MICROMETRIC AND PETROFABRIC STUDIES OF THE VAL VERDE TONALITE, SOUTHERN CALIFORNIA.

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SUMMARY

The Val Verde tunnel of the Metropolitan Water District of Southern California, located thirteen miles south of Riverside, California, passes through 27,000 feet of a single tonalite intrusive and across the intrusive contact into a body of quartz-biotite schist.

Micrometric analyses of the tonalite along the line of the tunnel have shown no progressive variation in the percentage of minerals present; but the albite content of the plagioclase increases toward the contact with the schist, and this correlates directly with the radioactivity and zircon content of the tonalite. The more acid border of the intrusive is believed to be due to assimilation of the quartz-biotite schist.

On the basis of mineralogic and radioactivity determinations, dark fine grained inclusions in the tonalite are believed to be xenoliths of schist and gabbro.

Petrofabric diagrams obtained from the plagioclase, biotite, and quartz of the tonalite indicate that the gneiss planes of the tonalite developed as a result of a combination of flow of the partially crystallized magma and post-magmatic deformation. The present linear direction in the rock may or may not represent the original direction of flow of the magma.

CHAPTER I

INTRODUCTION

Location and Area of District

In order to bring water from the Colorado River to Los Angeles and vicinity, the Metropolitan Water District of Southern California constructed a series of tunnels, one of which, the Val Verde tunnel, furnished the opportunity to collect the rock specimens on which the work discussed in this paper is chiefly based.

The railroad station of Val Verde from which the tunnel is named is located in Riverside County, California, twelve miles south of the town of Riverside in longitude 117°15' and latitude 33°50'. Beginning about a mile south of Val Verde, the tunnel extends for seven miles in a N.88°W. direction. Plate 1 shows the location of the Val Verde tunnel and gives also data on the various tunnels and canals which comprise the Colorado River aqueduct. A strip of country averaging about three miles in width on each side of the tunnel was mapped following the work underground. This area of approximately fifty square miles occurs within the Riverside quadrangle topographic sheet of the United States Geological Survey.

Field Work

The field work was started in the spring of 1935 and at this time the tunnel was already about one-third completed, work progressing simultaneously from four shafts. The pouring of concrete, however, had just begun, so that little was missed by not beginning the study earlier. Mapping of the geology and collection of specimens was soon brought up to date and was continued until completion of the tunnel in June, 1936. Part of the tunnel could not be examined satisfactorilly because of gunnite on the walls or could not be seen at all because of solid lagging on the walls and back. Thus, important shear zones and contacts were in many cases too completely hidden to permit careful examination, although commonly strike and dip could be obtained with reasonable accuracy, and grab samples were frequently obtained by reaching through gaps in the lagging. Over the last half mile of the tunnel (western end) abundant water plus heavy ground prohibited the collection of any samples. About the same distance was missed at the eastern end due to concreting activity, so that the total length of tunnel examined was 31,000 feet.

The geological work was divisible into two parts. First, the rock types and their relations to one another, and structures such as shear zones and joints were mapped. Secondly, at intervals of 100 feet, two specimens were collected, one from each side of the tunnel. These were knocked from the walls purely at random, except in special cases, so that the personal factor of choosing a sample because of its being unusual was largely eliminated. One of the specimens was carefully oriented by obtaining the dip of an upper surface parallel and normal to the line of the tunnel and arrows which were later reproduced in ink were marked on the surface so that the orientation of the specimen in the tunnel was reproducable later in the laboratory.

The stations within the tunnel were numbered according to their distance in hundreds of feet from the Colorado River along the line of the aqueduct. Specimens taken from the tunnel have been given a number corresponding to the stations from which they were taken. Specimen 11868, for example, is located 1,186,800 feet from the Colorado River, and specimen 11869 is 100 feet farther away from the river in a direction N.88°W. from 11868.

Purpose of the Investigation

The construction of the Val Verde tunnel afforded a unique opportunity to study a section through part of a batholith. The tunnel, for 27,000 feet of its length, passes through an apparently uniform tonalite intrusive whose western contact is exposed in the tunnel. Any information advancing our knowledge of batholiths is very worthwhile, and it was thought that possibly some light could be thrown on such questions as: How uniform is a uniform batholith, and what variation in composition can be expected? Is there a continuous variation as the contact is approached? How representative is a thin section of a hand specimen, and the hand specimen of the rock mass? How constant is the radioactivity of the rock and with what minerals are the radioactive elements associated? Are heavy mineral studies of an igneous rock reliable as a means of correlation and do they reflect general compositional changes in the rock?

A separate line of investigation concerned the structure of the tonalite. A parallelism of the plagioclase, hornblende, and biotite is evident throughout most of the mass. By making a petrofabric study of this rock as well as of the intruded schist it was hoped some information might be forthcoming concerning the structural history of the intrusive and the country rock; or, if no evidence were found by this procedure, this would indicate that the method might not be generally applicable to this type of intrusive.

Lastly, the tonalite contains varying amounts of dark inclusions. The origin of such has been discussed for many years and is still not satisfactorilly answered despite valuable papers on the subject. Are the dark bodies inclusions of foreign rock or segregations from the tonalite? If they are inclusions, from what rock have they been derived and in what manner have they been changed?

Acknowledgements

The kindness of the Metropolitan Water District and of Mr. R. W. Remp, resident engineer for the Dravo Contracting Company in permitting access to the tunnel and in cooperating in every way possible was the necessary prelude to the investigation. The writer wishes to acknowledge the assistance of professor Ian Campbell, Dr. J. R. Schultz, Mr. Cooper Hyde, and Mr. Ygnacio Bonillas, III, during part of the tunnel mapping, and professor Campbell's help throughout the investigation. Drs. H. S. Fairbairn of Queen's University and James Gilluly of the U.S.G.S. gave valuable advice on petrofabric procedure and interpretation. Radioactivity measurements were made by R.A.Clarke and F.W.Wright of the Physics department of the California Institute of Technology.

CHAPTER II

TOPOGRAPHY AND PHYSIOGRAPHY

The Val Verde district is a small part of a large, conspicuous topographic unit in southern California named the Perris Block by English (1925, p.54)[1]. This block is approximately 20 miles wide, bounded on the west by the Elsinore trough and on the east by the San Jacinto fault zone, and is of indefinite length, extending northward to the base of the San Gabriel Mountains and southward for some tens of miles. The region is one of generally low relief in marked contrast to the mountainous country on all sides. A surface has been developed on the block at an elevation varying between 1500 and 1900 feet, averaging 1700 feet, which some of the earlier workers (Dickerson, 1914, p.259; English, 1925, p.54; Hill, 1928, p.168) designated as a peneplain. The northern half of the Val Verde district is a part of this surface. Here scattered, rounded outcrops of weathered tonalite protrude above the cultivated fields, and in a few places hills of tonalite, granite, or schist rise 100 to 200 feet above this surface. In other parts of the Perris Block this "peneplain" is not underlain by bed rock, but rather has been built up by alluvium.

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1. In the bibliography authors are listed alphabetically and papers by a single author are arranged chronologically.

Rising rather abruptly above this 1700-foot surface are occasional monadnock-like masses with an average elevation of about 2100 feet. The Gavilan Hills, of which the southern half of the region mapped by the writer is a part, fall in this category. Park-like areas, comparable in flatness to the lower country occur here, with scattered hills rising 200 to 300 feet above. Intermittent stream valleys meander on this surface until the rapid descent to the lower "peneplain" is reached.

Hill (1928, p.168) considered these higher areas to be uplifted fault blocks. Dudley (1936), however, made a rather thorough study of this portion of the Perris Block and brings forth the only real evidence thus far produced to prove that what the earlier writers called a peneplain is a combination aggradational and degradational surface, that the upper surface was not produced by faulting, and that, in all, three surfaces have been cut. The first, or oldest, is the lowest, and is preserved only under the covering of alluvium. The second, the 1700 foot level and named by Dudley the Perris surface is a truncation of the first after alluvium had filled up the old valleys to this level. Following this period of erosion, aggradation similarly covered up the Perris surface to the 2100 foot level at which time the highest surface was carved from the monadnocks which had protruded above the Perris surface. Later exhumation has revealed the two upper erosional levels. Data from well logs, evidence deduced from the anomalous courses of presumably superposed streams, and lack of evidence of faulting to account for the monadnock-like masses have led him to accept this series of events as the most plausible for the physiographic history of the region. The writer has found nothing in the Val Verde district which would confute Dudley's thesis, and has found some support.

In the Val Verde district, the maximum relief is approximately 1000 feet. The greatest elevation is 2559 feet, attained by a hill of schist rising above the 2100 foot surface. The next highest hill, Gavilan Peak, is composed of gabbro. Schist and gabbro in general exhibit a tendency to resist erosion more effectively than the acid igneous rocks, excepting the fine-grained aplitic dikes.

The southern, higher part of the district drains northward through a series of canyons into the valley under which the tunnel was constructed and thence westward into Cajalco Canyon. The westward drainage into Cajalco Canyon is across the structural trend of the rocks and is not that normally to be expected. This anomalous cross-drainage is apparently a recent development, for three older stream valleys encountered in the tunnel at depths of from 100 to 200 feet below the present surface trend north or northwest as shown in plate 6. The present westward flowing stream may be superposed, having been developed on a thick covering of alluvium. This postulated origin for the stream valley supports Dudley's hypothesis that the present Perris surface is an exhumed one.

The northern half of the district drains mainly northward through Mockingbird Canyon into the Santa Ana River Valley.

CHAPTER III

DESCRIPTIVE GEOLOGY

Previous Geological Work

Following the completion of the writer's field work, a paper by Dudley (1935) was published dealing with the geology of an area of about 500 square miles on the Perris Block. The Val Verde district is a part of that mapped by Dudley. In general the map by Dudley and that by the writer coincide, but because of the reconnaissance nature of Dudley's mapping, minor points of interest are not shown on his map. Besides the excellent work by Dudley, nothing of any great scientific value has been published on the geology of this region. Early reports on the small gold mines developed in the southern part of the district were published by the California State Mining Bureau. Those by Goodyear (1888) and Fairbanks (1892) cursorily discuss the regional geology. Waring (1919) in connection with a treatise on the hydrography of this region, describes the general geology, but goes into no detail.

Professor E. S. Larsen of Harvard University is at present involved in a petrological study of the rocks in the country to the south and west of that studied by the writer. Hurlbut, formerly a graduate student working under professor Larsen, has published on the petrology of the igneous rocks in the San Luis Rey Quadrangle (1935), which is about thirty miles south of the Val Verde district. The rocks described by him are very similar to those in the Val Verde district.

General Statement

The dominant rocks of the Val Verde district are medium- to coarse-grained igneous rocks which have been intruded into a series of metamorphic rocks. The latter occur as isolated strips surrounded by intrusive rock. In order of probable decreasing age, the igneous rocks are: gabbro, tonalite, granite, and acid and basic dikes.

Metamorphic Rocks

The oldest rocks in the Val Verde district are metamorphosed sediments, named by Dudley (1935, p.493) the Elsinore Metamorphic Series. They occur as disconnected strips elongated parallel to the strike of the beds. These remnants of what may have been formerly a continuous blanket of sediments vary from a few hundred feet to several miles in length, and from a few tens of feet to about a mile in width. Within the Val Verde district, twelve of these bodies of metamorphic rocks were mapped (See pl.2).

Well indurated quartz-biotite schist which grades into quartzite in a few places is the dominant rock type. Schistosity is rarely apparent, the term "schist" being used because of the advanced stage of recrystallization. Near the contacts with the acid igneous rocks, injection or replacement gneiss has been produced. About ten miles south of the district, near the town of Elsinore, Dudley's mapping shows that the metamorphics are the chief type of rock, and here slates, metavolcanics, and marble occur besides schist and quartzite.

The strike of the schist averages approximately N.30°W. which is in conformity with the structural pattern of this part of southern California. The Elsinore and San Jacinto fault zones, the less important shears within the tunnel, the aplitic dikes, and the gneiss planes within the tonalite all have in general this same average strike. The dip is in most cases steep to the east, varying from about 25° in this direction to 65° to the west. The body of schist occurring in the tunnel has approximately a vertical dip. A notable exception to this structural picture is found in the case of two small bodies of schist located in the southwest corner of the area. The strike here is N.60° to 70° W., with an average dip of 75° to the north. Contrastingly, the beds of the much longer belt of schist 400 yards to the east vary in strike from N.10°E. to N.20°W. These two small bodies may be examples of blocks of the metamorphic rocks which sank into the granitic magma and were rotated from their former position.

Contortion of the beds of schist except at or near the contact with the tonalite is not generally conspicuous. Several examples of close drag folds with an amplitude of a few inches, however, were found. The best examples discovered occur approximately half a mile south of the western end of the tunnel about fifty feet west of the road. At this location the beds strike N.20°W. and dip 67°W.

Strong joints cross the beds striking N.65°E. and dipping 85°S. On the faces of these joints the drag folds show up clearly. Their axes plunge about 10° or less to the north. The shape of the folds indicates that this belt of schist was located on the west flank of an anticline. Possibly a synclinal axis in the schist existed to the west, the other limb being represented by the beds five miles to the west.

The schist is thought to be of Triassic age although no fossils have been reported from the Perris Block. The determination is based on a correlation of these metamorphics with those in the Santa Ana Mountains immediately to the west. Mendenhall (1912, p.505) states that the collection of fossils from the slates in the Santa Ana Mountains is "sufficient to determine the Triassic age of the slates". The correlation between the two localities is purely lithologic.

Igneous Rocks

The composition and structure of the igneous rocks, especially of the tonalite, will be discussed in detail in later chapters. Only the general characteristics and structural relations are described here.

GABBRO. The intrusive thought to be the oldest of the series is gabbro which has been named by the writer the Gavilan Peak gabbro. This rock outcrops in four localities in the western part of the district. Gavilan Peak, in the southwestern part of the mapped area, is composed entirely of fresh-appearing gabbro with the exception of a few narrow acid pegmatitic stringers which cut it. About a mile east of the Gavilan Mine is a second occurrence. In the western-central part of the district, although outcrops are not numerous, altered gabbro is found in the bottoms of many of the gulleys and may underlie a large area. Then a few small outcrops of gabbro occur in the north-central part of the district.

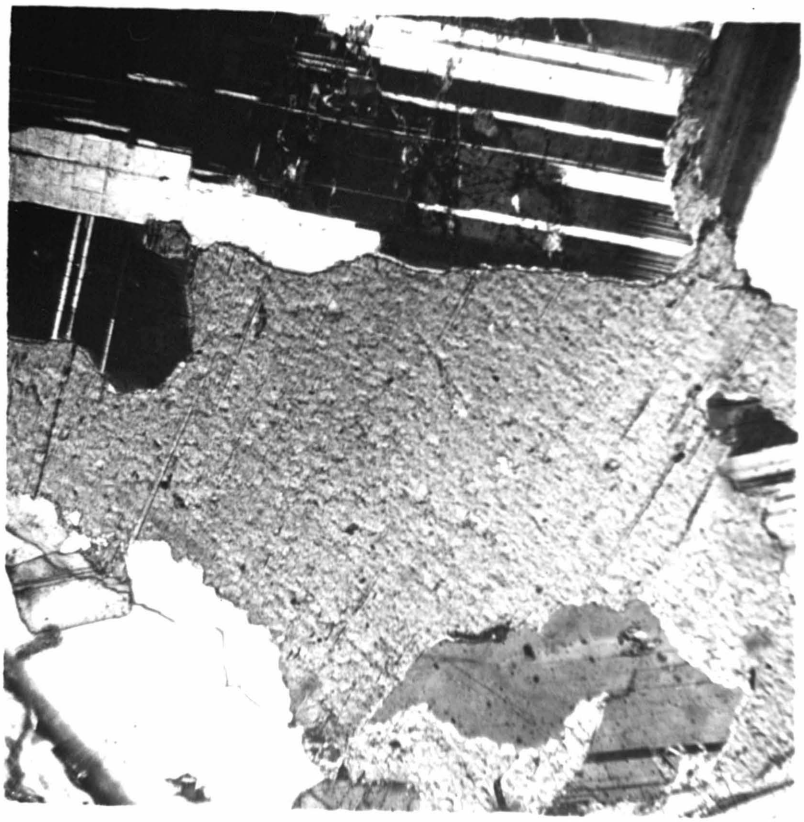
The gabbro is massive, dark-colored, medium-to coarse-grained, and hypidiomorphic. Poikilitic crystals of pyribole several millimeters in length are commonly visible in hand specimen. The plagioclase is, with one exception, basic bytownite, An_{85-90}. A specimen from Gavilan Peak contains 64% bytownite, 20% augite, 2% olivine, and 14% hornblende, an alteration product of the augite. A specimen from the area east of the Gavilan Mine contains less hornblende and more olivine and augite. Specimens from the western and northern localities taken a few feet from the contact with the tonalite contain no augite or olivine, in some cases contain biotite, and the hornblende is commonly poikilitic enclosing fine-grained andesine (See pl.3A.). A specimen from the outcrops in the northern part of the district contains 52% labradorite ($An._{57}$), 46% hornblende, and 2% magnetite and apatite.

The average grain size is about 1 sq. mm., but aggregates of the mafic minerals and a few of the feldspar crystals attain a diameter of 5 mm.

PLATE 3.

A. (Upper) Photomicrograph of gabbro at contact with tonalite showing poikilitic crystals of hornblende (dark) enclosing andesine. Without analyser; x 25

B. (Lower) Photomicrograph of tonalite showing vein-like projections of biotite cutting andesine. Crossed nicols. x 80. Sp.11868



That the gabbro is younger than the schist is shown by field relations in the extreme western part of the district. Here schist, gabbro, tonalite, and granite are intimately mingled. The schist dips directly into the gabbro, and bodies of the schist are cut off across the strike, and in some cases surrounded, by the gabbro.

TONALITE. The next youngest rock, presumably, is the Val Verde tonalite. This name for the rock has been preoccupied by "Perris Quartz Diorite" used by Dudley (1935, p.501). But Wilson, in conformity with the terminology of the writer, used the term "Val Verde tonalite" in his paper (1937). The reason for the two names having appeared in the literature is due to the fact that although Dudley's paper is dated two years before that of Wilson, the paper was not actually distributed until Wilson's manuscript had been sent to the printer. Because the specimens used by Wilson are the same as those studied by the writer, because these specimens came from the Val Verde tunnel, and because the rock is a typical tonalite, the term, "Val Verde tonalite", will be used.

The Val Verde tonalite is the predominant rock type outcropping over the entire eastern and central parts of the district. The tunnel for 27,000 of its 31,000 feet of length passes through this rock. In the western part, masses of the tonalite are separated from one another by bodies of schist, granite, and gabbro. On the basis of the mapping by Dudley (1935), the tonalite is believed to underlie an area of at least 150 square miles on the Perris Block.

The tonalite is light grey, medium-grained, and possesses a gneissoid structure which parallels in general the strike and dip of the schist. Discoidal masses of dark, fine-grained rock occur in variable quantities throughout the intrusive arranged parallel to the gneiss planes. These dark bodies are absent in some instances over areas in the tonalite as large as a few hundred feet in diameter, but otherwise are almost always present and in some places constitute 60% of the rock. The inclusions vary in maximum dimensions from an inch or less up to several tens of feet. In general the borders are sharp and definite, but in some cases they fray out into the tonalite and the dark bodies appear to have been almost entirely digested. A tendency exists for the inclusions to be larger and more angular where they are more numerous. The statement, however, of Dudley (1935, p.496), "It is notable in the Perris-Elsinore region that in many instances swarms of basic inclusions lie close to present schist contacts" was not found by the writer to be valid for the Val Verde district. The distribution of inclusions along the line of the tunnel is shown graphically in plate 6.

The tonalite varies only slightly in composition and general appearance from the eastern end of the tunnel to its border five miles to the west. Variations in composition will be discussed in a later chapter. The proportions, of the minerals for an average sample of the rock are as follows: andesine 57%, quartz 26%, biotite 12%, hornblende 4%, and orthoclase 1%. The andesine and hornblende are subhedral, and the biotite and quartz are anhedral. The orthoclase is in most cases anhedral and closely associated with the biotite. Commonly, however, small amounts of orthoclase occur as tiny rectangular blocks in the andesine aligned parallel to the cleavage directions. This suggests exsolution, but may be a replacement phenomenon. The biotite, quartz, and orthoclase are definitely later than the plagioclase (See pl.3B.). The plagioclase and hornblende are thought to have crystallized contemporaneously. The accessory minerals, occurring in small amounts, are apatite, zircon, sphene, magnetite, and pyrite, with rarely tourmaline. Wilson reported also monazite and anatase (1937, p.124).

The inclusions are much more variable than the host rock, but as an average, contain about 50% plagioclase varying in composition from bytownite to oligoclase, 10% quartz, and 40% hornblende and biotite, the hornblende commonly being more abundant than the biotite. Apatite, zircon, magnetite, and rarely sphene are the accessory minerals (Wilson, 1937, p. 129).

The average diameter of the grains in the tonalite is approximately 1.0mm., and that of the inclusions 0.25 mm. However, a small percentage of the grains of the former attain a maximum length of 3 to 5 mm., and in one specimen of the latter the grain size was 0.01 to 0.05 mm.

The texture of the tonalite is hypidiomorphic granular, and dominantly igneous as distinguished from metamorphic. The rock possesses two characteristics which indicate some deformation and recrystallization: (1) The contacts between the mineral grains are in most cases sutured, and the andesine grains are rarely bent or broken (See pl.4A). (2) The quartz grains not only commonly possess undulatory extinction but in some cases the grains are divided into a dozen or more segments having slightly different extinction directions and sharp boundaries (See pl.4B). The "segmented" quartz grains may represent quartz which has not entirely recrystallized following deformation which rotated the mineral grains (See Chapter IV).

The texture of the inclusions is xenomorphic granular. The xenomorphism of the grains, sutured contacts, small grain size and absence of an order of crystallization among the minerals indicates an advanced stage of recrystallization.

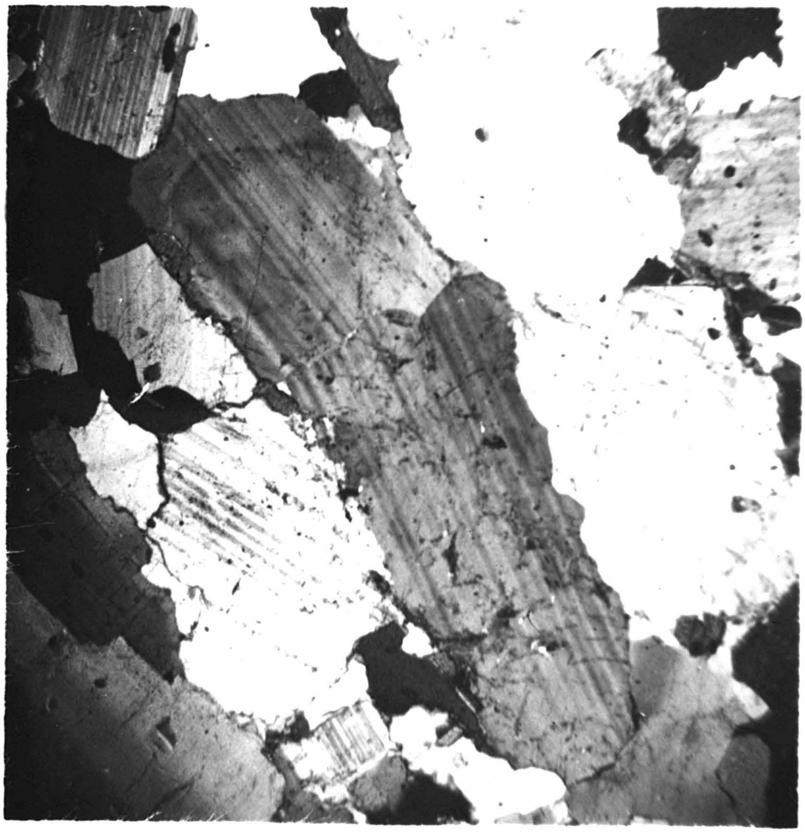
The tonalite intrudes the schist, is therefore younger, and probably is post-Triassic. The tonalite also clearly intrudes the gabbro in a few places.

GRANITE. Granite, which outcrops in the western part of the district and also occurs as dikes in the tonalite, is light-brown, medium-grained, and possesses a gneissoid structure parallel to that in the tonalite. Dark, fine-grained inclusions are sporadically present, but are not generally as abundant as they are in the tonalite.

PLATE 4.

A. (Upper) Photomicrograph of tonalite showing disrupted andesine crystal and sutured contacts of the andesine grains. Crossed nicols; x 50. Sp.11982

B. (Lower) Photomicrograph of tonalite showing two anhedral quartz grains divided into segments possessing different extinction angles. Crossed nicols; x 35. Sp.11868



Data on the relative ages of the tonalite and granite are somewhat contradictory. In the westernmost part of the district the granite is later than the tonalite, and granite dikes commonly intrude the tonalite in other parts of the district. On the other hand, the main tonalite-granite contact near the western end of the tunnel is well exposed for several hundred yards, and yet the exact boundary line between the two rock types is indefinite. The two appear to be gradational into one another. Either some of the granite is approximately coeval with the tonalite and some later, or it is all later.

The rock which the writer has called granite, was named by Dudley (1935, p.502) the "Cajalco Quartz Monzonite". The rock undoubtedly varies in composition from granite to quartz monzonite, but four specimens of the rock which were thought, in the field, to be typical of the locality are all granite. Quartz comprises about 30% of the rock, biotite about 5%, oligoclase 5 to 20%, and orthoclase and microcline 45% to 60%.

DIKES. Both acid and basic dikes are common cutting all the other rock types in the district. Most of the dikes are too small to show on the geologic map, but those shown give the typical configuration of these bodies. The dikes are in most cases planar bodies accordant with the structure of the country rock. Some of the late intrusives, however, are plug-like masses roughly circular in plan. This is true especially of the granites and aplites intruding the gabbro in the western part of the district, and many of the granites and aplites intruding the tonalite about a mile west of the Gavilan Mine also have this form. The writer has gained the general impression that dikes are more numerous in the gabbro than in any of the other rock types, a conclusion reached also by Donnelly in the Pala district, southern California (1936).

The pegmatite dikes consist of microcline and quartz, commonly in graphic intergrowth, coarse-grained biotite and a small amount of muscovite, and in some places tourmaline. The granite dikes are similar in composition and texture to the main granite intrusive. Two of the aplite dikes were thin-sectioned. One has the composition of a granite, and the other has the composition of an augite-quartz monzonite. The basic dikes are commonly very fine-grained and in some cases have chilled borders. The grain size averages 0.1 mm. in diameter or less. The plagioclase (basic andesine) occurs as euhedral laths, the hornblende and biotite are subhedral, and the quartz anhedral. The two basic dikes of which thin sections were made are fine-grained diorite. A Rosiwal analysis on one of them showed that the rock was composed of 57% andesine, 28% hornblende, 12% biotite, and 3% quartz.

The fact that the basic dikes commonly possess chilled borders whereas the acid ones show no indication of a fine-grained zone at the border is indicative of the acid-dikes' being intruded earlier than the basic while the country rock was still at a high temperature. Professor Campbell points out[1], however, that the basic dikes may have been intruded at a much higher temperature than that possessed by the tonalite magma and the acid dikes. Since it is the difference in temperature between the intruded magma and country rock which is responsible for chilled borders, the basic dikes, therefore, may be actually older than the acid dikes. In the only observed case of intersection of the dikes, a basic dike was cut by an aplite. This was at station 11772 in the tunnel.

AGE AND CORRELATION. The igneous rocks all intrude the Triassic metamorphic series and are earlier than the Eocene Alberhill clays (Dudley, 1935, p.505). In the Santa Ana Mountains igneous rocks similar to those in the Val Verde district are overlain unconformably by the Trabuco formation which is late lower, or early upper, Cretaceous[2]. It seems probable therefore, that the igneous rocks were emplaced during the Jurassic period, or at least during the Mesozoic era, and are comparable in age to intrusives of the Sierra Nevada.

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1. Campbell, Ian, Personal Communication, 1937.
2. Popenoe, W. P., Personal Communication, 1937.

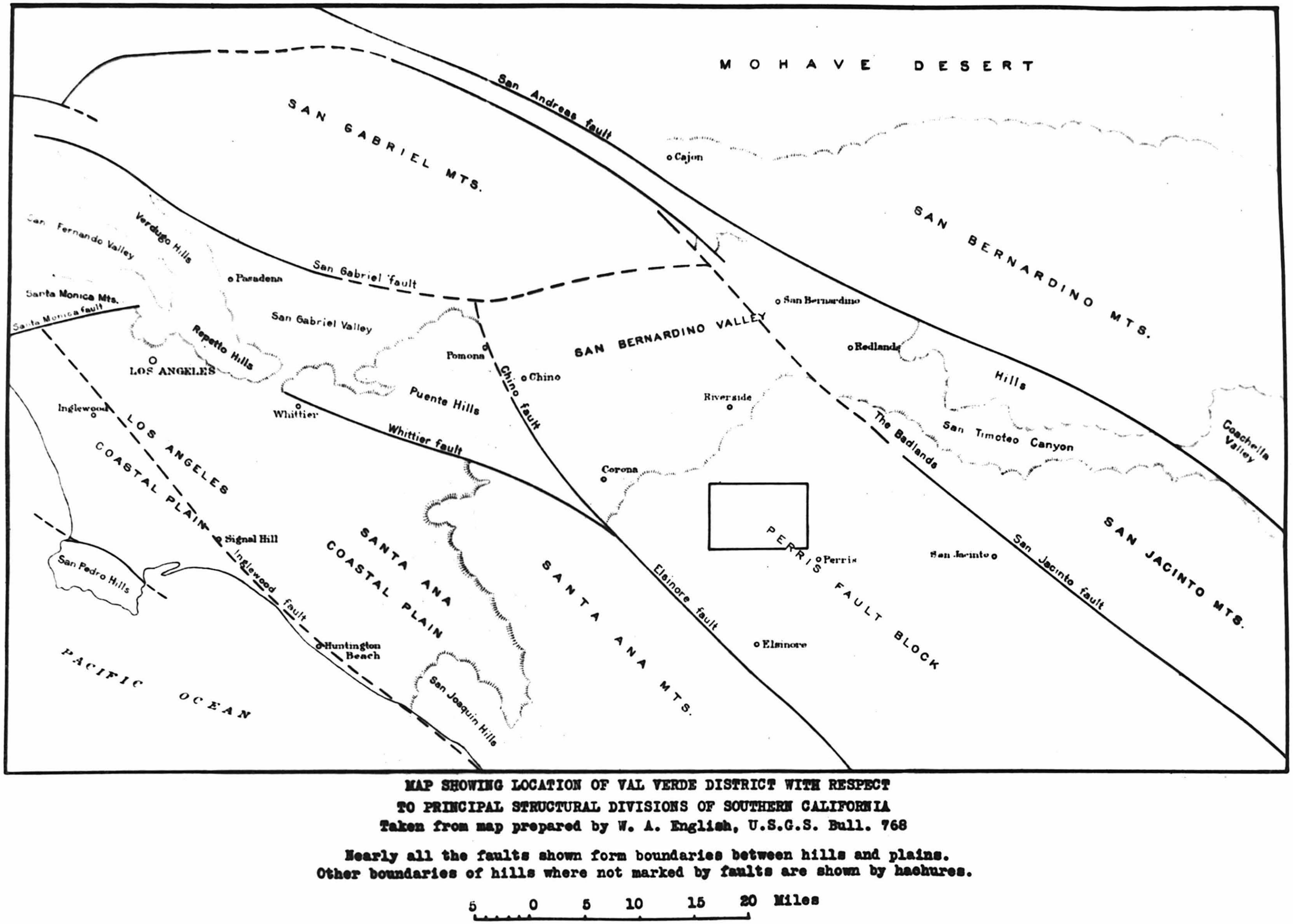
Structural Geology

The position of the Val Verde district with respect to the main structural features of southern California is shown in plate 5. The district is located between two major strike-slip faults, the San Jacinto on the east and the Elsinore on the west. These faults strike approximately N.30°W. and dip about vertically. The main structural features within the Val Verde district possess this same strike, but dip in most cases steeply to the east.

The structural trend within the Val Verde district is outlined by the narrow body of schist which crosses it from northwest to southeast. In the southern and central parts of the district the schist strikes N.20° to 30°W. and dips steeply to the northeast. In the northern part of the district the schist swings westward, assuming a N.60° to 65°W. strike and a slightly lower angle of dip. The gneiss planes in the tonalite and granite, the acid dikes, and the inclusions all faithfully follow this same trend. The gneiss planes in the tonalite, however, decrease in dip eastward from the contact with the schist and are essentially horizontal at the eastern end of the tunnel (see pl.6).

A few well developed drag folds with an amplitude of a few inches were found in the schist. The axes of the folds were approximately horizontal. Near the contact with the tonalite another type of fold occurs in the schist. The beds are commonly contorted and crinkled about an axis which

PLATE 5



MAP SHOWING LOCATION OF VAL VERDE DISTRICT WITH RESPECT TO PRINCIPAL STRUCTURAL DIVISIONS OF SOUTHERN CALIFORNIA

Taken from map prepared by W. A. English, U.S.G.S. Bull. 768

Nearly all the faults shown form boundaries between hills and plains. Other boundaries of hills where not marked by faults are shown by hachures.

parallels the dip of the schist. These folds are apparently related in some way to the intrusion of the tonalite and were formed subsequently to the drag folds.

Numerous faults and joints cutting the tonalite occur in the tunnel. The position of these is shown graphically in plate 6. In most cases the faults and joints strike in a general northerly direction and dip steeply. No constant relation between the faults, joints, flow structure, and dikes could be established. If the fractures connected with the intrusion of the tonalite are present, they cannot be differentiated from later structures. In a few cases some indication of the direction of movement along the shear zones was discovered. At station 11749 well developed slickensides are horizontal on a shear striking N.10°E. and dipping 80°E. At station 11792 a two-inch pegmatite dike striking N.70°W. and dipping 70°N. is cut by a fault striking N.15°W. and dipping 75°E. That part of the dike on the west side of the fault has been displaced horizontally one foot to the northwest with respect to that on the east side.

The largest shear zone is one located at the western contact of the schist and tonalite. It is represented by a zone of crushed and sheared rock and gouge ten to fifteen feet wide striking N.30°W. and dipping approximately vertically. As shown on plate 2, this fault has been traced on the surface for a distance of about four miles. Its continuation to the northwest and southeast could not be established. Evidence for the existence of the fault on the surface is of four kinds. First, the contact between the schist and tonalite is uniquely sharp and straight, unlike the true intrusive contacts exhibited elsewhere in the district. Second, a large spring, shown on the Riverside quadrangle topographic sheet, is located on the line of this shear zone where it crosses the small valley located about two miles north of the tunnel. Third, physiographic evidence, although not convincing, is suggestive in this connection. The valley just mentioned crosses the fault zone and then turns abruptly northwestward into Mockingbird Canyon which parallels the extension of the shear zone. The location of Mockingbird Canyon and the turn in direction of the stream valley may be related to the presence of the fault. The southeastern extension of the fault zone also leads into a prominent valley on the southern side of the Gavilan Hills, but this region was not mapped in sufficient detail to detect the presence of a fault. Fourth, the main body of schist is offset about 500 feet at the place where the fault crosses it. The west side has been shifted northwestward with respect to the east side. The displacement of the schist as mapped could not be established beyond all doubt, but it is the most reasonable interpretation of the field relations.

In summary, the evidence at hand indicates that horizontal displacement along northwest striking and steeply dipping faults with the west side moving northwest with respect to the east has been the dominant type of movement in this district in recent times. In this connection, Mayo (1937) finds evidence pointing to the fact that strike slip faulting was important in some parts of California prior to the emplacement of the Sierra Nevada batholith.

Economic Geology

Gold is the only commodity of any importance produced from the rocks of the Val Verde district. The old Gavilan Mine (See pl.2) was originally worked by Mexicans with arrastres, and between 1890 and 1892 was reopened and operated by a Riverside company (Sampson, 1935). The workings reached a depth of about 485 feet, and it is reported that between one and two million dollars worth of gold was recovered. A new mining company has opened a shaft about 300 feet south of the old Gavilan shaft and called it the Ida Leona Mine. Drifting is going on at the present time on the 50-foot level along a narrow quartz vein paralleling a shear which strikes N.65°E. and dips 40° to 60°S. A small amount of gold has been produced.

CHAPTER IV.

MICROMETRIC AND RADIOACTIVITY MEASUREMENTS

An important part of the investigation of the rocks from the Val Verde district was concerned with the variation in mineralogic composition and radioactivity of the tonalite. The problem was of particular interest because of the unique opportunity to study fresh samples of a rock collected at regular intervals over a distance of five miles across a single intrusive. The study of the heavy minerals was made by R. W. Wilson of the geology department, and of the radioactivity content by R. A. Clarke and F. H. Wright of the physics department of the California Institute of Technology.

The writer's contribution to the problem is divisible into four sections: (1) examination of the errors involved in sampling the rock; (2) determination of the variation in mineralogic composition of the tonalite along the line of the tunnel; (3) correlation of these data with those obtained from heavy mineral and radioactivity studies; and (4) application of the micrometric and radioactivity data to the problem of the origin of the inclusions.

Errors Involved in Sampling the Rock

A large number of papers has been published on the general problem of obtaining accurate quantitative data on the mineralogic composition of a rock. A recent paper by

Larsen and Miller (1935) summarizes this literature, so that only those publications directly related to the present study will be mentioned. A survey of these various contributions reveals the fact that the accuracy of any method of estimating the composition of a rock is partly dependent upon the type of rock being studied. A coarse-grained porphyritic rock in general introduces a larger error than a fine-grained one; and in some intrusives the variation in composition is rapid from point to point while in others the body is sufficiently homogeneous so that a grab sample is typical of an area several feet or several tens of feet in diameter. In short, the probable errors involved in sampling should be evaluated for the particular rock being studied before the compositional variation can be considered.

Two types of error are involved in micrometric analysis. The first is concerned with the determination of the composition of the thin section. The second is involved in the assumption that the thin section is representative of the hand specimen, and that the latter is typical of a larger mass of rock.

<u>ACCURACY IN DETERMINING THE COMPOSITION OF A THIN SECTION</u>. The linear method of Rosiwal (1898) was employed in this study using a Leitz six-spindle integrating stage. Parallel traverses were run across the section at equally spaced intervals of 1 mm. and the distance across each grain along the traverse was automatically registered. The spacing of

1 mm. was used because the average grain size is 1 sq. mm., and because this is a convenient unit to use. The method assumes first, that the rock is equigranular, and secondly, that the diameters measured are proportional to the volumes; and although the validity of this second premise has been questioned by Julien (1903) and Williams (1905), more recent investigations by Lincoln and Rietz (1913) and Johannsen (1919) have shown that this basic assumption is correct. Moreover, Thomson (1930, p.215) found that the linear method is slightly more accurate than the areal methods.

Several factors combine to introduce error into the measurement of a thin section. First, it is not always possible to identify positively every grain during the process of measuring. The position of the integrating stage is too high above the condensing lens to permit the use of interference figures. The nicols, however, could be rotated on the microscope used by the writer. The main difficulty lay in distinguishing andesine, cut in a manner such that the twinning was not visible, from quartz. Students in the petrology class who worked on these rocks experienced difficulty in this respect. As one becomes accustomed to the rock, however, these two minerals are seldom confused. Second, a slight error inevitably enters due to inaccurate measurements. This is mostly a personal error and increases as one's eyes become fatigued, but in some cases the boundaries between minerals are indefinite or are inclined so that the position of the boundary at the top and bottom of the thin section is different. If the contact between a colored and a transparent mineral is inclined, the colored mineral will generally be given a greater diameter than is correct unless this possibility is borne in mind. Third, the measuring method itself would be absolutely correct only if an infinite number of lines were run across the section. Greater accuracy than is obtained by spacing the traverses at 1 mm. intervals, however, is not necessary because of the larger errors due to the inhomogeneity of the rock.

In several cases sections were measured twice to determine how closely the values checked. The error for an individual mineral was in almost all cases less than one per cent and never greater than two per cent. This accuracy of about one per cent corresponds with that found by others, and there is little reason to doubt its correctness. Since the expected error is about one per cent, the values are listed only to the nearest per cent.

ACCURACY OF SAMPLING A ROCK BY A THIN SECTION. As Larsen and Miller point out (1935, p.263), the more difficult and yet important phase of the problem is how representative is a thin section of a hand specimen; and the writer has carried the inquiry one step farther to gain information on the question of how representative is a hand specimen of a larger rock mass.

Part of the error involved is inherent within the rock itself. In the case of a coarse-grained rock, absolute homogeneity within the area of a thin section is not to be expected. The larger the thin section, however, the more accurately will it sample the rock.

EXPERIMENTAL RESULTS. In order to test the accuracy of the measuring method, two oriented thin sections of the tonalite were used. Each was cut normal to the plane of gneissosity and parallel to the linear direction in the rock. Two measurements were then made of each thin section, one with the traverses paralleling the traces of the gneiss planes and the other with the traverses running normal to them. The area of the thin sections used was 500 sq. mm. or more. As the following table shows, the deviation from the average value of the two measurements was not greater than 1% for any constituent. This is not only evidence to prove that the micrometric method used is accurate to within about 1% for any constituent, but also shows that in the case of the tonalite it makes no difference in what direction with respect to the gneissosity the traverses are run.

TABLE 1.

Specimen 11868

	Parallel to Gneissosity	Normal to Gneissosity	Mean	Deviation from Mean
Length of traverse	611.3mm.	572.1mm.		
Plagioclase	51%	51%	51%	0%
Quartz	29	28	28.5	0.5
Orthoclase	1	1	1	0
Biotite	12	12	12	0
Hornblende	7	8	7.5	0.5

TABLE 1 (Cont'd.)

Specimen 11982

	Parallel to Gneissosity	Normal to Gneissosity	Mean	Deviation from Mean
Length of traverse	504.0mm.	482.8mm.		
Plagioclase	64%	62%	63%	1%
Quartz	22	22	22	0
Orthoclase	1	1	1	0
Biotite	13	15	14	1

Of importance to the investigation is the question of how large a thin section of the tonalite must be in order to be representative of the hand specimen. To test the size of section necessary to give dependable results, ten large thin sections were divided in half and the upper and lower halves run separately, a method used by Larsen and Miller (1935). The length of traverse across a half section averaged about 250 mm., or in other words, the area was about 250 sq. mm. The maximum deviation of any single constituent in one half from the average of the two halves was 5%. The average deviation from the mean in per cent for the ten sections was, for plagioclase 2.1, for quartz 1.1, for orthoclase 1.4, for biotite 1.7, and for hornblende 14.0. In table 2 are given the values for two of the sections. The first is the section possessing the least correspondence between the two halves, and the other is one showing close correspondence.

TABLE 2.

Specimen 11982 (Measured parallel to gneissosity)

	Lower ½	Upper ½	Weighted Av.	Max. Deviation from the Mean
Length of traverse	273.6mm.	231.4mm.		
Plagioclase	67%	60%	64%	4%
Quartz	23	21	22	1
Orthoclase	1	1	1	0
Biotite	9	18	13	5

Specimen 12024H.

	Lower ½	Upper ½	Weighted Av.	Max. Deviation from the Mean
Length of traverse	309.3mm.	322.4mm.		
Plagioclase	40%	39%	39.5%	0.5%
Quartz	27	28	27.5	0.5
Orthoclase	15	19	17	2
Biotite	9	9	9	0
Hornblende	9	5	7	2

The writer has concluded from the above experiment that since the per cent of a single constituent in a section with a length of traverse of 250 mm. may vary from the mean value of a section twice that size by as much as 4 to 5%, sections less than 250 sq. mm. should not be used in the micrometric study of the tonalite. Therefore, all sections used in studying the variation in the tonalite were larger than 250 sq. mm.

The next question concerns the accuracy of representing a hand specimen of the tonalite by a single thin section. Of three of the hand specimens, two sections were made. The chips from which the sections were made were taken at a distance apart of at least two inches.

TABLE 3.

Specimen	11982A	11982B	11868A	11868B	12024CA	12024CB
Length of traverse	412.1mm.	504.0	317.8	611.3	562.5	598.7
Plagioclase	63%	63%	52%	51%	42%	44%
Quartz	23	22	30	29	27	28
Orthoclase	1	1	1	1	14	14
Biotite	13	14	13	12	9	8
Hornblende	0	0	4	7	8	6

The correlation shown in table 3 is interesting in that the two large thin sections of the same hand specimen agree more closely than did the two halves of the same large section. The maximum deviation in a single thin section from the mean of the two sections of the same specimen for plagioclase, quartz, orthoclase and biotite is 1%, and for hornblende is 1.5%. The writer concludes from these data that one thin section as large as those used in the above study is sufficient as a sample of a hand specimen of the tonalite.

The final test made was on the accuracy of a hand specimen as a sample of a larger body of the rock. At station 12024 eight specimens of what appeared to be typical tonalite were taken. Later study revealed that the rock was actually granodioritic to quartz-monzonitic in composition. The area from which these specimens were taken was approximately six feet in diameter, and the distribution of the specimens is shown in the diagram on the following page.

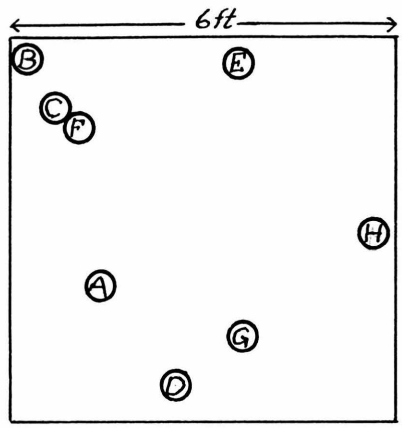


Table 4 lists the composition of the samples and gives finally the average deviation from the mean for each constituent. The samples are very close in composition except for number "E", which has a rather different plagioclase-orthoclase ratio from the others. The mineral with the largest average deviation from the mean is orthoclase with a value of 3.1% . If the tonalite along the tunnel is as uniform as the rock at this station, then variations in composition from point to point greater than about 3% for a single constituent are probably outside the limits of error of the sampling method. This variation in composition of an apparently uniform intrusive rock from one hand specimen to another, both of which appear to be typical, is of the same order of magnitude as that determined by Grout (1932, p.398). Actually the tonalite

TABLE 4

Composition of Eight Samples at Station 12024.

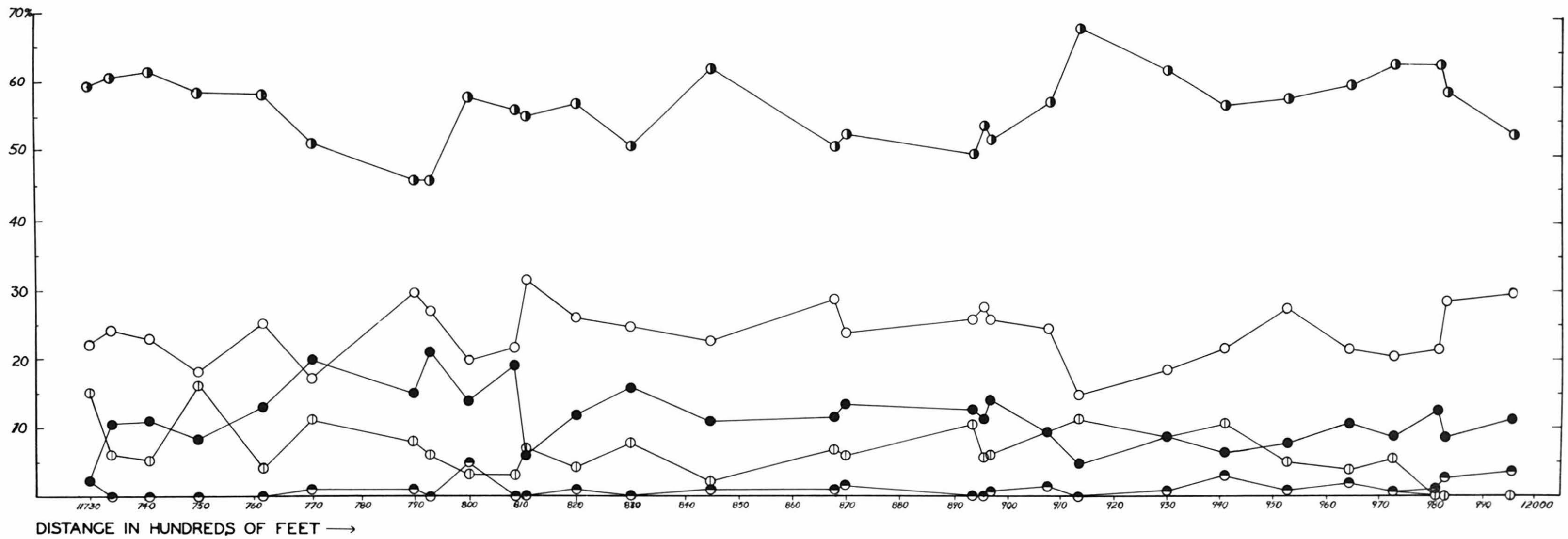
Sample No.	Length of traverse in mm.	Plagio-clase	Quartz	Ortho-clase	Bio-tite	Horn-blende
A.	447.5	42%	27%	15%	12%	4%
B.	519.6	44	28	13	9	6
C.	562.5	42	27	14	9	8
D.	460.3	44	29	11	11	5
E.	354.5	34	25	27	8	6
F.	598.7	44	28	14	8	6
G.	503.2	43	29	17	8	3
H.	631.7	40	27	17	9	7
Mean Value		41.8	27.5	16.0	9.2	5.6

Deviation from the Mean

Sample No.	Plagio-clase	Quartz	Ortho-clase	Biotite	Hornblende
A.	0.2%	0.5%	1.0%	2.8%	1.6%
B.	2.2	0.5	3.0	0.2	0.4
C.	0.2	0.5	1.0	0.2	2.4
D.	2.2	1.5	5.0	1.8	0.6
E.	7.8	2.5	11.0	1.2	0.4
F.	2.2	0.5	2.0	1.2	0.4
G.	1.2	1.5	1.0	1.2	2.6
H.	1.8	0.5	1.0	0.2	1.4
Av. Deviation from Mean	2.2	1.0	3.1	1.1	1.2

may be more uniform than the rock at station 12024 because it was found that in the vicinity of this station the igneous rock is varying more rapidly in composition than at any other place in the tunnel.

PLATE 7



GRAPH SHOWING VARIATION IN PERCENTAGES OF MINERAL CONSTITUENTS IN TONALITE

PLAGIOCLASE ◑ QUARTZ ○ BIOTITE ● HORNBLENDE ⦶ ORTHOCLASE ⊖

Variation in Mineralogic Composition of the Tonalite

Twenty nine thin sections all larger than 250 sq. mm. have been used to show the variation in composition of the tonalite along the line of the tunnel. The spacing of the samples from which the thin sections were made is not uniform due to the impossibility of securing fresh specimens from some parts of the tunnel. The distance between the samples averages about 1000 feet. Table 5 lists the composition of the specimens as determined from thin sections with an area greater than 250 sq. mm., and plate 7 shows graphically the variation in mineralogic composition of the tonalite. No mineral tends to increase or decrease regularly from east to west through the tunnel, although the tonalite near the western end contains in general slightly more orthoclase. The variation in composition of the plagioclase, however, is significant. As shown on the upper graph of plate 8, the plagioclase becomes more sodic toward the western end of the tunnel. Thus, the generalization may be made that the tonalite is more acidic toward the western end of the tunnel, or toward the border of the intrusive. Wilson (1937, p.129) came to this same conclusion from a study of the heavy accessory minerals. He found that toward the western end zircon increased in amount, apatite decreased, and there was an introduction of tourmaline, monazite, and anatase.

The more acidic border of the tonalite is believed to be due to assimilation of quartz-biotite schist. Incorpora-

TABLE 5

Specimen	Rock Type	Plagio-clase	Quartz	Ortho-clase	Bio-tite	Horn-blende	Radio-activity
F.11*	Gabbro	52%	0%	0%	0%	46%**	0
F.29	"	48	0	0	0	48	0
F.31	"	64	0	0	0	36***	0
11916	Diorite dike	57	3	0	12	28	11
F.36	Inclusion	53	4	0	13	30	25
11742	"	30	19	0	18	33	12
11912	"	45	21	0	21	13	19
11915	"	48	18	0	16	18	21
12022A	"						30
12022B	"						19
11980A	"						19
11980B	"						32
11983	"						19
B.456****	"	48	20	0	11	21	7
F.8	"	45	23	6	9	17	81
F.18	"	37	41	0	15	7	46

*The specimens marked "F" were taken from the surface and have the following locations:

F.8-- 3/4 mi. N. of west end of tunnel, 400 yds. west of schist-tonalite contact.
F.11- 1½ mi. NE. of west end of tunnel
F.12- 2 mi. N. of west end of tunnel
F.13- 1 3/4 mi. N. of west end of tunnel
F.16- 2 mi. west of west end of tunnel
F.18- 2¼ mi. W. of west end of tunnel
F.19- About 20 feet from F.18
F.22- 1500 ft. W. of F.18
F.23- 2000 ft. NW. of F.16
F.29- 2½ mi. W. of west end of tunnel
F.31- Gavilan Peak
F.36- 100 yds. N. of station 11930
F.37- 3/4 mi. S. of west end of tunnel

**Includes 2% apatite and magnetite
***Includes 20% augite and 2% olivine
****Specimen from Bernasconi Tunnel

TABLE 5 (Continued)

Specimen	Rock Type	Plagio-clase	Quartz	Ortho-clase	Bio-tite	Horn-blende	Radio-activity
F.19	Schist	38	25	0	17	20	55
F.22	"	48	7	0	12	33	25
12011	"	2	67	14	17*	0	42
12012	"	15	69	3	13*	0	32
F.37	"	1	84	0	15*	0	72
12021	"	0	76	0	24**	0	50
11730	Tonalite	59	22	2	2	15	35
11733	"						48
11734	"	60	24	0	10	6	
11741	"	61	23	0	11	5	15
11750	"	58	18	0	8	16	53
11751	"						9
11762	"	58	25	0	13	4	32
11767	"						22
11771	"	51	17	1	20	11	17
11779	"						19
11790	"	46	30	1	15	8	19
11793	"	46	27	0	6	21	9
11800	"	58	20	5	14	3	23
11809	"	56	22	0	19	3	34
11811	"	55	32	0	6	7	52
11820	"	57	26	1	12	4	25
11830	"	51	25	0	16	8	23
11831	"						24
11845	"	63	23	0	11	2	37
11868	"	51	29	1	12	7	
11870	"	54	23	2	16	5	23
11886	"						16
11894	"	50	26	0	13	11	27
11896	"	54	28	0	12	6	46
11897	"	52	26	1	15	6	
11908	"	58	27	2	11	2	
11910	"						45
11914	"	68	15	0	5	12	65
11927	"						43
11930	"	62	19	1	9	9	83
11941	"	57	22	3	7	11	83

*Includes 5% muscovite
** Includes 16% muscovite

TABLE 5 (Continued)

Specimen	Rock Type	Plagio-clase	Quartz	Ortho-clase	Bio-tite	Horn-blende	Radio-activity
11953	Tonalite	58	28	1	8	5	72
11965	"	60	22	3	11	4	92
11973	"	63	21	1	9	6	69
11980	"						60
11982	"	63	23	1	13	0	52
11983	"	59	29	3	9	0	50
11996	"	53	30	4	12	1	84
12022	"	54	18	0	20	8	
12022.5	"	62	15	3	9	11	60
12024	Granodiorite	42	28	16	9	5	95
12034	Granite	21	33	45	½	½	145
F.23	"	6	34	54	6	0	105
F.16	"	3	35	56	6	0	85
F.13	Aplite	11	33	56	0	0	52
F.12	Pegmatite						220

tion of this material into the tonalite magma would tend to make it more acidic; contact relations indicate that assimilation may have been important; and the increase in radioactivity of the tonalite near the schist is suggestive of assimilation since the schist averages higher in radioactivity than the tonalite. That variation in composition of an acid intrusive toward its border may commonly be due to assimilation of the country rock is supported by other evidence. A granodioritic intrusive in central Colorado (Behre, Osborn, and Rainwater, 1936, p.790) is slightly more basic toward the border where it is in contact with limestone. The writers proposed the explanation that the more basic border is due to assimilation of limestone. Lasky (1935) has found good evidence for believing that the more basic border of a granodiorite intrusive in New Mexico is due to assimilation of basalt. Mayo states[1] that in the vicinity of Island Pass in the Sierra Nevada, where granodiorite is in contact with basic tuffs and limestone, the border is commonly more basic, and that he has observed the reverse in localities where intrusive rock is in contact with acidic tuffs and quartz-mica schist.

Correlation of Mineralogic Data with Radioactivity Determinations

Samples of rock from the Val Verde district were examined by R. A. Clarke and F. H. Wright of the physics department of the California Institute of Technology for their radioactivity. In the following discussion the values listed for radioactivity are proportional to the number of alpha particles emitted per unit time per unit weight of sample[2]. As far as is now known, the only elements involved are members of the radium, thorium, and actinium series[3].

EXPERIMENTAL RESULTS. Radioactivity measurements were made on the tonalite from thirty five different stations along the tunnel, on several specimens of granodiorite, granite,

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1. Mayo, E. B., Personal Communication, 1937.

2. A paper by Clarke and Wright is in press giving a detailed description of apparatus and method, and giving more detailed results than those listed herein.

3. Clarke, R. A., Personal Communication, 1937.

schist, gabbro, and inclusions, and on a pegmatite dike, an aplite dike, and a fine-grained diorite dike. The results are listed in table 5 along with the mineralogical composition, and the data on the tonalite are plotted in plate 8.

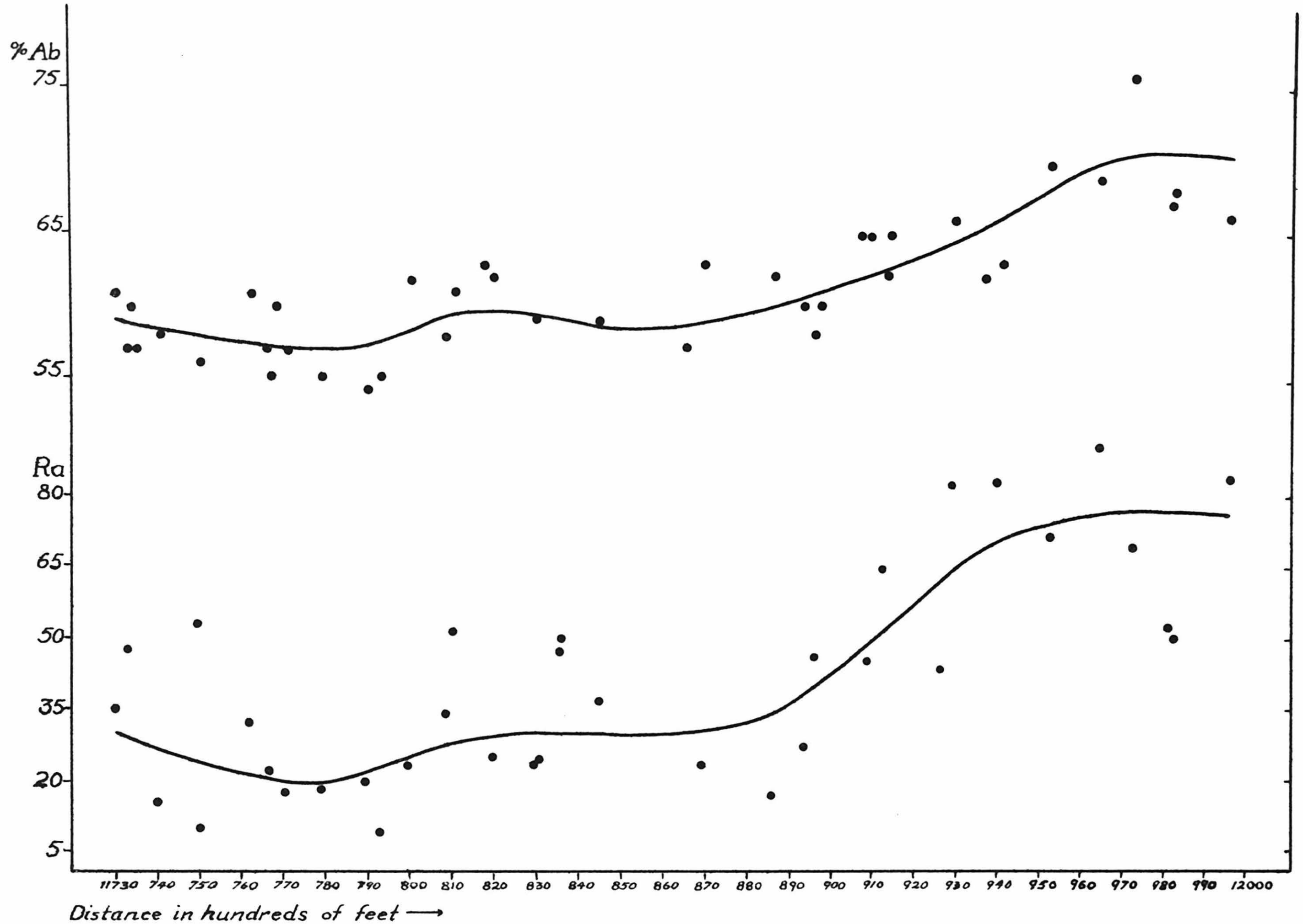
Although the points in the lower graph on plate 8 are rather scattered a curve has been drawn which correlates very well with the upper curve which is a plot of the albite content of the plagioclase along the tunnel. There may be some doubt as to the existence of the wave in the curves between stations 11760 and 11850, but the rise in both curves toward the west, or toward the contact with the schist is undoubtedly real.

A summary of the data concerning the correlation of radioactivity with <u>rock type</u> is given in table 6. These data show a direct relation between the radioactivity and the acidity of the rock.

TABLE 6

No. of specimens	Rock Type	Av. Value of Radioactivity
3	Gabbro	0
1	Diorite dike	11
10	"Gabbro" Inclusions	20
2	"Schist" Inclusions	64
35	Tonalite	42
6	Schist	46
1	Aplite	52
8	Granodiorite	95
3	Granite	112
1	Pegmatite	220

PLATE 8



UPPER GRAPH SHOWS VARIATION IN ALBITE CONTENT OF PLAGIOCLASE IN TONALITE

LOWER GRAPH SHOWS VARIATION IN RADIOACTIVITY OF TONALITE

LITERATURE. Lord Rayleigh, in 1905, was the first to point out the direct correlation between the radioactivity and acidity of rocks (Strutt, 1905). The data presented herein furnish additional proof of the correctness of the generalization. A series of papers since 1905 has dealt with the radioactivity of minerals and rocks. Waters (1905, and 1910) found that in the Cornish granite the radium was concentrated in anatase or rutile, in the Dalbeattie granite in allanite, and in the Mourne granite mainly in zircon and some titaniferous mineral. Fletcher, in studying the Leinster granite (1911) found that the radioactivity of the rock was due mostly to micas containing inclusions of zircon. Piggot and Merwin (1932) examined two granites with a high content of radioactive substances, one from Stone Mt. Georgia, and the other from North Jay, Maine. As a result of their work, they concluded that in mica-bearing granites, the radium is associated more with the micas than with the other constituents of the rock. Evans and Williams concluded from a study of the various types of lavas from Lassen Volcanic National Park (1935) that the amount of radium increases with the alkalies, especially potassium.

SOURCE OF RADIOACTIVITY. More work is to be done by Wright of the physics department on the radioactivity of the individual minerals of the Val Verde tonalite, but tentative conclusions may be reached concerning with what constituent of the rock the radioactive material is associated. An examination of plates 7 and 8 is sufficient to show that the data so far obtained indicate no correlation between the radium-thorium-actinium content of the tonalite and the perentage of biotite, quartz, or hornblende. A slight correlation exists between the low points in the plagioclase and radioactivity curves, butthis may be fortuitous. Also, orthoclase is slightly more abundant in the rock near the contact. It is possible that the radioactive substances are contained in zircon which Wilson (1937) found to increase in amount toward the western end of the tunnel; in this case the amount of zircon may vary directly with the albite content of the plagioclase. It is noteworthy, however, that the zircon occurs almost exclusively as inclusions, surrounded by pleochroic halos, in the biotite.

Origin of the Dark Inclusions in the Tonalite

LITERATURE. A nearly universal characteristic of light colored intrusive rocks is the presence in them of dark, fine- to medium-grained inclusions. Because of their prevalence and generally uncertain origin, these inclusions are frequently discussed in geologic literature, and a brief summary of the theories concerning their origin is given below.

A common explanation of the origin of the inclusions is that they are basic segregations from the magma which solidified forming the host rock. Knopf and Thelen (1905), Bastin (1911), and Pabst (1928) have expressed this view. The process by which the dark constituents of the magma segregated and were concentrated about centers to form the inclusions is obscure, and the value of the theory seems to lie mainly in the fact that it cannot be easily confuted.

Formerly several writers (Backstrom, 1893; Weed and Pirsson, 1896, p.87; and Daly, 1914, p.225) exployed a still more tenuous hypothesis, that of liquation, to explain the origin of the inclusions. This idea has fallen into disrepute even among its sponsers.

A third theory supposes that the inclusions are bodies of foreign rock which have broken from the walls and roof of the intrusive and have been incorporated in the magma. The magma has reacted with the blocks of country rock to a varying degree. This was the explanation used by Gilbert (1906, p.325) for the origin of the inclusions occurring in the Kings River country of the Sierra Nevada, California. Grout (1930, p.678) considered the inclusions in the Duluth gabbro to be xenoliths. Nockolds (1932 and 1937), and Thomas and Smith (1932) have been able to submit good evidence to prove that the inclusions studied by them are xenoliths of older rock. During the summer of 1933 the writer examined the inclusions in the Calumet granodiorite (Behre, Osborn, and Rainwater, 1936, p.788), and in many cases these were clearly blocks of the older shale, sandstone and dolomite. Hurlbut (1935) on the basis of microscopic evidence showed that the inclusions in the Bonsall tonalite in the San Luis Rey Quadrangle, thirty miles south of the Val Verde district, were derived from the San Marcos Mountain gabbro.

In summary it may be said that although all inclusions may not have been formed in the same manner, nevertheless, wherever good evidence as to their origin has been available this has pointed always in the same direction -- that the inclusions are xenoliths of the country rock.

DISCUSSION OF DATA. Two of the inclusions studied differed from the rest and are thought to have been originally schist. Specimen No. F.8 was taken from the center of a discoidal inclusion which was approximated five feet in diameter and one foot thick, located three-fourths of a mile north of the tunnel and 400 yards west of the tonalite-schist contact. Referring to table 5, it is seen that this inclusion contains 6% orthoclase, which is unusual for any of the medium basic or basic rocks in the district except the schist which in one case contains 14%. The plagioclase is oligoclase which is the plagioclase most commonly found in the schist, but is more acid than that in the enclosing rock. The value for the radioactivity content is 81 as compared with an average value of 20 for ten other inclusions which are thought to have been derived from the gabbro. The fact that the value for the radioactivity is higher than that for the schist specimens examined is not contradictory evidence, because in the first place the schist varies notably in radioactivity content, and in the second place injection of acid material from the tonalite into the inclusion may conceivably have raised the radioactivity content.

Specimen No. F.18 was taken from an inclusion in the tonalite located near the western edge of the district twenty feet from a schist-tonalite contact. Specimen No. F.19 is of the schist a few feet from the contact. Specimens F.18 and F.19 are similar in mineralogic content, nearly identical in grain size and texture, and possess comparable radio-activity values.

The other ten inclusions, which were examined for their radioactivity content or mineralogic composition or both, are thought to have been derived from the gabbro. In the first place, the composition of the plagioclase is suggestive. Specimens No. 11915 and F.36 were taken from near the center of inclusions having a maximum diameter greater than six feet and a thickness of one foot or more, located in or near that part of the tunnel in which inclusions comprise 50 to 60% of the rock (See pl.6). In both of these specimens some of the plagioclase grains have cores of labradorite or bytownite, varying in composition in the different grains from 60 to 80% anorthite molecule content. The only rock in the district containing plagioclase as basic as this is the gabbro. Most commonly the plagioclase in the gabbro is bytownite with an anorthite content of 85 to 90%, but in one case the plagioclase was labradorite, An_{57}. Data very similar to this on the plagioclase in the inclusions in the Bonsall tonalite, about thirty miles south of the Val Verde district, was the evidence used by Hurlbut (1935) to show that the inclusions are xenoliths of gabbro. If the other eight inclusions are gabbro xenoliths, as is thought, then the plagioclase has been changed by reaction with the tonalite magma. In the second place, the average value for the radioactivity of these ten inclusions is 20. This value is much lower than the average for the schist, and it is not probable that the radioactivity of the schist would be appreciably lowered by reaction with the tonalite. On the other hand, since the value for the radioactivity of the gabbro is 0, reaction with the tonalite could change this value only by raising it.

CONCLUSIONS. Because of the reasons given above, most of the inclusions studied are believed to have been derived from the gabbro, the others from the schist. This is assuming that the inclusions are xenoliths. Pabst (1928) described inclusions in the acidic intrusive rocks of the Sierra Nevada which are identical to those in the Val Verde district, and he decided that they were not xenoliths, but autoliths. His reasoning, however, the writer believes is open to question. He considered the inclusions autoliths because: (1) "The autoliths are composed of the same minerals as the enclosing granitic rocks," (p.368). This should be true also in the case of xenoliths immersed in a magma, however, if reaction is complete (See Bowen, 1928). (2) "Chemically and texturally the autoliths have the characters of igneous rocks." If the inclusions are xenoliths of gabbro, then they are of igneous origin. Furthermore, the inclusions in the Val Verde district do not possess a typical igneous texture in that no order of crystallization is apparent except that quartz is the latest forming constituent. This suggests recrystallization. (3) "Although they represent a concentration of what are believed to be the early crystallization constituents of granitic rocks, their fine grain does not permit the interpretation that they are merely the products of synneusis." The method by which Pabst believes the autoliths to have formed is obscure, but the fine-grained texture of the inclusions is doubtful evidence in support of their being autoliths. (4) "The autoliths show, under favorable circumstances, a flow structure conformable to that of the enclosing rock." The origin of the flow structure is somewhat in doubt, but recrystallized xenoliths moving with the magma would have the same opportunity for orientation of their grains as autoliths. (5) "The flattening and orientation of the autoliths in certain localities gives definite evidence that they were able to undergo plastic deformation at the time of the emplacement of the enclosing rock or even later. Moreover, they were then not fully crystallized." It is a well known principle that solid rock undergoes plastic deformation under conditions of high temperature and pressure. Moreover, autoliths would have to be firmly held together to remain intact during the movement of the magma to possess at consolidation the sharp boundaries exhibited by some of the inclusions. (6) "They are not restricted to any narrowly limited set of conditions as to nature of enclosing rock, relation to contact or position in the intrusive mass." The writer does not view this as evidence for the inclusions being either autoliths or xenoliths. (7) "The distribution of the autoliths is apparently related to magmatic movements at the time of intrusion." The writer found no evidence in the Val Verde district that the distribution of the inclusions was related to magmatic movements, but if this is the situation in the Sierra Nevada, the implication is still obscure.

In short, from Pabst's own arguments, the writer believes the case is not better for the inclusions' being autoliths than for their being xenoliths, and furthermore, the mineralogic and radioactivity data on the inclusions given earlier in the discussion is in support of their being xenoliths.

The origin of the fine-grained texture of the inclusions is an enigma. Were the inclusions basic segregations, one might reasonably expect the grain size to be large because of the long time available for crystallization. On the other hand, if, as thought by the writer, the inclusions are mostly xenoliths of gabbro, the fine-grained nature is still not definitely explained. A possible explanation, however, is here suggested. Joplin (1935) examined the problem of hybridization of basic rocks by acidic magma and found the following: In the first stage, a granoblastic texture is produced in the basic rock and granular masses of pyroxene and criss-cross flakes of biotite may form. During and following this stage large, highly poikilitic crystals of hornblende and/or biotite are developed. As Joplin points out, slight movement in the magma would disrupt the poikilitic crystals producing a fine-grained aggregate. This same process was observed in the case of the gabbro. The gabbro at Gavilan Peak is uncontaminated by the tonalite and it contains augite altering to uralite, and olivine. The gabbro in the western and northern parts of the district is closely associated with the tonalite, and thin sections of this gabbro contain only hornblende and biotite as the mafic constituents. Moreover, a thin section of a specimen of gabbro taken from the contact with the tonalite contains unusually large, highly poikilitic crystals of hornblende enclosing fine-grained andesine (See pl.3). If a block of this gabbro dropped into the tonalite, was flattened into a disc, and was carried along with the magma, the movement probably would be sufficient to disrupt the poikilitic crystals and produce a fine-grained rock.

The gabbro is a rock which would probably furnish inclusions to the tonalite more readily than the schist. The schist at its contacts tends to be assimilated and replaced by the tonalite rather than to break off into blocks; whereas the gabbro, because of its massive nature divides into large blocks which are surrounded by stringers and dike-like masses of the tonalite.

The distribution of the inclusions offers no clue as to their origin. Plate 6 shows that the inclusions are not most abundant as the schist contact is approached, but rather the greatest concentration of inclusions is in the vicinity of 11900. The localized swarms of inclusions may represent the fractured lower parts of roof pendents or large engulfed masses of the country rock.

CHAPTER V

STRUCTURAL PETROLOGY

Introduction

Although an important part of the groundwork of structural petrology was laid by two Americans-- Becker (1893), and Lieth (1905) --, the subject is primarily a European development. A paper by Bruno Sander (1911) first enunciated the fundamental principals of structural petrology, and much of the technique involved as well as the theory was developed by Walter Schmidt (1917 and 1925). Each of these men has now published a book -- Sander (1930), and Schmidt (1932) -- and these superbly cover the field as far as it has advanced.

A paper by E. B. Knopf (1933) was the first paper in English to summarize the previous work and to show the possibilities of this method of rock study. Since 1933 a series of publication in English has appeared. Those by Sander (1934), Gilluly (1934), Fairbairn (1934), Bell (1936), Ingerson (1936), Osborne and Lowther (1936), and Winchell (1937) are of particular interest. Several of these publications, especially Fairbairn's "Introduction to Petrofabric Analysis" lucidly explain the general technique and fundamental principals of structural petrology. In the following pages it is assumed that the reader is familiar with the contents of one or more of these publications and thus has at least an elementary knowledge of the field.

The methods of structural petrology were applied to the rocks of the Val Verde district in an effort to determine the origin of the gneissoid structure of the tonalite. It has been assumed by those of the Cloos school that this type of structure in an intrusive mass was developed during the emplacement of the partially crystallized magma, and that the orientation of the grains may therefore be used to determine the direction of flow of the magma. There is always the possibility, however, that the structure was impressed upon the tonalite by post-magmatic deformation. The problem is one which cannot be definitely settled at the present time, but the methods of structural petrology applied to the tonalite have introduced some interesting evidence.

Field and Laboratory Technique

In the field detailed mapping was confined mostly to the rocks within the tunnel, and the surrounding country was mapped on a scale commensurate with its importance to the problem. The work involved t e examination and plotting of all megastructures such as contacts, folds, faults, joints, schistosity, gneissosity, orientation of inclusions, and ~~of~~ the linear element in the tonalite. Oriented specimens were selected to be used in the laboratory study.

The laboratory technique involved first the grinding of oriented thin sections. A flat surface was ground on the specimen in the desired direction and an arrow marked on this plane. A chip containing this surface was broken off and the surface cemented to a glass slide on which an arrow had been scratched corresponding to the direction of the arrow on the chip. The accuracy of orientation of the resulting thin section was within two or three degrees. The accuracy of orientation of the specimens in the field was probably slightly less than this, but undoubtedly the error in the stated orientation of the thin section was not greater than ten degrees.

The oriented thin sections were examined by means of a Leitz Universal Stage. The direction of the optic axis of quartz grains, the poles to the cleavage planes in biotite, and the a-axis and poles to the 010 faces of plagioclase were measured and plotted. In the case of the tonalite all quartz and biotite grains occurring in a thin section were measured, and in some instances it was necessary to use two parallel thin sections to secure sufficient grains.

The data were recorded on an equal-area projection mounted on a Leitz turntable covered with a sheet of transparent paper. The projection of the points was made from the lower hemisphere to the equatorial plane of the sphere in conformity with the conventions established by Schmidt and followed by other workers in the field.

The number of points measured was next counted, a contour interval determined, and the diagram contoured using, in the process, two celluloid counters each of which has a circular area equal to 1% of the total area of the projection.

In a few cases it was advisable to rotate the diagrams ninety degrees after they had been contoured for comparison with other diagrams.

Tectonite Orientation Patterns

Sander (1911) formulated the principle that the deformation of rock masses is commonly produced by the integration of the partial movements within the mass. As "partial movement" he means "each movement of any element in a rock, as a result of which , after the deformation, and for the time under consideration, the rock retains its continuity" (Fairbairn, 1935A, p.32). Rocks wich have undergone deformation in this manner and whose grain orientation is resolvable into some tectonic pattern or symmetry are known as tectonites.

Tectonites have been divided into two groups depending upon the type of pattern exhibited by the grain orientation. S-tectonites, the first type, are characterized by having an orientation diagram which shows one clear cut maximum or two or more clearly separated maxima. B-tectonites, the second and more common type, show a girdle, complete or incomplete, and with or without important submaxima. Diagram No.13, pl. 12, is the type of orientation exhibited by S-tectonites. The quartz diagrams obtained from the schist (See pl.10) are B-tectonites. Most of the orientation patterns obtained from the quartz and biotite of the tonalite are intermediate in type between S- and B-tectonites.

Briefly, the inferred origin of the two types of orientation patterns is based on the various methods by which differential, or partial, movement may produce grain orientation. If the movement is produced by gliding along parallel shear surfaces, S-tectonites will normally be formed. If the movement, on the other hand, is of the rolling type, in which the grains tend to be rotated about an axis, a B-tectonite will probably be developed. The gliding planes within the minerals are commonly cleavage or twinning planes. In the case of quartz, gliding parallel to a prism face is thought to be the commonest method of translation, although some evidence has been found suggesting gliding parallel to a rhombohedral face. The explanation for the formation of a girdle of optic axes of quartz during rotation may lie in the fact that the crushing strength of quartz is nearly 10% greater parallel to c' than normal to this direction (Berndt, 1927). As a result, quartz crystals oriented originally with c' in the plane of rotation are more durable than those oriented otherwise. As deformation proceeds, grains rotated into this preferred position tend to remain thus with c' in the plane of rotation. Likewise, conditions of dynamic equilibrium demand that small grains which would be formed by crushing of larger grains, dissolve as larger grains increase in size. Furthermore, since the direction of easiest gliding in quartz as far as we now know is parallel to the prism, grains oriented with their c-axes sub-parallel to the direction of movement might escape crushing by gliding on planes parallel to the prism.

The surfaces in a rock along which material has moved or shearing has occurred are called <u>s-surfaces</u>, a non-commital term expressing the idea of schistosity, shear, or stratification. These are not always visible in the hand specimen but show up in the orientation diagram. From many clear cut cases that have been studied (Sander, 1930) in which the direction of shearing along a surface was known, it has been found that the optic axis of quartz tends to orient itself parallel to the surface and in the direction of movement, and the cleavage planes of mica and the 010 faces of feldspar tend to be aligned parallel to the surface. On the diagrams (pl. 11, 12, and 13) various s-surfaces have been marked by dashed lines corresponding to the concentrations of optic axes of quartz, cleavage planes of biotite, and 010 faces of feldspar.

A _plaiting surface_ is a visible surface within a rock along which shearing has _not_ taken place, (See Fairbairn, 1935B, p.598). It is formed largely by a dimensional arrangement of the grain fabric, and is the result of gliding, or shear movements which take place inclined to it. The surface thus corresponds to the AB plane of the strain ellipsoid, and the shearing surfaces inclined to it correspond to the planes of least distortion of the ellipsoid. Plaiting surfaces are thought to form by a combination of shearing on surfaces inclined to the plane and rotation. Through rotation minerals such as mica tend to be plaited in the AB plane of strain. If shearing is dominant over rotation, however, much of the mica may be caught up in the shear surfaces and rotate no farther. The gneiss planes in the tonalite possess the characteristics of plaiting surfaces.

Structural Petrology of the Schist

AXES OF REFERENCE. Following the method of Sander, three axes of reference were set up for the oriented hand specimens of the schist. The _b_-axis is the tectonic axis, or that direction paralleling the axes of drag folds and small crinkles in the rock. The a-axis is that direction lying in the plane of schistosity or ab plane, 90° from b. The c-axis is normal to the ab plane. In the field the b-axis is horizontal or dips at an angle less than ten degrees to the northwest and is directed in a general north to northwest direction. The a-axis, therefore, approximately parallels the dip of the beds, which is in most cases steep to the east.

ORIENTATION DIAGRAMS. Of four specimens of the schist, oriented thin sections were made and the orientation of the quartz and biotite studied. Plate 10 shows the results obtained on two of the specimens. Diagrams 1 to 4 are of biotite and quartz from two thin sections cut normal to the b-axis. Three features of diagrams 1 and 3 should be noted. First, the poles to the basal planes of the biotite are concentrated about c. Since the foliation, or ab, plane in the rock is outlined in the hand specimen by the basal planes of biotite flakes, this orientation is exactly as would be expected. Second, the biotite not only is concentrated at c, but forms a nearly complete girdle about b. Third, the biotite shows a tendency to extend from c toward b, or in other words, to be rotated in the plane normal to a.

The optic axes of quartz, as shown in diagrams 2 and 4 describe a girdle about b with no significant maxima. These diagrams indicate also a slight tendency for the optic axes of quartz to be rotated about a.

Diagrams 5 and 6 were made from thin sections cut normal to the a-axis of the schist. Diagrams comparable to these could be produced by rotation of diagrams 3 and 4 90° about the c-axis, but a new section cut normal to *a* was measured instead in order to find how closely the orientation patterns of minerals in two sections correspond. The correspondence is fairly good, but, especially in the case of quartz, obvious discrepencies are present. A lack of complete correspondence is apparently commonly found and may explain the fact that most writers show rotated patterns for their *a*- diagrams rather than diagrams from sections cut normal to *a*. Diagrams 5 and 6 are important in that they show more clearly than the others the tendency for the quartz and biotite to form girdles about *a* as well as about *b*.

JOINTS AND FAULTS. Joints are not conspicious in general in the schist, but in the body of schist half a mile south of the western end of the tunnel well developed joints are common striking approximately normal to the strike of the schist and dipping vertically or steeply to the south. These are thus approximately parallel to the *ac* plane of the fabric and undoubtedly represent the *ac* joints of Sander.

The main fault in the district lies along the western border of the schist and parallels the schistosity.

INTERPRETATION. The conclusions drawn from these diagrams are as follows: (1) The degree of concentration of points is too great and the orientation [patterns are too consistent in type for the orientation] of the minerals to be fortuitous. (2) Movement in the rock during its deformation was produced, in the case of biotite, by rotation of the grains, with accompanying recrystallization, into a preferred position with the basal planes parallel to the plane of schistosity, and by gliding parallel to the cleavage planes. (3) The quartz diagrams strongly support the contention that the quartz grains have been oriented chiefly by external rotation in a plane normal to b. Although the optic axes of the quartz are not concentrated in a, nevertheless it is most reasonable to assume that the shearing movement was parallel to the ab plane rather than along other planes, because if other shear planes were important these should show up either megascopically or in the orientation patterns. A case similar to this is described by Gilluly (1935). (4) The diagrams indicate a slight tendency toward rotation about a as well as about b. Diagrams 5 and 6 are the best illustrations of this. This would mean movement parallel to the schistosity and approximately parallel to the strike of the beds. It is reasonable to assume that this deformation was later than, and therefore superimposed upon, the earlier and more important deformation which produced the drag folds in the rock. As will be seen later, this second deformation is the one, and the only one, recorded in the tonalite diagrams. Were the main deformation of the schist the later one, it should also be more important in the tonalite.

Structural Petrology of the Tonalite

AXES OF REFERENCE. The axes of reference used for the tonalite have in general the same significance as in the case of the schist. The b-axis is parallel to the linear direction in the

PLATE 9

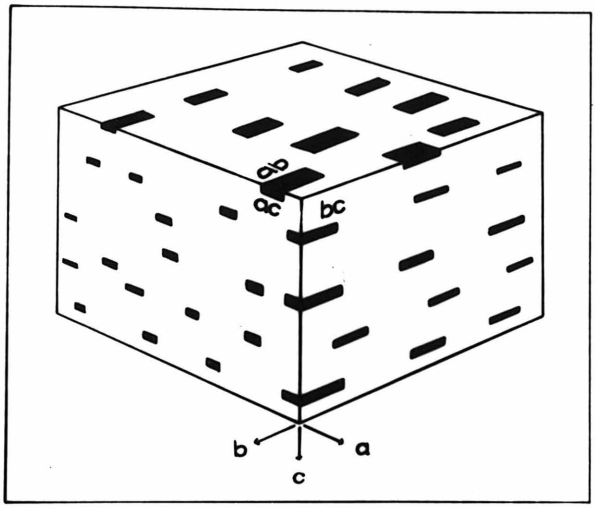
A. (Upper left) Index diagram illustrating relation of axes of reference to dimensional orientation of grains in tonalite.

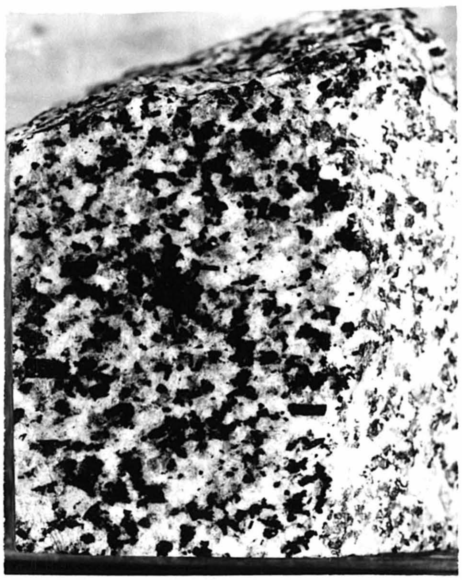
B. (Upper right) Photograph of ac face of sp. 11870 of tonalite. a is vertical; c is horizontal.

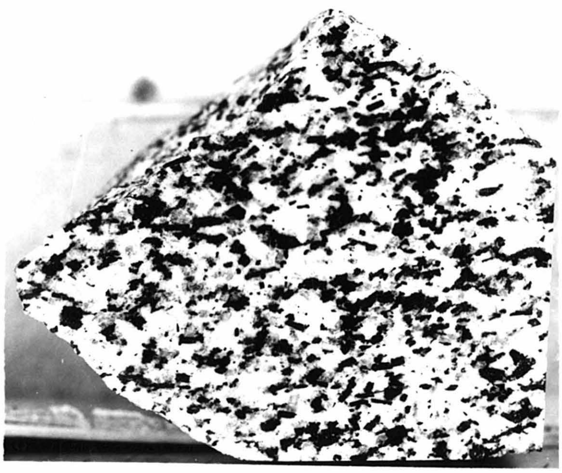
C. (Lower left) ab face of sp. 11870. a is vertical; b is horizontal.

D. (Lower right) bc face of sp. 11870. c is vertical, b is horizontal.

The photographs are natural size.


ab
ac
bc
b
a
c





rock. The a-axis lies in the plane of gneissosity, and is normal to b. The c-axis is normal to the ab plane, or the plane of gneissosity. Plate 9 illustrates the scheme of orientation and also gives an idea as to the degree to which the minerals are oriented in some of the tonalite specimens. The degree of orientation of the minerals is commonly not as high as in the specimen figured.

The c-axis of the tonalite parallels the c-axis of the schist since the gneiss planes parallel the schist planes. However, c gradually approaches the vertical as one goes east from the schist contact because of the flattening out of the gneiss planes (See pl.6). The b-axis in the tonalite is oriented 90° from that in the schist for the linear element parallels the dip of the gneiss planes rather than the strike. The a-axis of the tonalite is approximately horizontal, and is directed north to northwest following the the strike of the gneiss planes. It is thus parallel to the b-axis of the schist.

ORIENTATION DIAGRAMS. Nine specimens of the tonalite from the tunnel, distributed between stations 11734 and 12022, were examined by the methods of Sander and Schmidt. Typical diagrams obtained from four specimens of the tonalite and one specimen of an inclusion are shown in plates 11, 12, and 13.

The degree to which the linear element in the rock is developed was examined by plotting the a crystallographic axis of the plagioclase in sections cut normal to the linear direction. Diagrams 7 and 13 are illustrative of this.

Diagrams 8 and 14 are plots of the poles to the 010 faces of the plagioclase in the two specimens used for diagrams 7 and 13. A discontinuous girdle is present in the plane normal to b, and in this girdle conspicuous concentrations occur in two intersecting planes labelled S_1 and S_2, symmetrically arranged with respect to the ab plane.

The quartz diagrams 10, 16, and 18 possess in general the same characteristics. Diagram 10, however, has an additional concentration at a. Diagram 11 is from a thin section cut normal to that from which diagram 10 was produced, and then this has been rotated 90° about c to produce diagram 12 for direct comparison with No.10. The object, as in the case of the schist, was to observe how closely two sections of the same specimen, one normal to a and the other normal to b, would correspond. As in 10, a girdle is developed in 12 and a strong S_1 is present, but S_3 is weaker and not in exactly the same position, and S_2 is missing. Diagram 22, from an inclusion, and diagram 20 are similar and show the development of only one s-surface. The angles which the s-surfaces, produced by the arrangement ofthe optic axes of quartz, make with the ab plane were plotted for all the sections of the tonalite studied and are shown in diagram 24. With one exception, the s-surfaces all lie between 30 and 70 degrees from the ab plane. A rough correlation, which may be fortuitous, exists between the angle of the s-surfaces of quartz with the ab plane and the distance of the specimen from the schist contact. As shown in table 7, the angle, measured from the ab plane tends to increase eastward or away from the contact.

TABLE 7

Specimen		Angles of s-surfaces from ab plane in degrees
12022		30 and 28
11982		36
930	(F. 36)	35
897		37, 55, 65, and
870		55, and 50
868		55, 70, and 0
820		65
741		70
734		40, and 50

The biotite diagrams are similar to those of quartz, differing fundamentally only in the one respect that an s-surface sub-parallel to the ab plane is commonly developed (See diagram 23).

The orientation patterns obtained from the minerals in the Val Verde tonalite differ in important respects from those obtained by Hurlbut (1936, p:623) in the Bonsall tonalite of the San Luis Rey quadrangle, southern California, and from those obtained by Pabst (1936) from granodiorite in the Sierra Nevada. The quartz was unoriented in the specimens studied by these men and the 010 faces of plagioclase were aligned only parallel to the gneiss planes, with no indication of intersecting planes inclined to the gneissosity.

INTERPRETATION. Since the main object of this study is to uncover evidence on the origin of the gneissoid structure in the tonalite and thus to obtain a more complete picture of the history of the intrusive, let us take up in order the three possibilities: (1) that the structure was developed during the magmatic stage of the tonalite, (2) that the structure was developed after complete solidification of the rock, and (3) that the structure is a result of stresses operative on the rock both during and after solidification.

(1) In support of the hypothesis that the gneissoid structure is entirely a result of magmatic flow the following points may be listed: (a) The texture of the tonalite is essentially that of an igneous rock, in that the normal order of crystallization for a medium basic rock is present, and evidence of either recrystallization or cataclasis is slight. (b) The attitude of the gneiss planes and the direction of the linear element are that normally to be expected were the gneissosity the result of primary flow. That is, the gneiss planes are parallel to the schistosity of the country rock, and the linear direction is parallel to the dip. (c) The inclusions are oriented parallel to the gneissosity, and it is most reasonable to assume that the inclusions were oriented thus before complete solidification of the tonalite. (d) In the detailed studies of intrusives carried on by members of the Cloos school, such an arrangement of minerals as is found in the Val Verde tonalite is assumed to be primary and apparently no evidence to the contrary has been uncovered by them. Mayo reports[1] that intersecting planes of biotite,

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1. Mayo, E. B., Personal Communication, 1937.

hornblende, and plagioclase may be seen commonly on a face normal to the linear element in the intrusive rocks of the Sierra Nevada. He gives no explanation for this, but assumes it to be the result of magmatic flow, and he takes the acute bisector of the two planes as the planar direction in the rock. (e) Joint and fault patterns might be of use in distinguishing primary and secondary gneissosity, but the writer has not been able to use the fault and joint patterns mapped in the tunnel as evidence for any theory on the origin of the flow structure.

The only evidence opposing this first hypothesis on the origin of the flow structure in the tonalite is that furnished by the petrofabric diagrams. Petrofabric data have not been used by the Cloos school as complementary evidence and therefore their theories have not been generally opposed and have been applied to igneous rocks of all types without question. The intersecting planes in the rock formed by biotite flakes and the 010 faces of plagioclase are not readily explained as being the result of primary flow. A wavering of the flow lines is to be expected, but the development of two definite planes, or in some cases one, inclined to the plane of gneissosity is a different case. Moreover, the optic axes of quartz are oriented in a similar manner. The quartz grains are irregular and are not flattened or elongated in any direction bearing a constant relation to the optic axis. The arrangement of the quartz, therefore, is undoubtedly not the result of magmatic flow.

Furthermore, the optic axes of the quartz grains form a girdle normal to the linear direction in the rock, and, from studies of metamorphic rocks, this is assumed to mean rotation of the grains in a plane normal to the linear direction. If the orientation of the quartz is a result of post-magmatic deformation, then since the orientation of the biotite and plagioclase is of the same type as, and is correlatable with, the quartz orientation pattern, may not the arrangement of all of these minerals be the result of deformation following solidification of the tonalite?

(2) Two lines of evidence favor the hypothesis that the gneissosity was developed following the solidification of the tonalite: (a) The orientation patterns of the minerals can be explained by deformation following solidification of the rock. Much is yet unknown about the process of orientation of minerals during metamorphism, but patterns similar to those presented here-in have been found in metamorphic rocks. In the diagrams of the quartz, a girdle has developed normal to <u>b</u>, and <u>s</u>-surfaces occur inclined to the gneiss planes at angles varying between 30 and 70 degrees. This is interpreted to mean that during deformation the quartz grains rotated about an axis and also glided along lines which lay in the plane of rotation. A similar movement on the part of the plagioclase and biotite produced the observed plaiting structure which is a dimensional orientation of the grain fabric. (See p.57). In most of the biotite and plagioclase diagrams a strong concentration of the poles to basal planes and 010 faces, respectively,

occurs at c; or in other words, a large proportion of the grains lie in the plaiting surface. It is to be expected that during rotation such platy minerals would be aligned parallel to the surface bisecting the shear directions (See p.57). The elongation of the plagioclase and hornblende parallel to b is also compatible with this hypothesis, for in tectonites the direction of elongation is most commonly normal to the girdle of quartz and biotite.

The inclusions possess the same type of mineral orientation as the tonalite (Diagrams 21 and 22) but this is not necessarily proof that the orientation pattern was imposed upon the rock following solidification.

(b) In support of the theory that minerals in an igneous rock have in some cases been oriented by post-magmatic deformation, we have the results of petrofabric studies made on other intrusive bodies. Johs (1933) examined a quartz porphyry which possesses a linear structure paralleling that in the mica schist with which it is in contact. A quartz girdle normal to the linear direction is present in both rocks. He concluded that deformation had played some part in the orientation of the minerals of the quartz porphyry. A granite, which is largely massive, was studied by Maroschek (1933). Even though no linear direction in the rock was observable, girdles of quartz were found to occur, and these correlated with the joint pattern in the rock in the same manner as in the case of ordinary tectonites. In some of the gneisses studies by Sahlstein (1935) girdles of quartz were found to occur oriented at right angles to the gneiss planes and to the linear direction in the rock, a case similar to that of the Val Verde tonalite.

Two lines of evidence oppose the hypothesis that the arrangement of the minerals in the tonalite was produced entirely following solidification: (a) Since the inclusions are notably flattened parallel to the gneiss planes, the development of the gneissosity and the orientation of the inclusions probably occurred during the same stage in the history of the tonalite mass. If stresses in the solid rock were sufficient to flatten an inclusion several feet in diameter, evidences of cataclasis and recrystallization should be much more evident than they are. If the inclusions were flattened parallel to the gneiss planes during intrusion, then the gneiss planes must also have been formed then. (b) The gneiss planes dip steeply near the schist contact, but flatten out to the east. This flattening of the gneiss planes could be explained, if they are the result of magmatic flow, by a horizontal thrusting movement of the magma from the east during intrusion; but the structure is difficult to explain on the basis of post-magmatic deformation since the b tectonic axis is parallel to the dip.

(3) A third hypothesis on the origin of the gneissoid structure in the tonalite explains the structure as having been produced by a combination of flow before, and deformation following, solidification. The development of the gneissosity according to this postulate would be as follows: During the intrusion gneiss planes were developed to some extent parallel to the schistosity in the country rock, and the inclusions were flattened parallel to this gneissosity. Deformative stresses

which may have been active in the region during the intrusion, took effect on the tonalite after it possessed sufficient rigidity to transmit differential stress. The stresses were of such a nature that the rock tended to be sheared parallel to the strike of the contact, with resulting rotation of the minerals; and the existing gneiss planes in the rock influenced the attitude of the plane of rotation of the minerals to the extent that this plane was maintained normal to the gneiss planes. The gneiss planes were transformed into plaiting surfaces by the rearrangement of the mineral grains. The present linear direction in the rock, as exhibited by plagioclase and hornblende, may be parallel to that developed during magmatic flow, or may have been entirely produced during deformation and so may not be the same as the original flow direction. Since the 010 faces of the plagioclase have been arranged to some extent by apparently the same forces that produced the orientation of the quartz, the a-axes may also have been rearranged.

Conclusion

On the basis of the above discussion, the writer concludes that the gneissosity developed in the tonalite as a combined result of flow before complete solidification, and of post-magmatic deformation. The s-surfaces and girdles may have been produced before the magma was completely crystallized, but it is difficult to understand how shear planes could have developed if the rock were not essentially solid. The actual movement of the crystals within the mass and the strain producing the movement may have been small. The linear direction now visible within the rock may or may not have been the original flow direction.

The geologic history of the district may be divided into four stages: (1) During the Triassic Period arenaceous sediments were deposited. (2) Later in the Messozoic, after burial, consolidation, and recrystallization of the sedimentary series, the beds were folded along axes striking northwest. Shearing parallel to the beds accompanied the folding, rotating the grains about the tectonic axis. (3) Following the folding of the schist and before the lower Cretaceous, magma was injected into the schist and the partially crystalline magma assumed a flow structure parallel to the schistosity. Either before the rock had become entirely crystalline, or following this stage, shearing parallel to the strike and dip of the schistosity and gneissosity occurred. This altered the orientation of the quartz and biotite in the schist to a small extent, and effected a new orientation for the minerals in the tonalite. Movement along the strike slip faults which occur within and bordering the Perris Block (See pls. 2 and 5), may have been associated with the strike shearing in the schist and tonalite. (4) The history of the Perris Block during the tertiary period is incompletely know. At present the block appears to be down-dropped with respect to the district to the north, west, and east, and it also is apparently tilted downward toward the east.

PLATE 10

Fig. 1. Diagram of poles to basal planes of 308 biotite grains in sp. 12012 of quartz-biotite schist. Contours 5,4,3,2,1%.

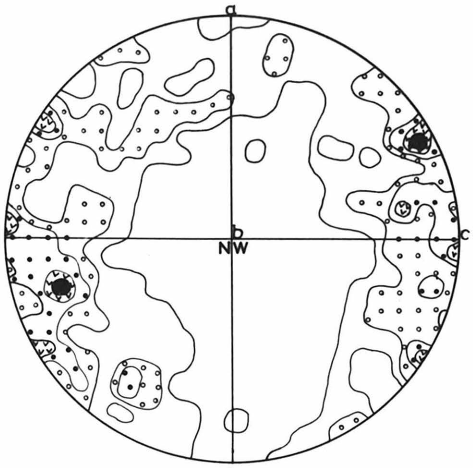
2. Diagram of optic axes of 183 quartz grains in sp. of fig. 1. Contours 5,4,3,2,1%.

3. Diagram of poles to basal planes of 343 biotite grains in sp. 12011 of quartz biotite schist. Contours 5,4,3,2,1%.

4. Diagram of optic axes of 319 quartz grains in sp. of fig. 3. Contours 5,4,3,2,1%.

5. Diagram of poles to basal planes of 173 biotite grains in sp. of fig. 3 from section normal to <u>a</u>. Contours 5,4,3,2,1%.

6. Diagram of optic axes of 272 quartz grains from thin section of fig. 5. Contours 5,4,3,2,1%.



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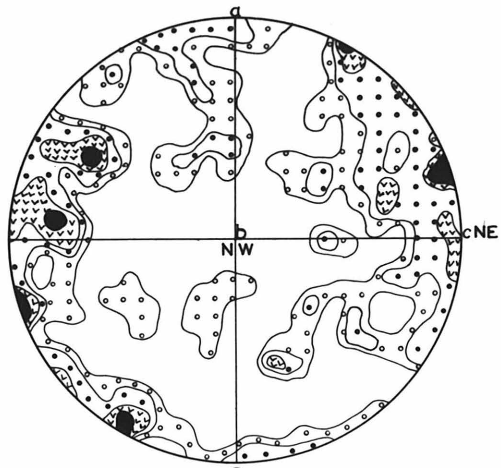

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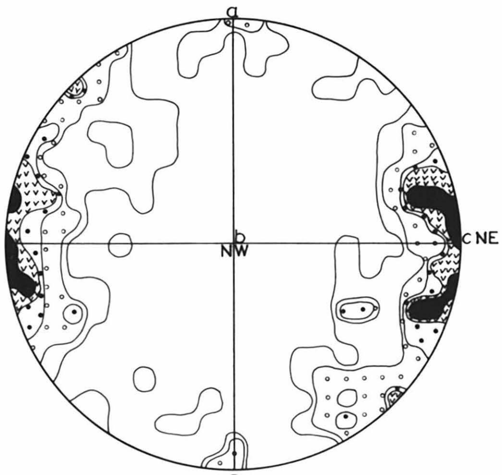

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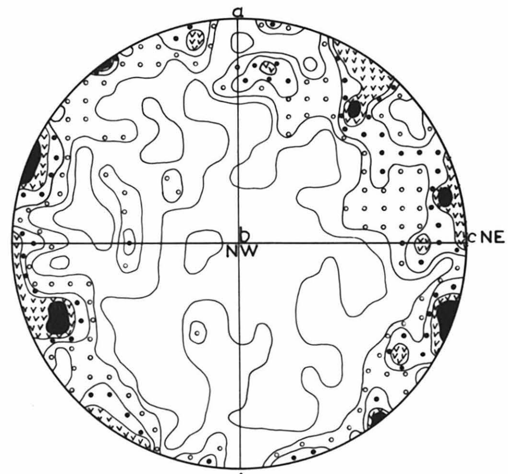

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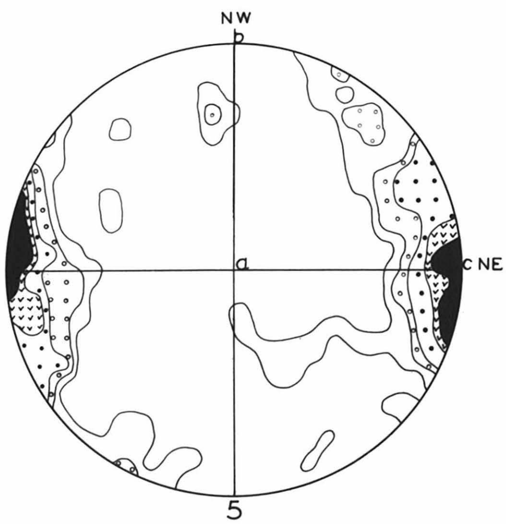

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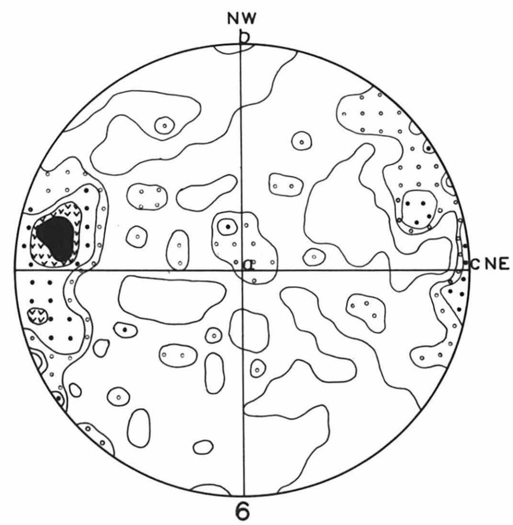

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PLATE 11.

Fig. 7. Diagram of a-axes of 106 andesine grains in sp. 11868 of tonalite. Contours 10,8,6,4,2%.

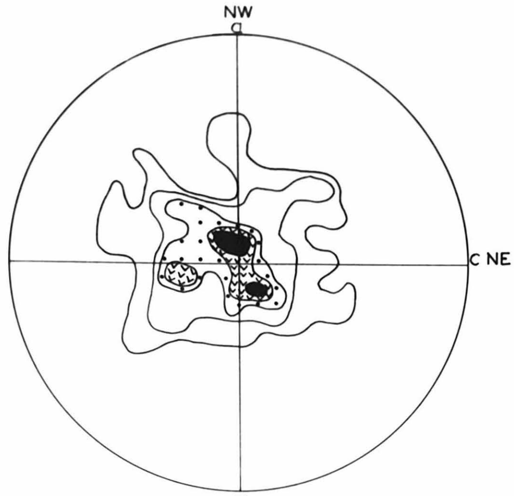
8. Diagram of poles to 010 faces 106 andesine grains in sp. of fig. 7. Contours 5,4,3,2,1%.

9. Diagram of poles to basal planes of 88 biotite grains in sp. of fig. 7. Contours 4,3,2,1%.

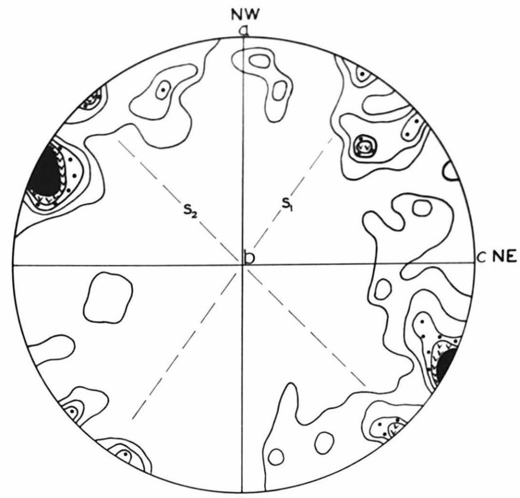
10. Diagram of optic axes of 185 quartz grains in sp. of fig. 7. Contours 5,4,3,2,1%.

11. Diagram of optic axes of 264 quartz grains in sp. of fig. 7 from section normal to <u>a</u>. Contours 4,3,2,1%.

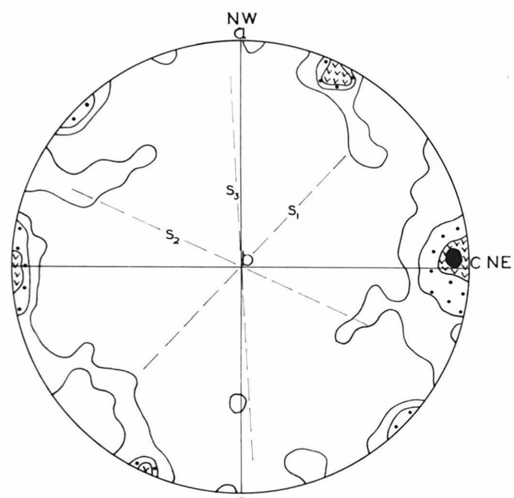
12. Rotation of diagram in fig. 11 90° about <u>c</u>.


NW
a
c NE

7


NW
a
s_2
s_1
b
c NE

8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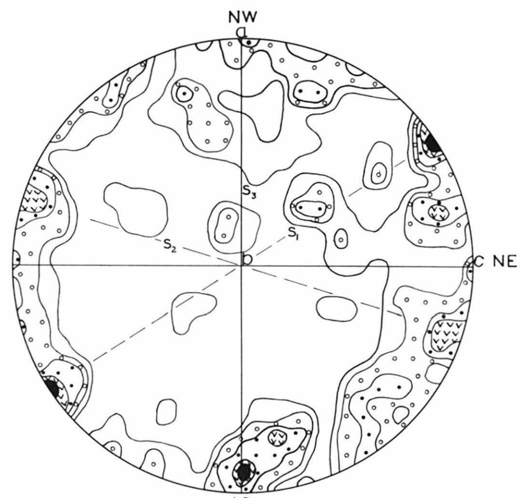
a
s_3
s_1
s_2
b
c NE

9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a
s_3
s_2
s_1
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c NE

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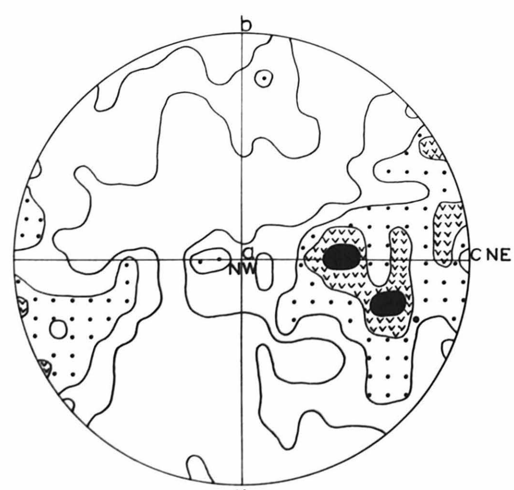
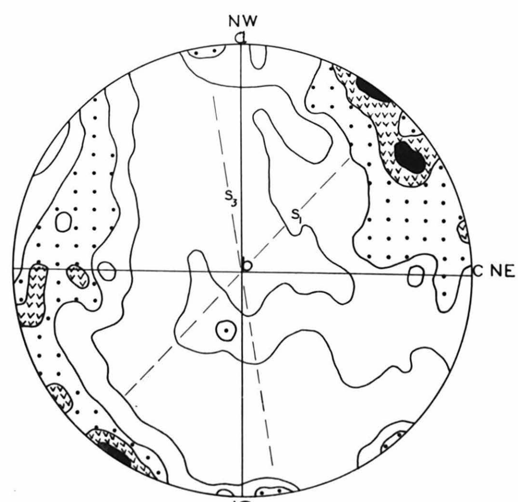

b
a
NW
c NE

11


NW
a
s_3
s_1
b
c NE

12

PLATE 12

Fig. 13. Diagram of a-axes of 130 andesine grains in sp. 11870 of tonalite. Contours 12, 10, 8,6,4,2%.

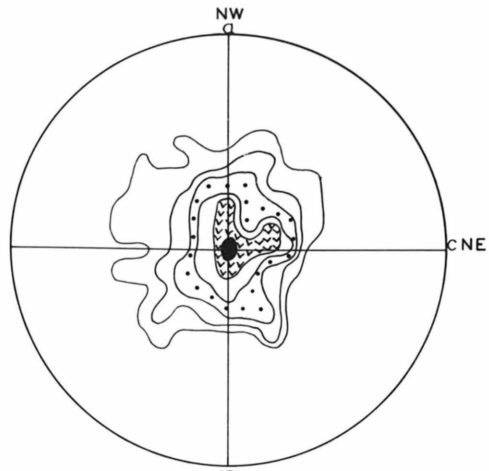
14. Diagram of poles to 010 faces of 130 andesine grains in sp. of fig. 13. Contours 10,8,6,4,2%.

15. Diagram of poles to basal planes of 69 biotite grains in sp. of fig. 13. Contours 4,3,2,1%.

16. Diagram of optic axes of 163 quartz grains in sp. of fig. 13. Contours 4,3,2,1%.

17. Diagram of poles to basal planes of 161 biotite grains in sp. 12022 of tonalite. Contours 3,2,1%.

18. Diagram of optic axes of 243 quartz grains in sp. of fig. 17. Contours 3,2,1%.



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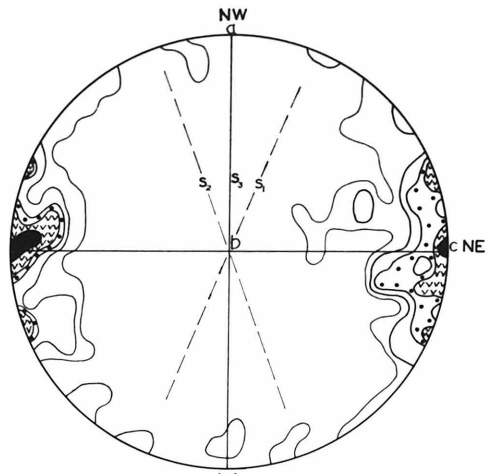

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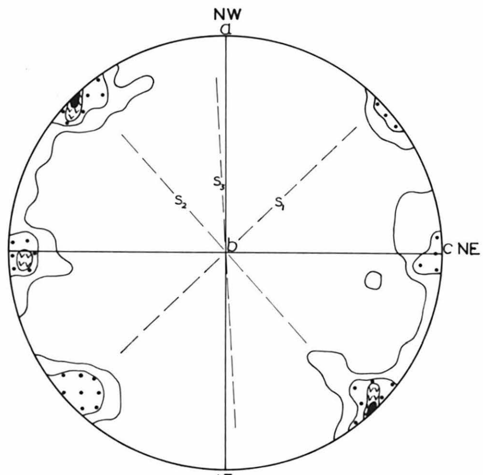

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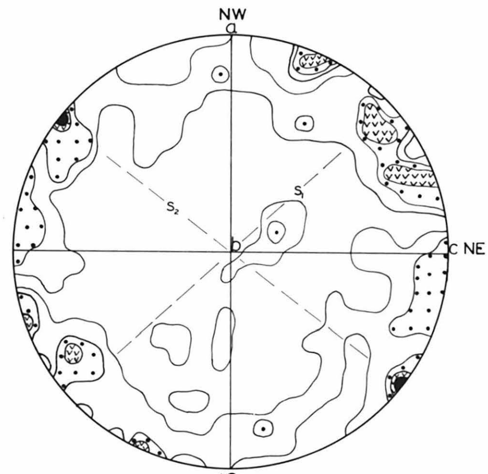

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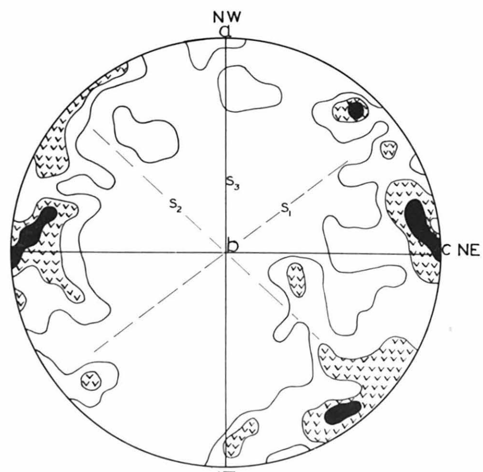

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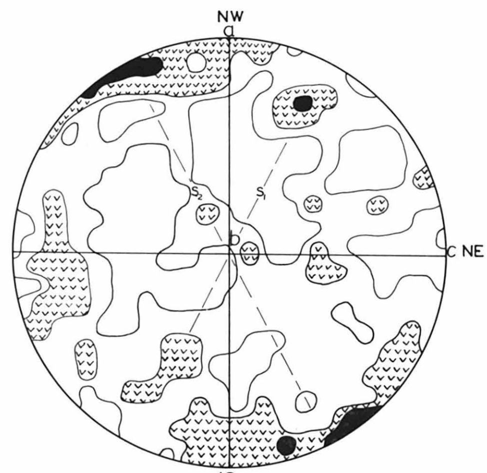

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PLATE 13.

Fig. 19. Diagram of poles to basal planes of 165 biotite grains in sp. 11982 of tonalite. Contours 4,3,2,1%.

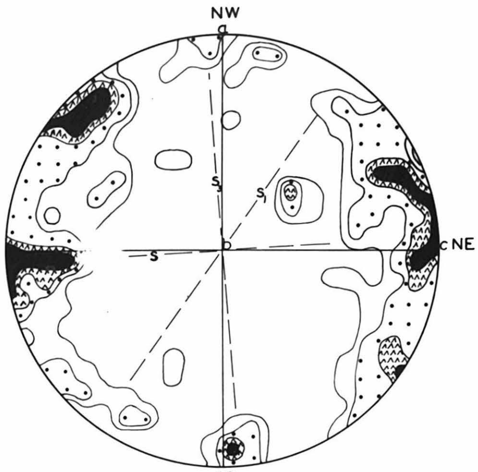
20. Diagram of optic axes of 260 quartz grains from sp. of fig. 19. Contours 4,3,2,1%.

21. Diagram of poles to basal planes of 143 biotite grains in sp. F.36 of an inclusion in the tonalite. Contours 6,4½,3,1½%.

22. Diagram of optic axes of 108 quartz grains in sp. of fig. 21. Contours 8,6,4,2%.

23. Diagram of orientation of s-surfaces of biotite in the nine specimens of tonalite examined.

24. Diagram of orientation of s-surfaces of quartz in nine specimens of tonalite examined.



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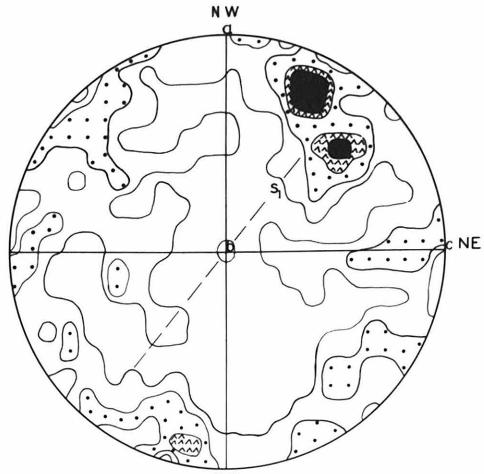

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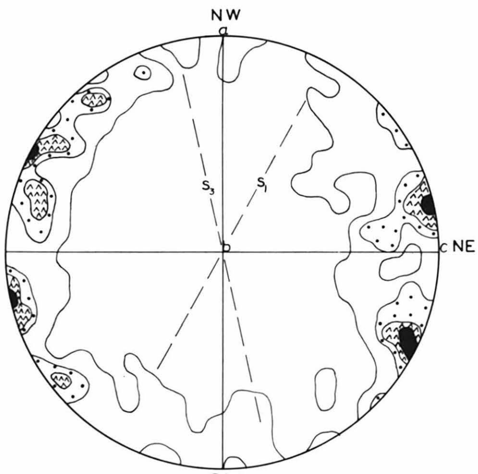

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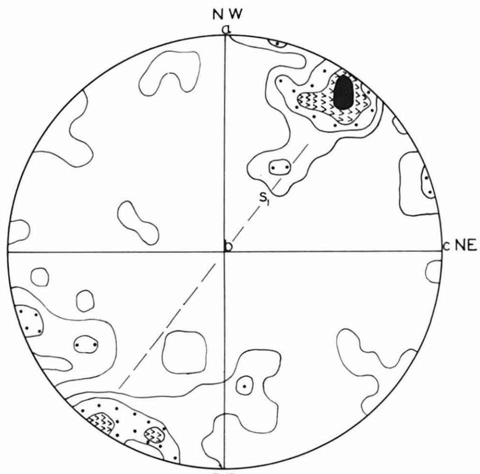

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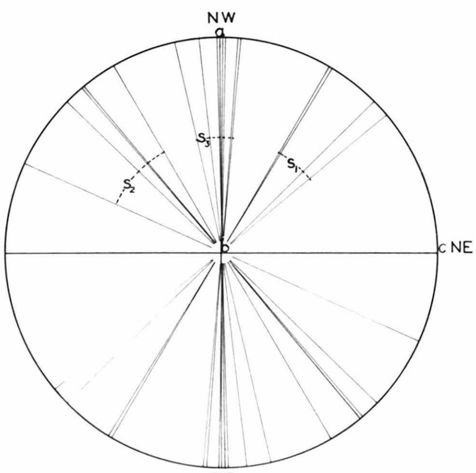

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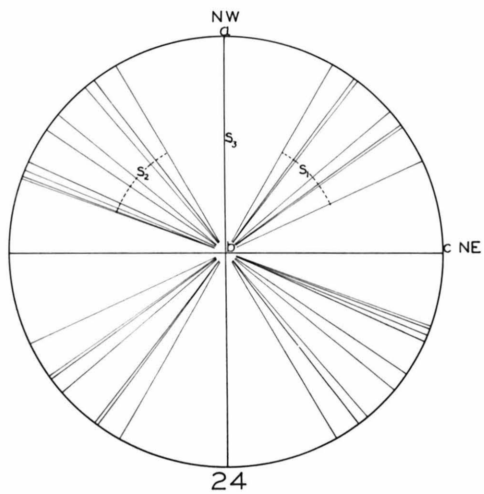

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