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DARK INCLUSIONS IN A TONALITE OF SOUTHERN CALIFORNIA*

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Dark inclusions in granitic rocks have long been a source of controversy, and it was with the hope of shedding light on the mooted question of their origin that the present inquiry was undertaken. While mapping the petrology of the San Luis Rey quadrangle in Southern California, Professor E. S. Larsen realized the suitability of that area for a study of inclusions. With the aid of his excellent map of the various bodies of intricate pattern, the work was greatly facilitated.

Utmost thanks are due to Professor Larsen for his helpful advice in both field and laboratory, and to Professor Charles Palache for a generous grant for field expenses from the Holden Fund of the Department of Mineralogy of Harvard University.

The Peninsular Range of Southern California is made up largely of a composite batholith of Jurassic age intruded into schists and quartzites that are metamorphosed and folded Triassic sedimentary rocks. The succession of intrusions has proceeded in the normal order with gabbro followed by increasingly more silicic rocks. The first intrusive is locally called the San Marcos Mountain gabbro, and is followed by a quartz diorite known as the Bonsall tonalite. Several more silicic rocks followed the tonalite. Although inclusions are to be found in all the rocks of this igneous sequence, the Bonsall tonalite carries them most abundantly, and, consequently, work was largely confined to this body.

THE SAN MARCOS MOUNTAIN GABBRO

Since in the opinion of the writer, most of the inclusions of the Bonsall tonalite were derived from the San Marcos Mountain gabbro, it seems well to preface the discussion of inclusions with a brief statement concerning the gabbro.

* A portion of a thesis submitted to Harvard University in partial fulfillment of the requirements of the doctorate.

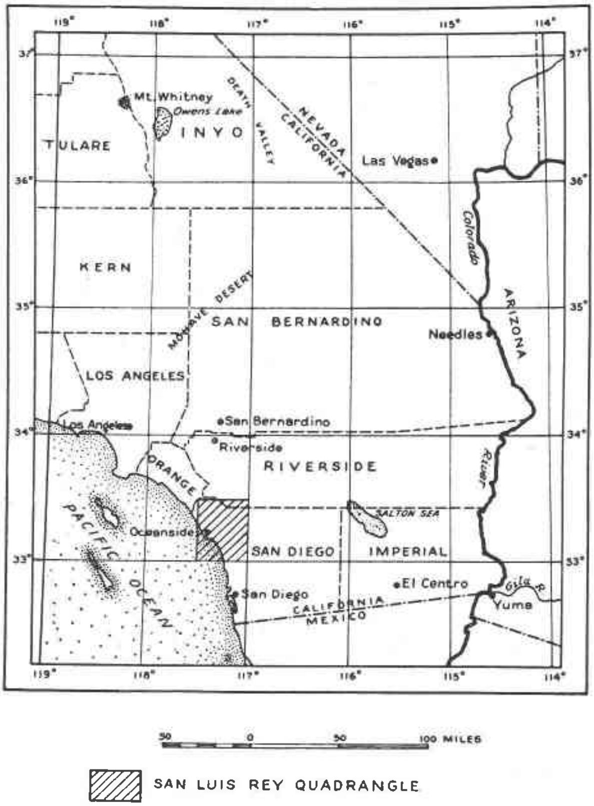

FIG. 1. Location of the San Luis Rey quadrangle.

According to Miller,[1] "The typical San Marcos Mountain gabbro is a medium-grained, dark gray, plutonic rock composed essentially of plagioclase feldspar and pyroxene. More or less uralitic hornblende is usually present." In some localities the pyroxene has been nearly completely altered to hornblende, and in these cases the large hornblende crystals poikilitically inclose the other mineral constituents.

Miller recognized three types of gabbro depending on the presence of minor constituents. These types are: first, the true gabbro carrying only pyroxene and hornblende as dark minerals; second,

[1] Miller, F. S., Petrology of the San Marcos Mountain Gabbro, San Luis Rey Quadrangle, California: *Thesis*, Ph.D. Harvard University, 1934.

gabbro carrying quartz and biotite; and, third, gabbro in which olivine occurs to the exclusion of quartz and biotite. Labradorite feldspar is the most abundant constituent of all the types. However, in the olivine-bearing rocks, the labradorite carries cores that have a composition between bytownite and anorthite. Frequently this calcic feldspar is present to the exclusion of the labradorite.

The Bonsall Tonalite

The Bonsall tonalite derives its name from the small village of Bonsall located slightly west of the central portion of the San Luis Rey quadrangle. Its boundaries, like those of the other igneous bodies of the area, are extremely irregular. Altogether the Bonsall tonalite underlies approximately one hundred square miles in the San Luis Rey quadrangle, thus making it the largest single unit of plutonic rock.

Marginal Assimilation. Field evidence in several instances points to the fact that the original differences in composition of the Bonsall tonalite have been emphasized locally by marginal assimilation at the contact of the San Marcos Mountain gabbro. On the geologic map of the San Luis Rey quadrangle, these two rocks are shown in contact with one another for several miles, but, in spite of this fact, it is impossible to trace the contact for even one hundred yards. The reason for this is that there is apparently no true contact between the two.

However, there are places where one can cross from one body to the other and continue to observe bed rock. If at one of these favored localities a traverse is made from tonalite to gabbro, the rock gradually becomes increasingly darker. One may start in rock that is unquestionably tonalite and as it gets darker it still retains the properties of the tonalite, but at the same time begins to resemble the gabbro. Over a distance of several hundred yards, therefore, there is a transition zone of intermediate rock, a hybrid, having been formed by the union of the two major intrusives. Such a complete gradation as exists points to a mutual assimilation. It seems not beyond the realm of possibility to postulate that after the gabbro had attained its present position in the earth's crust, but before it was completely solidified, the Bonsall tonalite was intruded. With one rock in a semi-solidified condition, and the other in a molten state a certain amount of mechanical commingling could take place with subsequent diffusion and chemical reaction.

Such a set of conditions one would expect to give rise to a hybrid rock at the contact of the two intrusives.

Conditions similar to these just noted are not uncommon in the literature. Harker[2] described hybrid rocks from Scotland formed in a similar manner. Likewise, Clapp[3] has attributed the origin of essexite to the commingling of two magmas. Goodspeed[4] also describes satellitic phases of a granite mass in Oregon due wholly or in part to hybridism. Other examples are common, and the amount of hybrid rock formed in most instances is considerably more than in the case under discussion.

Petrographic Description. The Bonsall tonalite is a medium-grained plutonic rock presenting in the outcrop a color of varying shades of gray which distinguishes it in the field from the other intrusives. When examined under the microscope, this rock shows a considerable variation in the relative proportions of its mineral constituents. Nevertheless, the composition does not vary between wide enough limits to permit many specimens to fall outside the restricted range of tonalite.

Zoned plagioclase, in thin tabular grains flattened parallel to (010) and slightly elongated along the *a*-axis, makes up at most localities well over 50% of the rock. Its average composition varies from An_{32} to An_{49}, but is usually about An_{40}. Quartz and orthoclase are interstitial to the plagioclase and dark minerals. The former makes up from 20% to 25% of the rock, while the latter in most places makes up less than 5%. At one locality, however, a light-colored tonalite carries 15% orthoclase. Hornblende and biotite each make up about 10% of the average rock. Their range in optical properties are:

	Hornblende	*Biotite*
Sign	(—)	(—)
2V	60°–75°	0°–5°
Orientation	$Y=b$, $Z\wedge c$ 20°–27°	$Y=b$, $X\wedge c$ 2°
Dispersion	$r>v$	
Pleochroism	X=pale yellow	
	Y=olive green	
	Z=deep green	
Indices	$\alpha=1.651$–1.671	$\alpha=1.605$–1.625
	$\beta=1.663$–1.683	β and $\gamma=1.642$–1.661
	$\gamma=1.673$–1.690	

[2] Harker, Alfred, The Natural History of Igneous Rocks, *New York*, **1909.**

[3] Clapp, C. H., Geology of the Igneous Rocks of Essex County, Massachusetts: *U. S. Geol. Survey, Bull.* vol. **704,** 1921.

[4] Goodspeed, G. E., Recrystallization of Xenoliths at Cornucopia, Oregon: *Bull. Geol. Soc. Am.*, vol. **42,** 1931.

The above data indicate a maximum difference in the proportion of the iron and magnesia end members of about 20% for the amphibole, and less than 15% for the biotite.

Pyroxene is a mineral absent from the Bonsall tonalite except at those places where there is a transition into the older gabbro. Here it is obvious that the pyroxene has been contributed to the hybrid rock by the gabbro.

CHEMICAL COMPOSITION. Two chemical analyses of the Bonsall tonalite were made, the results of which are given below. Analysis A is of rock that can be considered typical, and came from a locality two miles northeast of the San Luis Rey Mission. Analysis B is that of a light-colored tonalite that represents the most extreme silicic variation.

CHEMICAL ANALYSES,* NORMS AND MODES OF THE BONSALL TONALITE

	Chemical analyses	
	A	B
SiO_2	64.86	71.06
TiO_2	0.55	0.56
Al_2O_3	17.46	14.52
Fe_2O_3	1.80	1.39
FeO	2.80	1.93
MnO	0.30	0.02
MgO	1.36	0.36
CaO	5.26	3.10
Na_2O	3.38	3.39
K_2O	1.64	3.08
H_2O	0.50	0.34
P_2O_5	0.05	0.03
	99.96	99.68

* Analyses were made by F. A. Gonyer.

	Norms			Modes	
	A	B		A	B
Quartz	24.36%	31.74%	Quartz	26%	30%
Orthoclase	9.45	18.35	Orthoclase	4	15
Albite	28.82	28.82	Plagioclase	51 An_{41}	40 An_{32}
Anorthite	26.13	15.01	Biotite	13	7
Corundum	0.61	— —	Hornblende	6	8
Hypersthene	6.17	2.22			
Magnetite	2.55	2.09			
Ilmenite	1.06	1.06			
	99.15	99.29			

INCLUSIONS IN THE BONSALL TONALITE

NOMENCLATURE. Because of the widespread distribution of dark inclusions in granitic rocks, much has been written in recent years of their occurrence in various parts of the world. As a result, many terms have been introduced to denote various types observed by different investigators. Lacroix[5] was the first to make a formal classification and assign various names to those formed in different ways. However, few words have been introduced into the English literature that correspond to Lacroix's terms, and, due to the different English connotation, his cannot be taken directly.

Several English terms have been suggested to apply to specific types of inclusions. In 1900 Holland[6] proposed the term "autolith" to be applied to well-formed inclusions that have had their origin within the magma in contradistinction to xenolith or fragment foreign to the rock. "Basic concretion," and "basic segregation" have also been suggested, but their genetic implications, as in the case of autolith, prevent their general use.

In the present discussion, therefore, because of the short-comings of other words proposed, *inclusion* with necessary modifiers will be used. In the following pages "reaction inclusion" will be used in referring to the most abundant type in the Bonsall tonalite. The term is not considered a particularly suitable one, but it does convey the idea that is brought out in the following discussion; namely, that the inclusions are not segregations, but are foreign material and owe their present condition to reaction with the magma.

SPACE RELATIONS OF THE INCLUSIONS. Although the number of reaction inclusions is fairly uniform throughout the tonalite, there is a considerable variation in their abundance locally. At some places there are patches embracing a few square yards where the included material may make up as much as 30% of the volume of the rock, while at other places inclusions may be almost entirely wanting. It is seldom, however, that one finds even a single exposure without a few. Figure 2 shows the appearance of outcrops where inclusions are rather abundant. The large number of them is likely to lead one to over-estimate their volume percentage of the rock. The inclusions in figure 2A were found to make up 8%, and those in figure 2B 10% of the rock by volume.

[5] Lacroix, A., La Montagne Pelee et ses Eruptions, *Paris*, **1904.**

[6] Holland, Sir Thomas, The Charnockite Series: *Mem. Geol. Survey India*, vol. **28,** pp. 212–219, 1900.

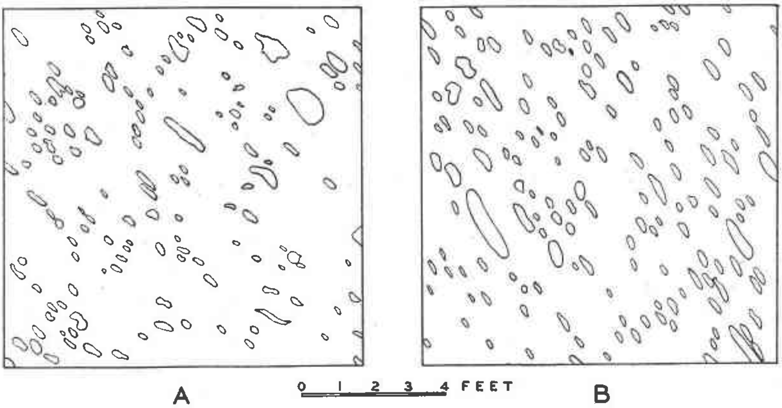

FIG. 2. Appearance of outcrops of Bonsall tonalite with abundant reaction inclusions.

The reaction inclusions show a rather small variation in size as will be seen from figure 2. The maximum dimension is, in general, from ten to twelve inches, but in extreme cases reaches as high as twenty-four inches or as low as one. However, because of the variation in shape, it is the volume rather than maximum dimension that should be considered in comparing inclusions.

SHAPE AND RELATION TO ROCK STRUCTURE. The shape of the reaction inclusions varies from a form approximating a sphere to a much flattened ellipsoid of revolution. If flattened inclusions are exposed on a surface cutting their long dimension, they appear as long narrow strips ranging up to two feet in length and down to $\frac{1}{4}$ inch in width; if exposed on a surface parallel to their long dimension, they appear as large disks with rounded outline. Moreover, wherever reaction inclusions are flattened, they show a nearly perfect parallelism, with the individual rarely varying more than a few degrees from the general strike. Not only do the inclusions show a parallel orientation, but the tabular and elongated minerals of the host rock, especially feldspar and hornblende, possess a definite alignment giving the rock a decided flow structure.

This flow structure is, in general, well marked throughout the whole mass of Bonsall tonalite, but locally becomes very poor and in places is entirely lacking. The reaction inclusions at such localities show no orientation, and are more or less rounded and equidimensional. Their shape, therefore, is closely related to the flow struc-

FIG. 3. A boulder of Bonsall tonalite showing on one face the streaked nature of the reaction inclusions; and on the other face, at right angles, the flattened character.

ture, which in turn represents the relative amount of movement of the magma.

The flattened nature of the inclusions where the movement has been great and the spheroidal character where movement was small or lacking point rather definitely to the fact that the inclusions were not rigid bodies, but must have been plastic during the emplacement of the rock. Good evidence of the plastic nature of the reaction inclusions, during at least the final movement of the magma, is shown at a locality where flow structure is pronounced and the inclusions greatly flattened. The flow structure, that is unusually constant in its direction, turns to bend around a large quartzite xenolith; and a tabular inclusion that lies within a few inches of the xenolith likewise bends to faithfully follow the flow lines.

STREAKING AND ITS RELATION TO REACTION INCLUSIONS. Not infrequently throughout the tonalite where there has been considerable movement there are streaks of dark rock alternating with lighter ones. There seems to be fairly good proof that these streaks are genetically related to the inclusions. The best evidence pointing

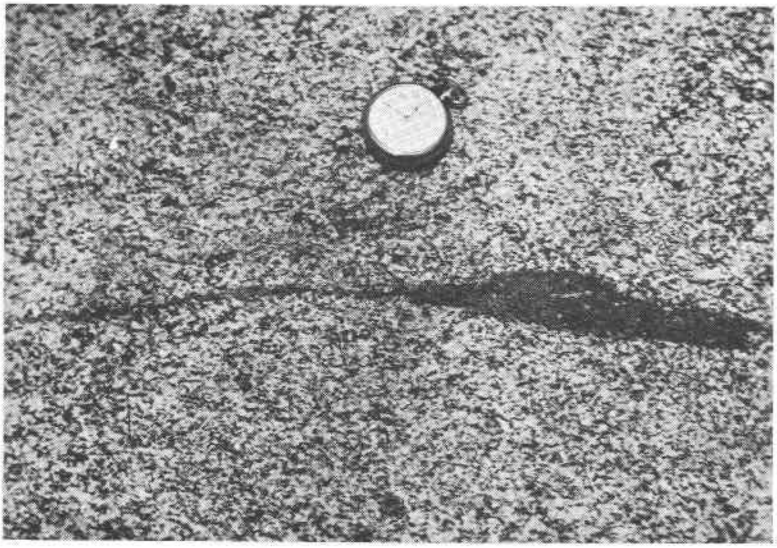

FIG. 4. A reaction inclusion being drawn out into a streak.

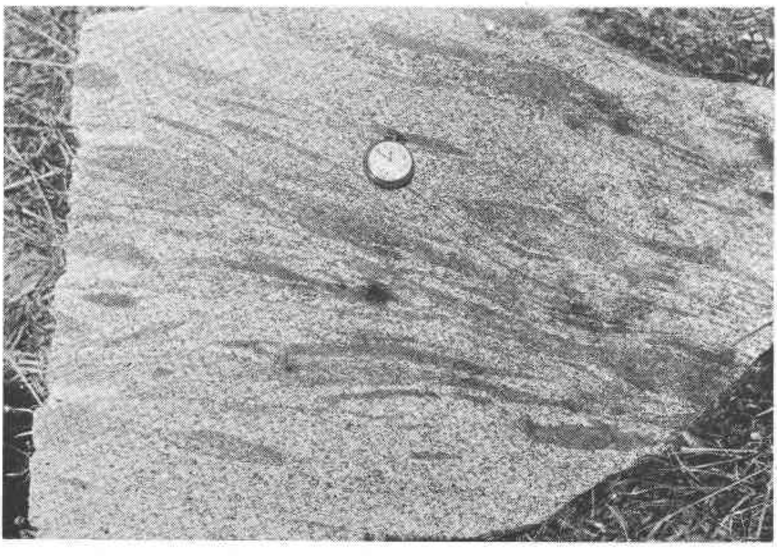

FIG. 5. Reaction inclusions being drawn out, and merging to form long streaks.

in this direction is the nature of some of the inclusions themselves, for not infrequently a definite inclusion can be found grading into or being drawn out into a streak. Where streaking is well developed, very few, if any inclusions are present, which points to the fact that inclusions that were there have been drawn out to form the dark streaks.

Another line of evidence substantiating the belief that the streaking is formed from inclusions is the very nature of the material itself. The texture of the inclusions is characteristic, being much finer and more compact than that of the host rock. Likewise, the mineral composition differs from that of the tonalite. Both of these properties are preserved to a large extent in the dark streaks. Thus streaking, as well as the flattening of inclusions, indicates that the plastic nature was acquired after the included material reached essentially its present location in the rock mass, and the last movement of the magma is recorded in its shape. If the inclusions were plastic during much movement, they would have undoubtedly lost their identity.

Regional Structure. By means of the well-oriented minerals and inclusions in the Bonsall tonalite, the regional structure of the whole mass was determined. The method employed by Cloos[7] was used in part but not in its entirety, for several of the features Cloos deems necessary were not found everywhere. However, the strike and dip of the plane of flow was taken on every available exposure, and the results are plotted in figure 6. It was found that in general the strike of the flow structure is about N 65° W, but locally varies considerably from this direction.

The attitude of the plane of flow is in most cases vertical, but occasionally dips slightly to the south. This northwest-southeast direction corresponds closely to the strike of the folded and metamorphosed Triassic rocks of this section of Southern California. It may well be that the northeast-southwest pressure that caused this folding was not completely relieved at the time of intrusion, but governed the movement of the magma.

It is interesting to note the effect of the older bodies of schist and gabbro on the direction taken by the flow lines. The best illustration of this is shown toward the eastern edge of the map. Here a long narrow strip of schist extends for several miles in approxi-

[7] Cloos, H., Tektonik und Magma, Band I, **1922**; Band II, **1924**; Band III, **1927**, *Abh. d. Pr. Geol. Landesanst. H. F.*, vol. **89**, Berlin.

mately a north-south direction. The flow lines of the tonalite on both sides of the strip of schist turn to parallel faithfully the contact.

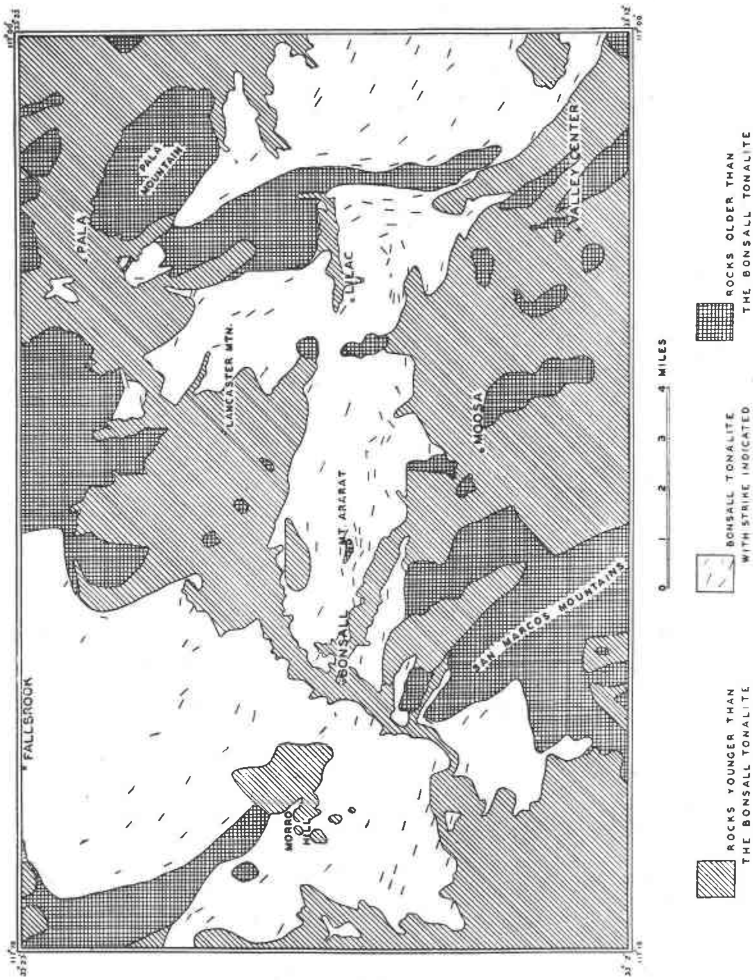

FIG. 6. The structure of the Bonsall tonalite.

PETROGRAPHIC DESCRIPTION OF THE REACTION INCLUSIONS. The average inclusion of the reaction type presents in the hand specimen a dark gray to black color sharply contrasted with the light gray of the enclosing tonalite. The boundaries between the two appear sharp to the unaided eye, but with a hand lens an occasional mineral grain can be seen to penetrate from the host into the inclusion. In a few cases, the contacts between the inclusion and tonalite are not sharp but show a gradual merging of the two. The texture of the inclusions is so fine grained that it is only with difficulty that one is able to distinguish individual minerals. However, hornblende, biotite, and occasionally feldspar are sometimes found in grains large enough to be recognized in the hand specimen.

Microscopically the reaction inclusions are all very similar to one another with a uniformly fine grain and hypidiomorphic texture. The principal minerals listed in the order of their abundance are: plagioclase, hornblende, biotite, quartz, orthoclase, and pyroxene. The first three make up the bulk of the inclusions and are present in all, while the last three are found only in small amounts and frequently may be lacking altogether.

Tabular plagioclase feldspar with a composition of about An_{45} is the chief constituent of the reaction inclusions. It is frequently zoned with only a small difference in composition between the core and rim, but occasionally the inner zone is found to be near the center of the labradorite group. One of the most outstanding features of the inclusions is the presence in many of them of zoned feldspar grains larger than the average with irregular and embayed cores with a composition of about An_{90}. These calcic cores are uniform in composition and sharply separated from the outer zones that are similar to the other feldspar. They are conspicuous in plane polarized light due to their high relief, and between crossed nicols due to their yellow interference color.

These conspicuously zoned feldspars are common constituents of many of the inclusions. In individual cases they may make up as much as 5% to 10% of the specimen, while in others they may be represented by one or two grains, or may be lacking altogether. Several scores of thin sections were examined that showed both the inclusion and the adjacent host rock; and, whenever this unusual type of feldspar was found, it was confined to the inclusion.

Both quartz and orthoclase are present in only small amounts in the reaction inclusions, and together rarely make up over 3 or 4%. They are invariably found together interstitial to the plagioclase and dark minerals.

Hornblende in small prismatic grains is the principal dark mineral of the reaction inclusions, and is present in amounts varying from 20% to 45%. In addition to these small prisms, there are frequently larger anhedral grains that may inclose the feldspar poikilitically. Biotite is found in the inclusions in amounts varying from 10% to 20%. It is frequently found developing from the hornblende along cleavage planes, and in places completely surrounds it.

Considered from the standpoint of the amount present, pyroxene is one of the rarest minerals in the reaction inclusions, but, nevertheless, it has an important bearing on their origin. In the many thin sections examined, pyroxene was found in only a few. Both augite and hypersthene were present, and in all cases were altering to hornblende. These inclusions both mineralogically and texturally, aside from the small amounts of pyroxene, appear similar to the others; and, if the process of alteration had been complete, they would be identical.

Of the accessory minerals in the reaction inclusions, magnetite is most important and may make up as much as 3% of the rock. Titantite is frequently present in its characteristic wedge-shaped grains. Occasional grains of apatite, zircon, carbonate, allanite, and pyrite were observed, but are unimportant.

Comparison of the Reaction Inclusions with the Bonsall Tonalite

Mineral Comparison. The foregoing petrographic descriptions of the inclusions and tonalite show that they are mineralogically very similar. Plagioclase feldspar, quartz, orthoclase, hornblende, and biotite in varying proportions are constituents of both. The chief variations in the mineral composition are shown in hornblende, biotite, and quartz, the dearth of quartz in the inclusions being balanced by an increase in the hornblende and biotite. Thus, the percentages of the other minerals remain nearly the same in both inclusions and host.

In order to compare the composition of the hornblende of the inclusions with that of the tonalite, the optical properties were determined on hornblende both from the inclusions and the adjacent rock. Determinations were made on specimens from ten separated localities to get a representative comparison. For all the hornblende the following properties were similar: Optically (−), $2V = 60°–75°$, $r > v$; $Y = b =$ olive green, $Z \wedge c\,20°–27° =$ deep green, $X =$ pale yellow. The indices of refraction vary somewhat as shown on the next page.

Inclusions	Tonalite
$\alpha=1.640–1.664$	$\alpha=1.651–1.671$
$\beta=1.652–1.669$	$\beta=1.663–1.683$
$\gamma=1.662–1.682$	$\gamma=1.673–1.690$

These data show a close relation between the various hornblendes, but indicate that the hornblendes of the inclusions are higher in magnesia and lower in iron than those of the tonalite.

A comparison of the optical properties of the biotite of host and inclusion showed in six out of ten specimens a higher refractive index of the biotite of the tonalite than for the corresponding inclusion. In the remaining four, the biotite of both gave the same refractive indices. Consequently, in the majority of specimens, the biotite of the tonalite is richer in iron than that of the inclusions.

A comparison of the plagioclase feldspar of the inclusions with that of the surrounding tonalite was made on the same specimens as the other mineral comparisons. The composition varied from place to place, but in all cases the feldspar of the inclusions, exclusive of the inner zones rich in anorthite, had essentially the same composition as that of the host rock immediately surrounding it.

Orientation. In order to determine the extent to which mineral orientation was present in the inclusions and compare it with the orientation of the surrounding rock, especially cut thin sections were made. These sections were large enough to include portions of both the inclusion and adjoining tonalite, and were cut at right angles to the flow structure. The method used to orient the mineral grains was that developed by Schmidt and Sander[8] with the use of the Fedorov stage. Each of the contour diagrams, figure 7, represents one mineral in either the inclusion or host rock. All of the counts were made on the same thin section, so that a direct comparison of corresponding minerals is possible.

Diagram A, figure 7, represents the plotting and contouring of 102 plagioclase feldspar grains of the tonalite, while diagram B is the same for 102 plagioclase grains of the inclusion. In both cases the pole of the side pinacoid was plotted, and a comparison of the two diagrams shows a similar orientation. Where possible the grains were further oriented by locating the trace of the basal cleavage. The feldspar grains thus completely oriented brought out the fact that there is not only a sub-parallel arrangement, but also the *a*-

[8] Schmidt, Walter, Tektonik und Verformungslehre, *Berlin*, **1932**; Sander, Bruno, Gefugekunde der Gestein, *Vienna*, **1930**.

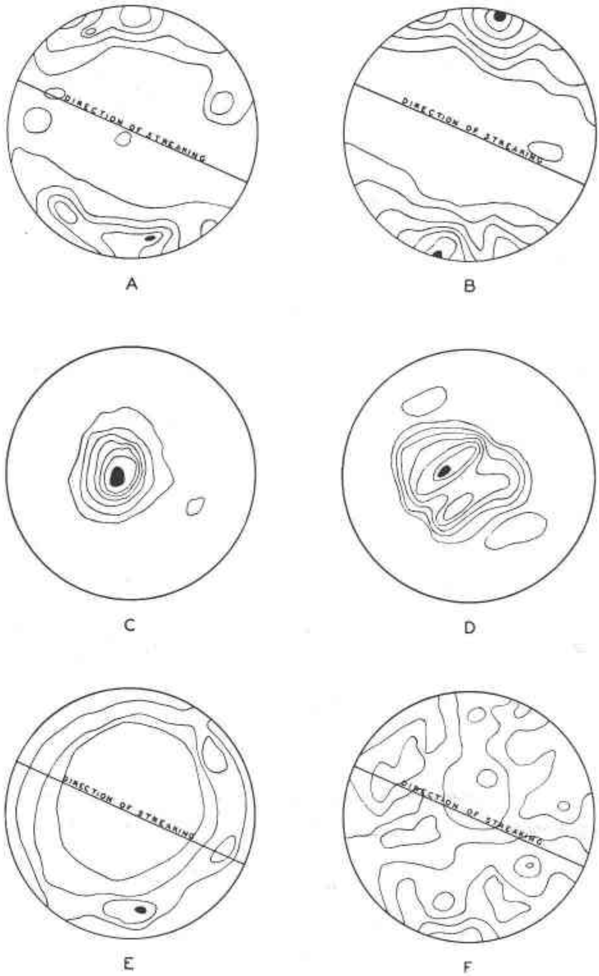

FIG. 7. The above diagrams are the contouring of the projections of minerals from both the tonalite and inclusion.

A. The poles to the (010) face of 102 feldspar grains of the tonalite. Contours equal 7–5, 4, 3, 2, and 1 per cent.

B. The poles to the (010) face of 102 feldspar grains of the inclusion. Contours equal 8–7, 6, 5, 4, 3, 2, and 1 per cent.

C. The *a*-axes of 102 feldspar grains of the inclusion. Contours equal 9–7, 6, 5, 4, 3, 2, and 1 per cent

D. The *c*-axes of 119 hornblende grains of the inclusion. Contours equal 9–7, 6, 5, 4, 3, 2, and 1 per cent.

E. The *b*-axes of 119 hornblende grains of the inclusion. Contours equal 7–5, 4, 3, 2, and 1 per cent.

F. The *c*-axes of 130 quartz grains of the tonalite. Contours equal 3, 2, and 1 per cent.

axes tend to be aligned in a given direction. The a-axis is the direction of elongation, and diagram C brings out the rather perfect arrangement in a linear direction.

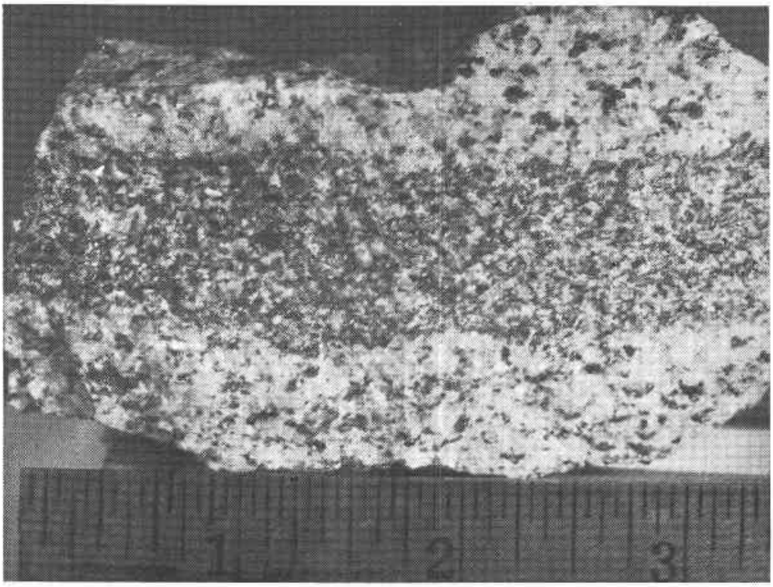

FIG. 8. A section across the flow structure of a flattened inclusion.

The directional orientation is brought out in a similar manner in the projection of 119 hornblende grains of the inclusion shown in diagram D, figure 7. Here the c-axes were plotted, and the grouping of the contours near the center of the diagram again indicates a linear orientation, for the hornblende is elongated parallel to the c-axis.

The hornblende grains were further oriented by plotting the b-axes. Here, as shown in diagram E, figure 7, there is no subparallel arrangement as in the case of the feldspar, for the hornblende grains are too equidimensional in the prism zone.

Diagram F, figure 7, is a projection of the c-axes of 130 quartz grains of the tonalite. The irregularity of the distribution of the contours shows at a glance that there is no systematic orientation. Since the quartz was the last mineral to form, one would not expect it to be oriented, for it crystallized after movement had ceased, and was not thus influenced by flow.

A comparison of diagrams A and B, figure 7, shows that a similar orientation of minerals is present in both the inclusions and tonalite but better developed in the inclusions. The rather perfect linear

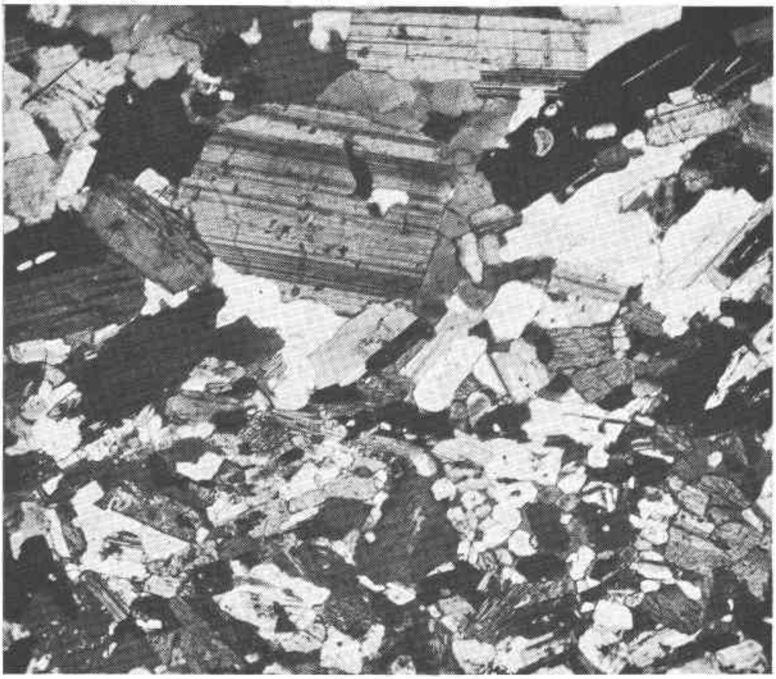

Fig. 9. Photomicrograph of the contact shown megascopically in Fig. 8. This is a portion of the thin section on which the mineral counts recorded in Fig. 7. were made. Crossed nicols, $\times 15$.

orientation of the minerals of the inclusions was not discovered until field work was completed. It may be that the orientation is radial in each individual reaction inclusion, rather than there being a constant direction throughout. Additional work should be done to determine its exact nature.

The Origin of Inclusions

Suggested Methods. There have been several methods suggested by which inclusions comparable to those of the Bonsall tonalite have originated. Chief of these, and apparently the most generally accepted, is that the inclusions are segregations or concretions rich in dark minerals, and that they and the rock surrounding them have come from a common magma. This is the hypothesis advanced by Knopf and Thelen[9] who conclude that, " . . . it is apparent that the inclusions represent basic segregations from the granitic magma, and are characterized by high concentrations of the so-called usual accessories." Grout[10] says that the dark spots are believed to "result from some obscure process of segregation or secretion." Likewise, Bastin[11] described in a porphyritic granite in Maine similar inclusions as "probably the result of combined flowage and basic segregation about many centers." Pabst,[12] in the use of the term "autolith" for the inclusions of the Sierra Nevada, implies that they are genetically related to the enclosing rock. Others, among them Grubenmann[13] and Riegner,[14] aside from stating that the inclusions are related to the enclosing rock, have avoided any further speculation regarding their origin.

Another explanation of the origin of inclusions that was formerly widely held is that of liquation. This idea was suggested by Backstrom,[15] Weed and Pirsson,[16] and Daly,[17] but is no longer considered applicable and has lost favor even among its former proponents.

Still another mechanism by which inclusions of the nature of those under discussion could form is by introduction of foreign material and its partial or complete reaction with the magma. This was suggested by Gilbert[18] in 1906 as the origin of dark inclusions

[9] Knopf, A., and Thelen, P., Sketch of the Geology of Mineral King, California: *Univ. of California Pubs. Geol.*, vol. **4,** 1905.

[10] Grout, F. F., Probable Extent of Abyssal Assimilation: *Bull. Geol. Soc. Am.*, vol. **41,** 1930.

[11] Bastin, E. S., The Geology of the Pegmatites and Associated Rocks of Maine: *U. S. Geol. Survey, Bull.* 445, 1911.

[12] Pabst, Adolf, Observations on Inclusions in the Granitic Rocks of the Sierra Nevada: *Univ. of California Publs. Geol.*, vol. **47,** pp. 325–386, 1928.

[13] Grubenmann, U., Über der Tonalitkern des Iffinger bei Meran: *Vierteljahres-schrift d. Naturf. Gesell. Zurich*, vol. **41,** 1896.

[14] Milch u. Riegner, Über Basische Konkretionen und Verwandte Konstitution-facies im Granit von Striegau: *Neues Jahrb. Beilb.*, vol. **29,** 1910.

[15] Backstrom, H., Causes of Magmatic Differentiation: *Journal of Geology*, vol. **1,** pp. 777–778, 1893.

[16] Weed and Pirsson, Geology of the Castle Mountains Mining District, Montana: *U. S. Geol. Survey, Bull.* vol. **139,** 1896.

[17] Daly, R. A., Igneous Rocks and Their Origin, *New York*, **1914.**

[18] Gilbert, G. K., Gravitational Assemblage in Granite: *Bull. Geol. Soc. Am.*, vol. **17,** 1906.

in Kings River County, California. More recently the same conclusion was reached by Nockolds[19] in the granite of Bibette Head, Alderney. Likewise, Thomas and Smith[20] describe inclusions from the Tregastel Plounanach granite, Côtes du Nord, France, where adequate data are at hand to prove that the inclusions are xenoliths of older rock.

The only logical conclusion that can be drawn from the data and observations presented in the preceding pages is in accord with these last-named authors; namely, that the reaction inclusions of the Bonsall tonalite are xenoliths of older rock included in that body, and altered by reaction.

Origin of the Reaction Inclusions. The San Marcos Mountain gabbro is the only granular igneous rock of this province older than the Bonsall tonalite, and hence a likely source of material included in it. Further, microscopic analysis brings out the fact that mineralogically the inclusions resemble the gabbro in several respects. The best evidence is the identification in the inclusions of plagioclase feldspar containing about 90% of the anorthite molecule. This feldspar is an exceedingly uncommon mineral in igneous rock, and is entirely absent from the Bonsall tonalite. However, feldspar of identical composition is common in the older gabbro. Moreover, hypersthene and augite, common minerals of the gabbro are both present in the inclusions but absent from the tonalite. When these facts are considered, the evidence pointing to the gabbro as the source of the reaction inclusions of the tonalite is not only impressive but convincing.

Action of Tonalite Magma on Gabbro Xenoliths. Even though there is adequate proof that the inclusions were contributed by the gabbro, the fact remains that in many ways they do not now resemble it. One can readily understand that with less evidence than is here at hand the inclusions might well be termed "autoliths," for they have so many features in common with the surrounding rock. In order for xenoliths of gabbro to lose their identity to such an extent, considerable reaction must have taken place between the original included rock and the magma. A comparison of the mineral composition of the gabbro and inclusions will serve to bring out the differences between the two and show the changes that have taken place.

[19] Nockolds, S. R., The Contaminated Granite of Bibette Head, Alderney: *Geol. Mag.*, vol. **69,** 1932.

[20] Thomas and Smith, Xenoliths of Igneous Origin in Tregastel Plounanach Granite Côtes du Nord, France: *Quart. Jour. Geol. Soc.*, vol. **88,** part 2, 1932.

The mineral compositions below can be considered typical, although considerable variation may be found in both. From this comparison, it can be seen that the two major differences between the reaction inclusions and the gabbro are found in the composition of the feldspar and in the dark minerals. What would be the effect

Mineral Comparison of Gabbro and Inclusion

	Aver. Gabbro	Aver. React. Incl.
Plagioclase	65% An_{60}	60% An_{45}
Hypersthene	10	trace
Augite	10	trace
Hornblende	13	20
Quartz	locally	3
Biotite	locally	16
Magnetite	2	1

on small gabbro fragments immersed for a long time in the tonalite magma? Would the products of the resulting reaction be quantitatively, as well as qualitatively, sufficient to account for the present differences?

Let us consider the reactions that would take place, following Bowen, on immersing a gabbro inclusion in a magma of the composition of the tonalite. To quote Bowen,[21] " . . . saturated granitic magma cannot dissolve inclusions of more basic rocks. The magma will, however, react with the inclusions and effect changes in them which give them a mineral constitution similar to that of the granite." In the present case, therefore, we would not expect solution but rather a reaction which would render the gabbro minerals similar to those of the tonalite. The high calcic feldspar of the gabbro with An_{75} would be out of equilibrium with the magma and would be made over into feldspar with more albite. Lime would be taken from the inclusions, and soda would be contributed by the magma. If sufficient time were available, the feldspar of the inclusion would eventually be made over so as to be identical with that of the host rock. However, zoning of the feldspar in both shows that cooling was too rapid to permit complete reaction. Equilibrium, therefore, was never attained, but the results approximate very closely what one would expect theoretically.

If reaction of the feldspar and magma took place according to the reaction principle, the net result would be a relative increase of lime over soda in the magma, and an increase of soda over lime in

[21] Bowen, N. L., The Evolution of the Igneous Rocks, *Princeton*, **1928**.

the inclusions. In the case of the dark minerals, the chemical interchange of material is not as simple. Nevertheless, the qualitative mineralogical changes are those one would expect. The dark mineral of the tonalite lowest in the reaction series is biotite. Therefore, according to Bowen, the magma was saturated with biotite and was also effectively saturated with olivine, pyroxene and hornblende, and could not dissolve them in spite of the marked contrast in composition. "But," to quote Bowen, "the magma can and will react with these minerals to convert them into biotite, usually by steps." This is apparently what has taken place in the gabbro xenoliths. The small amounts of olivine that are present in the gabbro would be the first minerals to react with the magma forming pyroxene. This, together with the original pyroxene, would then react to form hornblende. On continued cooling the hornblende thus formed would be converted to biotite with the introduction of the necessary potash. The process would go on until all the dark minerals were made over to biotite; or, due to subtraction of material necessary to produce biotite, the precipitation of minerals with which the magma is saturated brings reaction to an end. Following Bowen, the latter is apparently what happened, for the process was stopped before a large percentage of the hornblende was converted to biotite. However, it may have been that both hornblende and biotite were in equilibrium toward the end, and were crystallizing at the same time. This relation is shown in the tonalite where undoubtedly both minerals were at the same time in equilibrium with the magma, and hence it would be true for the inclusions.

Inasmuch as the gabbro is variable in composition and one cannot tell the percentages of hypersthene, augite, and hornblende of the original xenoliths, it is impossible to get for even one inclusion a quantitative estimate of the interchange of material. It was at first thought that a comparison of the chemial compositions of the gabbro and inclusions would aid in this respect; but, since both rocks have such a variable mineral composition, the comparison of individual analyses would have little significance.

In the comparison of the dark minerals of the tonalite with those of the inclusions, it was found that both the hornblende and biotite of the inclusions were richer in magnesia than the corresponding minerals of the host. This fact is additional evidence that equilibrium was not attained. From a chemical analysis of the gabbro it was estimated that the ratio of MgO:FeO as found in the ferromagnesian minerals is about 2.5:1, while from the analysis of the tonalite the same ratio is about 1:1. Although the ratios would vary slightly from place to place in both rocks, the comparison does give the order of magnitude. Diffusion, therefore, was apparently unable to take place fast enough to completely reduce the high ratio of MgO:FeO in the gabbro to that of the tonalite. Where reaction was more complete, the composition of the corresponding minerals in host and inclusion is found to be the same. This conclusion is substantiated by the comparisons of the dark minerals of the tonalite and inclusions. In six out of eight cases where the hornblende of the inclusion was richer in magnesia than that of the tonalite, the biotite also had a higher MgO ratio. In all of these instances feldspar with anorthite cores was found in the inclusions. On the other hand, in the two comparisons in which the corresponding hornblende had similar composition, there were no anorthite cores in the feldspar. Reaction here had been complete.