oriented grains as in pseudo-cataclasis.

Relationship to Enclosing Rocks. The Fargo stock lies entirely within the Thermal Canyon series, a rock in which most of the local details of bedding have been obliterated; in the immediate neighborhood of the stock, however, especially along the north-eastern and southern contacts, the attitude of the bedding can still be quite plainly seen. In almost every instance in which determinations can be made, the contact of the Fargo stock very nearly conforms to the attitude of the Thermal Canyon. In horizontal plan the bedding of the Thermal Canyon seems to sweep around the Fargo stock as if crowded aside by it; according to exposures afforded by the deeper canyons, the contact always dips outward at an angle slightly steeper than that of the bedding, which itself dips outward at angles which decrease progressively with distance from the intrusive. The physical relationship which appears to exist between these two rocks is very nearly that which would obtain had the magma of the Fargo stock been forced upwards through the more or less horizontally bedded rocks of the Thermal Canyon series, the latter being crowded aside and partly dragged upwards during the process.

Age. From the foregoing it is obvious that the most definite statement that can be made regarding the age of the Fargo intrusive is that it is younger than the Thermal Canyon series. This, admittedly, is a rather unsatisfactory statement, especially when it is remembered that the age of the Thermal Canyon itself was found to be more or less indeterminable.

Vaughan described a granite from the San Bernardino mountains, the cactus granite, which apparently is very similar lithologically to the Fargo; this rock he provisionally correlated with the Sierra Nevada intrusion.

If the recrystallization which produced the Thermal Canyon was brought about by intrusions during the late Jurassic, it is quite possible that the Fargo granite represents a slightly later phase of the same general epoch.

Associated Dikes and Sills. Throughout the entire area, but more especially in the portion south of the Berdoo Canyon numerous intrusive sheets of pink granite porphyry occur, most of which are very similar in mineralogical composition to the Fargo granite. These occur in various widths, usually from one or two inches up to ten or twelve feet, and are very persistent, individuals only a few inches wide often being traceable for several hundred feet.

The larger of these sheets are shown on the geologic map (Plate I); most of these occur along faults, many of which show evidences of movement since injection, such as shearing and slickensiding of the intrusive rock. Some of the wider masses, such as those along the north side of upper Indio Canyon, are conformable to the bedding of the enclosing rock.

The significance of these intrusive sheets in problems of engineering geology is discussed under a separate heading.

Bench Gravels

A large portion of the surface of the East Coachella Tunnel area is constituted by bench gravels. These occur in all of the deeper canyons in deposits which range from twenty to upward of three hundred and fifty feet in thickness, and are continuous with the deposits which form the floor of the Coachella Valley. They always consist of boulders of the rocks which prevail in the particular locality where they occur, that is, Berdoo series rocks in the western, and Thermal Canyon or Fargo rocks in the eastern portions of the area. The fragments are usually subangular in form, and vary in size from five or more feet across, to dimensions expectable in ordinary sand grains. Consolidation is usually sufficient to permit of the formation of vertical cliffs fifty to one hundred feet in height, the cementing medium, which is scarcely ever discernible in the field, being calcium carbonate.

Although these gravels are still being deposited, the rate of removal at the present time greatly exceeds that of deposition, so that existing deposits are now being deeply cut into. In Berdoo Canyon an interesting feature related to these bench gravels was disclosed by the tunnelling operations. In the neighborhood of the portal of Berdoo adit the present stream channel consists of a rock-floored trench some two hundred feet wide which lies against the south bank of the canyon. It has along its north side an array of flat-topped masses of solid rock some twenty to fifty feet in height and five hundred to one thousand feet in length, which are arranged end to end but separated from one another by "embrasures" of from fifty to one hundred feet in width, the wall thus constituted being backed by bench gravels. Berdoo adit was collared in one of these masses, but entered gravel within one hundred feet of the portal, the advance for the next thousand feet being through similar material.

The main tunnel itself crossed Berdoo Canyon at a point some two thousand feet farther upstream than that at which the adit was collared; on account of the steep gradient of the canyon as compared to the practical horizontality of the adit, this crossing was effected at a level much lower relative to the canyon floor than that at which the adit was collared. Nevertheless, here also the advance for a distance of nine hundred feet was entirely through gravel.

These conditions indicate that the canyon has been cut much more deeply than now appears, and that it has since become filled. The present stream constitutes a variety of intersequent stream, in that it has been displaced laterally southward by the accumulation of detrital material along the bases of the mountains to the north.

Age. The greater part of these gravels is quite probably of recent age; the deposits are unified throughout and represent continuous deposition to the present day. It is possible, however, that the lower portions of the deeper deposits, such as those in Berdoo and Indio, may be of Pleistocene age; accumulation of this material began with the last important uplift of the mountains, which, it seems reasonable to suppose, took place during the late Pleistocene.

Buttress Blocks. The rock masses which form the north bank of the present canyon constitute topographic features which, so far as the writer is aware, have never been described. The term "buttress blocks" is proposed for these features. Typically they consist of pier-like masses of rock which have been shaped by the downward cutting of intersequent streams the lateral displacement of which has resulted in their becoming perched on the sides of rock-filled canyons. (See Plate III)

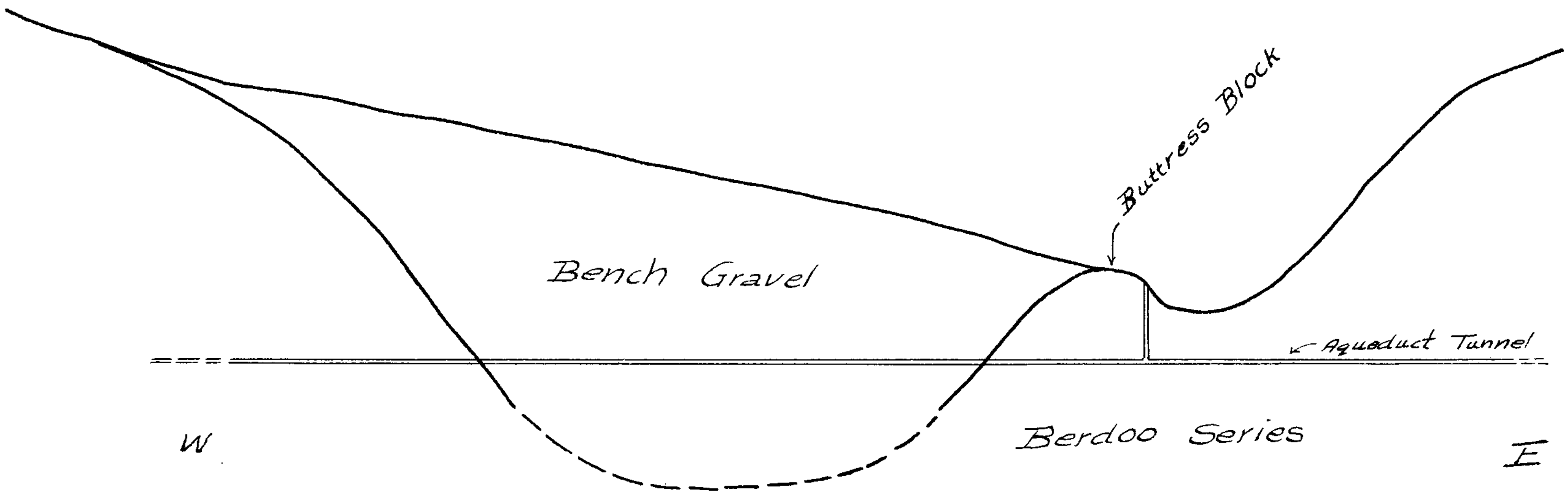


Plate III. Vertical Section along line of Tunnel, Berdoo Canyon, showing older gravel filled canyon and Buttress Block.

STRUCTURE

Introduction. A desert region of comparatively high relief usually offers exceptional advantages in the study of structure. As a rule the rocks are well exposed, and structural features commonly have a definite topographic expression. In rocks which are as homogeneous as those which constitute the Little San Bernardino mountains, however, the amount of relative displacement on faults is usually very difficult to determine, owing to the absence of distinctive beds or other features which would serve as horizon markers.

In studying the geologic structure of a region the degree of importance ascribed to the various phenomena depends largely upon the purpose for which the investigation is being made: the standard of comparison used by the geological engineer who seeks to foresee and dispose of such geologic problems as may present themselves during the execution of a given project, differs considerably from that used by the structural geologist who seeks to decipher the dynamic history of a region. In this study the standard of comparison used was that of the geological engineer, rather than that of the structural geologist. Accordingly, all faults and joint systems which were found to be sufficiently well developed to constitute problems in tunnelling operations were mapped and described, regardless of their possible lack of significance in the general regional setting.

Fault Systems. The more important faults of the East Coachella Tunnel area are to be found in the northwest portion, that is, in that portion which is composed of Berdoo series rocks. Here occur many faults of various degrees of development and of diverse attitudes. Although individual faults are often very impersistent both as regards apparent amount of movement and attitude, the faults of this portion of the area permit of separation on the basis of prevailing strike, into two groups. Of these, one, the most important both as regards number and degree of development of individual members, trends easterly, and includes such faults as those along Indio, Berdoo, and Pushawalla canyons, besides many others along which no canyons have been cut. (See Plate I.) The other, the members of which are less uniform and less conformable among themselves, trends northerly, and includes the faults in the neighborhood of Little Fargo Canyon, the upper portion of Pushawalla Canyon, and that along the West Pushawalla Canyon.

Displacement. It was not found possible to estimate the amount of displacement represented by any of the larger faults. This was because of the comparative uniformity of the Berdoo series: in many cases the rock appeared to be exactly the same on both walls of a fault, and where they did differ, it usually was a case of bringing one frequently occurring rock type against a contrasting but equally common type. There is not sufficient order to the arrangement of the lithologic members of the Berdoo series to render possible a correlation of beds, or of sequences of beds, from one fault block to another.

Direction of Movement. The comparative uniformity of the Berdoo series rendered impossible also a determination of the direction of movement on these faults. However, there are certain pecularities shown by members of both systems from which inferences may be drawn regarding the direction of movement with respect to the fault surface itself, that is, whether the faults were of the so-called strike-slip type, or whether their movement also included a vertical component. Most of the faults were found to be extremely sinuous; this condition in a rock as dense and difficultly compressible as the Berdoo series is not believed to be compatible with the idea of solely horizontal movement.

Also, Berdoo canyon, which has been carved along a member of the easterly system, is asymetrically situated with respect to its drainage basin:

the divide on the southerly side is only 1500 feet from the canyon, while that on the northerly side is over 12,000 feet distant. The rocks on the two sides of this canyon being similar, resistance to erosion in each case would be the same. The conditions observed are those which would obtain if the block north of the canyon were depressed along its southern edge, while the block south of the canyon remained stationary. In this connection it is interesting to note that tunnelling operations revealed that the gravels had been faulted along a line approximately parallel to, but slightly east of, the center line of the canyon.

Both of these conditions indicate a vertical component in the movement along the faults.

Order of Development. The general pattern of the faults in this area suggests contemporaniety of formation. The frequency with which members of one system swing into and join with members of the other indicates that both systems were forming at the same time, and in response to the same structural adjustments.

Causes of Faulting. The ascription of cause to faulting in cases in which neither the amount nor the direction of movement could be definitely ascertained, can at best be but conjectural. However, when the area is considered as a whole, certain general features can be noticed which seem to indicate a relationship between the forces which caused the deformation and those which brought about the recrystallization in the eastern portion of the area.

As can be seen on the map (Plate I) the more important faults occur in the Berdoo series rocks. The only exception to this rule is that constituted by the faults in the Fargo Canyon district, and even these, although occurring in Thermal Canyon series rocks, show in their attitude unmistakable relationship to those occurring in the Berdoo series.

Also, the two systems to which the faults of the area have been referred show a definite relationship to the contact of the Thermal Canyon series, to which the easterly system is very nearly parallel and the northerly system more or less at right angles.

These two sets of conditions, the limitation of the faults to the Berdoo series, and the relationship of the fault pattern to the contact of the Thermal Canyon series, could result through fracturing incidental to domical uplift in the area occupied by the Thermal Canyon, or to slumping in the surrounding areas. A relationship to igneous activity is suggested by the occurrence of dikes of granitic material similar to the Fargo granite along members of both fault systems.

It seems reasonable to suppose that the faulting could be brought about by domical uplife incidental to deep-seated igneous intrusion during the late Jurassic.

Evidences of Recent Movement. Throughout the East Coachella Tunnel area evidence of recency of movement is everywhere manifest. The prevailing land forms are quite incompatible with the idea of a stable land mass, and the drainage system, even in case of the wider canyons, has nowhere attained grade.

As can be seen on the general geologic map, this region is in the stage of the physiographic cycle which is known as early youth, yet the influence of structure on the distribution of the various units of the drainage system is as great as would normally obtain during maturity. This condition suggests recent uplift of a maturely dissected land mass.

The asymmetry of Berdoo canyon shows non-adjustment to present day erosional conditions; the faulting of the gravels shows that the fault along which the canyon has been cut is still active.

The Little San Bernardino mountains themselves quite probably were raised by movement on a fault along their southern base, of which, however, no trace could be found in the East Coachella Tunnel area on account of the thick deposits of recent gravels along the lower slopes of the mountains.

Age. Evidence of at least two periods of deformation are indicated in the East Coachella Tunnel area. During the first period, which preceded the intrusion of the Fargo stock, the two systems of faults mentioned above were probably formed. On the basis of its relationship to the intrusion of the Fargo stock, this period is assigned to the late Jurassic.

During a second period movement took place on most of these faults. The granitic material which had been injected along the older faults was sheared and slickensided. The fault along Berdoo Canyon, which shows no igneous intrusion, was probably formed by local block-faulting during this period.

The second period of deformation quite probably represents part of the diastrophism by which the mountains themselves were elevated. On account of the stage of dissection of the land forms resulting from it, this period is correlated with the deformation which took place in Southern California during the Pleistocene.

GEOLOGICAL ASPECTS OF TUNNEL EXCAVATION

Unfavorable Conditions. In some portions of the East Coachella Tunnel the rocks encountered were intensely indurated and had sufficient strength to stand unsupported for indefinite periods, so that excavation in these portions could proceed uninterruptedly, such supporting of ground as would from time to time be found necessary being attended to by special crews whose operations in no way interfered with the actual advancement of the tunnel. Not infrequently, however, ground conditions were such that artificial supports had to be installed immediately after blasting, the overlying rocks in these cases not being competent to bear their own weight after the removal of the natural support. Such conditions at best entail delays of a few days in the process of excavation, and if not properly disposed of, might conceivably result in the loss of the entire tunnel.

Faults and Joints. Since faults or joints were in the vast majority of cases the causes of these unfavorable conditions, a brief discussion of these, and of their normal surface expression, would seem to be warranted.

In this tunnel it was found that the amount of local disruption and shattering which affected rocks along the walls of faults was not necessarily proportional to the displacement on that fault. In a few cases faults were encountered in which the displacement was doubtless measureable in hundreds of feet, but in which the dislocation was confined to a single fissure, beyond the walls of which no deformation was discernible; this type of fault, unless its strike actually approached parallelism with the bearing of the tunnel, rarely required any especial attention at all.

Such faults may have a topographic expression quite at variance with their lack of significance in tunnelling operations.

On the other hand, systems of closely spaced parallel faults were encountered in which the movement was only a very few feet, but which caused a great deal of trouble through "running" of broken rock on the fault planes. These systems had no topographic expression at all, but in a region so nearly free from surface detritus as the Little San Bernardino mountains they could always be seen sufficiently clearly to permit of determination of attitude of individual members.

The attitude of a fault with respect to the bearing of the tunnel was found to be a very important factor in determining the amount of shattering which would be encountered in its vicinity. When it is remembered that the shattering in fault zones is always intensified by blasting incidental to tunnel excavation, it can be readily seen that under otherwise similar conditions the more closely the strike of a fault approaches the bearing of the tunnel, the more unfavorable the conditions for excavation.

The amount and direction of the dip of faults with respect to the line of advance of the tunnel are also of very great importance, especially in case of transverse faults: excepting faults which are absolutely horizontal, the lower the dip, the greater the amount of shattering which will be encountered. With respect to direction of dip, low-angle faults which dip in the same direction as the line of advance of the tunnel give more trouble than would similar faults which dipped in the opposite direction, because these actually constitute sources of danger before becoming exposed at all.

Multiple systems of faults or joints which intersect within and above the tunnel invariably result in caving and "blocky" ground. It is interesting to note that intersecting closely spaced joint systems may give more trouble than would similarly spaced gouge-filled fault systems.

<u>Dikes</u>. Dikes can be considered as faults or joints along which igneous material has been

injected; in tunnelling operations the significance of these is about the same as that of faults. Dikes along which somw faulting has taken place subsequent to injection are usually more subject to caving than ordinary faults, as the sheared igneous material seems to act as a lubricant.

Contacts. Igneous intrusive contacts are often marked by broad alteration zones within which the rock may be more or less disintegrated; when fracturing is added to these conditions the result is usually unfavorable to tunnelling operations.

The lower contacts of extrusives are almost invariably marked by deep zones of unconsolidated rock. During certain seasons of the year these contacts may furnish passage-ways for considerable volumes of water.

Favorable Conditions. In tunnelling operations today the question of time is often of more importance than that of cost, so that the conditions to be sought are those which would be most conducive to rapidity of advance. In case of soft rock, given to more or less running, such caves as occur almost invariably take place at the face during blasting. These not only effectively block off the face from all activities connected with further advancement until the caved material has all been removed, but if neglected may result in the loss of the tunnel, to say nothing of the fact that the undesired opening produced by the cave will have to be filled.

Hard rock, on the other hand, can be drilled more quickly with the powerful drills recently developed than can softer rock which tends to "ravel" or cave around the drill-steel; also, it invariably breaks off more readily in blasting, and, most important of all, it rarely requires any temporary support in advance of the permanent sheathing, thus permitting concentration of effort by the operators on the advancement of the tunnel. Such rock, if unaffected by any of the unfavorable conditions mentioned above, should constitute excellent tunnelling ground.

Surface gravels, if consolidated sufficiently to stand as vertical cliffs of ten to twenty feet, often constitute the very best of tunnelling ground; such material at Berdoo canyon, even though soft enough to permit of being dug out at will by hand, was said to have constituted the most nearly ideal ground encountered throughout the entire tunnel.

Plates IV to VII. Photomicrographs illustrating the progressive nature of the recrystallization in the transition zone between the Berdoo series and the Thermal Canyon series. Crossed nicols.X80.

Plate IV A- Slide 7837+75. Berdoo series near transition zone. Early stage recrystallization. Note selective nature of recrystallization, as shown by relatively narrow zone of pseudo-cataclastic material between orthoclase grains in center, as compared to wider zone between orthoclase and oligoclase (at extinction) towards lower right hand portion of field.

Plate IV B- Slide 7837+75. Finer grained portion of slide shown in Plate IV A. Zones of pseudo-cataclastic material slightly wider.

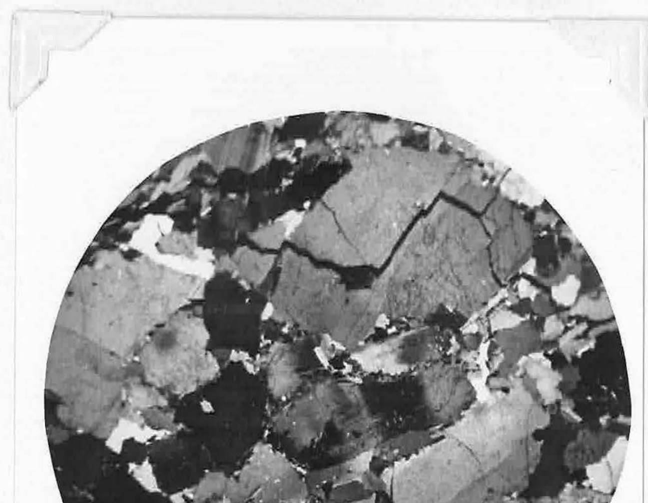


Plate V,A- Slide 7329+00. Transition zone. Grains of primary minerals completely surrounded by recrystallized minerals.

Plate V, B- Slide 7329+00. Note recrystallized biotite in upper central portion of field.

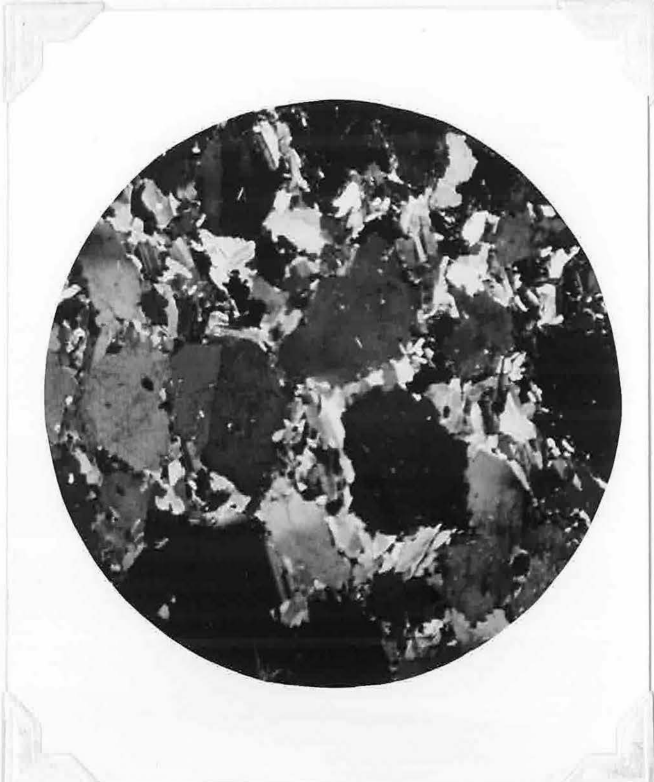
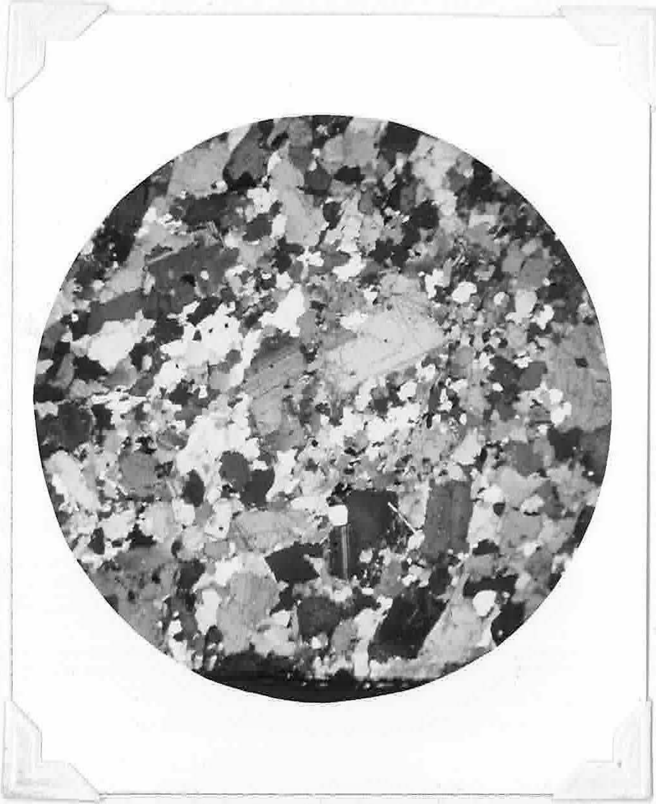


Plate VI, A- Slide 7751+55 Transition zone near Thermal Canyon series. Primary minerals almost entirely replaced. Recrystallized minerals becoming coarser grained.

Plate VI, B Slide 7396+70A. Transition zone. Large orthoclase grain completely surrounded recrystallized minerals.



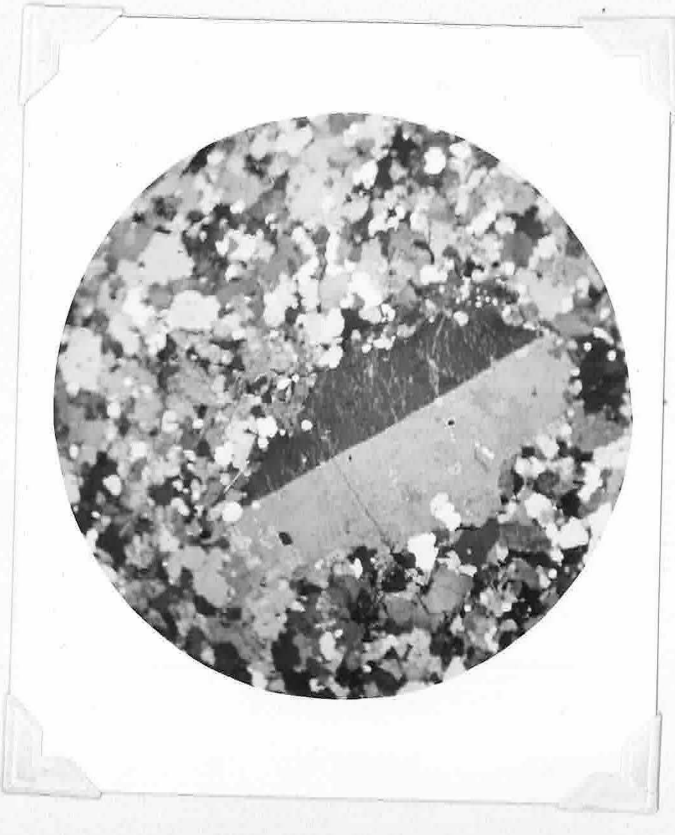
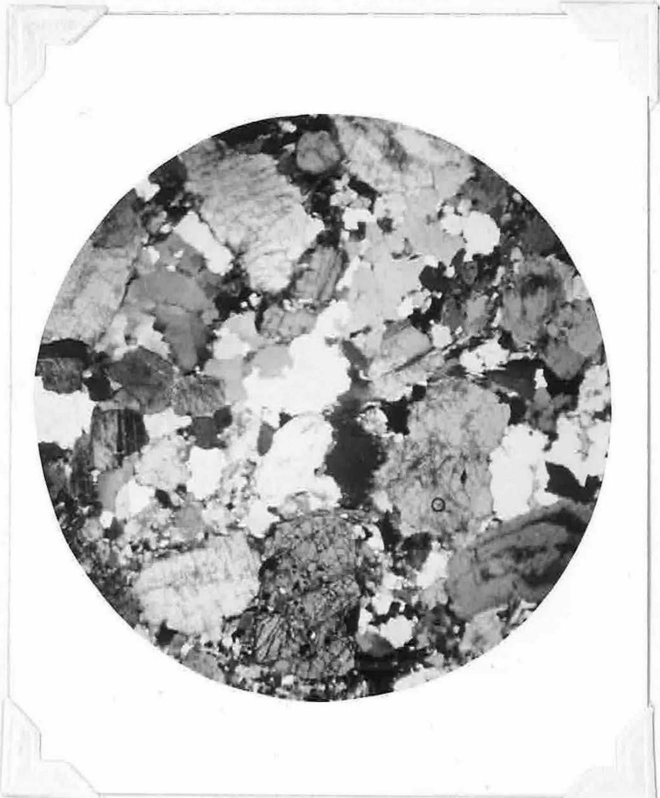
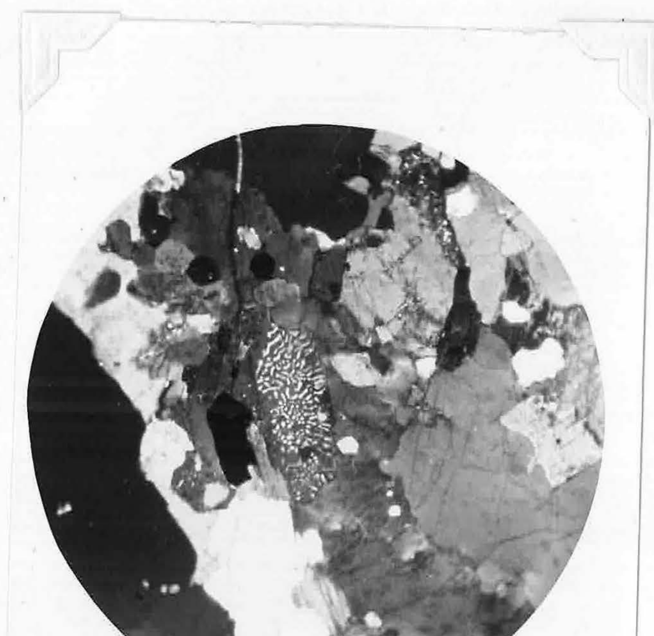


Plate VII, A. Slide 7290+10. Thermal Canyon series. Recrystallization almost complete. Texture approaching that of typical Thermal Canyon.

Plate VII, B. Slide 7900+23A Transition zone. Myrmekite replacing orthoclase. Crossed nicols. X240.





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A San Diego Fauna in the Vicinity of Val Verde, California.

By Donald D. MacLellan.

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Within the lowermost beds of the Saugus group in the Santa Clara Valley region as mapped by Kew (1) occur a series of conglomeratic and arenaceous sediments which have been known to carry a marine fauna, the age of which has not in every case been definitely determined. Mr. W. P. Popenoe of the California Institute suggested to the writer that a study of certain exposures of these sediments be made with an especial view towards determining their age, and whether they constituted a geologic formation distinct from those of both the Pico and Saugus groups as previously mapped. The findings of this study are herewith presented.

Results of Previous Work- The existence of a fossiliferous horizon near the base of the Saugus seems to have been suspected by early workers in this general area. Kew mentions that strata immediately below the horizon which he tentatively identified as the Pico-Saugus contact were fossiliferous. The first official notice which was given to this horizon seems to have been that by Dr. George H. Taylor, when in 1930 he reported finding a fossiliferous horizon "near the base of the Saugus".

In their description of the Pico and Saugus groups of the upper Santa Clara Valley Grant and Gale (2, p 33) mention a littoral zone which they found at the top of the Pico group and which carries a middle Pliocene fauna. This zone apparently is recognizable all the way from Fernando Pass to Holser Canyon; the easternmost exposure is at Elsmere Canyon, a branch of Newhall Creek, from which locality beds of this zone can be traced more or less continuously northwestward to beyond Pico Canyon. A continuation of the same zone, "possibly 100 feet higher" is reported as occurring on the north side of the Santa Clara Valley in the region of the San Martinez Grande and the San Martinez Chiquito canyons. This exposure has been tied in sufficiently definitely to the local topography as to leave little doubt of its being the rock described in this paper.

Dr. H. M. A. Rice (3) in 1934 studied an exposure of fossiliferous sandstones and conglomerates which overlie typical Pico group shales in the Weldon and Gavin Canyon areas, the location of which practically coincides with that of a portion of the littoral zone of Grant and Gale. Here he found a fauna of 51 species which is apparently very similar to that of the San Diego (middle Pliocene) formation.

On the opposite side of the Santa Susana Mountains, in Las Llajas Canyon, Dr. George H. Anderson (4) in 1933 found a small San Diego fauna in beds which are very similar lithologically to those found in the Santa Clara Valley and which apparently occupy the same stratigraphic position.

<u>Location</u>- The rocks examined in connection with this investigation are typically exposed near the community of Val Verde, which is situated in San Martinez Chiquito canyon two miles north of Delvalle, in the upper Santa Clara Valley (See map). Two exposures are especially noteworthy: one occurs along the summit of the northerly trending range of hills $^1/_8$th mile east of Val Verde, while the other occurs about one mile due west of Val Verde. The exposure

east of Val Verde can be approached from an automobile road which extends the base of the range on its southeast side. The exposure west of Val Verde can be reached by automobile by following the San Martinez Chiquito road westerly and turning south at a locality marked "County Park". Excavations made in connection with the grading of a road to a water tank on a hill due south of the "County Park" give excellent exposures of the beds here being discussed.

Stratigraphy- The lowermost beds in the San Martinez Chiquito region consist of members of the group mapped by Kew as Pico. They consist of powdery soft fine-grained argillaceous sandstones of a brownish gray color which only rarely show any traces of bedding. As exposed here these beds appear to be unfossiliferous. The base of this facies being nowhere exposed in this region, the thickness is unknown; local exposures indicate a thickness in excess of 500 feet.

The Pico group is overlain by a succession of beds which aggregate 1000 to 1200 feet in thickness, within which occur the fauna which this paper seeks to describe. Although varying within themselves, these beds constitute a distinct lithologic unit which contrasts strongly with both the underlying and overlying rocks. They are separated from the underlying Pico group beds by a sharp nonconformity the nature of which could not be more definitly determined on account of the lack of evidences of bedding in the Pico group.

The basal portion of these beds consist of 600 to 800 feet of poorly sorted conglomerate which appears to consist entirely of sub-angular grains and pebbles of granitic material which range in size from that of coarse sand up to three or four inches. No fossils were found in this portion of the beds.

Immediately overlying the conglomerate occurs 30 to 40 feet of yellowish gray well-bedded sandstone. This is followed by a bed, six inches to one foot in thickness, which is virtually a limestone, as it consists of a matted and cemented mass of scaly fragments of molluscan shells. None of these fragments were sufficiently large to permit of positive identification, although many bore a resemblance to the pelecypod Ostrea vespertina. This bed is followed by a succession of clastic sediments 50 to 100 feet in thickness which consist of well-bedded sandstone at the base but which becomes coarser and less regularly stratified with progress upward, the uppermost member being composed of poorly sorted material which is reminiscent of the basal portion of the formation.

Overlying this conglomerate, occasionally in unconformable relations, occurs a bed of medium to fine sandstone 10 to 20 feet in thickness, which is followed by a fossiliferous bed about one foot in thickness, from which a few of the specimens listed below were collected.

The second fossiliferous bed is followed by 200 to 300 feet of sands and fine-grained conglomerates, the coarser material being confined to the middle portions. Conformably overlying the clastics just mentioned occurs a bed two to five feet thick of coarse sandstone which is highly fossiliferous, and from which the greater portion of the fauna listed below was obtained. This bed is overlain by 20 to 30 feet of medium to coarse sandstone, bluish gray at the base but becoming limonitic towards the top. Limonite occurs both as a stain which permeates certain portions of the rock mass, and as concretions some of which attain dimensions of six to eight inches.

Two to three feet of gypsiferous and highly oxidized sandstone usually constitutes the uppermost bed of this group. This bed is truncated at a very small angle by a highly oxidized erosional surface which forms the separation between this group and the series which overlies it. This contact constitutes one of the more striking sedimentary features of the region, and is almost certainly the surface which Kew mapped as the Pico-Saugus contact along the range of hills east of Val Verde.

Unconformably overlying this group occurs a great thickness of fairly uniform, yellowish to grayish thin-bedded sandstones which persist to beyond the limits of the area here studied, and which constitutes the"Saugus" of Kew and others. Kew states(1, p 82) that

> "the greater part (of the Saugus) is of marine origin, but it grades eastward and northwand into strata that are probably of fluviatile origin or alluvial fan deposits."

The uniformity and persistence of the beds in this area suggest off-shore marine deposition. No fossils were found in these beds.

Fauna of the Val Verde Beds- As indicated above, the uppermost of the fossiliferous beds furnishes the best preserved material. However, as far as could be ascertained, they all seem to carry the same fauna. Below (Table I) is shown a list of the identifiable forms collected from the fossiliferous beds in the vicinity of Val Verde, together with their geologic range, and the geographic destribution of living forms. According to Grant and Gale all of these forms occur in the San Diego formation, which is usually accepted as being of middle Pliocene age; those forms which are also common to other geologic epochs are all long range forms which occur fairly generally throughout the upper Tertiary and later epochs.

Certain forms such as Terebratalia occidentalis, Arca trilineata, Dosinia ponderosa var. jacalitosana, Ostrea vespertina, Pecten bellus var. hemphilli, Pecten estrellanus var. cerrosensis, and Astraea gradata, are characteristic of the San Diego formation.

Although this fauna includes many species which are living today in cool north Pacific waters it can, never the less, be considered a warm water fauna since it includes no species which is confined exclusively to cool waters, and does include some species, such as Ostrea vespertina, Pecten purpuratus, Calyptrea trochiformis, and Kelletia kellettii, which are to be found only in sub-tropical to tropical waters.

Table I.

Fossils of the Val Verde Formation, San Martinez Chiquito Canyon,Upper Santa Clara Valley, California.

(The classification used is that of Grant and Gale).

	Miocene.	L.Plioc.	M.Plioc.	U.Plioc.	Pleist.	Recent.	Geographic Distribution.
Terebratalia occidentalis Dall			X		?		
Arca trilineata(Conrad)	X	X	X	X			
?Chione securis Shumard	X	X	X				
Dosinia ponderosa(Gray) var. jacalitosana Arnold	X	X	X				
Laevicardium sp							
Ostrea vespertina Conrad	X	X	X				
Panope generosa Gould	X	X	X	X	X	X	Puget Sound to Mexico.
Pecten bellus(Conrad)var.hemphilli Dall			X				
Pecten estrellanus(Conrad)var.cerrosensis Gabb		?	X				
Pecten hastatus Sowerby	X	X	X	X	X	X	Alaska to San Diego.
Pecten healeyi Arnoldvar.lohri.Hertlein?		X	X				
Pecten islandicus Muller var.hindsii Carpenter			X	X	X	X	Bering Sea to San Diego.
Pecten purpuratus Lamarck var.		X	X		X	X	Coquimbo,Chili to Ecuador.
Pododesmus macroschisma(Deshayes)		X	X		X	X	Bering Sea to Mexico.
Acteon painei Dall var.grandior Grant			X				
Astrea gradata Grant & Gale			X				
Astrea sp							
?Bittium attenuatum Carpenter					X	X	Alaska to Mexico.
Calyptraea trochiformis(Gmelin)	X	X	X			X	Panama to Peru.
Cancellaria tritonidae Gabb		X	X		X		
Cancellaria hemphilli Dall			X				
Cantharus humerosus(Gabb)		X	X		?		
?Clavus bottae Valenciennes			X		X	X	Warm to tropical oceans.
?Crepidula adunca Sowerby	X		X		X	X	Vancouver to Mexico.
?Crepidula onyx Sowerby	X	X	X		X	X	Monterey to Panama.
Gyreneum sp.cf.elsmerense English		X					
Kelletia kellettii(Forbes)		X	X		X	X	Sta.Barbara to Mexico.
?Lora sp.cf.pyramidalis(Strom)			?			X	Alaska to Monterey.
Mitrella sp.	Olig. to Recent					X	World wide.
Nassarius perpinguis(Hinds)	?	X	X	1	X	X	Puget Sound to Mexico.
Neverita reclusianàs(Deshayes)	Olig. to Recent					X	CrescentCity to Mexico.
Olivella sp.							
Purpura eldridgei(Arnold)		X	X				
Turritella cooperi Carpenter		X	X	X	X	X	Monterey to S.Diego.

Comparison with Pico Group Fauna- The great lithologic contrast which exists between the beds here being discussed and those of the underlying Pico group has already been indicated: these beds consist either of poorly sorted conglomerate or coarse sandstone, all being typical of littoral or near-shore deposition, while the exposed portion of the Pico group consists of fine-grained argillaceous sandstone such as would be deposited in fairly deep quiet waters. A similar contrast exists between the fauna of the two groups. The University of California's Fossil Locality No.1637 (ref.5, pp208-211), which is Grant and Gale's Locality No. 217, is located about three miles northeast of Val Verde, (See map), and probably represents the middle portion of the Pico group beds. Here a fauna of 45 specifically identifiable forms was collected by W. A. English in 1914. Of these 27, or almost 60%, are living forms, and the remainder all consist of long range forms, many of which have persisted from the Miocene or lower. The collection represents a typical cold water fauna in that 24 of the 27 living forms are to be found north of San Francisco. According to English this fauna is "lowest Pliocene" in age.

Of the 34 species collected by the writer in the Val Verde beds 28 were found to be specifically identifiable; these, as already mentioned, constitute a typical warm water fauna.

The fauna of the Val Verde beds have the following nine species in common with the lower Pliocene fauna referred to above:

(?)Chione securis var.	
Ostrea veachiiGabb	(O. vespertina of Grant& Gale)
(?)Pecten oweni Arnold	(P. healeyi var. lehri " "
Calyptrea radians(Lamarck)	(C. trochiformis " "
Chrysodomus arnoldi Rivers?	(Cantharus humerosus " "
(?)Crepidula onyx Sowerby	
Siphonalia kelleti Forbes	(Kelletia kellettii " "
Turritella cooperi Carpenter	
Pecten cerrosensis Gabb	(P. estrellanus var. cerrosensis " "

Of these six persist into the Recent, and all are long range forms of wide geographic distribution. Their presence in the Val Verde beds cannot therefore be considered as being of especial significance.

Summary and Conclusions- Between the Pico group and the Saugus group in the upper Santa Clara Valley occurs a succession of beds which differ lithologically and faunally with both the underlying and the overlying beds:

The Pico group is composed of fine-grained yellowish brown shaly sandstone which apparently represents deep water marine deposition, and which carries a cold water lower Pliocene fauna.

The Val Verde beds consist of coarse poorly sorted conglomerates and sandstones which represent sub-aerial and littoral deposition, and which in their upper portions carry a warm water middle Pliocene fauna.

The Saugus group unconformably overlies the Val Verde beds and consist of well-bedded medium to coarse sandstones which apparently represent off-shore, subaqueous deposition, and which are non-fossiliferous.

For these reasons it is concluded that the beds lying between the Pico group and the Saugus group in the Val Verde region constitute a distinct formation which is of San Diego, and therefore probably of middle Pliocene age.

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