PETROLOGY OF THE IGNEOUS COMPLEX NEAR LANG, CALIF.

A Thesis
Submitted in partial fulfillment
of the requirements for the degree
of
Master of Science

by

Chas. A. Dawson, Jr.

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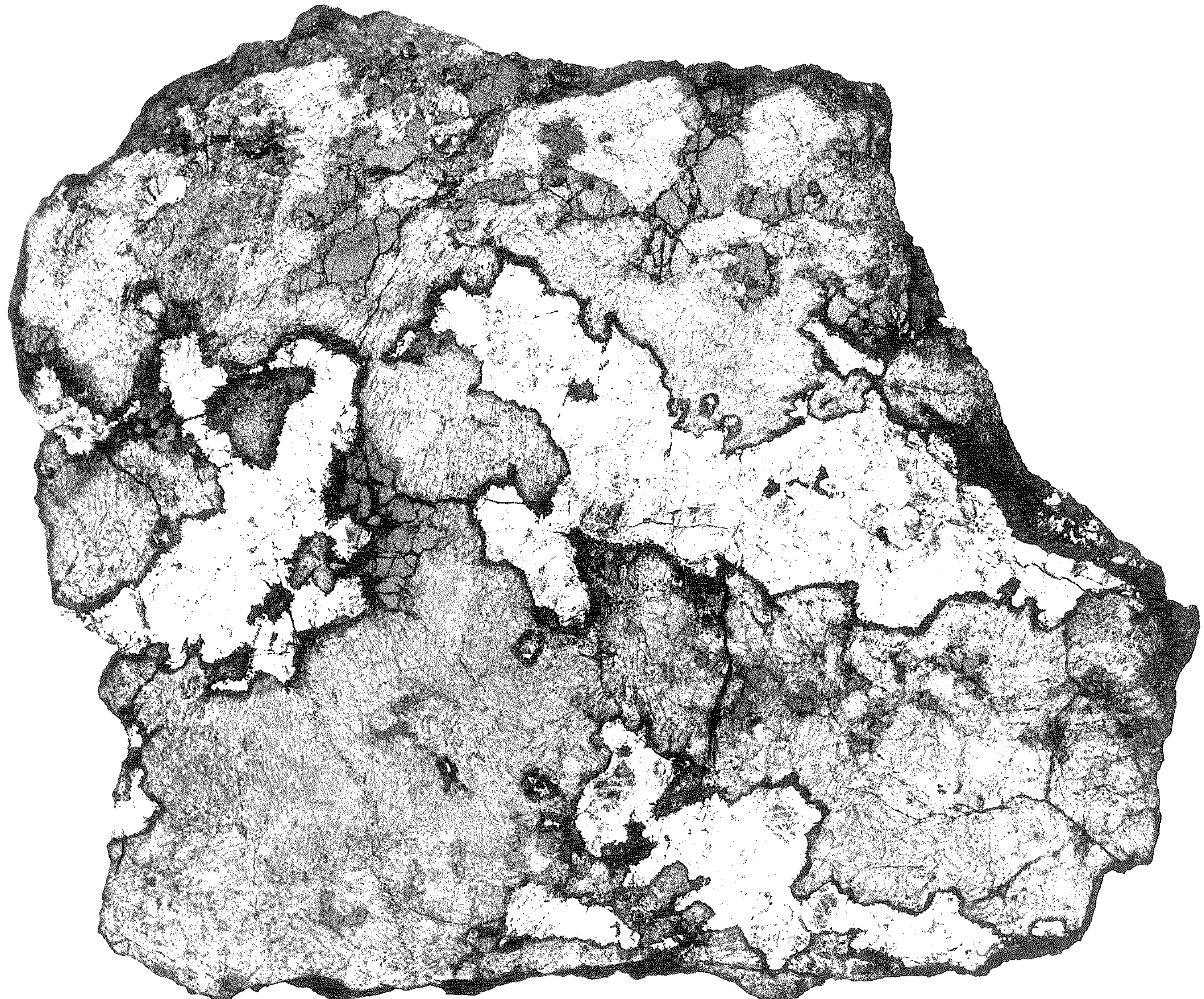

Frontispiece: Hand specimen of plain hybrid, 3/2 X
White is feldspar, light gray is actinolite altered from diopside(?), dark gray is magnetite, and black rim around feldspar is hornblende altered from augite(?).

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PETROLOGY OF THE IGNEOUS COMPLEX NEAR LANG, CALIF.

Introduction:

The region to be considered in this report is in Los Angeles County, Calif. and is included in the Lang Quadrangle surveyed in 1929 with a scale of 1 : 24,000 and a contour interval of 5 and 25 feet. The region is also shown on the San Fernando Quadrangle with a scale of 1: 62,500 and a contour interval of 50 feet. The area mapped is included between two canyons, Pole Canyon immediately south of Lang, and Little Bear Canyon about a mile and three quarters east of Lang,

The area may be reached on the Sierra Highway by turning east into Soledad Canyon just before the Sierra Highway enters Mint Canyon, a distance of about thirty-eight miles from Los Angeles. Lang is about five miles east of the junction of Mint Canyon with Soledad Canyon. The area may be reached by the Southern Pacific Lines which has a siding at Lang.

The problem was undertaken in partial fulfillment of the requirements for the degree of Master of Science at the Calif. Institute of Technology. The work has been done under the direction and guidance of Dr. Ian Campbell, Associate Professor of Petrology at the Calif. Institute.

Topography:

The San Gabriel Mountains, a small portion of the north-western part of which this report covers, are a deeply dissected, rugged fault-block range. Soledad Canyon, Little Bear Canyon, and Pole Canyon are cut some eight-hundred feet below their rims and in their steeper portions are bounded by nearly vertical walls.

Exposures:

By far the bulk of the field work in this area has been restricted to deep recently cut canyons, because it is only where the freshest rocks have been exposed that accurate interpretations can be drawn. Along Soledad Canyon the rocks are badly altered and sheared. In the upper parts of Little Bear and Pole Canyons, the rocks are likewise badly altered and often poorly exposed. The best exposures, then, are found near the mouths and central portions of Pole and Little Bear Canyons.

Previous Work:

Hershey (1) in 1902 published the first paper of importance on the crystalline rocks of the region.

Arnold and Strong (2) in 1905 contributed some petrographic descriptions of rock specimens collected along the trails north of Pasadena.

Kew (3) in 1924 published a paper on a large region but mapped the crystallines as simply "basement complex".

Nobel (4) 1927 and Hill (5) 1930 made additions to the knowledge of restricted areas.

Miller (6) was the first to make a complete study of the western San Gabriel Mountains. His "Geology of the Western San Gabriel Mts. of Calif." is a rather complete work on a large and complex area, but it necessarily omits many details and leaves a number of problems unsolved.

General Geologic Conditions:

The San Gabriel Mountains are a large fault block mass of pre-Cretaceous (possibly pre-Cambrian) metamorphic and igneous rocks. Around this are variably occuring Tertiary and Quaternary gravels. The mountain mass is believed to have been uplifted to its present height in Quaternary time. There are three great bounding faults: the Sierra Madre on the south, the San Andreas on the north-east and the Soledad-Lang fault on the north-west.

The metamorphic rocks consist of the metamorphosed Placerita sediments and the injected and mixed rocks which have been called the San Gabriel Formation. The latter is made up mostly of Placerita injected with Rubio Diorite and Echo Granite. The relation of these rocks to the Anorthosite and its related Mafic Phase is not too clear. Following the above, probably in Jurassic time, came the Wilson diorite, Parker diorite, Lowe granodiorite followed by aplite and pegmatite. In Tertiary time the region was intruded by lamprophyre dikes and in some places lavas were extruded. Around the generally rising mass, Miocene strata were laid down followed by Pliocene strata. The subsequent history has been one of dissection of the rising mass.

The relations of the Anorthosite to the Mafic Phase of the Anorthosite and the origin of some of the textures found in these rocks is the chief interest of the present report.

Approaching the area from the west along Soledad Canyon, one can see to the south-east, beyond the terrestrial Mint Canyon Formation

Fig. 1 Lang fault scarp, in distance, as seen when approaching the area from the west. Mint Canyon Formation in the foreground.

Fig. 2 Pure Anorthosite in upper Bear Canyon

through which one drives, the great fault scarp of the Lang fault. See Fig. 1. Soledad Canyon leads to the north of this very straight south-westward trending feature. Parallel and lying immediately to the north of Soledad Canyon is the east-west Soledad Canyon fault. To the south and east of these two intersecting faults is the San Gabriel Igneous mass. The siding, Lang, is just west of the intersection of these two faults. This north-western corner of the San Gabriel Mt. mass included between the two faults is an anorthosite complex consisting of two major portions: a dioritic phase which will in the remainder of this paper be called the Mafic Phase of the Anorthosite and a pure anorthosite. Fig. 2 shows a view of the pure anorthosite in upper Bear Canyon. Fig. 3 shows a view of the Mafic Phase in central Pole Canyon.

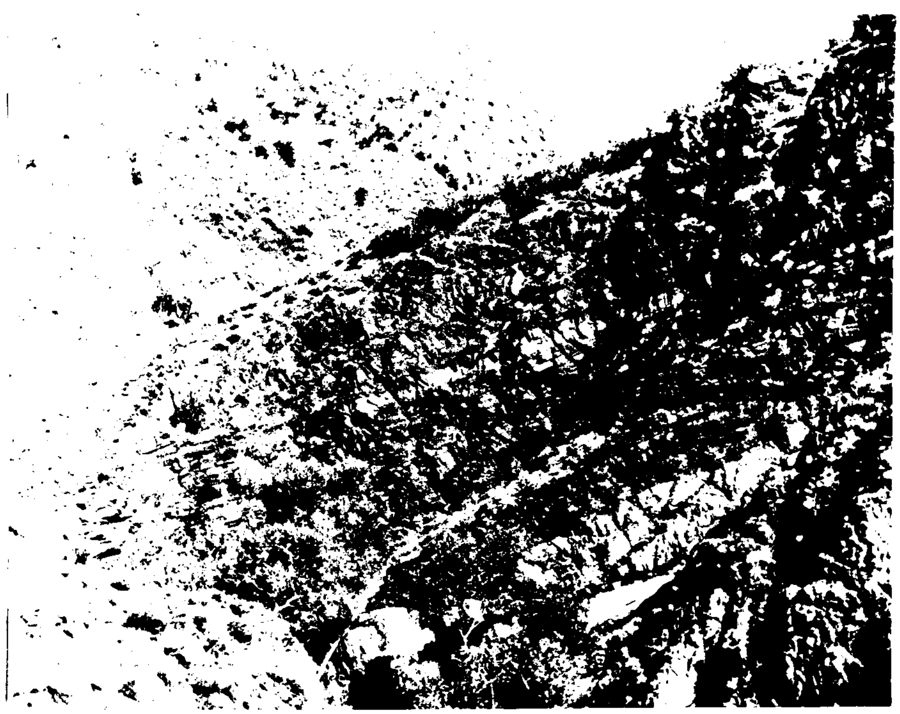


Fig. 3 View of Mafic Phase of Anorthosite in Pole Canyon

The rocks of the western fault scarp first seen upon approaching the area are the Mafic Phase types. About one and one half miles east of Lang, one comes upon a great mass of pure anorthosite which extends some ten miles to the east. The lower portion of (Little) Bear Canyon is the approximate locus of the contact between the two rock types. The contact trends to the south-east for about two miles, turns for a time to the west where it crosses the upper portion of Pole Canyon (the first major canyon to the west of Bear Canyon) and then turns to the east. In addition to this major contact there is a repetition of the contact by the Goat fault displacement of a small triangular block in the north-west corner of the mass. See Map.

CRYSTALLINE ROCKS:

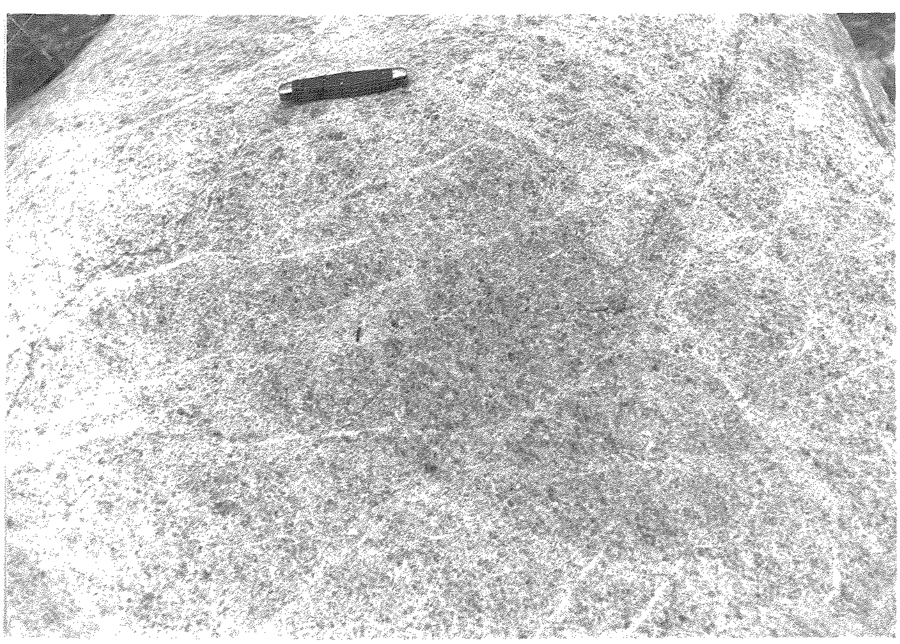
The crystalline rocks of this area are almost entirely related to the anorthosite complex. The two phases which make up the anorthosite complex will be considered separately and this will be followed by a consideration of the dike rocks which make up the remainder of the crystalline rocks.

Anorthosite:

The pure anorthosite occurs in two places. The first, occuring in the north-west corner of the igneous complex, makes up a portion of the triangular block formed by the Lang, Goat, and Soledad faults. It is well exposed in Soledad Canyon. To the north of the Canyon it is partly buried by recent alluvium. To the south it extends for a short distance and then stops at the contact with the Mafic Phase immediately to the north-east of Pole Canyon.

The second occurrence is east of the first. Bear Canyon forms the approximate western boundary of this larger anorthosite mass. The mouth of the canyon is in the Mafic Phase, but a short distance up the canyon the contact crosses it and the canyon remains in the pure anorthosite for the remainder of the distance with the contact moving well up on the west wall of the canyon. The pure anorthosite continues for a distance of some nine or ten miles toward the east.

In hand specimens most of the anorthosite has a fine mottled appearance which suggests by the size of the spots that the grain size averages about one quarter of an inch. Fig. 4 shows a typical mottled anorthosite boulder. In many cases it can be seen that the twinning striations on a single grain extend considerably beyond the limits of a single spot, and therefore it can be said that the average grain size of the anorthosite varies from one half inch to one inch.



Fig, 4 Mottled appearance of typical anorthosite

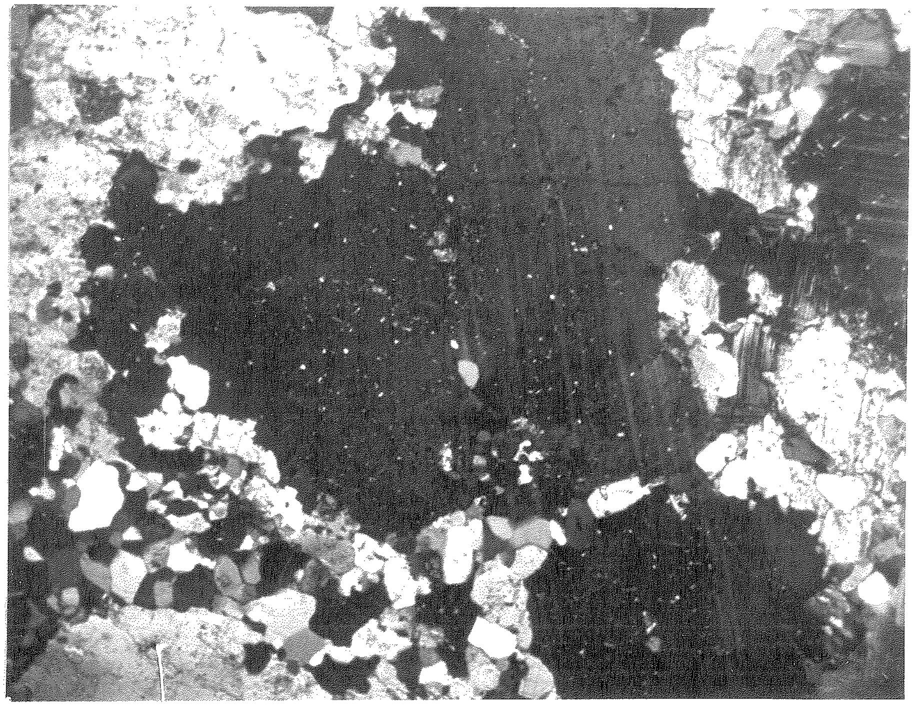


Fig. 5 Photomicrograph showing granulation of feldspar in anorthosite giving it a white color in hand specimen.

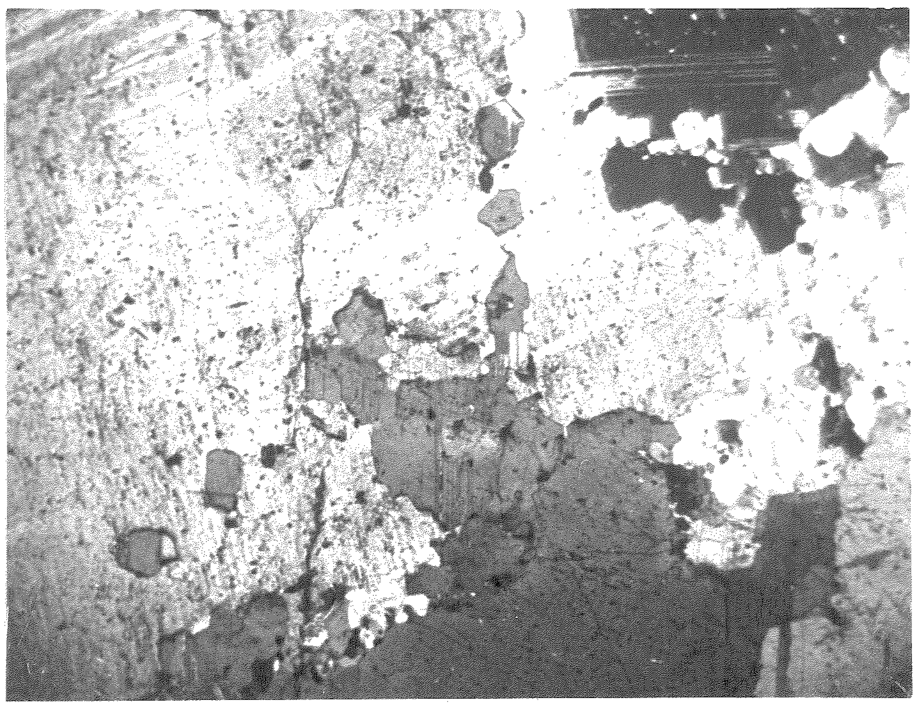


Fig. 6 Photomicrograph of ungranulated feldspar in anorthosite which in hand specimen retains a pale blue-gray color

Fig. 5 is a photomicrograph of a thin section of fractured and granulated anorthosite which, as a result of this granulation, is white in hand specimen. Fig. 6 is a photomicrograph of a thin section of fresh, blue-gray anorthosite which shows an absence of fractures and granulation. Fig. 7shows an outcrop in upper Bear Canyon which demonstrates on a large scale the effect of fracturing and alteration on the color of a rock. The rhombohedral fracture pattern in this rock shows how a minute fracture results in an alteration of as much as an inch on each side of the fracture.

Fig. 7 Effect of fracturing and alteration on the color of anorthosite as shown on a large scale in Bear Canyon.

The effect of alteration may be seen on a still larger scale in Soledad Canyon along the new road where the rock is a uniformly dull white. Usually the freshest and consequently darkest feldspars are to be found in stream boulders which, because of their freshness, have survived transportation. These are usually a pale blue-gray color. In the deepest parts of the canyon fresh feldspars may be seen in place.

The mottled appearance of the anorthosite appears to be the result of fracturing, granulation, and alteration which, singly or combined, produce white borders around fresher blue-gray areas.

In addition to the one-half to one inch size of feldspar grains, one may find feldspar crystals up to four inches long. These are mostly found in stream boulders and are rather uncommon.

In order to make a systematic study of the anorthosite, nine specimens of fairly pure anorthosite were taken along Bear Canyon from areas where there was a relatively high percentage of Mafic rocks to where the only Mafic rocks occurred as dikes. These were thin sectioned and studied under the microscope. Because of the frequent extensive alteration and the consequent small number of feldspar grains which would lend themselves to a determination of the composition by the common statistical method of Michel-Levy, it was found necessary to use the Federov Universal Stage. In this study there was found no relation between proximity to the contact with the more mafic phases of the anorthosite complex and the composition of the feldspar. In the group all degrees of alteration were observed, but almost all of the alteration was restricted to the larger grains leaving the fragmental finer grains, which are found abundantly surrounding the larger grains, in a fresh condition. All of these sections show considerable granulation. Fig. 5 is typical. A number of sections show bent twinning as illustrated in Fig. 8, and all exhibit nearly as much pericline twinning as albite.

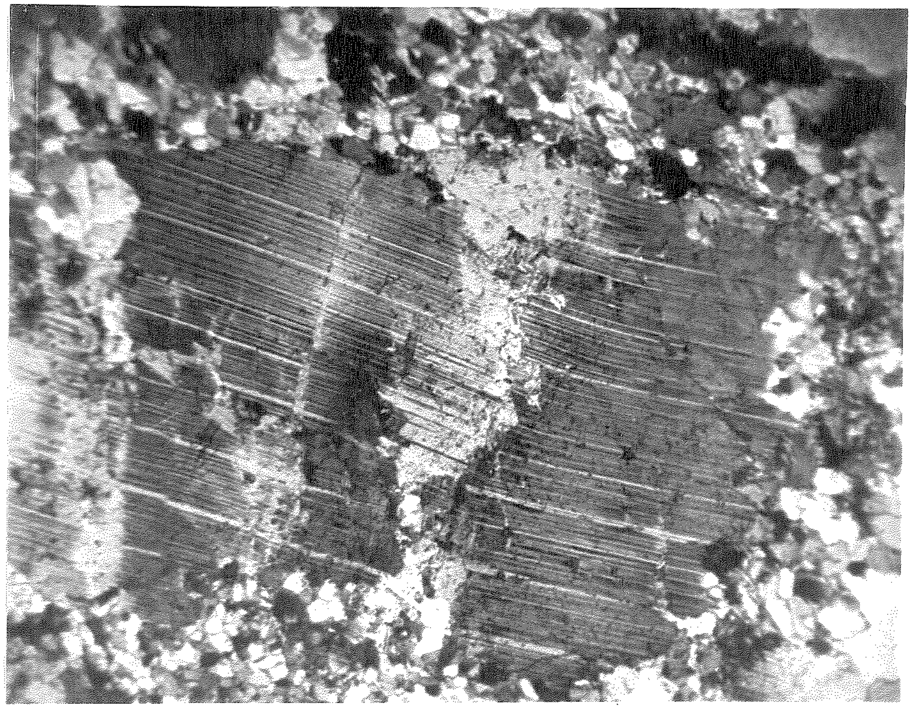


Fig. 8 Bent twinning lamellae in feldspar of anorthosite

With the Federov Stage the composition of the feldspar was found to vary from $An_{3.4}$ to $An_{4.0}$ This gives for the feldspar composition, Andesine varying toward Oligoclase. Plagioclase makes up more than ninety percent of the rock. The most important accessories are epidote, apatite, hornblende, and sphene. Orthoclase and frequently large amounts of muscovite occur but are probably related to later intrusive activity. Kaolin, sericite, and chlorite are the chief alteration minerals.

Perhaps equally as interesting as the composition of the anorthosites are the textures which may be seen in thin sections of these rocks. The most outstanding feature of the larger feldspar grains is the presence of two twinning systems. These are found intersecting and interpenetrating each other at various angles, but chiefly at right angles. Often pericline twinning lamellae are found in one albite twin but not in the adjacent albite twin. The twinning lamellae are usually narrow and often appear to be single lines both according to the albite and pericline laws. Rarely do twinning lamellae of either system cross the entire grain; either they stop where they intersect another twinning system or else they fade out into untwinned feldspar. The finer material surrounding the large grains also contains abundant pericline twinning which often occurs as broad clear twinning lamellae more typical of the albite law. It also shows a very interesting structure resembling secondary growth as is commonly seen in quartzites, with the boundary between the original grain and the new material marked ~~marked~~ by a narrow band or line resembling the banding of a zoned crystal. This is probably due to reversal in the zoning which makes the center and the outer edge of the grain have the same optical orientation while the band in between has an optical orientation which indicates that it has a higher percentage of albite molecules.

The problem of the origin of the twinning characteristics of these rocks offers an oportunity for some interesting speculation. The formation of twinning in feldspar must be the result of two of three conditions. 1. There must be a crystal lattice which will readily respond to conditions inducing twinning. 2. There must be changes in conditions during formation of the crystal, or 3, there must be changes in conditions following the formation of the crystal.

It is generally accepted that andesine is capable of twinning. In the rocks studied, it is known that some of the best twinning is found in the recrystalized, fine grained material which has essentially the same composition as the coarse grained material. This shows that the first requirement is satisfied.

It remains to be determined why much of the coarse grained material shows no twinning, and where twinning does occur, albite and pericline are almost equally abundant. The absence of twinning in much of the feldspar leads to the following. Although it cannot be definitely stated what the conditions are that induce twinning, it is fairly logical to assume that, since twinning itself represents a crystalline change of conditions, it must normally be the result of changing conditions in the magmatic or rock mass. The absence of twinning in the present case may mean that these changes required for the formation of twinning during the formation of the crystal have not occurred. In other words, untwinned andesine might be formed if it were allowed to grow sufficiently slowly and sufficiently free of disturbance. There remains the other possible reason why the feldspar is not twinned. This is that the twinning which may have formed, may have been destroyed by later agents. It may be said in general that the chemical state of a thing becomes increasingly simple as the entropy becomes increasingly great. Conversely, the physical state becomes increasingly complex as the entropy becomes increasingly great.

Since twinning is a condition of the physical state, a loss of it would violate the above general statement. Also, the presence of good twinning in the granulated and recrystalized material restricts the period of early twinning destruction to a time antedating the recrystalization of granulated material. This eliminates the most expectable forces that might destroy twinning, since they were accompanied by the formation of twinning. Consequently for lack of other evidence, it will be concluded that the untwinned andesine has never been twinned, and that this condition is due to the uniform conditions under which it formed.

We have a feldspar of the proper composition for twinning, but conditions have been so uniform that in many areas no twinning has occurred. If now we assume that a certain amount of twinning can be induced by strain, as has been postulated in the case of microcline, it may be that the twinning which is observed is the result of changing conditions following the formation of the crystal, as stated above in the third requirement for the formation of twinning. Although little can be proved in this direction, the evidence available certainly is suggestive of this view. Whenever bent twinning lamellae are found, the twinning is highly developed; see Fig. 8. Granulation and bent twinning show that the required forces were present to produce the necessary strain. The twinning which is found is typically discontinuous, rather than like the long clear cut andesine twins of a normally formed andesine crystal. Finally, there is the abundance of pericline twinning which is not common in ordinary dioritic rocks. This implies that some special process has been active here that does not occur in ordinary igneous rocks. The two proposed special conditions are very uniform conditions during formation and considerable dynamic activity following the formation of the rock. Since the first could not be expected to form twinning, the second will be considered to be the cause of abundant pericline twinning.

In conclusion then, the feldspar, although capable of twinning, was formed under such uniform conditions that twinning has been, at least, reduced in amount, and that following the solidification of the mass, a certain amount of discontinuous twinning has been induced by mechanical strain. This latter effect may be the cause of the high percentage of pericline twinning.

Mafic Phase of the Anorthosite:

In making a study of the Mafic Phase of the anorthosite, a procedure was used similar to that used in the study of the pure anorthosite. Pole Canyon lies well within the Mafic Phase of the Anorthosite, and from this canyon a series of samples was taken to supplement the rocks showing interesting textural relations which were taken from scattered localities throughout the area. These have been thin-sectioned and studied under the petrographic microscope. The Mafic Phase of the Anorthosite includes a great variety of rocks between which all gradations may be observed.

There are a few features, however, that are constantly found.

Mineralogically the rocks are diorites. The feldspar, so far as can be told, has the same composition, and usually the same appearance in hand specimen and under the microscope, as the feldspar in the pure anorthosite. The ferromagnesian minerals are almost exclusively actinolite and hornblende, and they usually make up fifty percent of the rock. Magnetite is usually prominent and apatite is occasionally so. In addition to these constant mineralogical characters, there are two textural relations found in a great percentage of the rocks. The first is the relation of the three most common minerals as shown in the frontispiece. This hand specimen shows a narrow reaction rim of hornblende between the feldspar and the actinolite. The second is the relation of the hornblende reaction rim to the feldspar, quartz and magnetite, as shown in Fig. 41.

The following classification will be used to separate the types and thereby limit the number of specific descriptions:

Banded Hybrids

Plain Hybrids

Spotted Diorites

Amphibolites

These will be described in the order given and then their variations will be included.

Banded Hybrids: Fig. 10 shows an outcrop in upper Bear Canyon showing typical banding in the Hybrids. Fig. 11 and fig. 12 show close-up views

Fig. 10 Banded Hybrids (primary banding) in upper Bear Canyon. Lamprophyre dike cutting primary banding at a high angle.

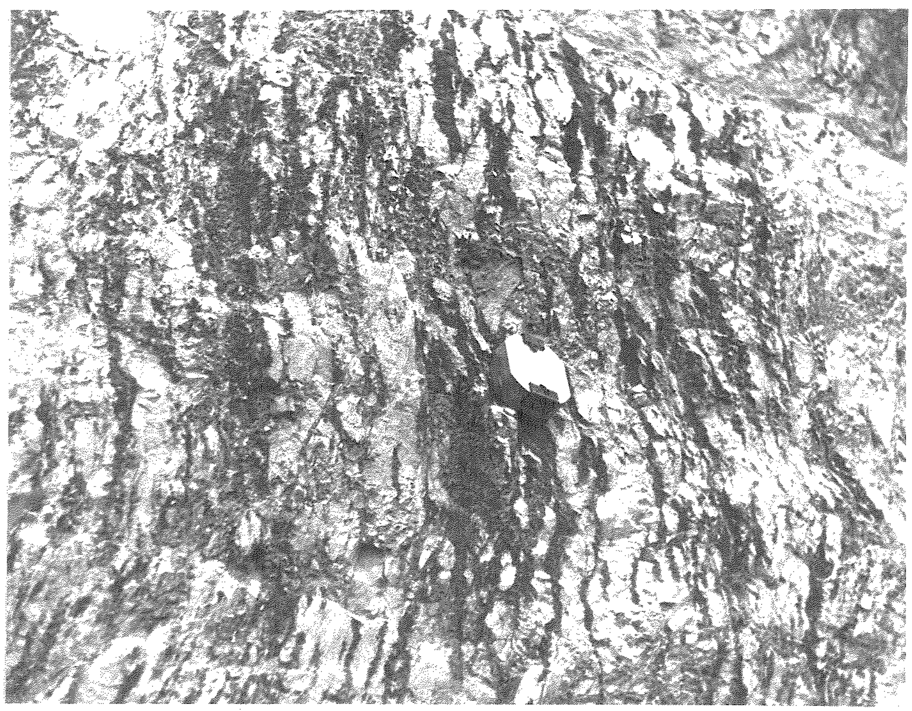


Fig. 11 Detail of fig. 10

Fig. 12 Detail of fig. 10

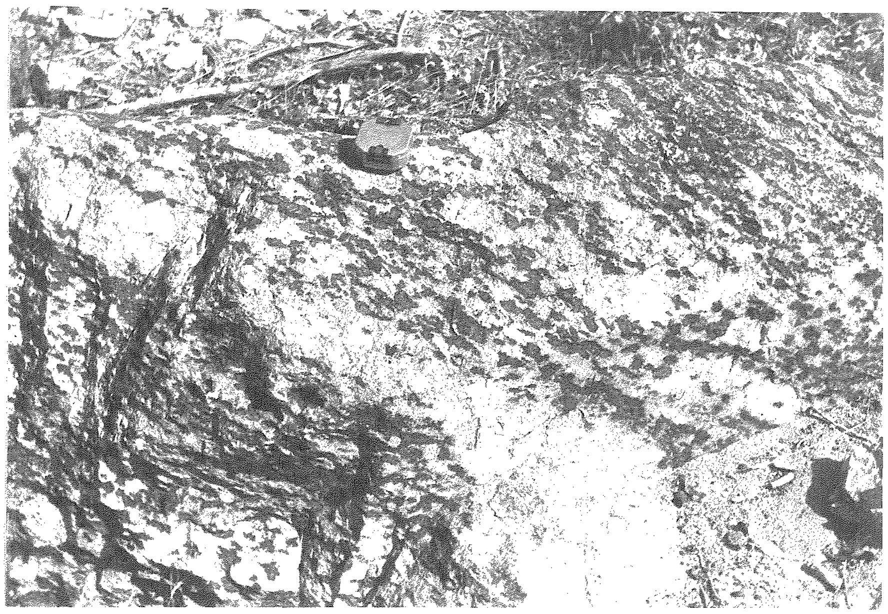


Fig. 13 Banded Hybrid in lower Bear Canyon

of this same outcrop. Fig. 13 shows a banded hybrid outcrop from lower Bear Canyon. In all of these pictures the variability of the ratio of ferromagnesian minerals to feldspar is obvious, and on the basis of this variability and the strong and variable banding, the rocks are thought to have been produced by mixing of the pure anorthosite with the Mafic Phase of the Anorthosite by primary movement during emplacement of the mass. The literature on the origin of primary banding has been reviewed by Robert R. Coats (7). Rhythmical accumulations of crystals, lit par lit injection, and movement of a partially solidified magma are the chief methods by which primary banding has been explained. Since the banding here found could not have been produced by either of the first two methods, there remains only movement of a partially solidified magma as a possible origin of these structures.

Included also within this group are the rock types shown in fig. 14. This picture shows masses resembling inclusions which have been more or less mixed with the enclosing rock and which have been elongated by movement within the mass. Masses of this type are thought to be either intruded masses into the Anorthosite which have been distorted by later movement or else local segregations of dark minerals in the Anorthosite.

Fig. 13 may be taken to be most typical of the Banded Hybrids. In the hand specimen, the rock is mottled with elongated patches of ferromagnesian minerals in a matrix of feldspar. The relative

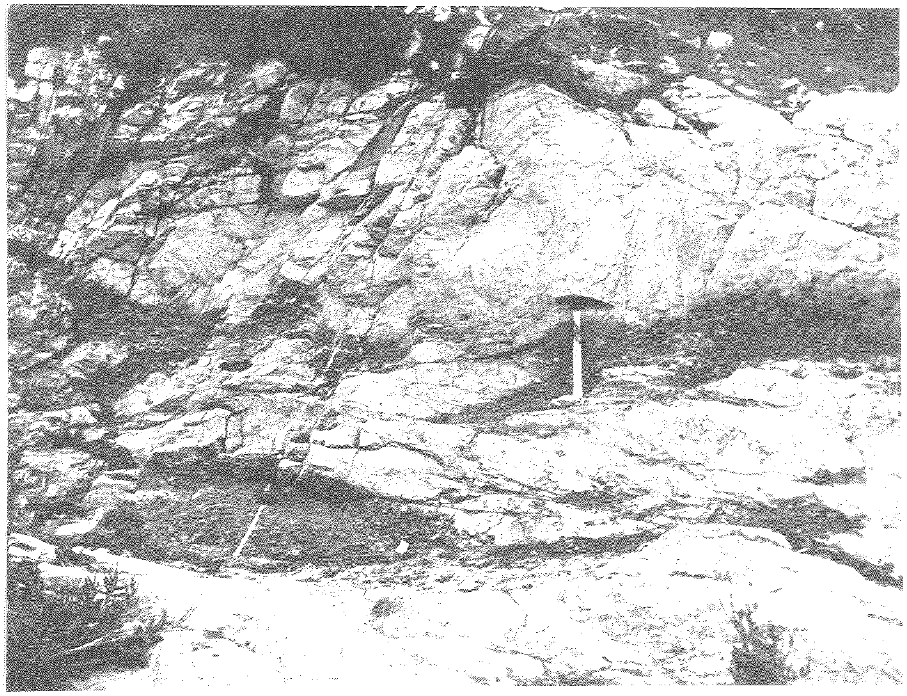


Fig. 14 Banded Hybrids included in the anorthosite in middle Bear Canyon.

quantities of minerals are so variable that a percentage tabulation is useless. The feldspar is blue-gray to white and the ferromagnesian minerals may be seen to be gray-green and black. Here, as is generally the case, a constant relation between the feldspar and two ferromagnesian minerals may be seen with the darker ferromagnesian mineral separating the lighter from the feldspar.

Under the microscope the feldspar is found to be andesine with a composition averaging An_4. The darker ferromagnesian mineral is a highly pleochroic hornblende. X::yellow, Y::green, Z::blue. It has a maximum extinction angle Z to C 18°, 2V :: 60° aprox. Biref.::0.016 (-) The lighter ferromagnesian mineral is colorless to variable pale green but is not pleochroic. It has the same extinction angle but seems to have a higher 2V, approaching 80°. It has a high birefringence of 0.028. (-) This lighter mineral is probably actinolite. Considerable amounts of brown biotite occur. It shows no pleochroic haloes. Magnetite occurs in appreciable quantities, and apatite is frequently found.

The chief variation in this rock type is in the amount of biotite. Accompanying an increase in the amount of biotite there is a corresponding decrease of actinolite and hornblende. Frequently biotite takes the place of all of the actinolite and possibly some hornblende. Apparently the limiting case in the direction of biotite increase is when the rock contains only feldspar, biotite, and magnetite.

Fig. 15 Transitional type between banded hybrids and plain hybrids. The dark band through the center of the rock containing the small feldspar inclusion is typical of the plain hybrids in that they appear to have been formed by introduction of basic material rather than by movement in a semi-solid rock mass, as is the case in the banded hybrids.

Fig.16 Plain Hybrid in upper Bear Canyon

Fig. 17 Plain Hybrid in Upper Bear Canyon. Note dark hornblende reaction rim between actinolite (gray) and feldspar (white). Note fractures in feldspar filled with hornblende.

Fig. 18 Reaction rims in the plain hybrids, Bear Canyon

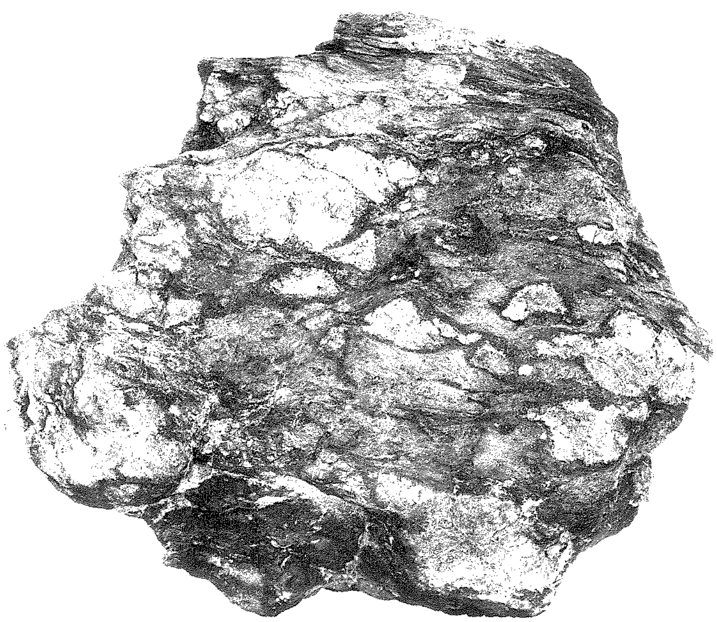


Fig. 19 Hand specimen ½ natural size which appears to have developed in part as a plain hybrid and in part as a banded hybrid. That is, partly by introduction of basic material and partly by movement.

Plain Hybrids: The second group of mafic rocks related to the anorthosite is called the plain hybrids. These rocks are gradational into the banded hybrids but do not seem to have had their origin so closely related to primary flow movement as the typical primary gneisses. Their formation seems to have resulted from introduction of material along fracture zones as is suggested by fig. 15 which is intermediate between the banded and plain hybrids. Figs. 16,17, and 18, taken in mid-Bear Canyon, give an excellent idea of the more typical appearance of these rocks in the field. It is fairly clear that movement has not been the dominant factor in the formation of the textures shown. Fig. 19 shows a hand specimen of a rock whose structure is thought to be due both to introduction of basic material and also to movement.

The mineralogy of the plain hybrids is the same as the banded hybrids with the exception that there is more actinolite and practically no biotite. The frontispiece is an excellent example of this group of rocks. All of the specimens of this group show the typical hornblende reaction rim around the feldspars. This same relation may be seen on a large scale near the end of the mine road between Bear and Pole Canyons. Fig. 20 shows an outcrop along this road. The reaction border is not too clearly shown in the picture due to the altered condition of the rocks, but it was found to be about one-half inch wide, while the tongues of actinolite are of comparably larger size.

Fig. 20 Reaction rim of hornblende shown on a large scale along the mine road between Bear and Pole Canyons.

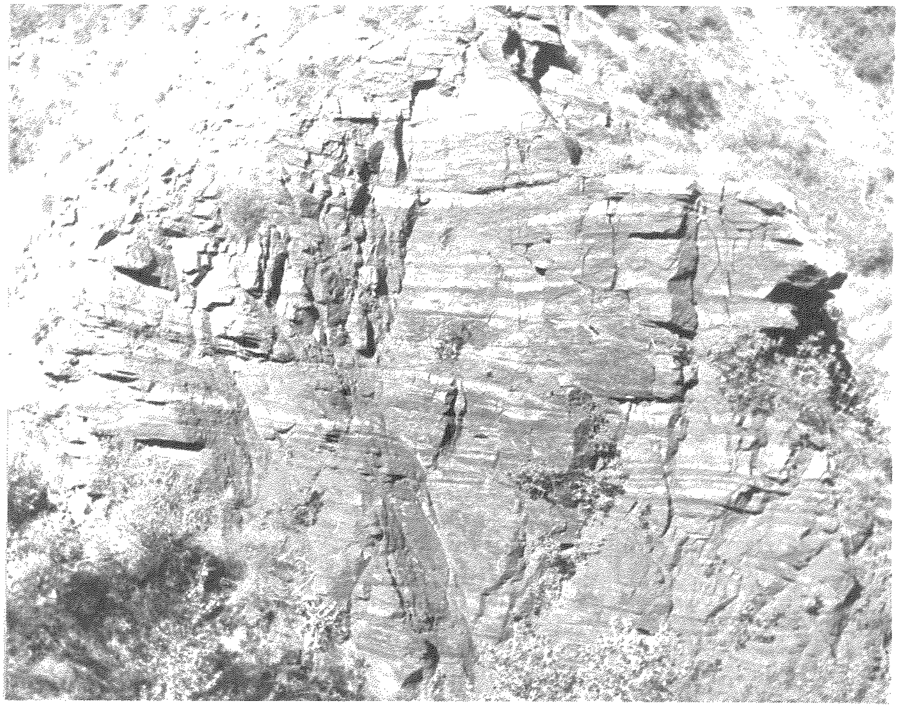


Fig. 21 Fifty foot outcrop of Spotted Diorite in Pole C.

<u>Spotted Diorites:</u> The third group, which is called the spotted diorites, make up most of the great mass of Mafic rocks west of the anorthosite-Mafic Phase contact. Fig. 21 shows an outcrop of these rocks in Pole Canyon. Fig. 22 shows a more typical outcrop of the spotted diorites. This picture was taken south of the map in Pole Canyon. These rocks do not seem to have developed their banding so much by mixing of two rock types as by movement of a rock which had a nearly uniform mineralogical composition, thereby producing a certain amount of segregation. In other words, these rocks do not vary greatly along their strike, while the banded hybrids vary almost

Fig. 22 Typical spotted diorite in Pole Canyon (off map)

Note the intersection of two directions of banding.

as much in this direction as they do across their strike. The spotted diorite is fairly uniform to the west of Pole Canyon as far as the Lang fault scarp and as far south as the head of Freel's Canyon (one and one-third miles south of Lang).

The name spotted diorite has been given to these rocks because, in the first place, they are of the composition of diorite, having practically the same composition as the banded hybrids. The feldspar is andesine. The ferromagnesian minerals are hornblende, actinolite, and biotite, in smaller amounts than in the banded hybrids. Magnetite is commonly found. Secondly they are called "spotted" because of a peculiar texture which many of the rocks have developed. Fig's. 23 and

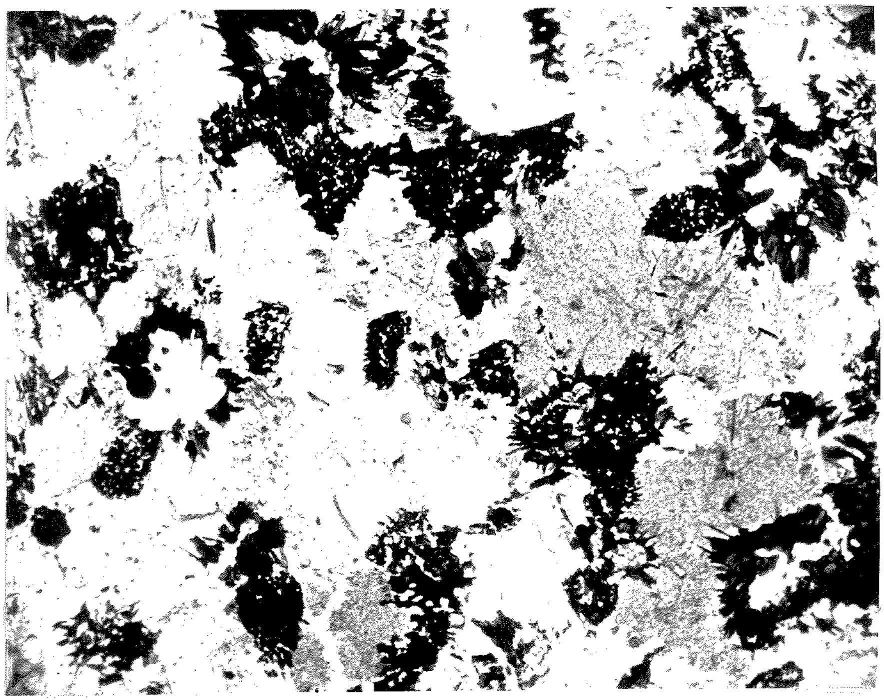


Fig. 23 Photomicrograph of spotted diorite, plain light showing spot development.

24 are photomicrographs which exhibit the tendency for star-like growths of hornblende crystals to develop from a center, producing a texture, which when seen in hand specimens, is made up of circular or oval spots and often rings of hornblende with a center made up of a fine grained mixture of quartz and hornblende. This rock is the most constant texturally of the four types, but there is considerable variation in the ratio of dark minerals to light as may be seen in the accompanying figures. Fig. 25 shows one of the more feldspathic varieties.

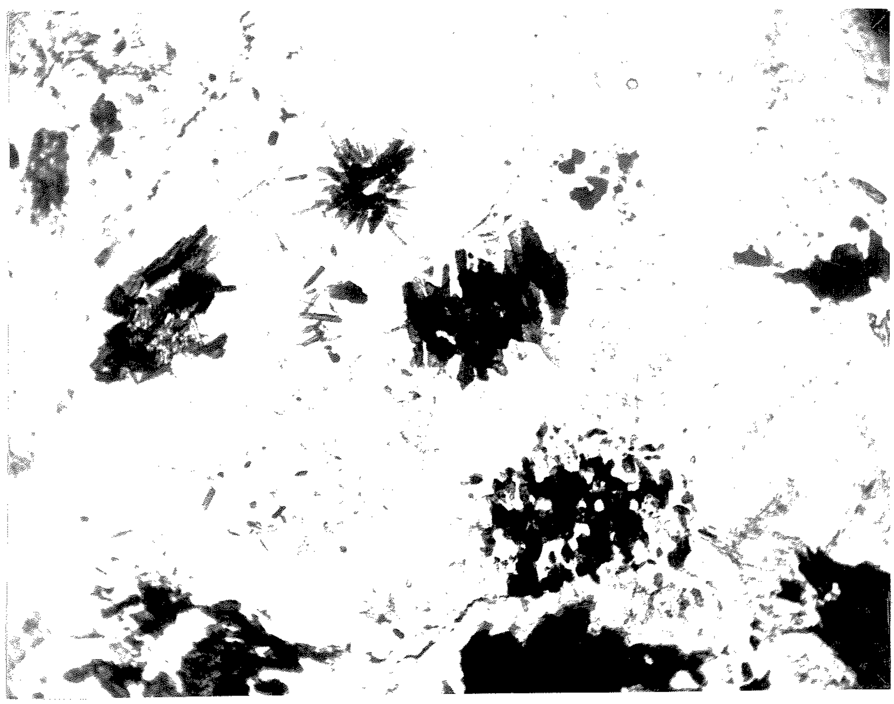


Fig. 24 Photomicrograph showing star like growth of hornblende in feldspar containing numerous inclusions.

Fig. 25 One of the more feldspathic spotted diorites in Pole Canyon, south of the map.

Amphibolites: The fourth and last group of rocks of importance making up the Mafic Phase of the anorthosite might equally well be considered to be later dike rocks, which in some cases they certainly are, but because of their direct relation to the anorthosite mass and their abundance in the Mafic Phase of the Anorthosite, they have been grouped with these rocks. This rock is an amphibolite. It is composed chiefly of actinolite with smaller amounts of hornblende, with relatively abundant apatite, and variable amounts of magnetite. It contains also variable amounts of feldspar. In many cases the apatite is so abundant and in such large crystals that it might be mistaken for feldspar. See fig. 26. In other cases the apatite occurs in swarms of small crystals about a millimeter in diameter. Fig. 27 shows an example of the rock when it contains considerable amounts of feldspar. The feldspar in the illustration occurs in elongate forms. the remaining light material is apatite. The amphibolite occurs in

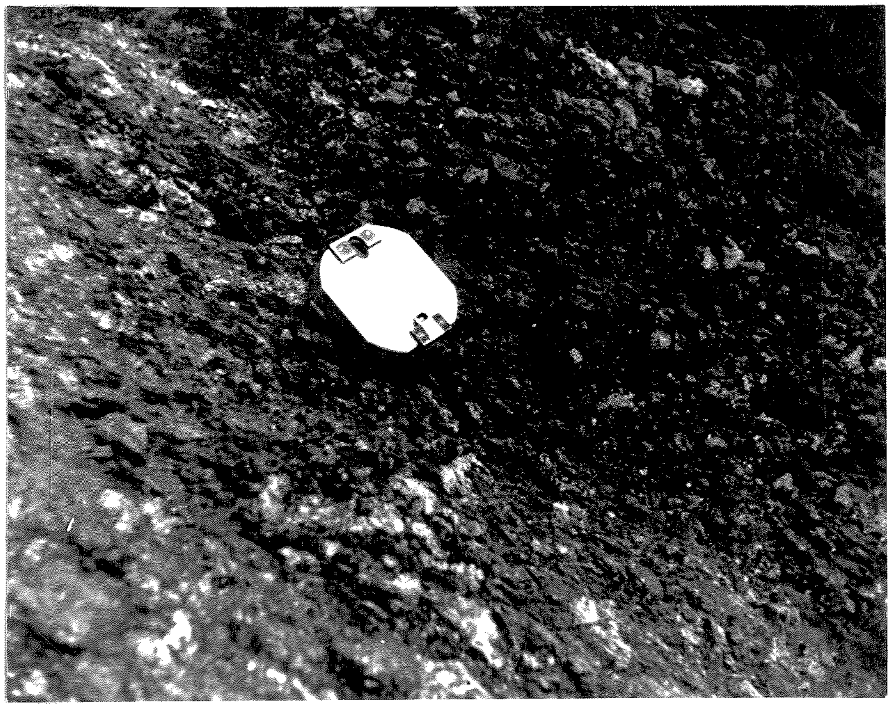


Fig. 26 Amphibolite; light material is apatite, dark material is mostly actinolite with some hornblende.

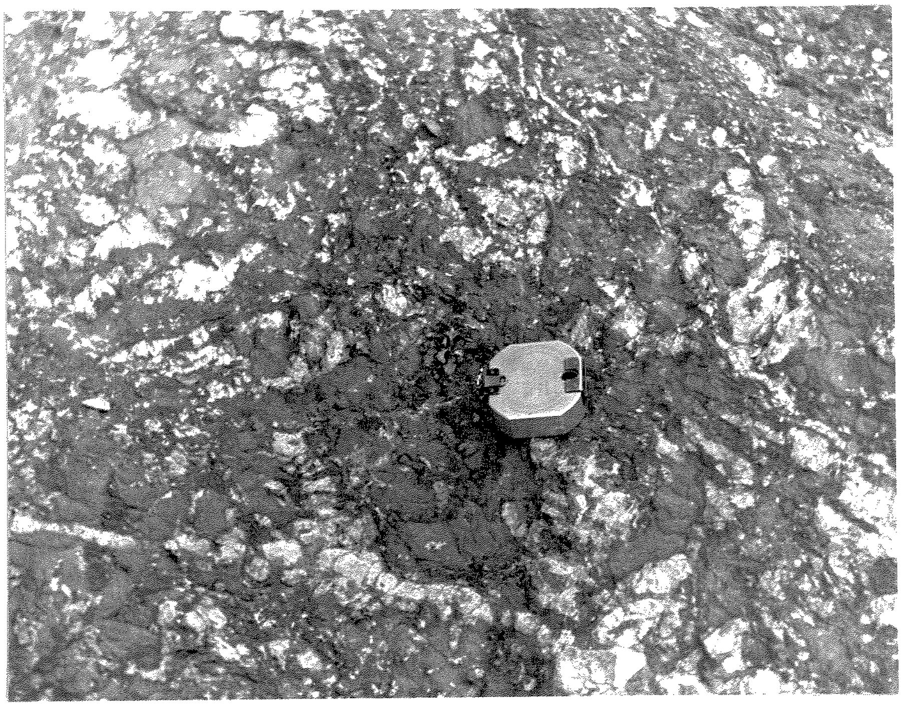


Fig. 27 Amphibolite containing feldspar

dike-like structures parallel to the general banding of the rocks in the Mafic Phase of the Anorthosite and also as rather irregular masses of generally lenticular form. Fig. 28, a picture taken in the bottom of a stream channel, shows the contact surface between anorthosite and a lenticular shaped amphibolite mass. The softer amphibolite has been largely removed by stream action and now exists only where it has been protected by the harder anorthosite. Wherever the amphibolite comes in close contact with the anorthosite, as may be seen in this case, the typical hornblende reaction rim is formed. The small white grains included in the actinolite and hornblende are apatite.

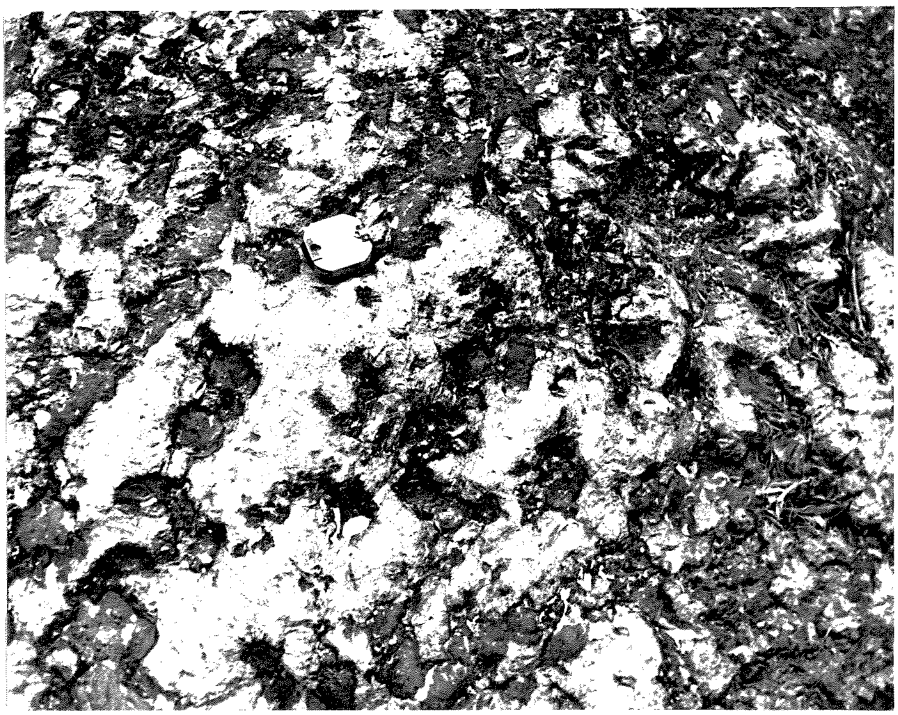


Fig. 28 Contact surface between anorthosite and amphibolite mass showing hornblende reaction rims

Probably related to these amphibolites are the magnetite deposits found in the region, one of which is located at the south end of the mine road between Bear and Pole Canyons. The transitional rocks are made up entirely of actinolite and magnetite. The magnetite deposits seem to be simply places where the actinolite occurs in minor quantities. The large masses of magnetite are not made up of accumulations of small crystals but are composed of crystals as large as two inches in diameter. Large apatite crystals frequently occur within the masses of almost solid magnetite, and rutile is frequently encountered. These magnetite deposits may be the result of the introduction of sufficiently large quantities of amphibolite so that differentiation could take place within the intruded mass by settling of the magnetite crystals and thereby form the present accumulations. A polished section was made of a piece of magnetite, and it was found to contain small amounts of ilmenite. Stream boulders of almost pure magnetite may be found in Pole Canyon as large as eighteen inches in diameter.

PETROGENESIS OF THE ANORTHOSITE COMPLEX:

The Anorthosite Problem:

The problem of the anorthosites is one which requires an explanation of the origin of a monomineralic plagioclase feldspar rock-mass. One must believe either that the magma from which such a rock was formed has always existed with its required composition, or else it has differentiated from a parent magma of basaltic or similar composition. The association of expectable differentiates with the anorthosite and the general acceptance of a parent magma makes differentiation an almost universally accepted origin for these rocks. The nature of the process of differentiation, however, is the chief subject of discussion.

N.L.Bowen (8) is the originator and chief supporter of the theory of gravitational crystal settling. He bases his choice of this origin on the following evidence. It has long been known that the temperatures of crystalization of magmas are much lower than the melting points of the individual minerals. This is due to the effect of mutual solution. Now if the melting point of an anorthosite rock is considered, it is found that a temperature as great as 1450° for $Ab_1\ An_2$ would be required, while Lodochnikow (9) states that Jaggar's precision measurements of the temperature of the Hawaiian Island lavas gives a value of only 750°- 850°. Previous measurements have given 1260°- 1230° and 1200°-1300°. Very few measurements have been recorded higher than 1260° while most are near 800°- 900°. These measurements recorded from normally high temperature magmas suggest that magmas as high as 1400° are not to be expected. Observations on contact effects, even on easily affected rocks, show that the mass has not been raised nearly to the temperature required for an anorthosite magma.

Bowen offered the following explanation for the origin of the anorthosites which he bases on the evidence of physical chemistry. " A consideration of the method whereby accumulation of plagioclase crystals might take place leads to the conclusion that the most promising is the separation by gravity of the femic constituents from gabbroic magma, while the plagioclase crystals which are basic bytownite, remain practically suspended. Then at a later diorite syenite composition the plagioclase crystals which are now labradorite accumulate by sinking and give masses of anorthosite at the same time leaving the liquid out of which they settle of a syenitic or granitic composition." (8) p. 242

The results of this manner of origin are that the anorthosite must contain a minimum of 15 or 20% bisilicate, quartz or orthoclase before it can intrude other rocks as small dikes. Secondly, anorthosite should not occur as an effusive rock. Its absence, however, as such, does not serve as very good evidence, since it is believed to form at great depth and would not, therefore, be apt to reach the surface in a fluid state. Anorthosite might be expected to show considerable cataclastic texture due to post formational movements. These features are fairly well exhibited in the field although a few exceptions have been stressed by opponents of the theory.

Bowen's chief adversaries are Harker, Iddings, Pirsson, Daly and Lodochnikow. It has been suggested that the anorthosite magma might be kept liquid by the presence of mineralizers, but the minerals which develop from such materials are not found in anorthosites. Lodochnikow points out that many of the New England pegmatites do not show the presence of mineralizers either, so he concludes that their presence is not alwary associated with typical minerals.

J.P.Iddings objects to the theory on the basis that the magma would be too viscous for crystals to settle, also due to super cooling (however such a phenomenon is possible under these circumstances) the interval between crystalization of the different minerals is too short for separation by settling to take place. One might say in answer to these objections that neither the viscosity not the time available for settling is known and consequently these factors cannot be used as evidence against the theory. In regard to the possibility of super cooled silicate solutions, it seems rather questionable whether such things are possible when silicates are in suspension in the magma. Also Lodochnikow's postulation that the rising of bubbles of mineralizer gases would produce convection currents sufficient to prevent crystal settling would make the existence of super cooled liquid difficult to accept.

L.V.Pirsson states that convection would more than make up for any settling of crystals and thereby prevent differentiation.
It appears that Pirsson and Iddings, in objecting to Bowen, have attempted to prove that differentiation is an impossibility, as evidenced by their statements, that in many places several thousand feet of rock show evidence that no differentiation has taken place, and implying that, if it did not occur in these cases, it would not occur at any other time, place or circumstance. Since these objections apply equally well to any theory of liquid differentiation, and therefore

to all types of differentiation, the evidence set up is an attempt to prove the impossibility of differentiation by any process. There is, however, abundant and excellent field evidence that such a process does occur.

Although there are published many objections to Bowen's theory it is surprising how many of them when subjected to unbiased analysis appear trivial, and also how many of the objections conflict with one another. The attack upon Bowen's theory unfortunately has not carried with it any expression of a mechanism by which liquid differentiation could take place. If such a process is to take place by diffusion, it is much moredifficult to accept than is crystal settling. If it is to take place by local diffusion and settling of small droplets, this is more nearly possible than by simple diffusion, but is still less expectable than by crystal settling. It appears then that this choice is given, whether to accept no theory on the origin of the anorthosite or else accept Bowen's theory. The latter is preferred until a better one is offered.

The Anorthosite Complex:

Because of the limited area which could be covered in detail during this study, a complete and satisfactory explanation of the origin of the Anorthosite is more than could be hoped for. It was found, however, that considerable information on the origin of these particular rocks could be found by a detailed study of the contact between the Anorthosite and the Mafic Phase of the Anorthosite. It was also felt that a knowledge of the pertogenesis of the Mafic Phase of the Anorthosite might indirectly give some idea of the origin of the pure Anorthosite.

The establishment of the genetic relation between the Mafic Phase of the Anorthosite and the pure Anorthosite is based on field evidence, mineralogical evidence, and on the evidence of physical chemistry. The field evidence consists of the association and comparable age relations shown in the field. The best mineralogical evidence is found in the nature of the feldspar. So far as can be determined, the feldspar of both rocks has the same composition. Both show an abundance of pericline twinning. Both show the same discontinuous twinning lamellae, and both show the same clouds of inclusions. Almost all theories dealing with the origin of anorthosite rock assume a parent magma which has differentiated into anorthosite and various more acidic and more basic associated rocks, so that when an anorthosite is found, the other associated rocks are immediately sought. On the basis of these facts, it is concluded that they are two related parts of a much greater unit which might be called the anorthosite complex. Let us first see what can be learned from the nature of the Anorthosite - Mafic Phase contact.

Anorthosite - Mafic Phase Contact:

The gradational nature of the contact necessitates that the contact is the result of one of three processes. It is of replacement origin, or it is due to large scale differentiation, or it is due to intrusion.

Origin by Replacement: If the contact is of replacement origin, either the Anorthosite is the replacement product of the Mafic Phase, or the Mafic Phase is a replacement product of the Anorthosite. If the Anorthosite formed by the replacement of the Mafic Phase, it would be difficult to explain why the amphibolites also were not replaced, since they were probably intruded into the Anorthosite at the time when the Mafic Phase - Anorthosite contact was being formed, and the amphibolites contain the same minerals as the Mafic Phase rocks. The regularity of the contact, which would consist of interfingering tongues of the two rock types if it were due to replacement, also eliminates such an origin. That the Mafic Phase is a replacement product of the Anorthosite, however, may on a small scale be demonstrated by the development of reaction rims. (See Petrogenic Problems Relating to Reaction Rims). If such a process as this has taken place over a considerable distance, however, it is expectable that the replacing solutions would, as in the preceding case, follow channels and thereby make an interfingering contact such as is typical of large scale replacement. No such structures as this have been found. The general mineralogical uniformity of the Mafic Phase of the Anorthosite also points to the improbability of a replacement origin over any considerable distance.

Origin by Immiscible Liquid Differentiation: The probability that the contact is due to this type of differentiation may also be eliminated. If one assumes the possibility of differentiation by immiscible liquids, in which two liquids were formed, one with the composition of andesine, and one with the composition of a diorite, one is confronted with the vigorous objections of N.L.Bowen which cannot be disregarded. Whatever the nature of the evidence which supposedly disproves Bowen's theory on the origin of the anorthosite in other parts of the world, no such evidence has been found by the author in the San Gabriel Mountains. The evidence which W.J.Miller cites in the way of disproving the Bowen theory has been examined in the area under study, and in each case, it was found to be based on misinterpretation or on evidence which is admittedly indecisive. Miller figures two illustrations of portions of the area studied which he claims are evidence that the pure Anorthosite intruded the Mafic Phase of the Anorthosite. Fig. 29 , taken on the south side of Soledad Canyon about a mile east of Lang, shows what Miller calls an intrusive contact, but which the author prefers to call the Goat fault on the basis of the topographic expression, straightness of the feature, the exposure of the fault at the west portal of the tunnel for the new road and the east portal of the nearestrailroad tunnel in Soledad Canyon (See fig. 30), and the dissimilarity to the typical gradational contacts in the area. A short distance to the west the fault intersects the typical contact zone and this apparent connection might mislead one to the conclusion that the contact shown above is intrusive. On the right side of the picture (fig. 29)

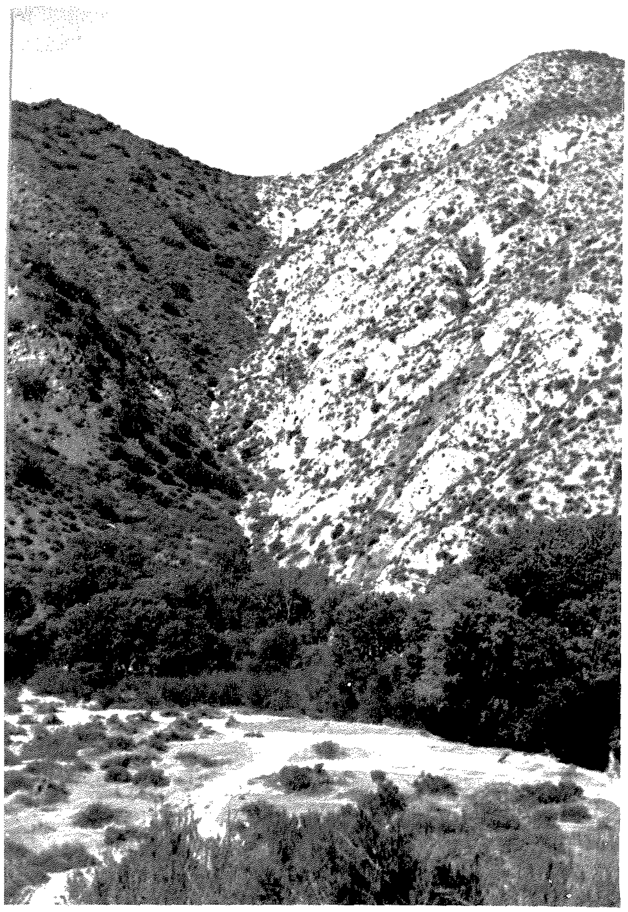


Fig. 29 Goat fault in Soledad Canyon On right, amphibolite dike in the Anorthosite

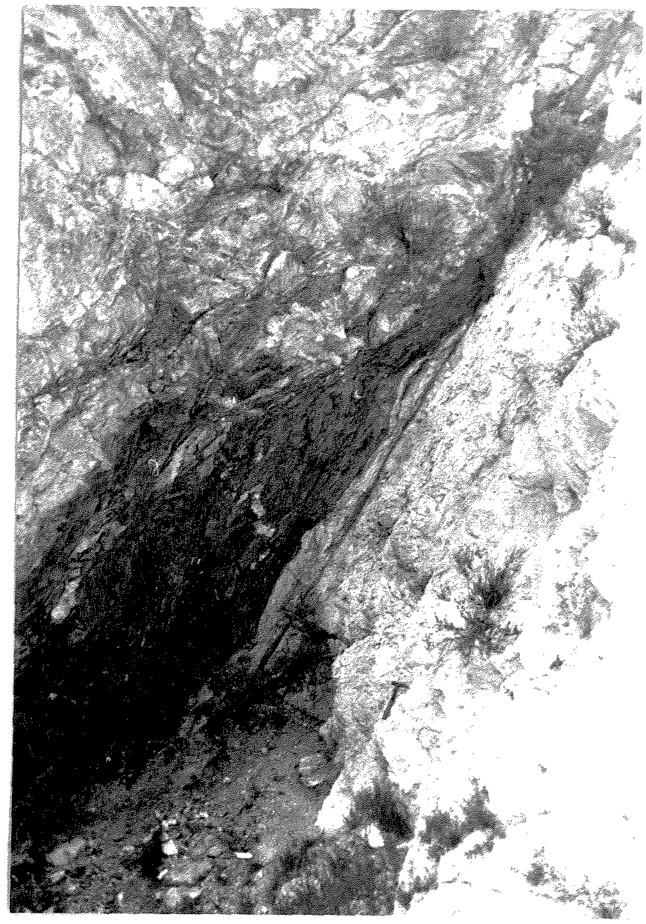


Fig. 30 Goat fault near east portal of railroad tunnel in Soledad Canyon, north-east of fig. 29

may be seen a long mass of dark rock which Miller stated was an inclusion of the basic rock in the intruding Anorthosite. In the first case the proximity of the"inclusion" to the contact has no significance since it is a fault contact. In the second case, the material making up the inclusion is what has been classified above as amphibolite, which is known to be a dike rock that has intruded the Anorthosite in a number of places in Bear Canyon as the last stage of the Anorthosite sequence of emplacements. Since the amphibolite cannot be said to be later than the Anorthosite in every case, it is still possible that the amphibolite "inclusion" was intruded into the Mafic Phase of the Anorthosite and at a later period broke out of it and was included in the pure Anorthosite during the latter's supposed intrusion. This, however, is an unlikely possibility, and the field evidence cannot therefore be taken as definite proof that the pure Anorthosite intruded the Mafic Phase of the Anorthosite, and that the mass is an inclusion rather than a dike.

The second illustration which Miller shows is at the mouth of Pole Canyon. Here he has failed to appreciate the age relation of the lamprophyre dikes to the pure Anorthosite, or else he has failed to distinguish the lamprophyre dike from the Mafic Phase of the Anorthosite. He finds here an inclusion of an elongate piece of anorthosite which has broken partly away from the enclosing anorthosite wall of a lamprophyre dike and is now found projecting into the lamprophyre dike. This, Miller interpreted to be a tongue of anorthosite intruding the Mafic Phase of the Anorthosite, whereas it is actually a dike of lamprophyre intruding mixed Mafic Phase and pure Anorthosite and including a piece of wall rock within it.

The last line of evidence which Miller gives to prove that the pure Anorthosite intruded the Mafic Phase of the Anorthosite, and which can be studied in the area covered by this report, is the presence of "inclusions of Metadiorite" in the Anorthosite. Fig. 31 shows an outcrop along the new road in Soledad Canyon about a mile east of Lang. Due to the extreme alteration of the rocks in most of

Soledad Canyon, it is difficult to make a mineralogical correlation between these rocks and the fresh rocks found in the deeper portions of Bear Canyon, but as far as can be told, the white rock is chiefly anorthosite (there is some pegmatite and aplite) and the dark rock is relatively recent (probably Tertiary) lamprophyre, which has intruded the anorthosite along numerous fractures in the Soledad fault zone. Within the canyon at a number of places, these basic rocks are seen to intersect and cross one another and follow fracture patterns as is typical of dikes. This together with the absence of similar structures, other than typical lamprophyre dikes, close to the contact in the deeply dissected portions of Bear Canyon, makes one feel that these structures are not inclusions but dikes. During a recent discussion given by Dr. Miller at a Geology Club meeting of the Calif. Inst. of Tech. on the subject of the anorthosites, he frankly admitted that he was not sure whether the structures in question were dikes or inclusions.

To conclude the discussion of W.J. Miller's findings of evidence that the Anorthosite intruded the Mafic Phase of the Anorthosite as an immiscible segregated liquid as opposed to Bowen's view that the anorthosite never existed in a liquid state, there appears to be no evidence in this area that Miller was correct and that Bowen was incorrect. Since there is a great deal of positive evidence, based on physical chemistry, and negative structural evidence that the Anorthosite could not have occurred as a liquid mass, the possibility that the pure Anorthosite - Mafic Phase contact is due to immiscible liquid differentiation is eliminated.

<u>Origin by Crystal Settling Differentiation:</u> The problem of whether the contact between the pure and Mafic Phase of the Anorthosite could be produced by crystal settling has yet to be settled before the possibility of a contact origin by differentiation can be eliminated. Although it is believed that some such process as crystal settling has been the fundamental process by which the Anorthosite has come into being, it is not believed, however, to be the process which produced the present contact. In the later stages of the process of segregating the Anorthosite from the diorite there must have been great amounts of intermediate rocks formed as a result of the capture of descending femic minerals by feldspars at relative rest with a resulting lowering of the feldspar group into the region of more femic minerals. Coats (7) has suggested a process similar to this for the formation of banding in basic rocks. A process of this type should produce a widely gradational contact considering the large amounts of material involved. Although many such gradational areas may be seen within the Mafic Phase of the Anorthosite, the contact between the pure Anorthosite and the Mafic Phase of the Anorthosite is relatively sharp, with an average width of about 500 ft. Bowen stated that if all of the units of differentiation were exposed they would be, from top to bottom, syenite or granite, anorthosite, gabbro, amphibolite, and magnetite. The presence of amphibolite only in dikes, and the probable similar origin for the magnetite deposits, and their

distribution without regard to the spacial relations which Bowen stated should occur, as also the absence of appreciable quantities of syenite, lead one to believe that only a small part of the entire complex is present, and this not in its proper relation. In addition to this, the fact that the banding is approximately parallel to the contact suggests that the movement which formed the contact was parallel to it and therefore would not be due to group settling of crystal masses. It may be concluded, then, that the present pure Anorthosite - Mafic Phase contact is a structural feature brought about by movement following segregation.

Origin by Intrusion: Since a replacement origin and one due to large scale differentiation for the Anorthosite - Mafic Phase contact have been eliminated, there remains only the possibility of an intrusive contact. Since the possibility of an anorthosite magma is not acceptable and since the Mafic Phase of the Anorthosite shows the presence of banding over a large area, it can only be that the process of emplacement was one in which the Mafic Phase intruded the Anorthosite. That the banding found in the Mafic Phase has no relation to later metamorphic activity may be proved by the preence of two directions of banding, one cut off by the other, as shown in fig. 22. This structure must be the result of successive intrusions of the Mafic magma. At the time of the Mafic Phase intrusion the pure Anorthosite was probably sufficiently solid, in most cases, to move as a unit, while the Mafic Phase was only sufficiently solid to develop banding over a

Fig.31 Lamprophyre dikes intruding the Anorthosite in the Soledad fault zone, Soledad Canyon.

Fig. 32 Photomicrograph of reaction rim shown in the hand specimen in frontispiece. At bottom, fine grained is actinolite. In center, dark gray, hornblende. Top, light gray, feldspar. Plain light.

considerable distance. Some evidence that the Mafic Phase intruded the Anorthosite may be found at the mouth of Pole Canyon where the Mafic rocks show a strong drag or viscous flow effect as if they had been forced up from below. See map. The result of the semi-solid condition of the two units was that when the two masses were forced by probably nearly vertical movement against one another, they mixed freely at the contact producing the banded hybrids and distorted the Mafic mass sufficiently to develop banding in the spotted diorites.

Petrogenesis of the Mafic Phase of the Anorthosite:

The Hornblende Reaction Rims: Foremost among petrogenic problems concerning the Mafic Phase of the Anorthosite is the problem of the origin of the hornblende reaction rims. Three types of hornblende reaction rims have been observed: the actinolite-hornblende-feldspar rims best shown in the plain hybrids, the actinolite-hornblende-feldspar rims in the spotted diorites, and the magnetite-hornblende-feldspar rims in the spotted diorites.

In plain hybrids:

The specimen shown in the frontispiece is one of the best to show the relations. Fig. 32 is a photomicrograph of a portion of this same rock. In the hand specimen, the outlines of the feldspar grains may easily be determined by examining it in reflected light. In the largest mass of feldspar shown in the frontispiece, there are about thirty crystals which makes them average about one centimeter in diameter. In the thin section, fig. 32 however, the actinolite, (gray at bottom) can be seen to be very fine grained, averaging about one-half mm. in diameter. In addition to this anomaleus grain size relation, there are textures which lead one to the belief that the actinolite is a replacement, alteration or inversion product from some earlier mineral. If the frontispiece is examined closely in the areas of actinolite, one will see that there are areas which show parallel narrow bands running through them to form by their incorporation, a larger unit which is in contact with similar areas with bands running in other directions. Fig's. 33, 34, 35, and 36 show similar areas under the microscope with plane light. These

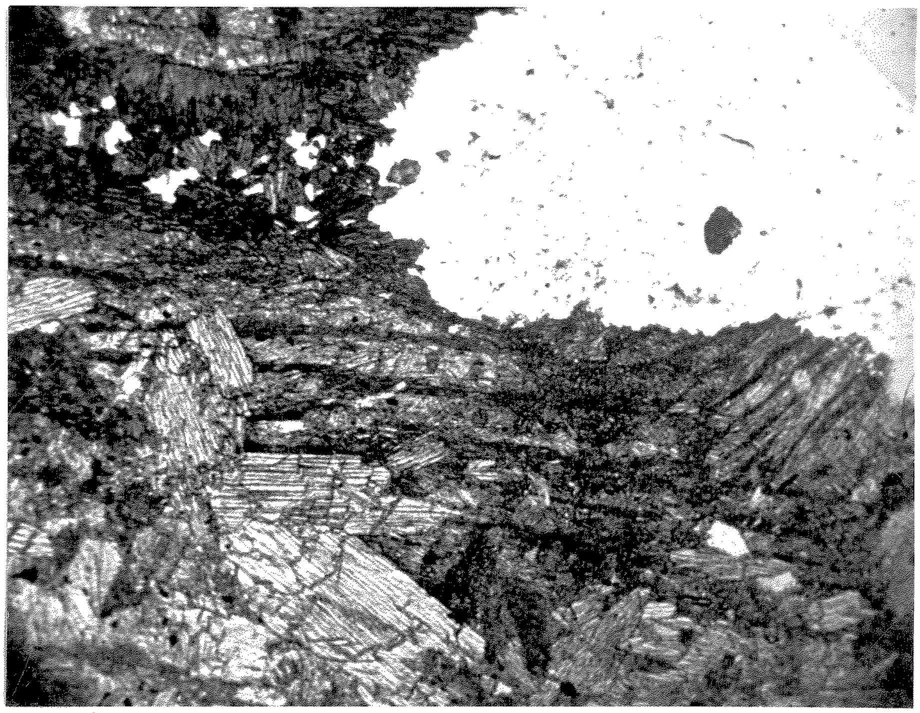


Fig. 33 Photomicrograph showing relict textures in the actinolite of the plain hybrids. Note two directions of banding, intersecting.

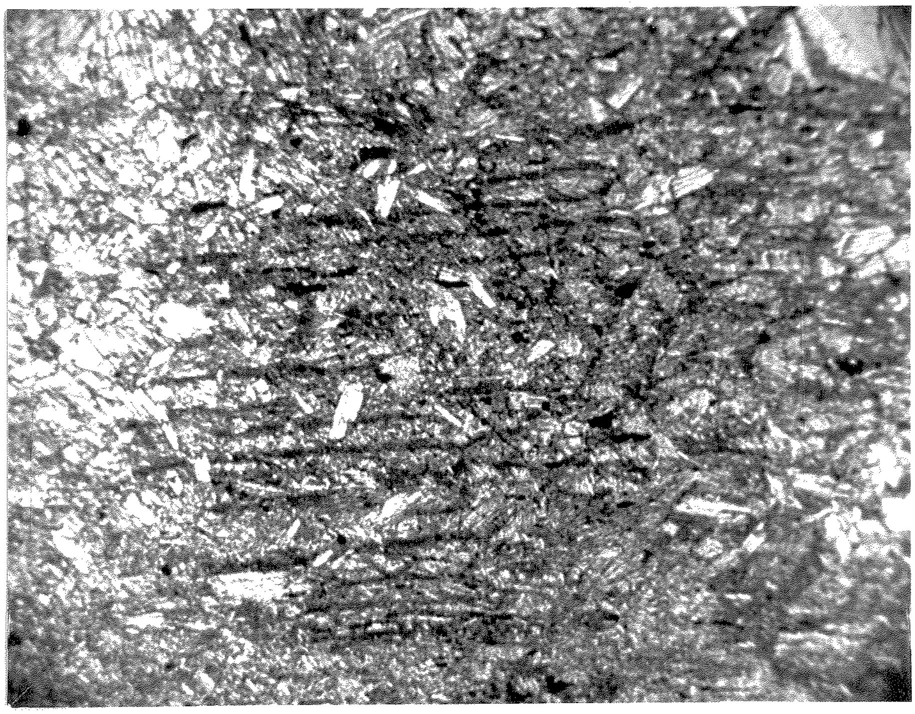


Fig. 34 Relict structure in actinolite of plain hybrids

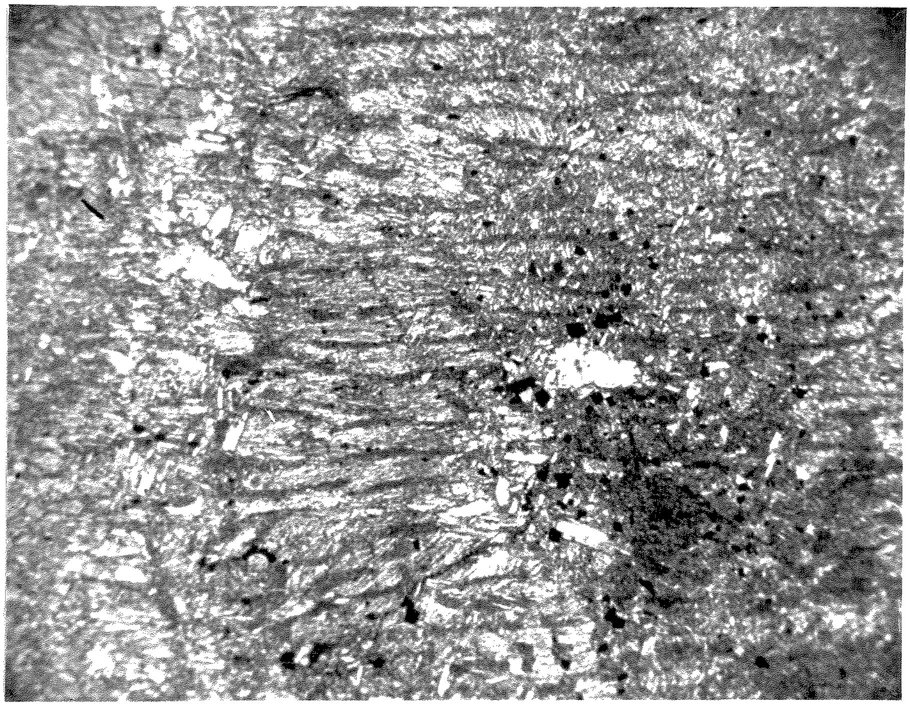


Fig. 35 Relict structure in actinolite of plain hybrids

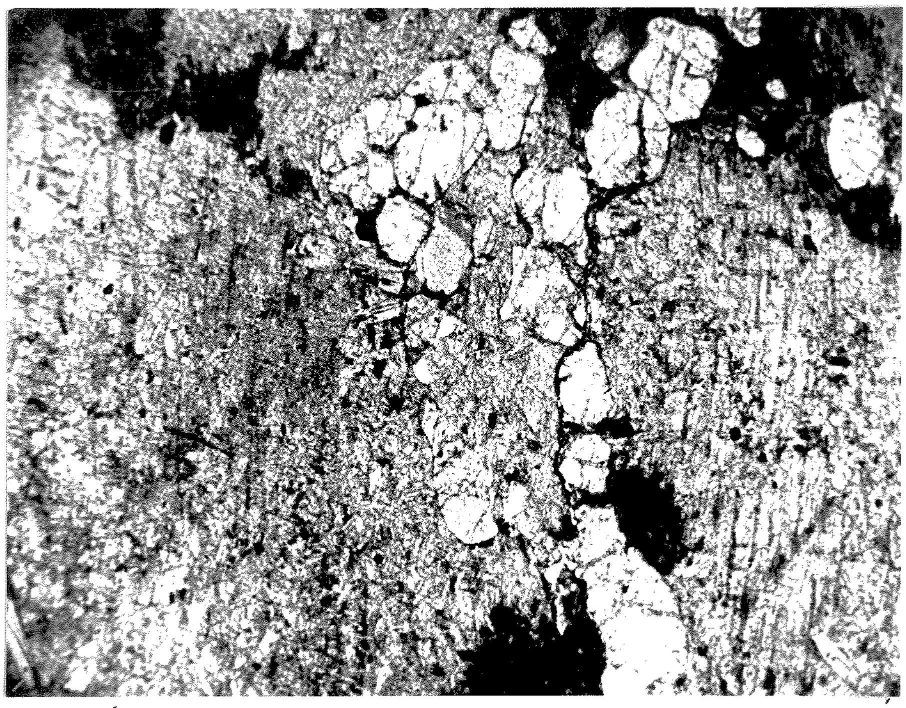


Fig. 36 Relic structure in actinolite of plain hybrids

bands appear to be a little greener than the remainder of the mineral but seem to be made up of the same mineral, actinolite, as the lighter areas. Fig. 33 shows the intersection of two sets of such lines, indicating that they are not due to fracturing along lines of stress, but more probably related to the crystal directions of an earlier mineral. In the thin sections thereappear to be two types of actinolite, a very fine actinolite which makes up the ground mass, and in which the relic textures are preserved as shown in Fig. 36, and the coarser actinolite crystals which usually interrupt the relic textures whenever they occur, as shown in thin sections 34 and 35. In the hand specimen shown in the frontispiece, there is an area of actinolite between the upper two feldspar areas which appears to have one orientation. If this represents an earlier crystal, the material must have been very coarsely crystalized, since this is nearly an inch in diameter. This is much more nearly comparable in size to the feldspars and suggests that this early mineral and the feldspar formed under nearly the same conditions controling crystal growth before the former mineral was altered to actinolite.

The question as to what this early mineral may have been is a difficult one to answer. On the basis of mineralogy, one would expect the mineral to be a pyroxene, which would probably be in the diopside-hedenbergite group close to diopside. The presence of considerable limonite staining suggests that the end product equation would be something like the following:

Magnetite Diopside Actinolite Calcite Limonite

$$Fe_3O_4 + 4CaMgSi_2O_6 + 2CO_2 + nH_2O \rightarrow H_2Ca_2(Mg,Fe)_5Si_8O_{24} + 2CaCO_3 + Fe_2O_3 \cdot nH_2O$$

In regard to the relic structures, there is the difficulty that if the bands found here are relic twinning bands, it is seldom that such a structure is developed so abundantly in diopside. Although the bands may be the result of cleavage, and might more easily be explained as relic structures on this basis, the present structures more closely resemble twinning lamellae. If the original mineral were feldspar, the twinning lamellae would be accounted for, but it would be expected that an aluminous mineral like feldspar would produce hornblende instead of actinolite, if conditions for such a replacement were existant. Qualitative chemical tests were made of the actinolite to see if aluminum was present, but the results were conflicting, partly because of the unreliability of the chemical procedure. The evidence is far from conclusive as to what the original mineral was, but it is preferred to consider it to be in the diopside-hedenbergite group near diopside until further evidence is obtained to the contrary.

Another rock specimen suggests that there might have been more than one mineral which has altered to actinolite. Fig. 37 shows a thin section of a rock which, seen in hand specimen, is composed of apatite, actinolite and magnetite, with strange gray areas unlike any of the minerals composing the Mafic Phase of the Anorthosites. When this is examined under the microscope, it is found to be an intimate mixture of magnetite and actinolite, with the magnetite

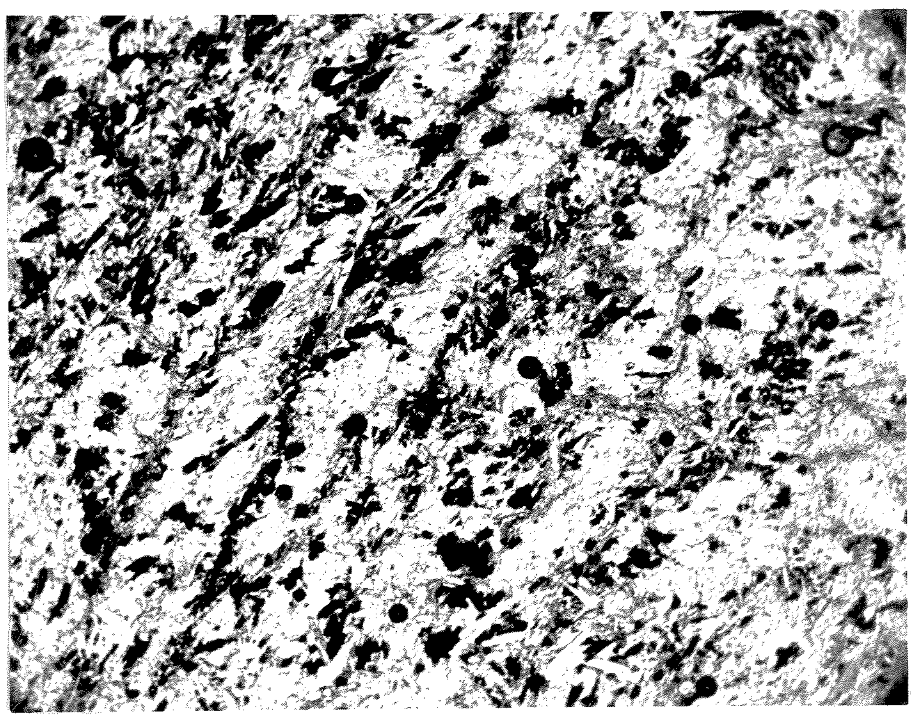


Fig. 37 Intimate actinolite-magnetite mixture, probably an alteration of a pyroxene near hedenbergite.

forming bands in the rock. The large areas of magnetite are surrounded by areas of actinolite which include very little magnetite, and it is concluded, therefore, that the large areas of magnetite are formed by the segregation of the fine magnetite. There appear to be two explanations for this fine mixture of magnetite with actinolite. The first is that the magnetite was introduced into the rock at a late stage in its history, but this does not explain why there is no finely disseminated material near the large areas of magnetite. The preferred explanation, therefore, is that the magnetite is a reaction product of the conversion of an earlier mineral by uralitization to actinolite and magnetite, both because of the distribution of the disseminated magnetite along probable cleavage lines, and the absence of disseminated magnetite near areas of magnetite concentration. The original mineral which would contain the required elements would be in the diopside-hedenbergite series close to hedenbergite.

It therefore appears that the actinolite which makes up most of the ferromagnesian material in the rock has altered mostly from diopside and partly from hedenbergite.

Returning now to the larger features shown in the handspecimen (frontispiece) and thin section, fig, 32, there appear to be a number of ways in which the feldspar-hornblende-actinolite relation may have formed. To determine the origin of this relation, two questions must be answered. What are the age relations of the ferromagnesian minerals to the feldspar? When did the reaction rim form? The first question involves three possibilities. First the feldspar might have intruded the ferromagnesian minerals; second, both minerals might have formed simultaneously; third, the ferromagnesian mineral might have intruded the feldspar. The second question involves two possibilities. First, the reaction rim formed at the time of the introduction of one mineral into the other, or second, it formed at some later period of time.

Due to the fact that there may have been originally diopside where actinolite occurs and augite where hornblende occurs in these rocks, the following combinations are possible. (The reaction rim minerals will be shown in capitals.)

1. feldspar magma intrudes diopside → AUGITE or HORNBLENDE + Andesine
   later uralitization: diopside ↓ actinolite; AUGITE ↓ HORNBLENDE
2. feldspar magma intrudes actinolite → HORNBLENDE + Andesine
3. femic magma intrudes feldspar → AUGITE or HORNBLENDE + Diopside
   later uralitization: AUGITE ↓ HORNBLENDE; Diopside ↓ Actinolite
4. femic magma intrudes feldspar → HORNBLENDE + Actinolite
5. feldspar and ferromagnesians form simultaneously: Andesine + Diopside
   later uralitization: Andesine ↘ and Diopside ↙ HORNBLENDE; Diopside ↘ Actinolite

The occurrence of fractures in the feldspar which are filled with ferromagnesian material as shown in fig. 17 and the occurrence of beautifully developed dendritic replacement patterns along similar fractures in the feldspars show beyond doubt that the ferromagnesian material intruded the feldspar. This mafic material, however, may either have been a part of the original intruding mafic magma, or since it is restricted to small quantities, it may be due to later minor introduction of material accompanying uralitization. If this latter is true, it implies that the feldspar might have originally intruded the ferromagnesian minerals. But, it this were true, one would expect to find some fractures in the ferromagnesian minerals filled with andesine feldspar. These, however, are not found. From this it can be concluded that either both minerals formed simultaneously or else a mafic magma intruded the feldspar. From the fact that the feldspar crystals occur in large clusters and the ferromagnesian minerals also occur in large clusters, the possibility that both minerals formed simultaneously may be eliminated, for if this were true, the feldspar and mafic minerals would be intermingled as in a normal diorite. In answer then to the question of the age relations of ferromagnesian minerals to feldspar, it can be said that a mafic magma intruded the feldspar and therefore the feldspars are older than the ferromagnesian minerals.

In regard to the question of when the reaction rim formed, if it formed at the time of the introduction of the mafic magma, it would probably be augite, which, during the period of uralitization would alter to hornblende while the early diopside was altering to actinolite. On the other hand, the reaction between the feldspar and the diopside might not have taken place until the latter had changed to actinolite, in which case, the hornblende would be the stable product. The microscopic evidence on this point is conflicting. The hornblende crystals, although of very small size, in a given area usually all have one orientation. This may be simply the result of the tendency for the crystals to grow perpendicular to the contact between the mafic mineral and the feldspar, or it may be that they are the alteration products of larger earlier pyroxene (augite) crystals. It might be thought that the shape of the hornblende crystal groups would give the answer to this problem, but the evidence here is not clear. Although there are many hornblende groups that are fairly short, there are also many slender needle shaped crystals. These needle shaped crystals, however, may be the result of a recrystalizing process which would take place at a time when augite was altering to hornblende. Many of the hornblende crystal groups appear to have been partly replaced by the adjacent feldspar, but since the evidence is clear that the ferromagnesian minerals intruded the feldspar, this minor replacement of the hornblende fits well into the view that the reaction rim, as we see it now, is at least a recrystalization of the hornblende and probably a recrystalization of an earlier augite reaction rim to form hornblende. In addition to this insufficient evidence there is the observed field evidence that the width of the reaction rim is proportional to the size of the intruding mass of ferromagnesian material. If we assume that there has been a closed system, for which there is some evidence, the above could only be explained on the basis that the amount of replacement which went on at the border was proportional to the amount of specific heat of the intruding magma times the amount of magma in relation to the cooling surface. This requires that the reaction rim formed at the time of the intrusion of the basic magma and was, therefore, probably composed of augite. Case (3) page 53, therefore, appears to be the best explanation of the age relations of the minerals of this rock type.

For the sake of simplicity in discussing the mineralogical relations at the reaction rim it can be assumed that the minerals occurring there have always been hornblende and actinolite instead of their pyroxenic equivalents, since it is generally accepted that under the proper conditions these minerals can alter from augite and diopside. If fig. 32 is examined closely, it can be seen that at the contact between the hornblende and the actinolite, there is a string of small white dots. When these are examined under the microscepe, they are found to be quartz. This is a remarkable mineral to find in a rock of this type and more remarkable for it to occur in the rock only in this relation. If the equation for the reaction between actinolite and feldspar to produce hornblende is written, it becomes obvious why quartz should occur in this rock, and why it is concentrated at this point. Before an equation can be written and balanced, it is necessary to have at least some idea of the composition of the reacting substances. The feldspar was determined to be andesine An_4, which has a combined formula of $Na_3Ca_2Al_7Si_{13}O_{40}$. Since the ratio of Mg to Fe is variable in both actinolite and hornblende, the equation can be written:

$$\underset{\text{actinolite}}{H_2Ca_2(Mg,Fe)_5Si_8O_{24}} + \underset{Ab_6An_4}{Na_3Ca_2Al_7Si_{13}O_{40}} \rightarrow \underset{\text{hornblende}}{2H_2NaCa_2(Mg,Fe)_4Al_3Si_6O_{24}} + \underset{\text{quartz}}{9SiO_2}$$

The formulas for all minerals used in this paper have been taken from Winchell(10). A small amount of Fe and H_2O added to the left side of the above equation with the removal of an atom of Na and Al from the right balances the equation perfectly. It may appear from the ratio of two molecules of hornblende to nine of quartz that there is too much quartz formed by this equation, but it is really not as much as it appears to be. The approximate molecular weight of hornblende is 1038; quartz is 60. If these are divided by their respective densities, the relative volumes will be obtained, which gives for the ratio of quartz to hornblende, according to the reaction, one third quartz to two thirds hornblende. In some places along the reaction rim there are concentrations of quartz, so the above equation probably describes the process fairly accurately.

<u>In spotted diorites</u>: ACTINOLITE-HORNBLENDE-FELDSPAR RIMS

Although the above described reaction appears to have taken place at a time of the introduction of the ferromagnesian minerals, there are other occurrences of reaction rims which lead one to believe that they did not form at the time of the precipitation of the first ferromagnesians, but delayed reacting until temperatures were sufficiently low, or hydrous solution sufficiently abundant, for hornblende to be the stable mineral. This second type of hornblende reaction rim was found in the spotted diorites. Fig. 38 shows a photomicrograph of this second type of reaction rim. Fig. 39 is a higher magnification of the same area. The figures show a medium sized grain which has the pale greenish color of actinolite, but which does not show the proper

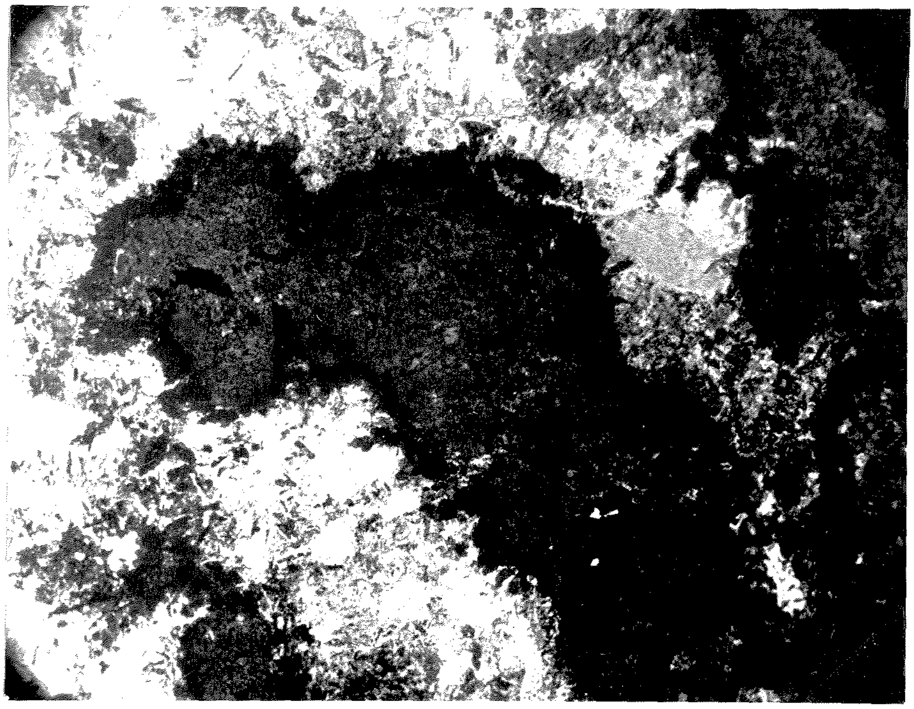


Fig. 38 Photomicrograph of actinolite-hornblende-feldspar reaction rim in the spotted diorite

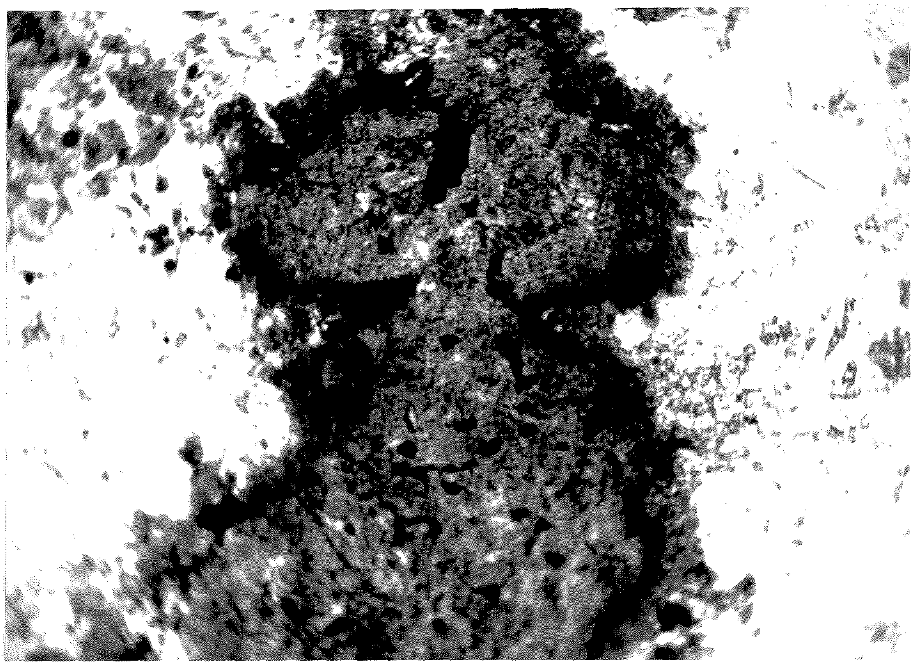


Fig. 39 Higher power of same area as fig. 38

birefringence. From the fact that the entire ground mass area extinguishes in one position, it is obvious that it was originally one grain, although there are many small variously oriented actinolite grains scattered through it. Close to the border of this pale green grain there is a narrow band of hornblende (black) with a wider calcite and epidote band (gray) surrounding the hornblende.

The smooth curved border which outlines this grain is certainly not a natural crystal border, and therefore must be formed by some special process. There are a number of ways in which it might have developed. The ferromagnesian mineral might have been intruded as solution, with the result that, as in the hybrids, a hornblende reaction rim was formed, but the composition of the feldspar might not have been right for the direct replacement of any appreciable quantity of feldspar, and so instead, the feldspar was saussurized to calcite and epidote. Or secondly, the ferromagnesian mineral might have been formed, partly resorbed, giving it its characteristic shape, the surrounding feldspars crystalized, and at some later time such as when the pyroxenes were uralitized to actinolite, the reaction between the ferromagnesian mineral and feldspar might have taken place with the production of hornblende, epidote and calcite. Thirdly the hornblende might have been formed by either of the above processes which removed some of the feldspar constituents and thereby made the feldspar more susceptable to later altering solutions. Later alteration then produced the calcite and epidote. In this last case the shape of the grain would be due to replacement activity.

The fact that the groundmass of the ferromagnesian mineral extinguishes all at once and was therefore only one crystal makes it unlikely that the mineral was introduced as a solution into a cavity, since one would expect such a cavity to contain more than one crystal or to be relatively fine grained. This eliminates the first possibility. The resorbed appearance in thin section looks rather convincing, but it has taken place on such a small scale that when the section is examined without the microscope, it seems more likely that it is the result of a replacement process. The development of hornblende, etc. at the contact with the feldspar might have taken place as the feldspars were forming around the ferromagnesian mineral, but like the reaction rim in the typical spots of the spotted diorites (to be described shortly), it is believed to have formed at a later stage, perhaps at the time of the uralitization of the pyroxenes. It is thought that the formation of the calcite and epidote might be a still later process, because cutting the section is a small vein which is lined with biotite and filled with calcite, quartz, and epidote. See fig. 40. Such an occurrence is more typical of epithermal alteration than mesothermal sausseritization.

In spotted diorites: MAGNETITE-HORNBLENDE-FELDSPAR RIMS

The last type of reaction rim, which is the most abundantly produced, is found in the spotted diorites. Fig. 41 is a photomicrograph

Fig. 40 Photomicrograph of vein in spotted diorite containing biotite (black), calcite (gray), and quartz (white), which is probably related to the alteration of the feldspars around the reaction rims.

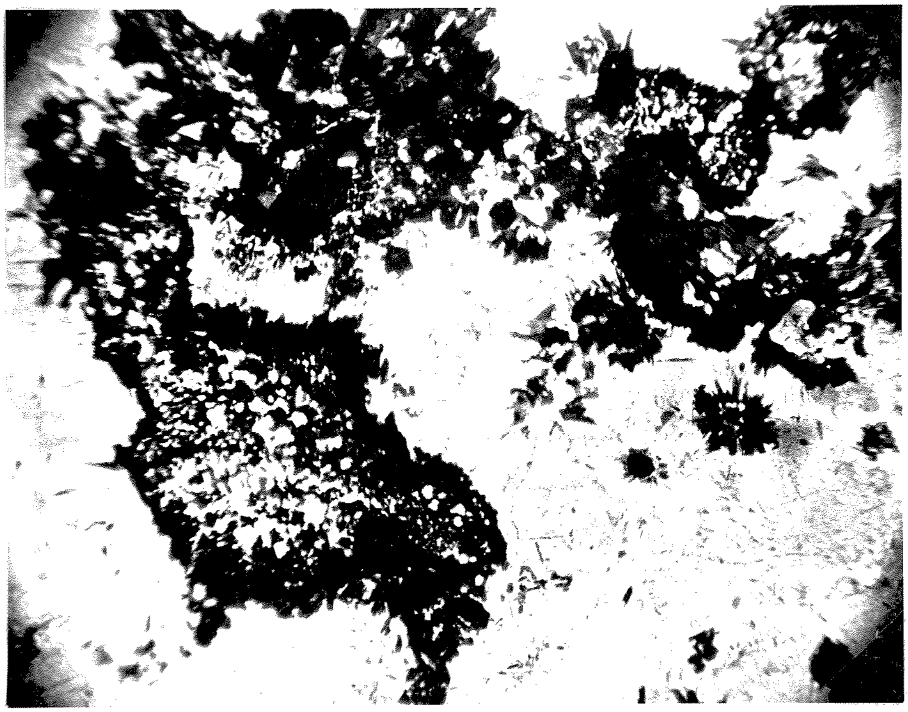


Fig. 41 Photomicrograph of spot development in spotted diorites.

showing an area of one of these rocks. At (A),fig. 41, is a magnetite crystal with two quartz grains at one end surrounded by a tiny ring of hornblende. At (B) is a smaller magnetite crystal surrounded by a ring of small quartz grains, and this is surrounded by a larger hornblende ring. At (C) there is no magnetite left; there is a large area of mixed quartz and hornblende, and the whole is surrounded by a ring of hornblende. It is believed that this, to a certain extent, indicates an evolutionary series. That is, first we have just magnetite in feldspar. A reaction between these two minerals begins with the formation of hornblende and quartz. The reaction continues until all of the magnetite has been used up and there remains only quartz, hornblende and feldspar. Why one magnetite grain should be replaced more than another is difficult to answer, unless it is due to titaniferous impurities or to more resistant crystal structure, such as is often recognized in the replacement of the surface of crystals of ore minerals. If these are the true conditions, it is to be concluded that the spotted diorites were originally mostly feldspar with large quantities of magnetite included in them. At a later period, probably when uralitization of the pyroxenes was taking place, the reaction between the feldspar and magnetite produced the hornblende reaction rims.

The mineralogical relations in the spots is of interest. Assuming a closed system, it appears possible in this case to make a fairly accurate measure of the reaction products and thereby determine the nature of the process with more assurance. First of all, it should be realized that here we are dealing with bodies which approach spherical shape, and so it will be seen that the proportion of shell, or outer hornblende, to the proportion inside of the shell, depends upon where the sphere is cross sectioned, and that at the center of a sphere there should be a higher percentage of centrally located minerals showing, than in any other section. Both because of the size of the spot (C) fig. 41, and the high percentage of quartz exposed, this spot was chosen for measurement.

The volume of a shpere is proportional to the cube of the radius. Likewise, the volume of a shell is proportional to the cube of the outer radius minus the cube of the inner radius, or $R_1^3 - R_2^3$ and the percentage of material in the shell as compared to the entire sphere including the shell is $R_1^3 - R_2^3 / R_1^3$. In measuring (C), R_1 was found to be 1.8cm. and R_2 was found to be 1.3cm. $\overline{1.8}^3 - \overline{1.3}^3 / \overline{1.8}^3 = 62\%$ hornblende in the outer ring. This leaves 38% inside of the hornblende shell,but about half of this is hornblende and therefore there is about 20% quartz and 80% hornblende. The molecular weight of hornblende is 1038 and quartz is 60. The relative mol volumes are respectively 346 and 20.4 or approximately 17 : 1. In other words, for the same volume, there must be 17 quartz molecules for every hornblende molecule. Since there is only 20% quartz by volume, the equation which will describe the reaction must produce 7 molecules of quartz for every 2 of hornblende. If the reaction products are taken in this proportion, it should be possible to work backward and find what composition the feldspar would have to be in order to make the reaction with magnetite produce the observed results.

common hornblende	quartz	magnetite	required elements

$$2H_2NaCa_2Fe_4Al_3Si_6O_{24} + 7SiO_2 = 8Fe + 2H_2O + Na_2Ca_4Al_6Si_{19}O_{50}$$
$$= 2(NaCa_2Al_3Si_9O_{25})$$

A close approximation to such a feldspar is found in labradorite Ab_1An_2 $NaCa_2Al_5Si_7O_{24}$ but the Al : Si ratio is not correct. If the feldspar were considered which contained more of the anorthite molecules, the percentage of Al would be increased but at the expense of Si, and vice versa if a feldspar richer in albite were considered. At this point a number of things may be called to ones aid. The composition of the feldspar occurring in the section cannot be determined by the use of extinction angles, since there are no twinning lamellae, and the presence of a perthite-like structure in the feldspar makes an index determination very difficult. (The characteristics of these feldspars will be considered at length below.) The feldspars are filled with acicular and platy inclusions which may be a source of required material, although they seem to be mostly composed of hornblende. Or if one does not accept a closed system, one may have an introduction of calcium and a removal of sodium.

By way of summary of the character of the hornblende reaction rims, it may be said that there are two major types, those which have developed between a ferromagnesian mineral and feldspar, and those which have developed between magnetite and a feldspar. The first group was found to have developed under two situations. The first of these was by the introduction of a mafic magma into a feldspar rock with a probable formation of the reaction rim at the time of the intrusion, and later a conversion of the resulting diopside mass and augite reaction rim to an actinolite mass and a hornblende reaction rim. The second of these, which occurs only on a microscopic scale, was found to have developed probably at a time of widespread conversion of pyroxenes to amphiboles. The second major type, which has given the spotted diorites their name, has probably also developed during the period of conversion of pyroxenes to amphiboles.

Probably much could still be done in the way of developing a more convincing proof of the origin of these features, but because of the variability in the composition of the various units involved, quantitative chemical analyses would be necessary to positively prove their origin, and this would offer some trouble because of the difficulties in obtaining pure samples of the units.

The Relation of Biotite to Hornblende, etc:

The second most important petrogenic problem related to the origin of the Mafic Phase of the Anorthosites is one dealing with the relation of biotite to the other minerals. Fig. 42 shows a typical association of biotite with magnetite. This relation never appears in the form of radiating crystals of biotite around magnetite, but in general, the biotite is scattered erratically about the magnetite, increasing in amount close to the magnetite. Hornblende often also occurs mixed with the biotite, and it may occur in isolated patches, but these are usually not in contact with magnetite. It appears in many cases that the magnetite is introduced at a late stage, and that the biotite is in part an alteration of the hornblende, which is brought about by the introduction of mineralizing solutions, which lower the melting point of the magnetite making it possible to have this normally high temperature mineral occur as a final stage in the petrogenic history of the rock. It is entirely possible, however, that the magnetite is not introduced into the rock at a late stage, but gives this appearance because of recrystalization at a time when widespread uralitization was taking place. If this is the case, it is equally possible that the biotite had not replaced the hornblende

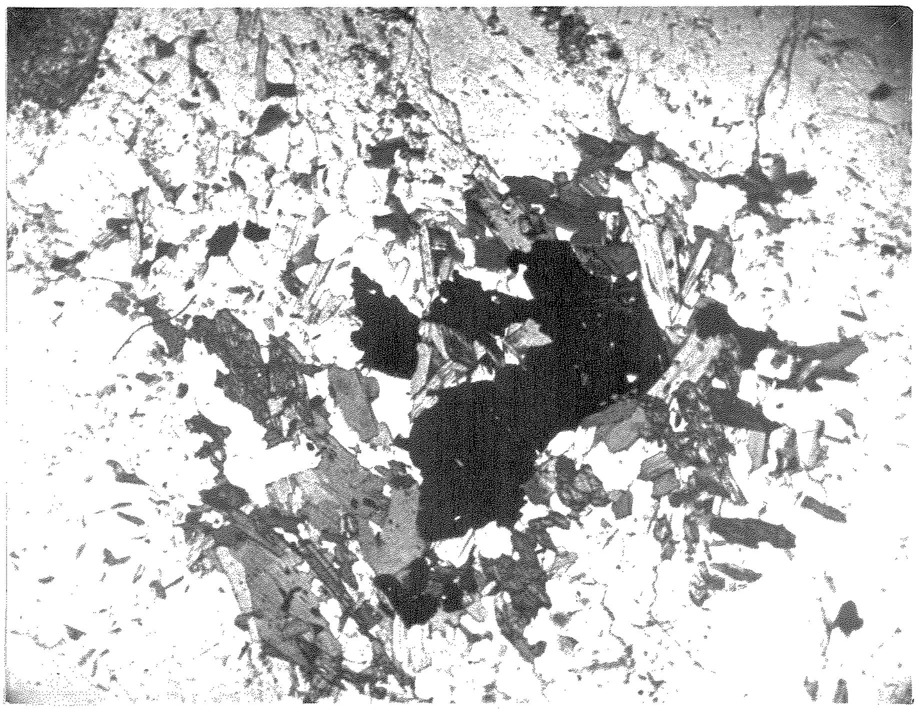


Fig. 42 Photomicrograph of association of biotite with magnetite in Mafic Phase of Anorthosite.

but has developed simultaneously with it as a result of the presence of potassium or lack of calcium. Why such a condition should be associated with magnetite is difficult to explain.

The Feldspar Petrogenesis:

As has already been mentioned the feldspars of this region are remarkable for the abundance of pericline twinning. Figs. 43 and 44 show feldspar grains in the center of the field showing only pericline twinning. These pictures were taken on the Federov Universal Stage, and the grains are so oriented that, if they were albite twins, one would be looking at the 010 zone with the lamellae parallel to the vertical cross hair, and the twins would consequently have the same

Fig. 43 Photomicrograph of pericline twinning on the Federov Universal Stage.

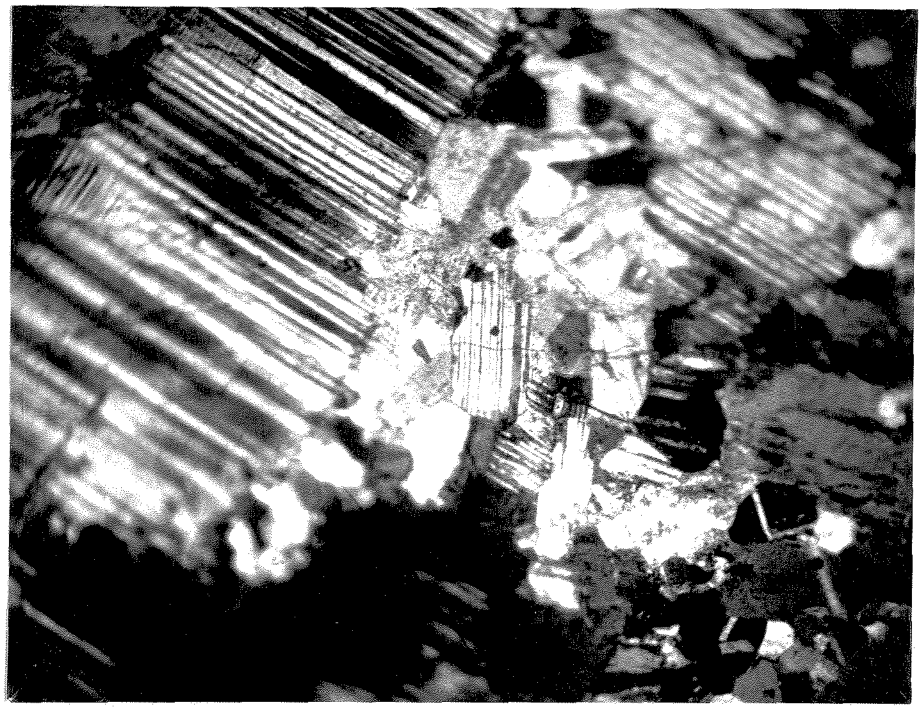


Fig. 44 Photomicrograph of pericline twinning on the Federov Universal Stage.

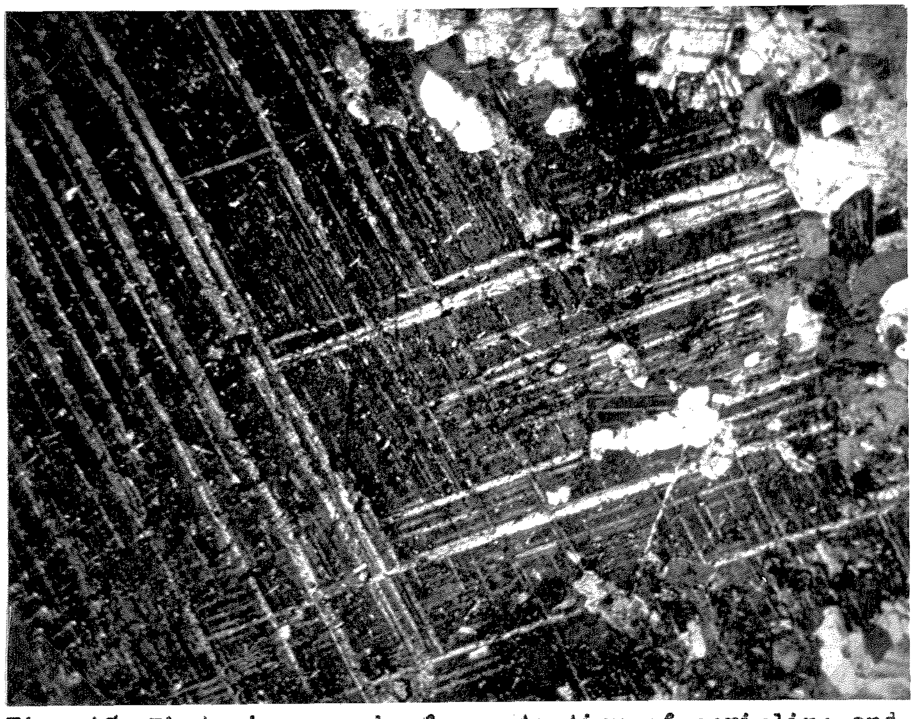


Fig. 45 Photomicrograph of penetration of pericline and albite twinning in Mafic Phase of Anorthosite.

birefringent color. Since this is obviously not the case, the twin is not albite but pericline. A more typical occurrence of the presence of two twinning systems is shown in fig. 45, in which an intimate penetration is shown. This type of occurrence is typical for both the Anorthosite and the Mafic Phase of the Anorthosite, except in the places where spot development has gone on to a considerable extent.

Where spot development is abundant, the feldspar has completely changed its appearance. No longer are there to be found twinning lamellae of any type, and in their place a perthite-like texture as illustrated in fig. 46 appears.

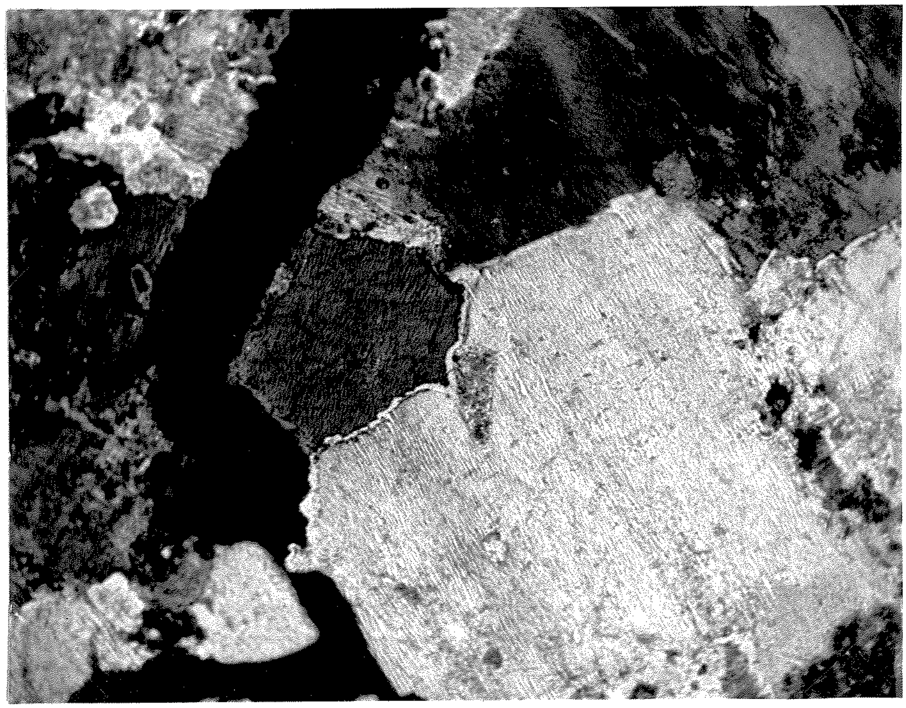


Fig. 46 Photomicrograph of perthite-like texture in the feldspars near areas of extensive spot development in the spotted diorites.

This texture is produced by the interfingering of spindle shaped stringers of high index material in a ground mass of low index. The high index is distinctly high and appears to be somewhere near anorthite, and the low index is lower than balsam and is probably close to that of albite. In addition to this there are occasional grains which contain practically none of the high index mineral and have developed an excellent, nearly rectangular, cleavage which is very open, and in the thin section is filled by balsam. See fig. 47. This structure closely resembles the cleavage produced by loss of volume as frequently observed in ore minerals. The narrow borders

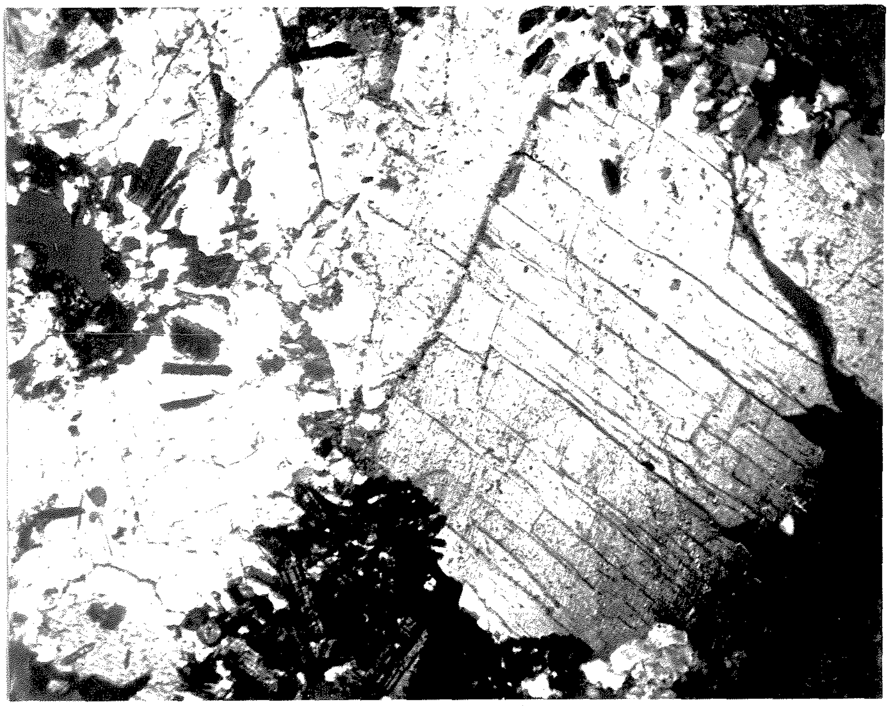


Fig. 47 Shrinkage cleavage in the feldspar associated with spot development in the spotted diorites.

which surround almost all of the grains have about the same index as balsam. They show no twinning, and they may be quartz.

The best explanation for the unusual texture developed in the feldspars seems to be that the reactions which took place when the spots were growing, extracted some of the constituents of the feldspar from each of the components, that is from both the albite molecule and from the anorthite molecule. To recall the last suggested reaction for the formation of hornblende from magnetite and feldspar, it was noted that in order to balance the reaction, calcium had to be added and sodium subtracted. If this deficiency of calcium was obtained by breaking up the anorthite molecule and the surplus of sodium was put in its place, it is quite possible that the resulting mineral would no longer form a solid solution, since the two elements are not equivalent and a change in the Si -Al ratio would be necessary to convert the anorthite to albite and thereby maintain conditions for a solid solution. If this is what has happened, as a consequence the twinning would be destroyed; the two feldspars would separate out of solid solution, and if the exchange of elements was not volumetrically equal, shrinkage cleavage might develop.

DIKE ROCKS:

Found intruding the Anorthosite complex at various times following its emplacement, are a series of dikes of widely varying composition. These in the order of their intrusion are: 1. amphibolite, 2. lamprophyre, and 3. pegmatite, aplite, and granodiorite. The relations of the last group are not well shown in this area and are therefore included in one group.

Amphibolite Dikes:

Fig. 48 shows one of the largest and best exposed amphibolite dikes in Bear Canyon. Fig. 49 is a close-up picture, about half way

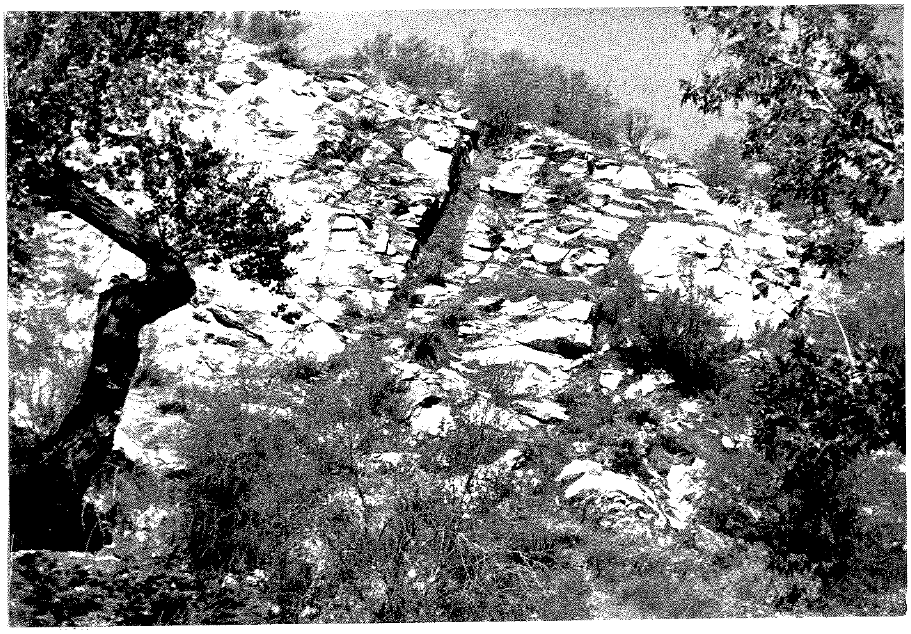


Fig. 48 Amphibolite dike in Bear Canyon

Fig. 49 Detail of contact between amphibolite dike and anorthosite wall rock showing the cross cutting relation of the dike to the primary banding in the anorthosite. Bear C.fig.48

Fig. 50 A smaller amphibolite dike in Bear Canyon which appears to be a feeder to a large lenticular mass above.

up the cliff, of the contact between the dike and the anorthosite. This clearly shows that the amphibolite is not an inclusion in the anorthosite, for it cuts the primary banding of the anorthosite at right angles. Fig. 50 shows another occurrence of an amphibolite dike in Bear Canyon. Fig. 51 shows a close-up view of the same dike. This dike leads upward into a larger lenticular mass, for which it was possibly the feeder. This larger mass is shown on the map about half way up Bear Canyon. The irregular shape of the mass as mapped is due to erosion. About three-quarters of the way up Bear Canyon

Fig. 51 Detail of amphibolite dike shown in fig.50

Fig. 52 Amphibolite dike in Bear Canyon showing relative amounts of feldspar(large white crystals at bottom of picture) apatite,(remaining white material) and amphiboles (dark).

is another mass of amphibolite which outcrops chiefly on the east wall of the canyon. Around the corner to the south-east of this point the mass may be seen in section, on the north wall of the canyon. It consists of a series of tongues and dikes as shown in Plate I.

In the Mafic Phase of the Anorthosite there are numerous outcrops of this same rock type which occur interlaminated with the banded spotted diorites which occur there.

Mineralogically the amphibolite dikes which occur in the Anorthosite are identical with the occurrences in the Mafic Phase of the Anorthosite. Fig. 49 shows a feldspar inclusion under the label on the pick and another above it. The remainder of the white material is apatite. Fig. 51 shows a close up of the other dike which contains neither feldspar nor apatite. It consists almost entirely of amphibole with minor amounts of magnetite. Fig. 52 shows a fairly fresh surface of one of the dikes in the bottom of Bear Canyon about half way up the canyon. Some large masses of feldspar may be seen at the bottom of the picture; the remaining white material is apatite. The ground mass, as usual, is a mixture of actinolite and hornblende. Fig. 28 shows the contact between this dike and the Anorthosite with the relations as previously described.

Gold has been reported from these amphibolites by a number of the natives in the region.

<u>Lamprophyre dikes:</u>

Because of the fact that in the relatively rigid Anorthosite

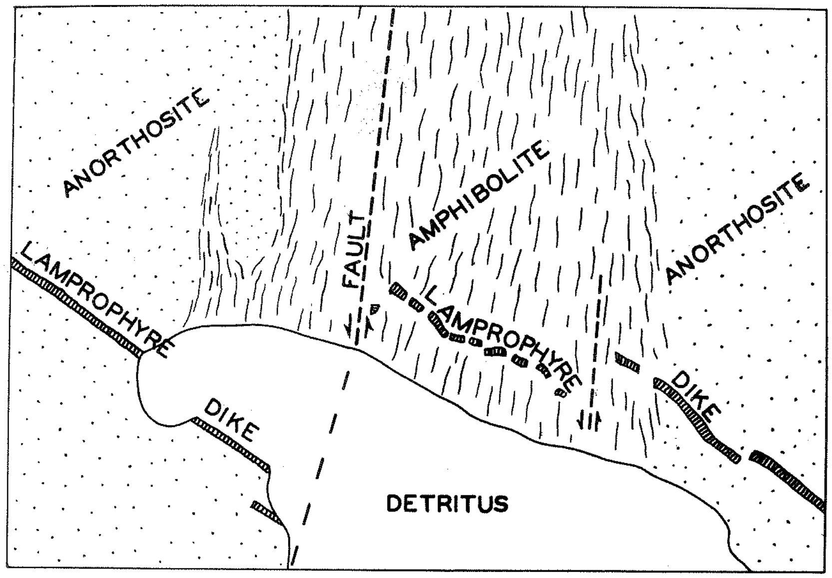


Fig. 53 Lamprophyre dike cutting amphibolite dike which due to later movement in the amphibolite has been broken and displaced. Upper Bear Canyon.

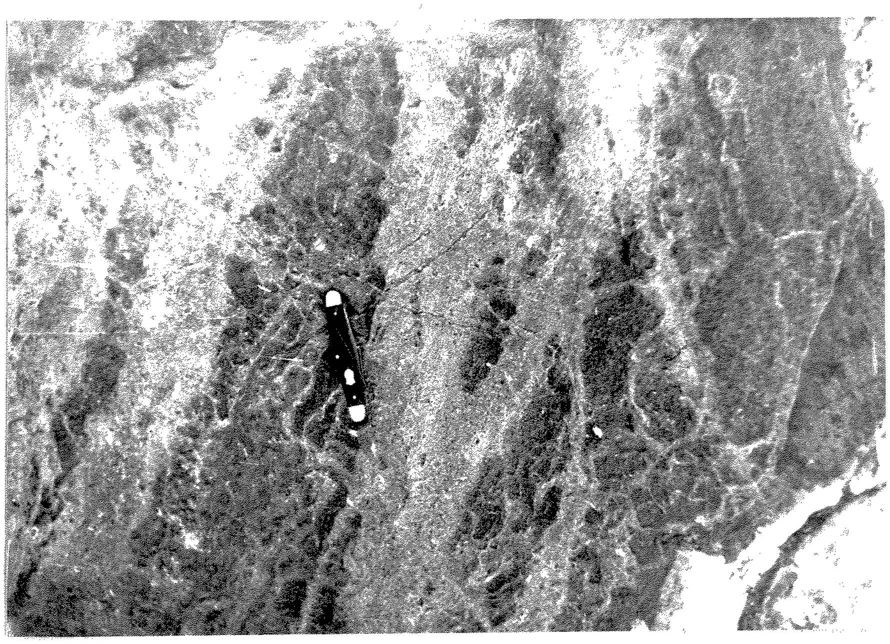


Fig. 54 Material introduced into lamprophyre dike probably during later pegmatitic activity

the amphibolite dikes have acted largely as zones of weakness, it required two months work before the relation of the amphibolite to the lamprophyres was found. Fig. 53 shows the relation of the amphibolite to the lamprophyres. Later a better example showing that the lamprophyres cut the amphibolites was found, but it was in such an inaccessible place that a picture could not be obtained.

The lamprophyres are massive to somewhat schistose with the coarser grained examples being massive. They are dark gray to black and frequently contain introduced materials as shown in fig. 54. The introduced material has a fairly high percentage of quartz, some orthoclase and more biotite than hornblende.

One of the schistose dikes which as a result of its development of foliation was very fine grained with an average grain size of 0.2mm. had the following composition:

Andesine	$Ab_{62}An_{38}$	40% by volume
Hornblende		40%
Biotite		15%
Sphene		5%

This rock was fairly fresh. The hornblende had a pleochroism of yellow-green to blue-green.

More frequently the dikes had an average grain size of one-half mm. Dikes containing introduced material often showed considerable alteration as in the following:

Andesine	60% by volume
Hornblende	30%
Epidote	5%
Chlorite	3%
Sphene	2%

The andesine was largely altered to calcite and sericite. Epidote and chlorite were probably alterations of hornblende. The absence of biotite in the above rock is not unique with dikes containing introduced material,as another dike rich in introduced material contained 15 % biotite.

A polished section was made of one of these dikes and found to contain small amounts of marcasite,which is suggestive of shallow depth replacement.

The lamprophyre dikes are clustered in three localities, upper Bear Canyon, Soledad Canyon and lower Landgard Canyon (located between Bear and Pole Canyons). They occur scattered more or less in other localities, but in the above three, they are generally larger and follow a more consistent structural pattern.

With the development of foliation which is greatly emphasized by weathering, it is not surprising that when these dikes were intruded into a fracture zone and later due to movement in the zone, they were reduced in many cases to almost nothing but gouge, that it is difficult to prove that they were not originally schist inclusions in the Anorthosite. This is the situation in Soledad Canyon where Miller has reported the presence of old schist inclusions.(Refer to bottom of page 19, fig. 31 for further discussion of this matter.) The opposite conclusion on this matter was based on the fact that if these bodies are schist inclusions, it should be possible to find somewhere in the deeply dissected portions of Bear Canyon some fresh examples of these inclusions, but wherever the rocks are fresh, only dikes can be found. It is logical, therefore, to consider that all of the bodies are dikes until some inclusions are found that can be definitely recognized as such.

Foliation and Development of Ptygmatic Folds:

Because of certain structures to be described later which will give some information on the temperature of mafic dikes and the origin of ptygmatic folding, it is necessary to prove that these lamprophyres are dikes and not inclusions. Fig. 10, in Bear Canyon, shows one of the dikes cutting the primary banding at a high angle which could not occur if the body were an inclusion. A few hundred feet up the canyon from this point, one can see similar dikes in a 200 ft. vertical section. See plate I. These long slim bodies may also be seen to cross one another, and for this reason, also, they could not be inclusions. Occasionally a small inclusion of anorthosite may be found in one of the dikes.

In upper Bear Canyon (see map, station 55) may be found one of the larger dikes which has split into two smaller dikes. Fig. 55 shows this dike from across the canyon. Here may be found some interesting information on the possibility of remelting anorthosite. Extending downward from the mass of anorthosite forming the crotch of the fork is a thin stringer of anorthosite. This band of anorthosite extends downward, across the canyon, and far up on the other side. Fig. 56 shows a detail of the lower quarter of fig. 55. Fig. 57 shows

Fig. 55

Fig. 56

Fig. 55 Lamprophyre dike in upper Bear Canyon (station 55) which has split, remelted some of the anorthosite in the fork and carried it into the center of the dike. Later oscillatory movement in the dike has folded the included anorthosite band into ptygmatic folds, and at the same time it has developed a variable schistosity in the dike.

Fig. 56 Detail of the lower quarter of fig. 55 showing the ptygmatic folding of the anorthosite band.

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a photomicrograph of some of the ptygmatic material. It has the same composition as the other anorthosite in the area, but it will be noted that it is very fine grained, averaging in grain size about 0.2mm. as compared to the section in fig. 6 which has an average grain size of 20mm.

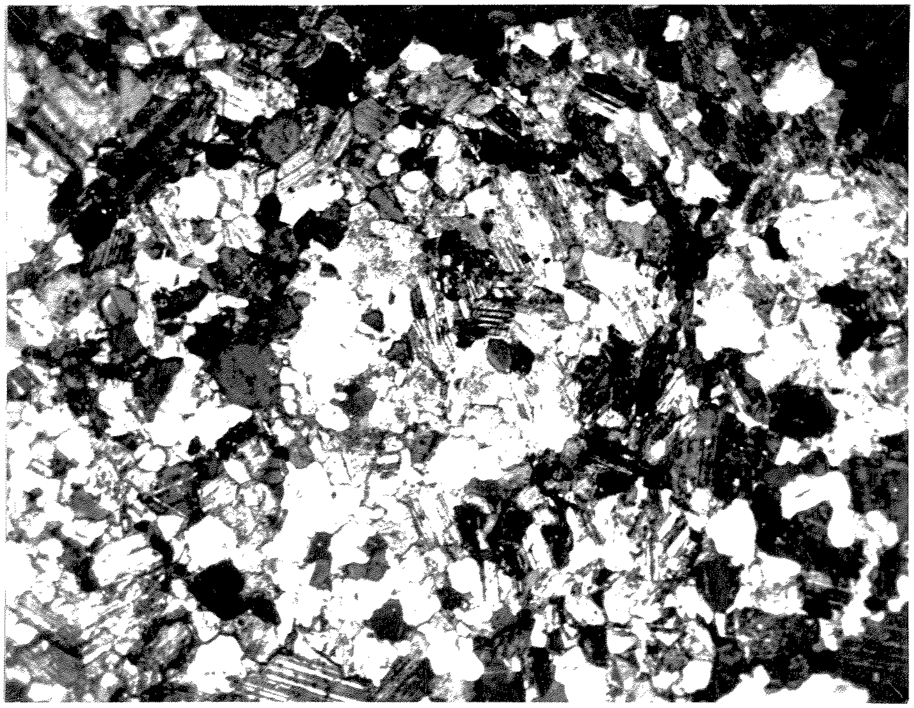


Fig. 57 Photomicrograph of ptygmatic material of fig. 56

This stringer of anorthosite because of its shape and fine grain size could not be considered to be an inclusion. There remains only the possibilities that it was intruded as a dikelet into the lamprophyre, or it was remelted from the enclosing walls of the lamprophyre dike and carried into the dike. The stringer is continuous with the crotch of anorthosite where the dike splits. If it were a dike, it would have to be the same age as the enclosing anorthosite, or it would have to be later. If it were the same age as the enclosing anorthosite, the lamprophyre dike would be an inclusion in the anorthosite and the feldspar stringer would have about the same grain size as that enclosing the lamprophyre. This, however, is not the case since the lamprophyre is not an inclusion, and the average grain size in the stringer is about 1 / 100th. as coarse as the enclosing anorthosite. If the stringer were a dikelet, it would be an unexpected coincidence that it should enter the lamprophyre at the end of the long slim crotch where the lamprophyre splits and remain centrally located in the dike for a distance as much as 75 feet, at which point it dwindles away. The explanation, therefore, which best fits the observed facts is that the lamprophyre dike intruded the anorthosite, remelted some of it, and due to lateral movement or vertical oscillatory movement of the magma, carried some of the remelted material into the dike. The material which was melted along the crotch of the dike was carried into the center while the material remelted along the outer edges remained along these edges. This latter effect is frequently found in the lamprophyre dikes of the region and was thought before close examination to be the effect of later dioritic intrusion along the borders, but it apparently is due to incorporation of remelted feldspar in the lamprophyres.

Bowen recognized the possibility of remelting anorthosite but stated that there was no evidence to indicate that such a phenomenon occurs on a large scale as evidenced by the lack of extrusives. The present evidence is not contradictory to Bowen's views, but it does indicate that a small amount of material may be remelted by a basic dike. The temperature required to dry melt anorthosite with a composition of andesine An_4 is 1250°C. The amount of mineralizers in a magma of this type are typically low, and so their importance in the remelting of the feldspar is doubted.

This occurrence also gives a possible clue to the origin of ptygmatic folding. Along the borders of many of these dikes and sometimes along the entire dike foliation resembling schistosity has developed. This is most noticable toward the boarders where small amounts of anorthosite have been incorporated in the dike. It is fairly obvious from examining the uppermost double loop in fig. 56 that the material which was formerly between the two broad ends of the anorthosite band has been drawn out into two loops. The schistosity which has developed as a result of the shearing is parallel to the direction of shearing as indicated by the looping of the band of anorthosite. This is believed to have developed at a time when the dike acted as a highly viscous liquid.

Undoubtedly during a period of intrusion of a magma into a system of dikes. there must be great changes in the pressure of the intruding magma accompanying the fracturing of the country rock, and subsequent filling of the fractures to form dikes. If fractures which opened up in the present case were at about 45^{o} to the maximum load, one would visualize the process as follows: A system of fractures in the Anorthosite were formed and filled with a basic magma. As this magma was crystalizing a new fracture somewhere in the dike system occurred releasing the hydrostatic pressure in the magmatic column. The overburden in response to this release of support settled, but gradually the pressure in the magmatic column built up again to its former value forcing the overburden back to its former position. Now another fracture developed in the dike system and the whole cycle was repeated. This vascillation of the magma in and out of the entire dike system as a result of the opening of new fractures is believed to have been the cause of the schistose borders of many of the dikes and of the ptygmatic folding in the dike under consideration.

Pegmatite, Aplite, and Granodiorite:

The later group of dikes consist of pegmatite, aplite and granodiorite. Fig. 58 shows some of the granodiorite intimately intruded into the Anorthosite. This picture is typical of large areas of rocks to the east of Bear Canyon. Fig. 59 shows an aplite dike cutting some banded hybrid. Fig. 60 shows the relation of these two rocks to the lamprophyre. The granodiorite occurs as a thin border of variable width along the upper side of the aplite dike

Fig. 58 Intimate penetration of anorthosite by granodiorite dikes east of Bear Canyon.

Fig. 59 Aplite dike in Bear Canyon cutting banded hybrid.

Fig. 60 Aplite dike in Bear Canyon cutting anorthosite and lamprophyre dike. Note narrow border of granodiorite along upper edge of aplite dike. The gray band along the upper edge of the lamprophyre is due to incorporation of anorthosite in the lamprophyre.

and both cut the lamprophyre. Often it is difficult to follow the aplites as they cut through the anorthosite, because they are so nearly the same color, as can be seen in fig. 60. True pegmatites are not well exposed in the area, but may be seen to be associated with the aplites. The granodiorites are distributed quite widely, but they are found mostly in the Anorthosite mass and increase in number toward the east. The aplites are next most common and are scattered throughout the anorthosite. The pegmatites are least common in dikes, but they occur intimately penetrating fractures in the Anorthosite, so that one might be lead to think from the appearance of many anorthosite outcrops that muscovite, which is one of the chief constituents of the pegmatite, is a characteristic mineral in the Anorthosite.

The pegmatites in this area are mostly pink in color. They are moderately coarse grained. They contain lower percentages of quartz than most pegmatites and are made up of about equal quantities of microcline and orthoclase (untwinned microcline?). The chief accessory mineral is muscovite which in some places makes up an appreciable amount of the rock. In Soledad Canyon, just east of the mouth of Bear Canyon, there is an excavation where muscovite has been mined. on a small scale.

In the aplites, garnets are occasionally developed. Variable amounts of muscovite are found. Aside from this they are rather typical.

Gradational with the aplites are the granodiorites and related rocks. The chief ferromagnesian mineral in these rocks is biotite with occasional hornblende crystals.

The relations between these rocks is not clear and since they occur in minor quantities in the area intensively studied, little time has been devoted to their study.

AGE RELATIONS OFTHE IGNEOUS UNITS:

Miller gives the following sequence: Sequence found by author:

preCambrian?

Placerita metasediments
Rubio Diorite
Echo Granite and pegmatite
Anorthosite

late Jurassic?

Wilson Diorite
Parker Qtz. Diorite
Qtz. Syenite
Lowe Granodiorite
Lamphophyre

Anorthosite
Mafic Phase of Anorthosite
Amphibolite dikes
Lamprophyre dikes
Pegmatite, aplite, etc.

Miller's age relation of the Anorthosite to the Rubio Diorite is based on the following findings. Rubio Diorite, which he states is somewhat like some of the basic phases of the Anorthosite, is contained as inclusions in the Echo Granite. The Anorthosite, he states, intruded the Echo Granite. And on the basis of this, the Anorthosite, he states, is younger than the Rubio Diorite. If his evidence that the Anorthosite intruded the Echo Granite is no better than his evidence that the Anorthosite intruded the Mafic Phase of the Anorthosite, it is quite possible that the Rubio Diorite is younger than the Anorthosite, and the Echo Granite is younger than the Rubio Diorite. If the lamprophyre dikes found in the Lang region are the same as the Rubio Diorite, it will be seen that the sequence thus proposed agrees perfectly with the sequence found in the Lang region. Since Miller stated that the lamprophyre dikes in Soledad Canyon might be inclusions of Rubio metadiorite, the similarity of these two rocks was obvious. To compare them a trip was taken to Rubio Canyon. In hand specimen the finer grained phases of the diorite were found to be identical with the lamprophyres. The only difference under the microscope is in the presence of sphene in the lamprophyres and zircon in the diorite. In addition to the above suggestive relations, there is the fact that the pegmatites of the Lang region have been found cutting dikes which Miller has called lamprophyres, but Miller states that the last acidic dikes to invade the region came before the lamprophyres. Either there has been another period of intrusion of aplite, pegmatite, etc which Miller has missed, or else the lamprophyres found in the Lang region are related to the Rubio Diorite, and the lamprophyres found by Miller to be definitely younger than the pegmatites, etc. are absent in the Lang region. Because many of the relations which Miller has described have not been observed by the author, it is difficult to do more than suggest possible relations as has been done on page 87.

SEDIMENTARY ROCKS:

The only sedimentary rocks occurring in this area are the Mint Canyon formation, Quaternary Terrace Alluvium, and Quaternary Stream Alluvium.

Mint Canyon Formation:

Lying to the north and west of the Igneous Complex is a series of poorly stratified and poorly sorted terrestrial deposits which extend to the north for about five miles and form an important unit in the Santa Clara synclinal basin. Fig. 61 shows a typical outcrop of the gently dipping Mint Canyon beds. This formation is dated by an occurrence in it of a Neohipparion skull which is of middle Miocene age.

The sediments are quite variable in composition. From previous studies in the area (11), it was found that there occurs at the base of the Mint Canyon formation a high percentage of lava detritus, the source of which was some Oligocene(?) lavas. To the west of the Lang fault there are exposed some sediments which contain about thirty percent lava material and as a consequence have a pink

Fig. 61 Mint Canyon formation seen from Soledad Canyon.

coloration. These, therefore, must be not very high in the stratigraphic section. The other Mint Canyon beds in thisregion are gray in color. At the head of Freel's Canyon (one and one-third miles south of Lang) the sediments are composed of lava pebbles in considerable amounts; large numbers of old metamorphics, mostly gneisses, and occasional anorthosite pebbles. The lava pebbles are mostly acidic types and so do not color the formation. The typical spotted diorites or other Mafic Phase rocks are not found in the sediments.

The sediments vary from conglomerate to sandstone. The conglomerate contains boulders in this region up to twelve inches, but most of them average two inches. The conglomeratic members are usually thin and often consist of a single layer of pebbles between adjacent sandstone beds. The occurrence of Sulphur Springs in Soledad Canyon suggests the presence of close by volcanics.

Quaternary Terraces:

Occurring in numerous places throughout the region there are to be found terrace deposits. These are probably all of recent or late Pleistocene age judging from their state of preservation and distribution. Most of the detritus is angular, but some places have considerable subrounded material. A typical occurrence of the terraces in Soledad Canyon contained 90% anorthosite, about 5% fine grained basic dike material, undoubtedly from the lamprophyres, and about 5% pegmatite and related types. The largest boulders in this area averaged eight inches, but in many places very large masses measuring feet in diameter occur. Fig.

Fig. 62 shows an outdrop of the large terrace east of the legend

Fig. 62 Large terrace deposit east of the legend on themap. Note angularity of material. Dog on cliff, standing two feet high, serves as measure of coarseness of material.

on the map. The dog at the edge of the cliff stands two feet high and gives a measure of the coarseness of this material. This and its angularity indicates that the material is of local origin. Fig. 63 shows a spur projecting into Soledad Canyon just east of Bear Canyon. The terrace material which caps this spur is typical of the terrace deposits. Fig. 64 shows the poor sorting and variable nature of the terrace deposits along the new road on the north side of Soledad Canyon. The deposits of which this is a part may be found by mapping to be an old river channel which carried a stream flowing

Fig. 63 Quaternary terrace material on a spur in Soledad C.

Fig. 64 Terrace material along the new road in Soledad C.

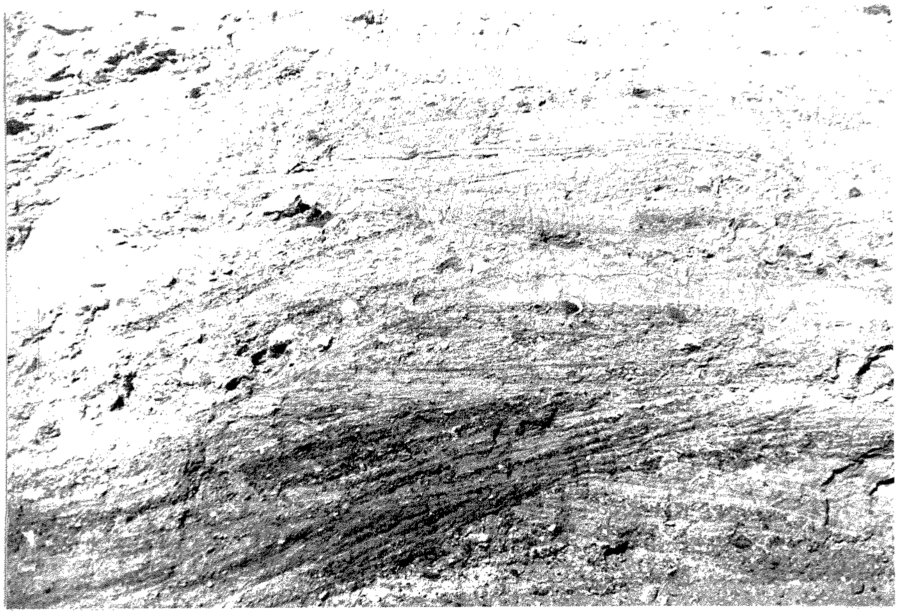


Fig. 65 Cross bedding in terrace deposits along the new road in Soledad Canyon

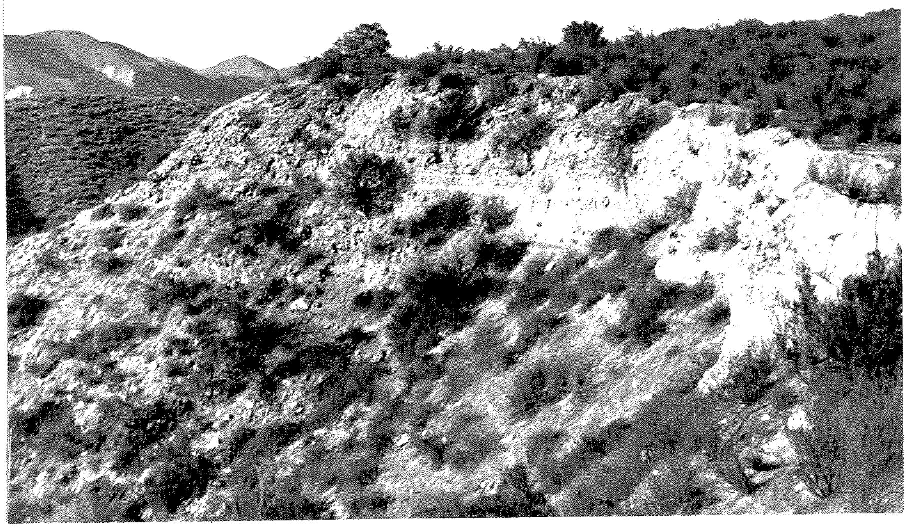


Fig. 66 Terrace deposits north of Soledad Canyon near point from which plate II was taken.

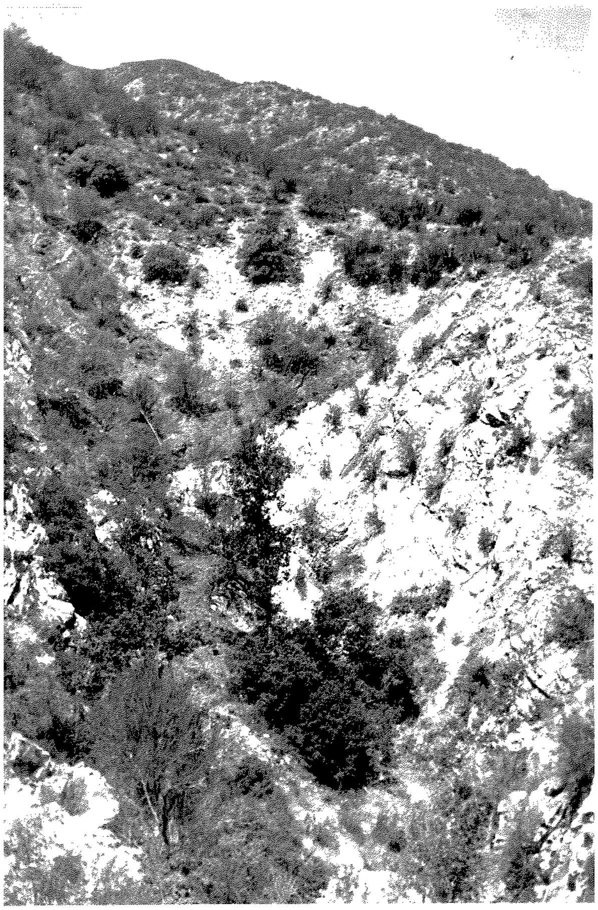
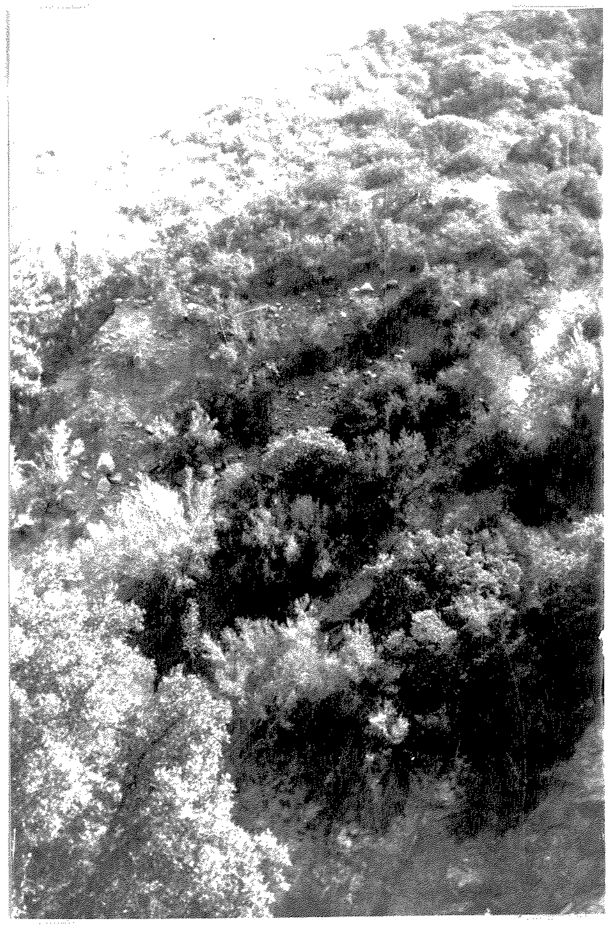


Fig. 67 Terrace alluvium filling old stream channel in central Bear C.



Fig, 68 Terrace alluvium in upper Pole Canyon, $1\frac{1}{4}$ miles S-E of edge of map.

in approximately the direction in which the picture was taken. Fig. 65 shows some of the cross bedding in these deposits. Fig. 66 shows some higher terrace deposits close to the point from which plate II was taken. Fig. 67 shows an old stream channel in central Bear Canyon about 100 ft. above the present stream channel. Fig. 68 shows some terrace gravels in upper Pole Canyon about one and one quarter south-east of the edge of the map.

Bear and Pole Canyons contain very little Quaternary Alluvium except at their mouths. Soledad Canyon contains considerable Alluvium.

STRUCTURE:

The structural history of the rocks of this region is almost as complex as is their petrogenic history. The earliest history of the region is most clearly shown in the upper portions of Bear Canyon as shown in the detail map.

Following the production of the primary banding in the Anorthosite came the irregular intrusions of amphibolite masses. Following this at a considerably later period there was north-south vertical tension jointing and filling by the lamprophyre dikes. In general the primary banding, amphibole dikes and lamprophyres were all parallel making their age relations difficult to determine. There were some exceptions to this trend, however, especially in the case of the lamprophyres, which also filled low angle fractures as shown in fig. 10. Next came a period of chiefly N 70°W tension fracturing and introduction of pegmatites, aplites, etc. This must have been a period of extremely intense diastrophism for the Anorthosites were intensely fractured, making it difficult to find a cubic foot of rock which does not contain fine veinlets of silicious material. Fig. 7 shows an area where these minute fracture planes have only developed in three directions. It was probably at this same time that the lamprophyre dikes were replaced by considerable amounts of quartz. A still later period of deformation is evidenced by the fracturing of the pegmatites and intense bending of the muscovite 'books' occurring in the pegmatite. This is probably also related to the large number of open joints throughout the Anorthosite.

The recent structure of this region is dominated by faulting. Three major faults have been mapped, Soledad fault, Lang fault, and Goat fault. Where Soledad fault is well exposed on the north side of Soledad Canyon, it can be seen to dip about 60° north. Toward the east it is buried under alluvium, and toward the west it is buried under terrace deposits. This fault is of post Miocene age as evidenced by the displacement of the Anorthosite up against the middle Miocene Mint Canyon formation. It is earlier than the terrace deposits or the physiographic surfaces which have developed over it. The fracture zone which was filled by the lamprophyre dikes is probably an expression of a much earlier Soledad Fault. Miller (6) states that the lamprophyres are of mid-Miocene age. It the dikes were intruded at the same time as the Mint Canyon formation was being laid down, then the fractures which they followed existed before the present Soledad fault displacement took place. It may be concluded, therefore, that the fracture zone has been in existance at least since middle Miocene time, and may have been one of the causes which induced the deposition of the Mint Canyon formation. Although the relations are rather obscure, to the west of the mouth of Bear Canyon, it appears that some Mint Canyon sediments have been deposited on the igneous block south of Soledad fault, and so the fault movement might have been in part contemporaneous with the deposition of the Mint Canyon formation.

The Lang fault forms the western boundary of the Igneous Complex and has formed the scarp shown in fig. 1. The fault is not as well exposed as is Soledad fault, but because of its straightness, it is thought to be a high angle fault. It cannot be traced north of Soledad Canyon and is therefore thought to be of the same age as the Soledad fault.

The Goat fault which breaks off the corner formed by the intersection of the Soledad fault and Lang fault, runs from the west portal of the new Soledad Canyon road tunnel, through a goat ranch, across a spur in Soledad Canyon, up the south wall of Soledad Canyon, south-west across Pole Canyon until it meets the Lang fault.

Fig. 69 Goat fault at the west portal of the new road tunnel in Soledad Canyon.

At the west portal of the tunnel it is small and is dipping 80° south-east. Fig. 69 shows the west portal of the tunnel. Fig. 70 taken from the south wall of Soledad Canyon, shows the trend and place where it crosses the spur in the canyon. Fig. 30 shows the fault in the spur looking toward the south-west. Fractured inclusions of aplite dike in the fault zone indicate that movement has been up on the east (left side of the picture). In other words, as the Igneous Complex has been brought up with respect to the surrounding sediments, the north-west corner of the mass between Soledad and Lang faults has broken off along the Goat fault and lagged behind. In this way the Mafic Phase of the Anorthosite has been brought up in contact with

Fig. 70 Goat fault crossing Soledad Canyon looking toward the north-east.

the pure Anorthosite, and so one might conclude that the contact between the two phases dipped toward the east although in the vicinity of the contact the primary banding is nearly vertical. The eastward dip of the contact is confirmed to a certain degree by the repetition of the contact a short distance toward the south-west where again Mafic Phase rocks are encountered. Mafic Phase rocks continue to the Lang fault. The Goat fault is thought to be of the same age as the Soledad and Lang faults. All three in their latest movement are probably of pleistocene age as indicated by their present topographic expression.

GEOMORPHOLOGY:

The physiographic history of this region has been rather complex. Plate II shows the various surfaces that have developed in the sediments north of Soledad Canyon. Surface (A) is the oldest and occurs over an area of about one-half square mile. Considerably lower is surface (B) which occurs only in small patches. Fig. 66 shows a terrace deposit on this surface. Surface (C) is the present degradational surface which is removing surface (B) rapidly and will eventually also remove (A) provided it is not interrupted.

In the Igneous Complex the map clearly shows an old surface along which the mine road between Bear and Pole Canyons has been built. Into this surface has been cut Bear, Pole and Soledad Canyons with wide V shaped cross sections as can be seen in the case of Bear Canyon in Plate II. On the walls of these canyons, especially Bear and Pole, there are numerous terraces as have been illustrated under the

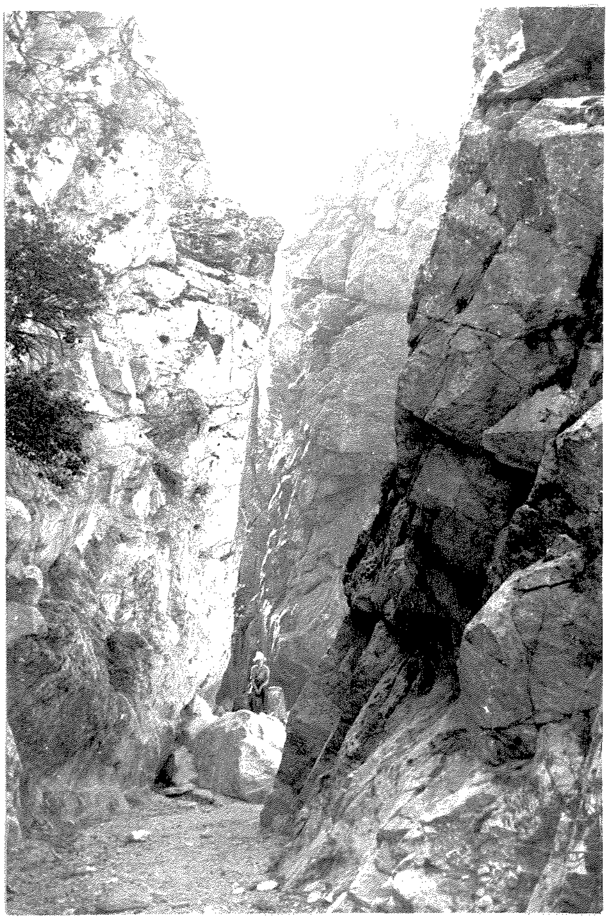


Fig. 71 Recent gorge near the mouth of Bear Canyon

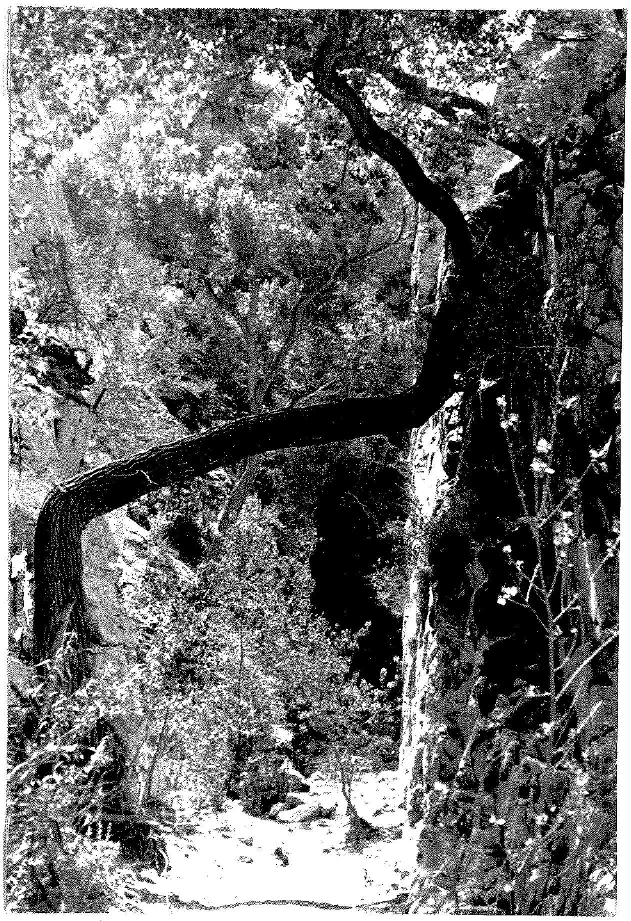


Fig. 72 Recent gorge in upper Bear C.

heading Quaternary Terraces. In the center of this V shaped canyon there has developed a recent gorge which is deepest at the mouth of the canyon and diminishes in depth up the canyon. Fig. 71 shows the deepest portion near the mouth of Bear Canyon. Fig. 72 shows a smaller gorge about three-quarters of the way up Bear Canyon. About one-half mile above this point (off map) the canyon is quite open.

Fig. 73 shows the size of one of the boulders in the upper part of Bear Canyon and also the polish which has developed from stream action. Fig. 74 shows how weathering affects the banded hybrids.

Fig.73 Stream boulder in upper Bear Canyon which has developed a high polish due to stream action.

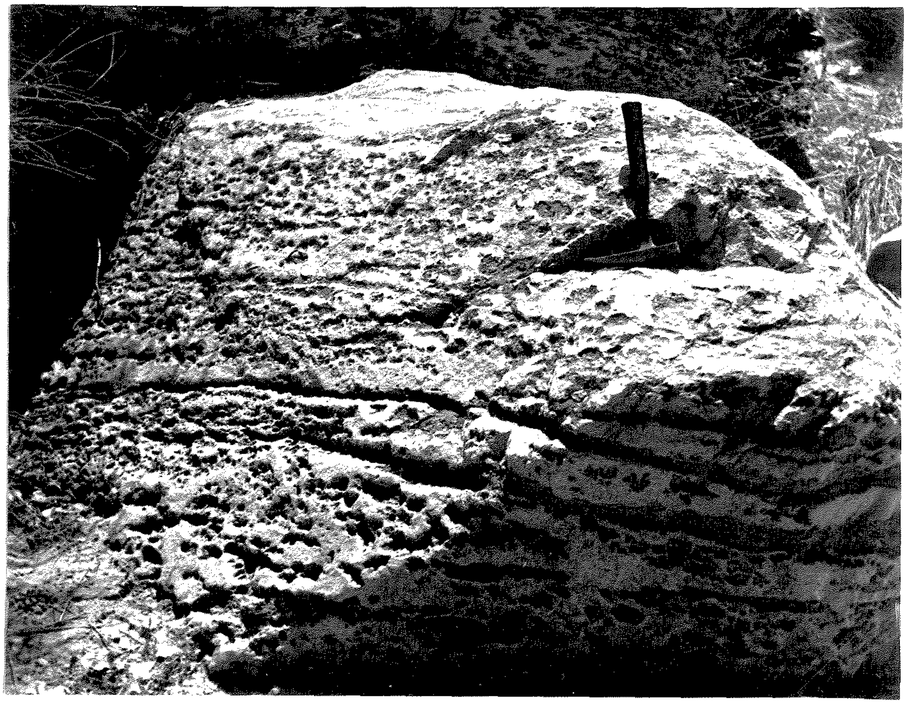


Fig. 74 Effect of weathering and stream action on the banded hybrids. Bear Canyon.

It is difficult to correlate the old surface on top of the Igneous Complex with the surfaces in the sediments, but it can probably be safely said that it is as old, if not older than any of the surfaces in the Mint Canyon formation.

HISTORICAL GEOLOGY:

The purpose of a geological report is two fold, first to find what occurs in a given region, and second, to determine the time and manner of its origin. It may be seen that the foregoing fulfills the first requirement in that it is a collection and evaluation of data. Now follows an explanation of how it may be best fitted together in a chronological order, and thereby the second requirement is fulfilled.

Judging from the size of the crystals found in the anorthosite and the way in which they must have formed, the entire process is believed to be one in which cooling took place at an extremely slow rate and at great depth. Ordinarily the primary magma is thought to be of the composition of basalt, but in view of the fact that the anorthosite is made up almost entirely of andesine, the parent magma may have had the composition of an andesite. At any rate, the magma cooled slowly and differentiated by crystal settling, producing at least three phases (possibly more but only three are to be found at the present time); a pure Anorthosite, a mixed andesine-magnetite phase with variable amounts of included ferromagnesians, and a ferromagnesian-magnetite-apatite phase. The Anorthosite finally became a fairly rigid mass. At this time mountain making forces pushed the partly solidified andesine-magnetite-ferromagnesian phase up into contact with the more rigid Anorthosite producing widespread banding in the Mafic Phase, and mixing of the pure Anorthosite with the Mafic Phase at the contact, producing the hybrids.

At about the same time, the third phase of the differentiation, the amphibolite, was introduced; in some places it formed sharply bounded dikes; in others where the rocks were not as solid it formed lens shaped bodies. Wherever this mass came in contact with the pure Anorthosite, it reacted with it, forming, probably, augite reaction rims. As it cooled, apatite, magnetite and finally diopside came out of solution. In some cases either magnetite was the chief mineral that was carried in or more probably a sufficiently large mass of magnetite-diopside-apatite was introduced so that differentiation could take place, producing large masses of magnetite at the base of the chamber. This is the probable source of the magnetite deposits found in the area.

The above events, judging from similar areas in other parts of the world, probably took place in the preCambrian.

The next hypothicated event is one of widespread uralitization in which the diopside was altered to actinolite and the augite reaction rims were altered to hornblende reaction rims, now so obvious throughout the area. Probably at the same time the diopside which was included in the spotted diorites altered to actinolite and produced a microscopic reaction rim of hornblende around it. Also the magnetite inclusions in the spotted diorite reacted with the feldspar forming hornblende rings with quartz inside, giving the spotted diorites their present appearance and consequently their name.

Sometime in preJurassic time, tension fracturing took place with the resulting introduction of lamprophyres. Variations in the hydrstatic pressure in the magmatic column during the cooling process produced variable degrees of schistosity and developed ptygmatic folding in remelted feldspar which has been carried into the dikes.

Possibly during the Nevadian Revolution in post Jurassic pre Cretaceous time, the region was again fractured and intimately intruded by pegmatite and related rock types. Considerable amounts of silicic material was introduced into the lamprophyre dikes, replacing them, and depositing maraasite in small quantities. This period of diastrophism is undoubtedly the greatest which the rocks of the region have suffered.

In middle Miocene time, after another period of minor disturbance, in which the adjacent Escondido formation (Oligocene?) was folded isoclinally, the Anorthosites were sufficiently exposed so as to contribute an appreciable amount of detritus to the Mint Canyon formation.

Finally in the Pleistocene movement took place along the Soledad, Lang and Goat faults lifting the range in a series of stages, accompanied by corresponding terrace deposits, to it present position.

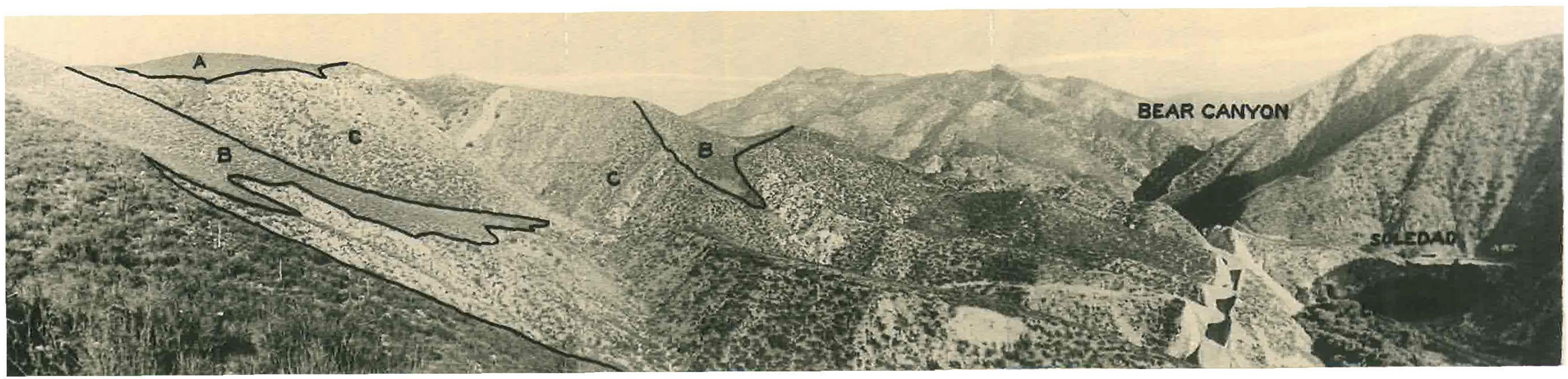
Bibliography

1. Hershey, O.H.
   1902a. Some crystalline rocks of southern California. Am.Geol. vol. 29:273-290
   1902b. Some Tertiary formations of southern California. Am. Geol. vol.29:349-372
2. Arnold,R., and Strong, A.M.
   1905 Some crystalline rocks of the SanGabriel Mts., Calif. Geol. Soc. Am. Bull., vol. 16:183-204
3. Kew, W.S.W.
   1924 Geology and oil resources of a part of Los Angeles and Ventura counties, California. U.S.G.S.,Bull 753,197p;
4. Noble, L.F.
   1927 The San Andreas fault and some other active faults in the desert region of southern California. Seis. Soc. Am.,Bull.,vol. 17:25-39
5. Hill, M.L.
   1930 Structure of the San Gabriel Mountains north of Los Angeles, California. Univ. Calif. Publ.,Bull.Geol.Sci. vol. 19: 137-170
6. Miller, W.J.
   1934 Geology of the western San Gabriel Mountains of Calif. Univ. of Calif. at Los Angeles Pub. in Math. and Phys. Sci. vol.1 No. 1, pp.1-114
7. Coats, R.R.
   1936 Primary banding in basic plutonic rocks, Jour. Geol. vol XLIV, No.3,: 407-419
8. Bowen, N.L.
   1917 The problem of the anorthosites, Am. Jour. Geol.vol.,25
9. Lodochinkow
   1925 Discussion of Bowen's paper on the anorthosites. Am. Jour.Geol., vol.XXXIII
10. Winchell, A.N.
    1933 Elements of optical mineralogy. Part II
11. Dawson, C.A.
    1935 The geology of a portion of the Mint Canyon region,Calif. Unpublished Senior Thesis. Calif. Inst. Tech.

Plate I Composite of fifteen photographs covering a horizontal angle of 160°. The center of the picture is facing approximately north. The view is of the north wall of Bear Canyon, to the left is down stream. The wedge shaped bodies on the ridge about a third of the way from the left edge of the picture are amphibolite. About a third of the way from the right edge of the picture is one of the better exposed lamprophyre dikes intersected by a smaller dike to the left of it

Plate II

Erosional surfaces developed north of Soledad Canyon


A
B
C
C
B
BEAR CANYON
SOLEDAD

Dawson_ca-1937