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PETROLOGIC RESULTS OF A STUDY OF THE MINERALS FROM THE TERTIARY VOLCANIC ROCKS OF THE SAN JUAN REGION, COLORADO[44]

Esper S. Larsen, John Irving, F. A. Gonyer, and Esper S. Larsen, 3rd
Harvard University, Cambridge, Mass.

(*Continued from p. 257 (April, 1938)*)

8. ORTHOCLASE

Esper S. Larsen and Esper S. Larsen, 3rd

Occurrence and Associations

Orthoclase and related alkalic feldspars are not abundant in the lavas of the San Juan region, except in the groundmass. The sanidine variety of orthoclase is present as phenocrysts in about half the rhyolites and rhyolitic quartz latites of the Potosi volcanic series and in most of the rhyolite of the Hinsdale formation. Local rhyolite bodies of the Hinsdale formation, such as the obsidian of the No Agua volcano, New Mexico, contain no sanidine phenocrysts. Sanidine phenocrysts rarely constitute over 15 per cent of a rock and in most instances much less than that. Nearly all the sanidine-bearing rhyolitic rocks of the Potosi series carry plagioclase phenocrysts (chiefly oligoclase or oligoclase-andesine), whereas those of the Hinsdale formation contain little or no plagioclase. Quartz phenocrysts are present in over half of the quartz latites that carry sanidine phenocrysts; they are present in all of the Hinsdale and Sunshine Peak rhyolites, but they are not common in the rhyolites of the Potosi series.

Biotite is present in all the rhyolitic rocks that possess sanidine phenocrysts, and it is commonly the chief or only ferro-magnesian silicate in such rocks. Hornblende associated with biotite, and rarely with augite and biotite, is present in most of the quartz latites that carry sanidine. Rhyolitic rocks with appreciable amounts of augite, but without hornblende, very rarely contain sanidine phenocrysts, although

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such rocks have essentially the same chemical compositions as those with phenocrysts of hornblende, sanidine and other minerals.

Sanidine also occurs as an erratic constituent, probably as foreign crystals, in some of the quartz latites, andesites and basalts. Some of the Fisher quartz latites and andesitic quartz latites contain rather abundant sanidine crystals as large as 20 millimeters or more across. They are associated with equally large phenocrysts of plagioclase, mafic minerals and, in some rocks, quartz. These sanidine crystals are much rounded from resorption, and in many of the rocks they are surrounded by a layer of sodic plagioclase, similar to the orthoclase of the rapakivi granites.

Sanidine is also present in some of the andesites and andesite-basalts of the Hinsdale formation, where it is associated, in most cases, with quartz, plagioclase with very sodic cores and calcic borders, pyroxene and olivine. It is much resorbed. The rock of Ortiz Peak, near Tres Piedra, New Mexico, is a good illustration of this, and a partial analysis of the orthoclase from that rock is shown in Table 11.

Description

All the potash feldspar phenocrysts, even the erratic phenocrysts in the andesites and basalts, are glassy sanidine. The rhyolite of the Hinsdale formation, the rhyolites of the Valles Mountains, New Mexico, and the Sunshine Peak rhyolite show the blue iridescence of moonstone.

Table 10. Analyses of Sanidine Phenocrysts from the Lavas of the San Juan Region by F. A. Gonyer

	DN2017	SCxx	SC906
SiO_2	65.06	64.39	66.08
TiO_2		none	none
Al_2O_3	19.24	19.23	19.34
Fe_2O_3	0.30	0.54	0.14
FeO			
MnO		none	none
MgO	0.09	0.08	none
CaO	0.28	0.60	0.70
Na_2O	2.66	4.04	6.06
K_2O	11.86	10.25	7.36
H_2O-	0.04	0.08	
H_2O+	0.34	0.31	0.16
	99.87	99.52	99.84
Sp. Gr.	2.564	2.589	

The localities of the specimens are given under Table 11.

The blue iridescent sanidines have over 50 per cent of the albite molecule. A careful examination of these with a microscope shows that they contain very thin lamellae of intergrown albite, which are believed to be due to unmixing. The other sanidines appear to be homogeneous.

Complete analyses of three of the sanidine phenocrysts have been made and are given in Table 10. Alkali and lime determinations have been made on three additional sanidine phenocrysts, alkali determinations on five others, and lime and alkali determinations on all the rocks from which the 11 sanidines were separated. The alkali and lime contents of the 11 sanidines, and of the rocks from which they came, the anorthite content of the plagioclase phenocrysts of the rocks, and the optical properties of the sanidines are given in Table 11.

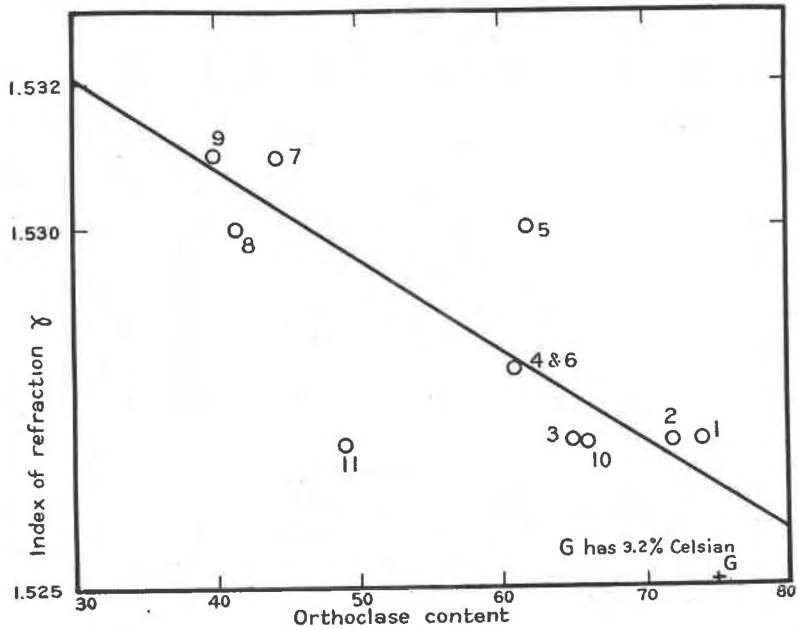

FIG. 28. Relation between γ index of refraction and orthoclase content of sanidines from the lavas of the San Juan region.

The indices of refraction of the sanidines, given in Table 11, were determined with sodium light and are accurate to ± 0.001. In Fig. 28, γ is plotted against the Or content of the sanidine. Nine of the sanidine points in this figure determine a straight line such that none of the nine is distant from the line by more than the limit of error of the determination of the indices. Points in the figure corresponding to sanidines from rocks 5 and 11 (Table 11) are erratic for some reason, perhaps due to some different heat history. The CaO content does not appear

TABLE 11. ALKALI CONTENT OF SANIDINE PHENOCRYSTS AND OF THE ROCKS IN WHICH
CRYSTS, AND THE OPTICAL

Number on figures	Rock	Sanidine			Rock			An in plagioclase
		CaO	Na_2O	K_2O	CaO	Na_2O	K_2O	
1	DN2017	0.28	2.66	11.86	3.46	3.49	3.98	34
2	Lag 1059		2.78	11.32	3.68	3.60	4.05	26
3	C2018		3.78	10.72		3.34	5.18	29
4	SCK		4.01	9.71	0.76	3.22	5.40	26
5	SCxx	0.60	4.04	10.25	1.70	3.80	5.25	37
6	U3027		4.26	10.35	1.08	3.70	6.15	29
7	SC906	0.70	6.06	7.36	0.39	3.80	5.20	
8	SV78		6.26	6.77	0.14	4.49	4.40	6
9	JL7	0.40	6.55	6.56	0.12	4.34	4.22	
10	SC1740	0.49	3.57	11.07	4.03	3.59	3.74	45
11	NM213	0.61	5.32	7.61	7.40	3.04	2.18	30

DN2017. Alboroto quartz latite from Del Norte Quadrangle. Quarry 4 miles southeast of Del Norte.

Lag1059. Alboroto quartz latite. Alder Creek in the Creede Quadrangle.

C2018. Cavernous rhyolite at the base of the Piedra rhyolite. Between Sheep and Four Mile Creeks. Cochetopa Quadrangle.

SCK. Latite-rhyolite of the Piedra rhyolite. Upper horizon at South Clear Creek Falls. Eastern part of San Cristobal Quadrangle.

SCxx. Quartz latite obsidian of the Piedra rhyolite. Eastern part of San Cristobal Quadrangle. Road on north side of Rio Grande and north of the mouth of Spring Creek.

U3027. Tridymite rhyolite at base of the Alboroto quartz latite. Northwestern part of Uncompahgre Quadrangle, along road to Pine Creek Mesa at an elevation of 8350 feet.

SC906. Rhyolite of the Hinsdale formation. Northeastern part of San Cristobal Quadrangle. Head of Spring Creek.

SV78. Rhyolite of the Hinsdale formation from small cone, Old Baldy Mountain, in northeastern part of the Summitville Quadrangle.

JL7. Rhyolite of Valles Grande Mountains west of Santa Fe, New Mexico. One quarter of a mile below Seven Springs in Cebolla Creek, about 1 mile southeast of Rancho Rhea.

to be the cause. Barium oxide was not determined and it may be responsible. If α and β indices were plotted in the same way, the results would be similar. In general, the Or content of sanidines can be determined to $\pm 10\%$ by determining one index of refraction to ± 0.001. The curve in Fig. 28 agrees well with that given by Winchell.[45] Neither 2V nor the extinction angle ($\alpha \wedge a$) varies regularly with Or content.

The one true sanidine discussed in Spencer's[46] recent paper on the potash-soda feldspars contains over 3% of the celsian molecule and its γ index falls below the curve here presented (G of Fig. 28).

[45] Winchell, A. N., Studies in the feldspar group: *Jour. Geol.*, vol. **33**, p. 720, 1925.

[46] Spencer, E., The potash-soda-feldspars. I. Thermal stability: *Min. Mag.*, vol. **24**, no. 156, plate XVIII specimen G, 1937.

THEY OCCUR, THE ANORTHITE CONTENT OF THE ACCOMPANYING PLAGIOCLASE PHENO-
PROPERTIES OF THE SANIDINES.

Sanidine			α	β	γ	2V	$\alpha \wedge a$
Or	Ab	An					
74	24	1½	1.522	1.527	1.527	Small	7°
72	25		1.522	1.527	1.527	10°+?	7°
65	32		1.522	1.527	1.527	10°–20°?	8°
61	36		1.523	1.528	1.528	20°±?	13°
62	35	3	1.525	1.530	1.530	41°	17°
61	36		1.522	1.528	1.528	34°	9°
44½	52	3½	1.525	1.530+	1.531	41°	11°
41½	55½	3	1.525	1.530	1.530	20°–30°?	10°
40	57	2	1.525	1.531	1.531	20°±?	9°
66	31	2½	1.521	1.527	1.527	21°	11°
49	48	3	1.521+	1.527	1.527	?	8°

SC1740. (same as 1683). Fisher latite-andesite. Northeastern part of San Cristobal Quadrangle near head of Mineral Creek at an elevation of 11,400 feet.

NM213. Basalt. Ortez Peak, near No Agua, New Mexico.

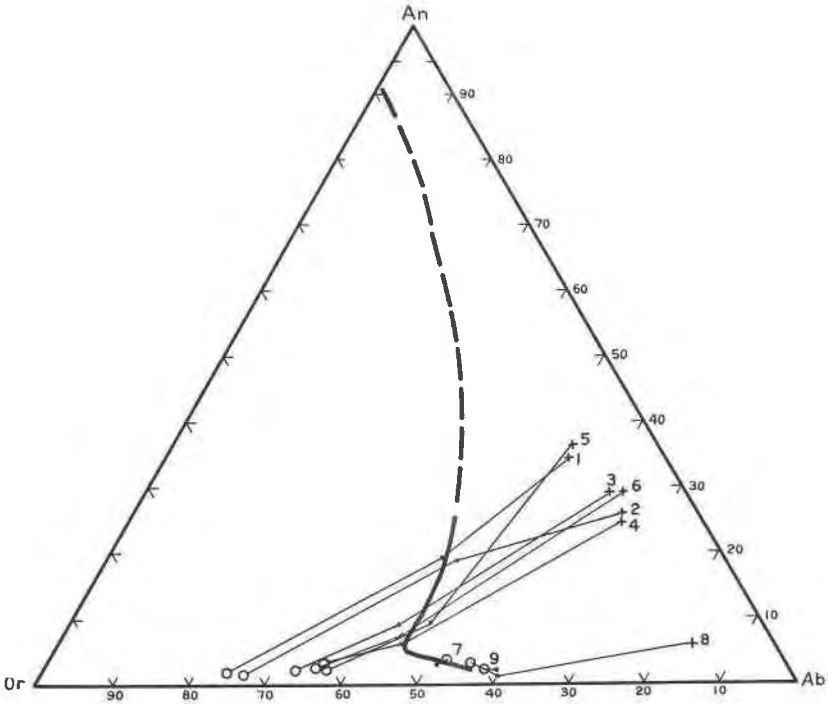

FIG. 29. Relation between sanidine phenocrysts, plagioclase phenocrysts and normative feldspars of the enclosing rocks.

Sanidine is represented by circles, plagioclase by crosses and rock by dots.

The sanidines are all low in lime and carry a maximum of 3½ per cent of anorthite. They range from 24 to 57 per cent in albite content. There is no clear relation between the percentages of anorthite and albite.

In Fig. 29 the compositions of the normative feldspars, the sanidine phenocrysts and the plagioclase phenocrysts of nine rocks are plotted on a triangular diagram. For each rock the dot representing the normative

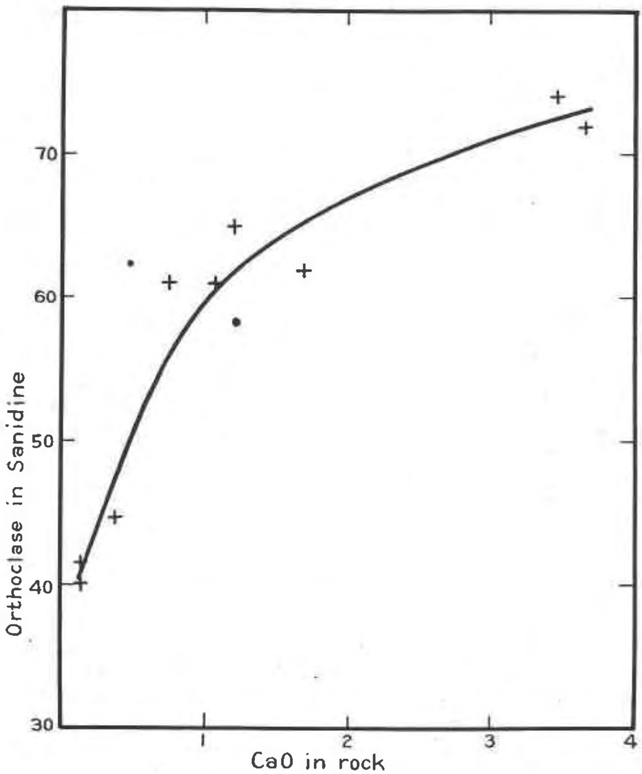

FIG. 30. Relation between CaO content of rocks and orthoclase content of sanidine phenocrysts.

feldspar is joined by lines to the circle representing the sanidine, and to the cross representing the plagioclase. Two of the rocks contain no plagioclase phenocrysts. Complete analyses were available for rocks SC1059, SCxx, U3027, and SC906; and alkali and lime determinations on the others. A complete analysis was available for the plagioclase from rock SCxx, alkali and CaO determinations for C2017 and U3027, and careful optical determinations on the others.

Of the eleven rocks from which sanidine phenocrysts were separated and analyzed, two, SC174 and MN213, are believed to have acquired the sanidine phenocrysts from a foreign source and they will not be further considered. The remaining nine fall into two main groups. The first group contains phenocrysts of sanidine and a plagioclase, near oligoclase-andesine. Two of these, C2017 and Lag1059, have phenocrysts of quartz, biotite and hornblende as well as feldspar. Such rocks make up a large part of the Alboroto quartz latite, and similar rocks are present in the Piedra rhyolite. These rocks have a moderate lime content, and the sanidine phenocrysts are low in soda. The other four rocks of this group have phenocrysts of feldspar and biotite. Such rocks are abundant and widespread in the three rhyolitic divisions of the Potosi volcanic series. These rocks are rather low in lime and the sanidines have a moderate soda content. The second major group contains phenocrysts of quartz, sanidine, and biotite. Rarely they contain a few phenocrysts of albite. Such rocks are absent from the Potosi series, but they make up most of the rhyolite in the Hinsdale formation, the younger rhyolite of the Valles Mountains, New Mexico, the Sunshine Peak rhyolite, and some small intrusive bodies. These rocks are all low in CaO, and the sanidine phenocrysts carry more of the albite molecule than orthoclase. In all three rocks the relative proportions of albite and orthoclase are nearly the same in the sanidine phenocrysts and in the normative feldspar of the rocks in which they are found.

Figure 30 is a plot showing the relation between the CaO content of the rock and the orthoclase content of the sanidine phenocrysts. This curve shows a rather regular decrease in the orthoclase content of the sanidine phenocrysts, with decrease in the total lime content of the rocks in which they occur.

Significance to Petrogenesis

In Fig. 29 a curve has been drawn to show the field boundary between sanidine and plagioclase for the lavas of the San Juan region. This curve has a sharp turn at about 5 per cent of anorthite. This break in the curve may be due to the fact that the four points just above the break are for rocks without quartz, while the others have quartz. It may be due to some other complication or to imperfection of the data.

The field boundary between plagioclase and sanidine is of the eutectic type in liquids with over about 5 per cent of anorthite in the normative feldspar, but there is probably a reaction relation between the two feldspars in liquids with less anorthite. This is shown by the fact that in the course of crystallization the sanidines are low in soda in the early stages, become richer in soda as crystallization proceeds, and finally become richer in the albite molecule than the normative feldspar of the rock in which they occur. A reaction relation between sodic plagioclase and sanidine is also suggested by the fact that the plagioclase phenocrysts of the lavas of the San Juan region rarely become more sodic than calcic oligoclase, and in rocks more alkalic than those that carry such plagioclase, orthoclase forms the only feldspar phenocrysts.[47] Nearly all the rhyolitic rocks of the San Juan region that have plagioclase as the only feldspar fall in the plagioclase field.

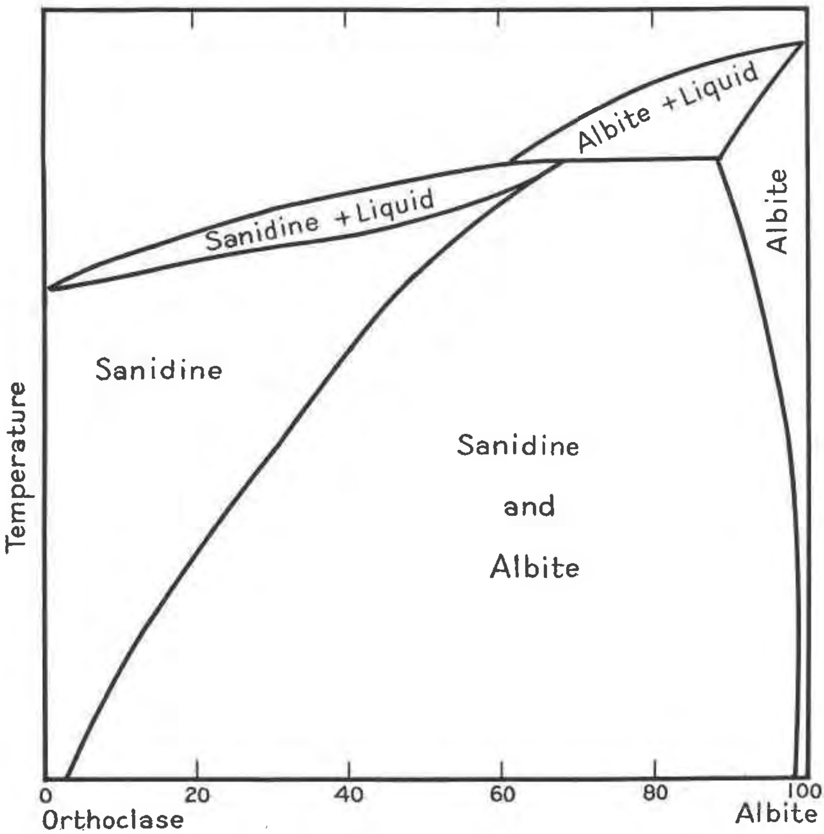

FIG. 31. Curve of crystallization of albite and orthoclase in rocks of the San Juan Mountains.

Figure 31 is a hypothetical curve of crystallization of albite and orthoclase as indicated by the rocks of the San Juan Mountains. This figure is a vertical section through the triangular diagram, orthoclase-albite-SiO_2+mineralizers and a small amount of other constituents, along the

[47] This Journal, vol. **23**, p. 244, 1938.

field boundary between quartz and feldspar. The system would have about 35 per cent of SiO_2, some mineralizers, and a small amount of other constituents in addition to orthoclase and albite.

The data in Figs. 29 and 31 can be used to explain the potash-rich rhyolites by a process of fractional crystallization, since the separation of soda-rich sanidine from rocks like those numbered 7 and 9 would enrich the liquid in potash. As the quartz and sanidine phenocrysts appear to be present in approximately the same proportion as they are present in the norm of the rock, the chief change in this process of separating crystals would be to increase the potash content and decrease that of soda. Such potash-rich rocks should be relatively high in silica, and low in lime and the femic constituents. In the variation diagrams of the lavas of the San Juan region and in rocks from other similar provinces, a few of the rocks at the extreme rhyolite end of the diagrams indicate a sharp increase in potash and decrease in soda, without much other change. These are the potash-rich rhyolites. Numerous rock analyses fall on the variation curves just before the change in slope of the curves for the alkalies, but very few fall on the steeper parts of the curves that represent the potash-rich rhyolites. It seems, therefore, that only under exceptional conditions does differentiation proceed to the potash-rich rocks.

9. MINOR ACCESSORIES

ESPER S. LARSEN

In nearly all the basaltic rocks the iron and iron-titanium oxides occur as black magnetite and ilmenite, except in the fragmental and highly vesicular rocks near volcanic vents and in other places where there is evidence of pneumatolytic action. In these red basaltic rocks the mafic minerals are commonly altered. A considerable number of the andesitic rocks, as well as nearly all of the rhyolitic rocks with felsitic groundmass, have the red iron oxide. The rhyolitic glasses, however, have the black iron oxide. In the rhyolites with glassy bases the glassy part has the black oxide, and the red oxide appears abruptly as the groundmass becomes microcrystalline. This abrupt change is well shown where red spherulites are imbedded in black obsidian. The change in the state of oxidation of the iron obviously took place with the crystallization of the groundmass.

Fluorapatite is present in small amount in all the lavas. Zircon is a very minor accessory in the rocks of the area, and it is in unusually small amount, or entirely lacking, in most of the biotite-augite-quartz latites and rhyolites of the Treasure Mountain quartz latite. Even when a heavy liquid and electromagnet concentration of the minerals of these rocks was made, many showed little or no zircon.

Sphene is a common accessory in the rocks. It is nearly as abundant, and in nearly as large phenocrysts, as biotite or hornblende in many of the quartz latites of the Alboroto and Piedra formations. Here sphene is associated with phenocrysts of orthoclase, quartz, plagioclase, biotite, hornblende, and in some cases augite; while it is lacking, or in small amount, in the Treasure Mountain quartz latite, which has about the same chemical composition as the Piedra and Alboroto rocks, but which has phenocrysts of plagioclase, biotite and augite. In general, sphene appears to be more abundant in rocks with hornblende.

Augite and hornblende are present in very small amount in the rhyolites of the area and are found only in a small proportion of the thin sections. However, they are found in small amount—less than 0.1 per cent—in most of the rhyolites, if grains of powdered rock are separated with bromoform and an electromagnet.

10. SUMMARY AND CONCLUSIONS

The volcanic rocks of the San Juan region of Colorado form a great pile that is about 100 miles across and that exceeds 5000 feet in thickness over much of this area. They have been studied in some detail and have been mapped as stratigraphic units. Each unit is composed of many flows and clastic beds. They range in age from Miocene to Quaternary. Long intervals of erosion separate several of the formations. Most of the chemical analyses of the rocks fall near a smooth variation diagram.

The three silica minerals, quartz, tridymite and cristobalite, are abundant in the province and present in nearly equal amounts. Quartz is found as phenocrysts in many of the rhyolitic rocks, as rare foreign grains in a few of the andesites and olivine basalts, and in the groundmasses of some of the lavas, especially in the less siliceous lavas. Tridymite is present in the porous parts of many of the rhyolitic rocks, and in the coarser streaks of the groundmass. It also cements some of the rhyolite tuffs. It is present in the cavities of some of the andesites and basalts. Cristobalite is present as rounded balls perched on the walls of the larger gas cavities of the andesites and basalts, and intergrown with feldspar in the spherulites and dense microfelsitic groundmasses of the rhyolitic rocks. Tridymite crystallized as an unstable form in the presence of abundant mineralizers. Cristobalite also crystallized as an unstable form, either by gas transfer in the larger gas cavities or where crystallization was rapid and not "lubricated" by mineralizers.

Clinopyroxene is the chief mafic mineral in most of the andesites and basalts. It is present with biotite or biotite and hornblende in many of the quartz latites, and it is present in small amount in some of the rhyolites. In the basalts it is interstitial to the feldspar and is of the pigeonite variety. In the other rocks it forms phenocrysts with or without hypersthene and is augite with a moderate iron content.

Hypersthene is rare in rocks with less than 54 per cent of SiO_2, it is present in most of the rocks with from 57 to 59 per cent of SiO_2, and is uncommon in most rocks with more than 65 per cent of SiO_2.

Olivine occurs in rocks with as much as 56 per cent of SiO_2, and as much as 12 per cent of normative quartz.

In any rock the ratio MgO/Fe_2O_3+MnO is fairly systematic between the augites and olivines, and it is larger in the olivines than in the augites. In the hypersthene this ratio is less systematic but is commonly nearly the same as in the augites that accompany the hypersthene.

The pyroxene phenocrysts in rocks of about the same chemical composition show considerable variation in iron content, and there is no systematic variation in the iron content of the pyroxenes in rocks that range from pyroxene andesite to rhyolite.

Hornblende is absent from lavas with less than 53 per cent of SiO_2, and biotite is rare in rocks with less than 57 per cent of SiO_2. Both biotite and hornblende are less abundant in andesites than in latite-andesites, and they are both present in most of the quartz latites. Biotite is commonly the only mafic mineral in the rhyolites except for traces of augite and hornblende. In three formations, each widespread and made up of many flows, the quartz latites have essentially the same range in chemical composition, but the rocks of one formation have phenocrysts of orthoclase, quartz, plagioclase, biotite, hornblende, sphene and augite; those of another lack augite, but otherwise have the same phenocrysts; and those of a third, have phenocrysts of augite, biotite and plagioclase.

The hornblendes vary from green hornblende, in which about two-thirds of the iron is in the ferrous state, to basaltic hornblende in which over 80 per cent of the iron is in the ferric state. The biotites vary from those in which most of the iron is FeO ($\beta=1.63$), to those in which the iron is almost entirely Fe_2O_3 ($\beta=1.75$). In both the hornblendes and biotites the chief chemical difference between the varieties is in the state of oxidation of the iron.

Resorption of the hornblende and biotite is more extensive in the andesites than in the rhyolites, and it is nearly absent in the glassy rocks. In the early stages of the resorption of these minerals, the pyroxene and iron oxide remain near the original hornblende or biotite crystals; as the process proceeds they are more widely scattered in the groundmass; and finally, in the centers of some of the granular intrusive bodies, all evidence of the original minerals is destroyed and ordinary-looking pyroxene rocks result.

The resorption of hornblende and biotite, and the oxidation of the iron in these minerals, are favored by near-surface conditions. In part these changes took place before the rocks reached the surface, but a large part took place after eruption. Both the resorption of these minerals and the oxidation of their iron are less extensive in the glassy rocks than in the more slowly cooled rocks with crystalline groundmasses. Both these processes are associated with loss of water by the magma, and water may be the oxidizing agent.

The crystallization of biotite and hornblende rather than pyroxene is largely determined by abundance of water in the magma.

In the basalts, plagioclase phenocrysts are very rare and in the silica-rich rhyolites they are absent, or present in very small amount. All the plagioclase phenocrysts have some zoning. In about 10 per cent of the lavas some of the plagioclase phenocrysts have cores that have from 10 to 30 per cent more anorthite than the main outer part, and an equal number of the rocks have plagioclase with cores that have from 10 to 30 per cent less anorthite than the main plagioclase. Both the calcic and sodic cores show extensive resorption and are sharply bounded against the outer zone. About 15 per cent of the rocks have plagioclase phenocrysts of two kinds that differ in anorthite content by from 10 to 30 per cent.

Plots of the anorthite content of the plagioclase phenocrysts against chemical composition of the rocks in which they occur, or against the groundmass or normative plagioclase of the rocks, or the groundmasses in which they occur, show little relation between the plagioclase phenocrysts and the inclosing rocks. In the andesite basalts the plagioclase phenocrysts range from An_{20} to An_{82}; in the quartz latites, near the rhyolites, they range from An_{12} to An_{55}. The average plagioclase in the basalts is more calcic than those in the andesites, and they are still less calcic in the average quartz latite.

By using only those rocks that appear from the microscopic study to have plagioclase phenocrysts that crystallized in place, a curve for the course of crystallization of the plagioclase of the lavas in the San Juan region is drawn. It is very different from the curve derived from the melting phenomena of the plagioclase. In many of the rhyolites the plagioclase phenocrysts contain about 25 to 30 per cent of anorthite, and more sodic feldspars are very rare.

Phenocrysts of labradorite contain only one or two per cent of the orthoclase molecule, those of andesine have about 6 per cent, and those of oligoclase-andesine, from 8 to 12 per cent.

The alkalic feldspar phenocrysts are all of the sanidine variety. They are present in very few of the basalts, andesites and andesitic quartz latites, and where present in such rocks there is good evidence that they are foreign crystals. Sanidine phenocrysts are present in nearly half the rhyolitic quartz latites and in most of the lime-poor rhyolites. In the quartz latites they are invariably associated with oligoclase or sodic andesine and, in some rocks, with quartz. In the rhyolites they are associated with quartz and rare albite.

The anorthite content of the sanidine phenocrysts ranges from $1\frac{1}{2}$ to $3\frac{1}{2}$ per cent. The albite content of sanidines from quartz latites, which have about 3.7 per cent of CaO, is 25 per cent. It increases as the lime in the rock decreases, and the sanidine from ryholites with about a tenth of a per cent of CaO contains 55 to 57 per cent of albite. In the quartz latites the sanidine contains a much larger proportion of potash feldspar than the normative feldspar of the enclosing rock, whereas in the lime-poor rhyolites it contains as much or even more. These data indicate a reaction relation between orthoclase and plagioclase in such rocks, and show that separation of quartz and sanidine from an ordinary rhyolite can form a potash-rich rhyolite.

The indices of refraction of sanidine with 25 per cent of the albite molecule are: $\alpha=1.522$, $\beta=1.527$, $\gamma=1.527$; those for sanidine with 55 per cent of the albite molcule are $\alpha=1.525$, $\beta=1.530$, $\gamma=1.531$.

Many of the plagioclase and other phenocrysts of the lavas of the San Juan region did not crystallize from a magma of the composition of the rock in which we find them, but must have been derived from the partial assimilation of other rocks, or by the mixing of two magmas, one or both of which carried crystals. The quartz and sanidine phenocrysts in the andesites and basalts must be foreign. The uniform distribution of the phenocrysts in widespread lava flows, and groups of flows, show that there must have been a thorough mixing of very large masses of magma.