

PETROLOGIC RESULTS OF A STUDY OF THE MINERALS
FROM THE TERTIARY VOLCANIC ROCKS OF THE
SAN JUAN REGION, COLORADO²⁴

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5. THE AMPHIBOLES

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OCCURRENCE

Amphiboles are one of the chief mafic minerals in the San Juan area but they are somewhat subordinate to diopside and biotite, both in absolute amount and in the number of lavas which carry them. Amphiboles are absent from the basaltic rocks and from the andesites near the basalts, namely from all rocks with less than 53 per cent of SiO_2 . Biotite is very rare in rocks with less than 57 per cent of SiO_2 . Both biotite and hornblende are less common and less abundant in the andesites than in the latite-andesites. They are present in most of the quartz latites. In the Alboroto quartz latites, amphiboles are present together with phenocrysts of biotite, plagioclase, orthoclase, quartz and titanite, and rarely diopside. In the Piedra quartz latites they are present together with the same assemblage of minerals as in the Alboroto with the addition of diopside. In the Treasure Mountain quartz latites, which contain phenocrysts of plagioclase, biotite, and diopside, amphiboles are entirely absent.

In the rhyolites, biotite is commonly the only mafic mineral present in appreciable amounts, but many of them show either hornblende or pyroxene, or both, in such small amounts that either several thin sections must be examined, or a heavy liquid separation made to find them; their proportion is less than 0.1 per cent.

In the granular intrusive rocks hornblende is probably somewhat less common than in the lavas. It is rare as a hydrothermal mineral. In many of the gas cavities of the andesitic lavas tiny needles of hornblende are present with tridymite or cristobalite and other minerals.

RESORPTION

In most of the lavas the amphiboles show more or less resorption and this resorption appears to be more extensive in the andesites than in the rhyolites. It is nearly or quite lacking in the rocks with glassy ground-

²⁴ Published with the permission of the Director of the U. S. Geological Survey, Washington, D.C.

mass, indicating that much of the resorption took place after the lavas were erupted. This is also indicated by the fact that the dust of iron oxide left from the hornblende is not strewn about. All stages of resorption were found, from incipient etching and staining by iron oxide on the borders of the crystals, to complete removal of the amphibole. The stages in the resorption are excellently shown in the stocks and associated dikes of the small intrusive of Fisher diorite of Red Mountain near the southeastern corner of the San Cristobal quadrangle, a few miles south of Piedra Peak. Here the small apophyses and the border of the mass carry abundant hornblende phenocrysts (showing little or no resorption) in a fine groundmass that has a little diopside and hypersthene. In the larger bodies, and farther from the contact, the resorption of the hornblende becomes progressively greater. A dust of black iron ore, some reddish brown grains of hematite (?), some diopside, feldspar and some undetermined material are deposited where the hornblende has been removed. The groundmass becomes coarser and contains tiny grains of pyroxene.

Farther in from the contacts the resorption proceeds through a stage where only remnants of hornblende remain to one in which only the dust of iron oxide marks the former presence of hornblende. At this stage the amount of pyroxene is greater, the grains are larger and they are not spatially associated with the resorbed hornblende. Finally, in the granular rock all signs of the hornblende have been removed and the pyroxene has all the appearances of a normal early crystallized mineral.

In many of the lavas, hornblende shows similar resorption but it has not been followed step by step. A group of andesites of Fisher age in the southeastern part of the San Cristobal quadrangle, on both sides of Red Mountain Creek, show the resorption very well. Some specimens have phenocrysts of quartz and hornblende with little resorption, others show all stages in the resorption of both minerals, even to their complete disappearance. The resorbed quartz grains show the coronas of tiny diopside grains characteristic of quartz phenocrysts in basalts. As the hornblende is resorbed, diopside appears, first in and near the resorbed hornblende, then scattered through the groundmass, and finally as phenocrysts. The rocks in which the quartz and hornblende have been resorbed have tridymite in the gas cavities.

The resorption of hornblende yields chiefly magnetite, hematite, feldspar, and a pyroxene much poorer in total iron than the hornblende from which it was derived, as shown by the optical properties of the pyroxene. In a few specimens irregular shreds of pale biotite are present; in one, some matted, pale green hornblende. In some of the specimens tiny rods or irregular growths of diopside grow out from the resorbed

hornblende. Much of the pyroxene in and about the resorbed hornblendes is brown from partial oxidation of its iron.

Figures 9 and 10 are photomicrographs to show the stages in the resorption of the hornblende.

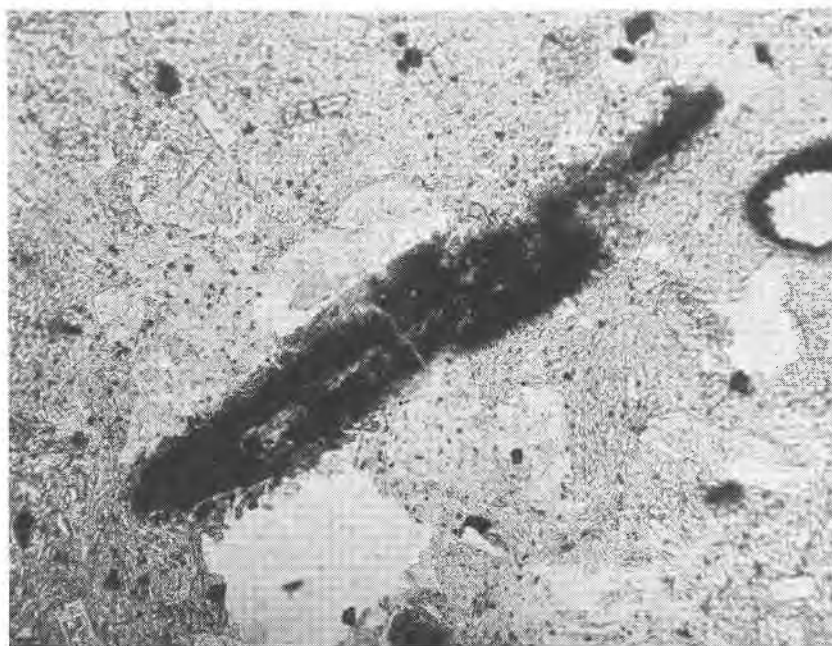


FIG. 9. Hornblende partly resorbed and nearly opaque from dust of iron oxide. Some brown hornblende remains in the lower left-hand part. Photomicrograph in plane-polarized light of Conejos andesite (SV 113) from Summitville quadrangle near head of Alamosa Creek and one mile southeast of Summit Peak. 40X.

	Brown DN 3005	Green SC 2838	Green DN 2017
Or	6.1	5.0	6.1
Ab	11.5	17.2	11.5
An	11.4	19.2	16.4
di	33.0	28.5	29.5
hy	17.5	30.2	28.6
mg	4.2	7.1	6.9
il	3.9	3.5	3.2
hm	11.2		

Tridymite is probably more abundant in the gas cavities of the rocks in which the hornblende and biotite have been resorbed and the iron oxidized, than in the other rocks.

A study of the norms of the hornblendes tells us, approximately, the minerals that should form from the resorption of hornblende. Accordingly, the norms of the three analyzed hornblendes are given above after recalculating nepheline to albite and olivine to hypersthene, as silica would be furnished by the residual siliceous liquid (groundmass).

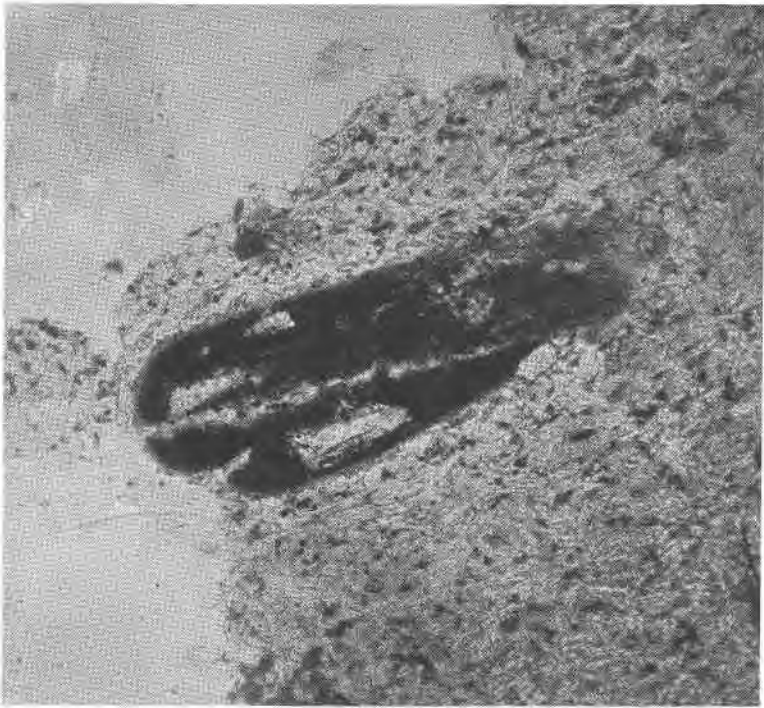


FIG. 10. Hornblende completely replaced by iron oxide. Photomicrograph in plane-polarized light of latite-andesite of lower horizon of the Sheep Mountain andesite (Sa 483). Saguache quadrangle, south slope of Saguache River, about $\frac{1}{4}$ mile below the mouth of Ford Creek at an elevation of 8400 feet. 50 \times .

The actual minerals formed are feldspar, pyroxene and iron ore. The feldspar is more sodic than that calculated from the hornblende and has no doubt had material from the groundmass added. The pyroxene is mostly diopside but some hypersthene is also formed. Probably some adjustment between the hornblende and the groundmass would be required to furnish lime for the diopside, but the amount would be small.

CONDITIONS THAT DETERMINE WHETHER PYROXENE OR
HORNBLENDE SHALL CRYSTALLIZE

Recently Kennedy²⁵ has discussed the conditions under which hornblende crystallizes from igneous rocks, and concluded that when the MgO-CaO-FeO ratio falls in the field where a homogeneous pyroxene cannot form, hornblende is favored. The three analyzed amphiboles from the San Juan Region fall in the hornblende field of Kennedy. However, several facts observed in the San Juan Region seem to show that composition is not the dominant factor determining the formation of hornblende.

1. Many of the hornblende-bearing rocks carry both diopside and hypersthene.

2. The pyroxene andesites and quartz latites grade into the hornblende rocks and many of the pyroxene rocks contain diopside and hypersthene in such proportions as to fall in the hornblende field.

3. Excepting the rocks with less than 53 per cent of SiO₂, there appears to be no connection between the presence of hornblende or pyroxene and the chemical composition of the rock. Hornblende and pyroxene rocks fall on the same variation diagram. Both hornblende and pyroxene rocks commonly have both diopside and hypersthene in the norm, though a few lack hypersthene and have wollastonite.

4. Resorption of hornblende is almost invariable in the lavas and shallow intrusives, unless cooling was rapid. Pyroxene is invariably formed as a result of this resorption. Pyroxene in rocks lacking all direct evidence of hornblende is formed from the resorption of hornblende.

5. The clinopyroxene of the rocks within the compositional range in which hornblende is found carries little clinohypersthene. The excess (Mg,Fe)O goes largely into hypersthene in the andesites and into biotite in the rhyolites and quartz latites.

The conditions that determine whether amphibole or pyroxene are to form in a rock of the composition of a quartz latite must be either physical conditions of crystallization (such as pressure) or concentration of the minor constituents (such as the mineralizers). The presence of amphibole and biotite in the gas cavities of the lavas of the San Juan and their common occurrence in many shallow hydrothermal deposits in other places seems to eliminate pressure as a determining condition, but fit well with the conclusion that abundance of mineralizers determines the formation of amphibole and biotite. The fact that both amphi-

²⁵ Kennedy, W. Q., The influence of chemical factors on the crystallization of hornblende in igneous rocks: *Mineral. Mag.*, vol. 24, pp. 203-7, 1935.

boles and biotites are hydrous minerals, while the pyroxenes are anhydrous, fits this explanation.

The history of the crystallization of the magma of the stock south of Piedra Peak is believed to have been about as follows: The magma as erupted to the position where exposed, which was not far from the surface, carried phenocrysts of plagioclase, hornblende, and biotite. The water and other gases escaped, and the hornblende and biotite were no longer in equilibrium with the mineralizer-poor liquid and were resorbed, leaving most of their iron oxide as hematite and magnetite, and precipitating pyroxene, partly at a distance. As the resorption proceeded the pyroxene grains increased in size and finally the hornblende and biotite were completely removed and even the iron ore was moved and recrystallized. The final rock was a granular pyroxene rock with nothing to show that hornblende and biotite had once been the dark minerals.

It will be shown in the following section that both brown basaltic hornblende and common green hornblende are present in the lavas and that the basaltic hornblende differs from the common hornblende only in that the former has little H_2O and most of its iron is in the ferric state. The possibility that the state of oxidation of the iron might determine the formation of hornblende or pyroxene was considered but analyses of series of rocks with hornblende, and of other series with pyroxene, show no apparent difference in the state of oxidation of the iron even though the hornblendes are much higher in ferric oxide than are the pyroxenes.

DESCRIPTION

The amphiboles of the lavas are in part typical brown basaltic hornblende, in part common green hornblende. Those in the andesitic rocks tend to be basaltic, while those in the rhyolites are all common hornblende. The type of the hornblende does not depend entirely on the bulk composition of the rock. In the Alboroto lavas some of the quartz latites have basaltic hornblende while others have common green hornblende, yet the two types of rock are otherwise practically identical in the proportion and character of the phenocrysts and of the groundmass. A basaltic and a common hornblende from two such similar Alboroto latites have been analyzed and studied. One is a typical green hornblende, the other a typical basaltic hornblende, and the only important chemical difference is in the state of oxidation of the iron. The analyses (by F. A. Gonyer) and other properties of these hornblendes, together with one from an andesite dike, are given in Table 4.

TABLE 4. ANALYSES AND PROPERTIES OF AMPHIBOLES FROM THE SAN JUAN REGION, COLORADO

	1 DN 3005	1a free of apatite	2 C 2017	2a free of apatite	3 SC 2838		
SiO ₂	44.34	45.17	45.44	46.12	43.95		
TiO ₂	2.08	2.11	1.67	1.70	1.81		
Al ₂ O ₃	7.55	7.68	9.41	9.60	11.40		
Fe ₂ O ₃	14.04	14.30	4.81	4.91	4.69		
FeO	2.77	2.81	8.97	9.15	9.02		
MnO	0.41	0.41	0.34	0.34	0.14		
MgO	13.21	13.44	13.04	13.29	13.73		
CaO	11.96	11.18	11.71	11.13	11.12		
Na ₂ O	1.35	1.35	1.34	1.37	2.08		
K ₂ O	1.07	1.09	1.06	1.08	0.86		
H ₂ O—	0.06	0.06	0.19	0.19			
H ₂ O+	0.19	0.19	0.63	0.65	0.79		
P ₂ O ₅	0.79		0.71				
F	0.35	0.35	0.80	0.80	n.d.		
	100.17	100.14	100.12	100.33	99.59		
Less O for F	0.14	0.14	0.33	0.33			
	100.03	100.00	99.79	100.00			
G.	3.246		3.188				
Atomic Ratios (O=24)							
Si	0.668		0.679		0.653		
Al	0.135		0.166		0.197		
Ti	0.024		0.018		0.021		
Fe'''	0.160		0.054		0.055		
Fe''+Mg+Mn	0.338		0.408		0.418		
Ca	0.178		0.173		0.176		
Na	0.060		0.060		0.075		
H	0.043		0.082		0.079		
F	0.017		0.040		n.d.		
Optical Properties							
	1	2	3	4	5	6	7
				SC 906	Lag 1021	Con A	
α	1.675	1.652	1.658	1.640	1.671	1.69	1.612
β	1.715	1.675	1.673	1.653	1.684		1.622
γ	1.735	1.680	1.683	1.665	1.695	1.76	1.633
Opt. Char.	—	—	—	—	—		
2V	Large	med. large	large	near 90°			near 90°
Disp.	r < v rather	r < v easily		r < v easily			

Pleochroism	strong	perc.		perc.			
$\alpha =$	Pale yellow	Pale yellow	Pale yellow low brown	Paler than 3	Paler than 1	Darker than 1	Colorless
$\beta =$	Rather dark chestnut brown	Greenish brown	Light brown	Paler than 3	Paler than 1	Darker than 1	Colorless
$\gamma =$	Dark chestnut brown	Olive green	Dark olive brown	Paler than 3	Paler than 1	Darker than 1	Colorless
$\gamma \wedge c$	5°	14½°	13½°	18½°	7°	3°	25°

1. Basaltic hornblende from Alboroto quartz latite (DN 3005), rock quarry about 8 miles southeast of Del Norte, on slope north of Dry Gulch.

1a. Analysis 1 computed free of apatite.

2. Green hornblende from Alboroto quartz latite (C 2017). Cochetopa quadrangle, Sheep Creek, near mouth of Bear Creek.

2a. Analysis 2 computed free of apatite.

3. Green hornblende from an andesite dike cutting Potosi volcanics at an elevation of 12,000 feet on the east side of the peak with an elevation of 12,880 feet near the southeast corner of the San Cristobal quadrangle.

4. Green hornblende from Hinsdale rhyolite (SC 906) from the northeastern part of San Cristobal quadrangle at the head of Big Spring Gulch along road between Creede and Lake City.

5. Pale brown hornblende from Fisher quartz latite (Lag 1021) in Creede quadrangle, north of Rio Grande, between Farmers and Bellows Creeks, draw on west slope of hill 9740 elevation, at 9100 feet elevation.

6. Basaltic hornblende from Los Pinos quartz latite (Con A) from northeast slope of Green Mountain in the extreme northern part of the Conejos quadrangle.

7. Cotton-like needles of amphibole in the gas cavities of the andesite of the Hinsdale andesite volcanic dome of Cerro Aire, New Mexico, about 4 miles east of No. Agua, New Mexico. The amphibole is probably related to soda tremolite. An amphibole from the cavities of the Hinsdale andesite-basalt from Elk Mountain, in the Creede quadrangle, has $\alpha = 1.63$, brownish, $\gamma = 1.645$, greenish brown, $Z \wedge c = 13^\circ$.

There appears to be every gradation between typical basaltic hornblende and common green hornblende. The optical data in column 4 indicates a hornblende with less Fe_2O_3 than that of columns 2 and 3, that of column 5 is intermediate between 1 and 2, and 6 is even richer in Fe_2O_3 than 1.

All three analyzed hornblendes fit the formula for the amphiboles $(Ca, Na)_2(Na)_{0-1}(Mg, Fe'')_1(Mg, Fe''', Fe''', Al)_4(Al, Si)_2Si_6O_{22}(O, OH, F)_2$. All are rather low in Si, high in total iron, moderate in alkalis, and low in $OH + F$.²⁶

No basaltic hornblende was found in the obsidians or other rocks with rhyolitic glass, but hornblende is rare in rocks so rich in silica as these

²⁶ Kawano, Y., Chemical formula of basaltic hornblende: *Proc. Imp. Acad. Japan*, vol. 10, pp. 349-352, 1934.

glasses. In the glassy rocks the biotite and hornblende phenocrysts are less resorbed and iron stained than in the crystalline lavas. In no rocks were both types of hornblende found together, nor was anything seen to indicate that one is derived from the other. However, in the quartz latites of the Highwood Mountains of Montana, the original brown basaltic hornblende is replaced to all degrees by a common green hornblende. The replacement is probably hydrothermal or very late magmatic.

Two specimens of Los Pinos quartz latite are especially instructive. Both were collected from the northeast slope of Green Mountain in the northern part of the Conejos quadrangle. The rocks are very much alike except for the groundmass. Both rocks have abundant large phenocrysts of andesine and biotite and fewer of hornblende, pyroxene and magnetite. One has a gray, glassy groundmass, the other a reddish-brown microcrystalline groundmass. The rock with a glassy groundmass has more phenocrysts of plagioclase and biotite and fewer of diopside than the one with a crystalline groundmass.

Chemically, the two rocks are very similar, the chief differences being that the glassy rock has one per cent more water and $1\frac{1}{2}$ per cent more FeO, and correspondingly less Fe₂O₃, than the holocrystalline rock. The glassy rock has a common green hornblende ($\gamma=1.68$) and a biotite with $\gamma=1.655$, neither of which show appreciable resorption, while the holocrystalline rock has a dark brown basaltic hornblende ($\gamma=1.76$), and a biotite with $\gamma=1.723$, both of which show much resorption.

Kôzu and Yoshiki²⁷ have shown that two quartz andesites from the volcano Sambé, Japan, are very similar except for color, and that the red-brown lava has basaltic hornblende and high index biotite, while the gray lava has green hornblende and low index biotite.

A statistical study of 20 analyzed San Juan lavas that contain hornblende—listed below—show no appreciable tendency for basaltic hornblende to be concentrated either in the red or brownish rocks.

TYPE OF HORNBLENDE

Color of Rock	Basaltic	Common pale brown	Green
Gray to black	5	2	2
Reddish gray	1		1
Red and brown	4	3	1
Nearly white	1		1

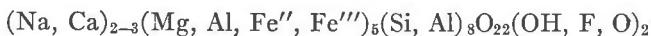
²⁷ Kôzu, S. and Yoshiki, B., Thermo-optic studies of anomite-basaltic hornblende-quartz-andesite in association with biotite-common hornblende-quartz-andesite, which together form the volcano Sambé in Japan: *Science Reports, Tôhoku Imp. Univ., Ser. III*, vol. 3, pp. 180-193, 1929.

None of the five rocks with rhyolitic glass had basaltic hornblende, but such hornblende is rare in rocks of the composition of these. The biotite associated with the basaltic hornblende in every case has an index of refraction (γ) greater than 1.70, while all the light brown or green hornblendes are associated with a biotite with γ less than 1.67. There appears to be little difference in the extent of the resorption in the two types of hornblende. The hornblendes in the andesitic rocks are in nearly all cases basaltic, those in the quartz latites are divided between the three types, and those of the rhyolites are nearly all green.

CONDITIONS UNDER WHICH BASALTIC AND COMMON HORNBLLENDE FORM

Kôzu, Yoshiki, and Kani²⁸ have shown that common hornblende heated to 750°C. changed to brown basaltic hornblende and that the change is caused by a loss of H₂O and oxidation of the iron. The fact that in the San Juan lavas the basaltic hornblende tends to be in the high-temperature andesites and absent in the low-temperature rhyolites may give some clue as to the temperature range of the magmas.

The evidence from the San Juan lavas indicates that temperature is not the only condition that determines the kind of hornblende formed, since lavas of essentially the same character, over a wide range of composition, may have either kind of hornblende. As shown by the amphibole formula



if Fe'' is replaced by Fe''' some replacement, such as OH by O, must take place, and the analyses bear this out. Hence, the oxidation of iron in an amphibole should be accompanied by a loss of H.

6. BIOTITE

BY ESPER S. LARSEN, F. A. GONYER, AND JOHN IRVING

DESCRIPTION

Biotite is practically absent from the basalts and pyroxene andesites of the San Juan area. As the rocks increase in silica content, biotite begins to make its appearance at about the same composition as free silica (58% SiO₂), in the latite-andesites, and it is present in nearly all the rocks with more than that amount of SiO₂. In the less siliceous rocks

²⁸ Kôzu, S. Yoshiki, B., and Kani, K., Note on the study of the transformation of common hornblende into basaltic hornblende at 750°C.: *Science Reports, Tôhoku Imp. Univ., Ser. III*, vol. 3, pp. 143-159, 1927.

Kôzu, S. and Yoshiki, B., The dissociation temperature of brown hornblende and its rapid expansion at this temperature: *Science Reports of Tôhoku Imp. Univ., Ser. III*, vol. 3, pp. 107-117, 1927.

it is subordinate to the other mafic minerals but as the rocks become richer in silica and alkalic feldspar, biotite constitutes a larger proportion of the mafic minerals; and in most of the rocks with over 60% of SiO_2 it is the chief, and in many rocks the only mafic mineral. However, as the proportion of mafic minerals decreases rapidly as the silica increases, the total amount of biotite is greatest in the quartz latites. Biotite comprises only a few per cent of most rocks, but it slightly exceeds 10 per cent in a few.

Biotite is present also in many of the granular intrusive rocks, even in the gabbros, but it is usually in small amount. In the gabbros it is a very late mineral to crystallize, while in the granites it is one of the early crystals. Light-colored biotite is rather common as a high-temperature hydrothermal mineral.

Biotite is commonly associated with quartz and alkali feldspar, except in some of the gabbros. It is commonly associated with hornblende, among the mafic minerals, less commonly with pyroxene where hornblende is lacking. It was not found in effusive rocks that contain olivine.

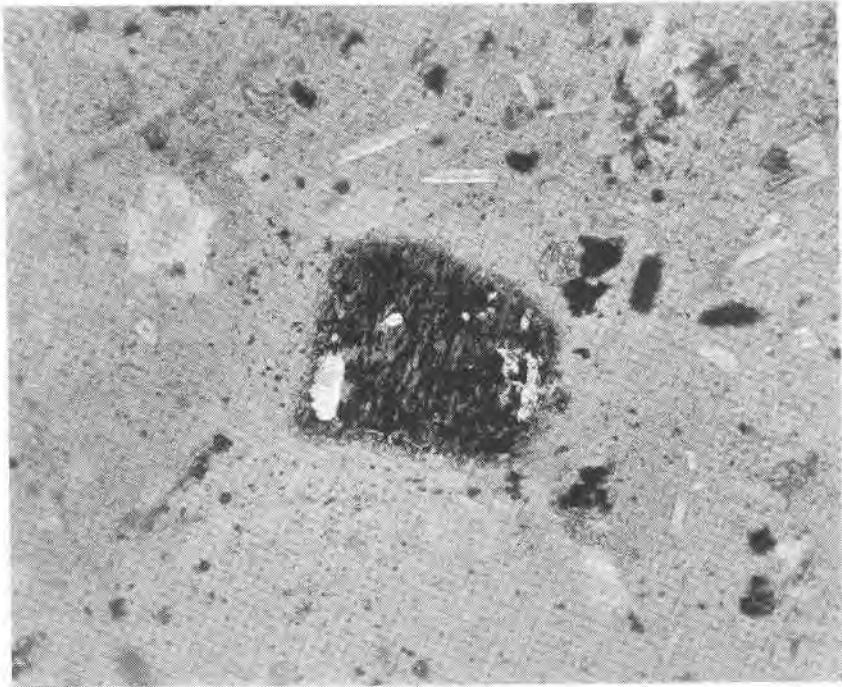


FIG. 11. Biotite with resorption and development of pyroxene and other minerals about the border, and with some iron in the main part of the crystals, but otherwise fresh. Fisher latite-andesite (SC 1663)—northeastern part of the San Cristobal quadrangle, near head of Mineral Creek on west side at an elevation of 11,400 feet. 45 \times .

RESORPTION

The biotites of the extrusive rocks commonly show resorption and, while the extent of the resorption varies greatly in rocks of the same composition, on the average it is greater in the less siliceous rocks, and may be almost entirely lacking in the rhyolites. All stages in the resorption have been followed from slight reaction on the borders to complete removal, leaving only a dust of iron oxide to show the original presence of biotite. In the earliest stage of the resorption, the borders of the grains are frayed and are more deeply colored. Pyroxene or a reddish alteration product in tiny prisms, or as a lacework, are concentrated next to the border. Grains of iron ore are scattered through the biotite and parts of the biotite are bleached. On further resorption an outer zone of the biotite is replaced by fine-grained feldspar, red and black ore, and pyroxene; and the inner part is biotite with grains of red and black ore. At a later stage all the biotite is replaced. In some a little pale biotite is formed and rarely epidote or piedmontite. Finally, all evidence of the original biotite is destroyed. Three types of the resorption are shown in Figs. 11, 12, and 13.



FIG. 12. Two biotite crystals resorbed to a dust of iron oxide, pyroxene, etc., in the central part of the figure but fresh except for a little iron stain to the right and left. Fisher latite-andesite, northern part of San Cristobal quadrangle, west of Lake San Cristobal on ridge south of Grassy Mountain, at an elevation of 11,400 feet. 45X.

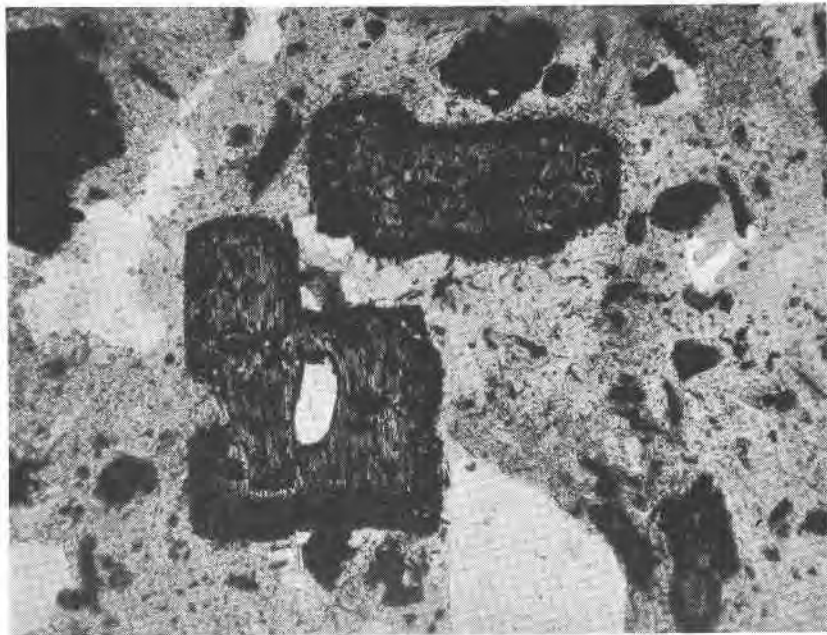


FIG. 13. Two biotite crystals with opaque reaction rims and opaque ore scattered throughout the main parts of the crystals. Fisher latite-andesite (SV 1315) from northern part of San Cristobal quadrangle, north of Cascade Gulch and on northwest slope of hill with 13,100 contour at 13,100 feet elevation. $45\times$.

DESCRIPTION

The biotites of the extrusive rocks have variable indices of refraction which, except in a few rhyolites, are considerably higher than those of the granular rocks. The value of γ has been measured for nearly all of the biotites of the analyzed extrusive rocks, and is plotted against the position in the plots used in the chemistry and the approximate SiO_2 content in Fig. 14. The values of γ vary from 1.63 to 1.73. They fall into three groups with a few intermediate values. A group in which γ varies from 1.70 to 1.73 includes nearly all the biotites from the less siliceous rocks—latite-andesites—and nearly half of those from the quartz latites, but few from the rhyolites. Another group in which γ ranges from 1.65 to 1.68 includes the biotites from most of the rocks with moderate silica content. A third group, in which γ ranges from 1.63 to 1.64, includes most of the biotites from the highly siliceous rhyolite.

A fourth group includes biotite in the granular rocks, whether gabbro or granite. The crystals are free from resorption, are light colored, have very small $2V$, considerable dispersion ($r < v$) and indices of refraction (β) ranging in five specimens from 1.629 to 1.641. They are believed to

be low in Fe_2O_3 . Similar biotites are present in small amounts in the gas cavities and porous parts of some of the lavas where they are associated with tridymite. Biotites of this group are not included in the plot.

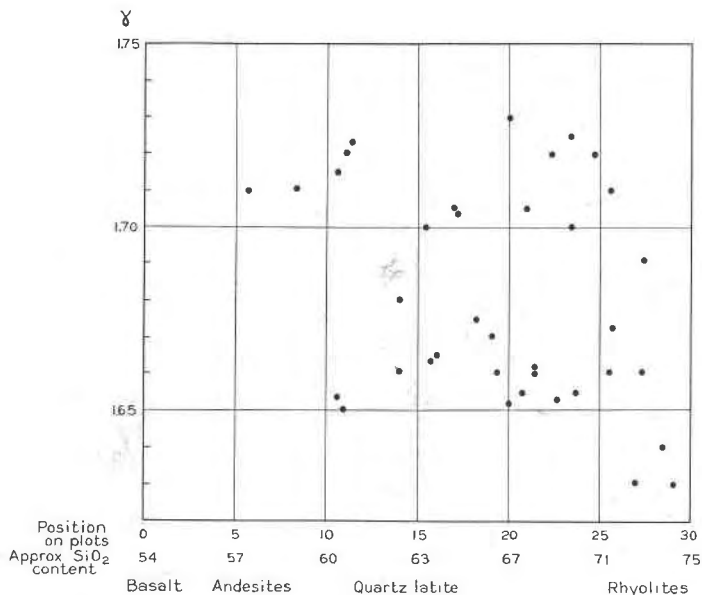


FIG. 14. The index of refraction (γ) of the biotites of the analyzed extrusive rocks of the San Juan Region, Colorado, plotted against the composition of the rock in which they occur.

All of the biotites studied have strong dispersion of the optic axes with $r < v$. The axial angles are rather variable and are unusually large for biotite. Those with low indices of refraction have smaller axial angles, and those with γ near 1.63 have the very small angle common in biotite.

Four of the biotites have been analyzed by F. A. Gonyer and their analyses and optical properties are given in Table 5.

TABLE 5. ANALYSES AND OPTICAL PROPERTIES OF BIOTITES FROM THE SAN JUAN LAVAS

	1 SC xx	2 C 2017	3 DN 3006	4 Con A
SiO_2	38.56	39.14	39.25	37.24
TiO_2	4.95	4.27	3.63	4.19
Al_2O_3	14.12	13.10	12.90	14.14
Fe_2O_3	5.51	12.94	17.13	17.71
FeO	8.25	5.05	1.85	0.53
MnO	0.20	0.14	0.23	0.07

MgO	15.59	12.75	12.91	13.81
CaO	1.06	1.64	1.97	0.87
BaO	0.43	—	0.41	—
SrO	none	—	none	—
Na ₂ O	0.81	0.70	1.10	0.68
K ₂ O	8.68	6.55	6.87	6.36
H ₂ O—	—	0.58	—	—
H ₂ O+	1.03	2.41	1.32	0.63
F	1.25	1.11	1.01	0.37
	100.44	100.38	100.58	96.60 ²⁹
Less O for F	0.53	0.46	0.43	
	99.91	99.92	100.15	
G.	2.984	2.862		

Ratios in Biotite formula³⁰ W₄(X, Y)₁₂(Z₁₆O₄₀)(O, OH, F)₂

W = K, Na, little Ca

X = Mg, Fe, Mn, Ti

Y = Al, Fe^{'''}(Ti)

Z = Si:Al ≥ 5:3

(K, Na, Ca)	4.2	3.4	4.0	3.1
(Mg, Fe ^{''})	9.1	7.0	6.4	6.5
Ti	1.1	1.0	0.8	1.0
(Al, Fe ^{'''})	6.3	7.5	8.5	9.2
Si	11.6	11.6	11.8	11.4
O	44.8	42.0	45.0	46.0
(OH, F)	3.2	6.0	3.0	2.0
α	1.592 ± 0.005	1.594	1.605 ± 0.01	1.610
β	1.650	1.671	1.716	1.722
γ	1.651	1.672	1.720	1.723
2E _{Na} range	36 to 59°	16 to 43°	35 to 61°	33 to 54°
2E _{Na} average	52°	26°	47°	48°
Total Fe (as FeO)+MnO	13.40	16.84	17.50	16.54
SiO ₂ content of rock	71	66½	67	60

1. (SC xx) From Piedra rhyolite glass, eastern part of San Cristobal quadrangle, road north of Rio Grande and 1 mile east of Clear Creek.

2. (C 2017) From Alboroto latite (has green hornblende, see analysis 2 of the hornblendes), Cochetopa quadrangle, Sheep Creek near mouth of Bear Creek.

3. (DN 3006) From Treasure Mountain latite (has augite but no hornblende), Del Norte quadrangle, 5 miles southeast of Del Norte, north fork of gulch between Lime and Raton Gulches, ¼ mile from lower contact of Treasure Mountain formation.

4. (Con A) From Los Pinos andesite-latite (is red in color and has basaltic hornblende, optical data 6 of hornblendes). Northeast slope of Green Ridge in the extreme northern part of Conejos quadrangle.

²⁹ Sample probably retained a little bromoform from heavy liquid separation.

³⁰ After Harry Berman, personal communication.

The analyses show that the difference chemically between the biotites with high indices of refraction and those with low indices of refraction is chiefly in the state of oxidation of the iron, which is almost entirely ferric in the high index minerals. The OH+F may be lower in the high index biotites. Analysis 1 is also lower in total iron and higher in MgO.

The biotites with high indices of refraction (>1.70) are associated with dark brown basaltic hornblende; those with intermediate indices (1.66 to 1.70) are associated with light brown, less commonly green hornblende; and those with low indices (<1.66) are associated with green hornblende. Hence high Fe_2O_3 biotite and high Fe_2O_3 hornblende form under about the same conditions. Possibly biotite is a little more readily oxidized. Kôzu and Yoshiki³¹ have shown that the two kinds of biotite are in different lavas of Sambô volcano and have studied the change in low index biotite on heating. They found that on heating, the γ index of refraction changed from 1.655 to 1.703, and the axial angle, $2E$, from 38.4° to 48.5° . The change takes place gradually and mostly between the temperatures 500° to 800° . In the rocks, they found a low index of refraction for the hornblende and biotite in bread-crust bombs, somewhat higher values for the minerals in a gray andesite, and very high values for those in a red andesite. Their values are given below.

Hornblendes

	Bread-crust bomb	Gray andesite	Red andesite
α' on cleavage	1.661	1.675	1.692
γ' on cleavage	1.673	1.685	1.707
Ext. on cleavage	17°	11°	ca. 0°
α	Pale green	Light brownish yellow	Yellowish green
β	Green	Brownish yellow	Brown
γ	Bright green	Greenish brown	Dark reddish brown
FeO content		10.97	7.69
Loss ign.		0.23	0.08

Biotites

α		1.589	1.597
γ	1.641	1.655	1.703
$2E$	near 0°	38.4°	41.7°
FeO content		10.32	5.96
Loss ign.		2.76	1.53

³¹ Kôzu, S. and Yoshiki, B., Thermo-optic studies of anomite-basaltic hornblende-quartz-andesite in association with biotite-common hornblende-quartz-andesite, which together form the volcano Sambô, Japan: *Sci. Reports Tôhoku Imperial University, Ser. III*, vol. 3, pp. 177-193, 1929.

CONCLUSIONS

(1) In part, the character of the hornblende and biotite is determined before the final eruption of the lava, but probably after it has reached a position near the surface. In considerable part the change from common to basaltic hornblende, and from low to high ferric iron biotite, takes place after eruption and during the crystallization of the groundmass.

(2) High Fe_2O_3 and low H_2O in both hornblende (basaltic) and biotite are more common in rocks at the andesitic end of the series and were not found in rocks near the extreme rhyolitic end.

(3) The conditions favoring the formation of Fe_2O_3 -rich hornblende and biotite are probably approximately expressed by the mass action equation: $2\text{FeO} + \text{H}_2\text{O} \rightleftharpoons \text{Fe}_2\text{O}_3 + 2\text{H}$, and the geological conditions are probably temperature, sufficient H_2O concentration, and escape of H as formed.

(4) Probably the same conditions favor the oxidation of the iron in lavas near the vents and in the crystalline parts of flows. This oxidation is not common in basaltic rocks, except as expressed by the replacement of olivine by iddingsite. The hydrogen of volcanic gases is at least in part derived from the reaction of H_2O on FeO near the surface.

(5) The resorption of hornblende and biotite is favored by near-surface conditions; it may begin before the magma is erupted to the surface but much of it takes place after eruption. It is somewhat more common in rocks near the andesites in composition than in those near the rhyolites.

(6) The material of the hornblende, after resorption, goes chiefly into iron ore, feldspar and pyroxene; the pyroxene being much lower in total iron than the hornblende. The resorption of biotite yields feldspar as well as iron ore and pyroxene.

(7) The condition that favors the crystallization of hornblende and biotite rather than pyroxene from a magma is probably abundance of mineralizers.