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

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7. THE PLAGIOCLASE FELDSPARS

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Contents

Occurrence

Plagioclase is the chief mineral among the phenocrysts of the San Juan lavas. In the basalts, plagioclase phenocrysts are generally absent; in the pyroxene andesites they are almost invariably present but in moderate amount; they are present in nearly all the rocks between andesite-latite and latite-rhyolite. They decrease in amount in the rhyolites, and some of the silica-rich rhyolites carry no plagioclase phenocrysts at all.

In most of the rocks the phenocrysts are fairly uniform in size and average about 3 to 5 millimeters in length. Exceptional rocks from nearly all the formations have much larger crystals—up to or exceeding 20 millimeters in length. The Fisher and Los Pinos latite-andesites and some of the Hinsdale andesite-basalt commonly have large phenocrysts.

In the basalts and pyroxene andesites the plagioclase phenocrysts form thin plates, but in the more siliceous rocks they occur in thicker tablets.

Method of Determining the Plagioclase

In this study the plagioclases were determined in thin section by the usual methods. In some of the zoned feldspars the Fedorov stage was used. In every specimen the final and most reliable determination was made by measuring the indices of refraction by the immersion method. For rocks with abundant plagioclase, a part of the powdered rock was used, otherwise the feldspar was concentrated by removing most of the femic minerals and the groundmass with an electromagnet or a heavy liquid. The determinations are believed to be correct to within about $\pm 3\%$ of the anorthite content.

Variation in the Composition of Plagioclase in a Single Rock

Types of Variation

Homma[32] has given an excellent and detailed classification of the types of zoning in plagioclase. Nearly all of Homma's types have been found in the San Juan lavas, but the commonest are the three varieties of wavy-oscillatory; namely, irregular-oscillatory, normal oscillatory and non-oscillatory. In most of the specimens there is considerable variation in the types of zoning, and even a single crystal may show some variation in different parts. However, unless the rock has two distinct feldspars, there is some system in the variation, and much of the lack of uniformity is due to absence of a core or a zone, or due to the thickening or thinning of zones, or the manner in which the crystal is cut by the thin section. Two types of multiple structures in which there is a change in the composition, usually accompanied by resorption, are also common in San Juan lavas.

The following is a simplification of Homma's classification of the varia-

[32] Homma F., The classification of the zonal structure of plagioclase: *Mem. College Sci., Kyota Imp. Univ.*, Ser. B., vol. **11**, pp. 135–155, 1936.

tions in the plagioclase of a single rock, which for the present purpose seems desirable.

Even (with little variation in composition)

The calcic phenocrysts of some of the basalts and pyroxene andesites are rather uniform in composition, except for a thin sodic envelope. Such phenocrysts commonly have "checkerboard" inclusions of the groundmass.

The plagioclase crystals of some of the granular rocks are nearly homogeneous as are those in many of the basalts which lack plagioclase phenocrysts. Also the plagioclase in the groundmass of some of the other rocks possess fairly uniform composition.

Normal

Feldspars that become more sodic from center to border are the main type found in the San Juan lavas, but they usually show an irregular gradation with some interruptions and oscillations.

Reverse

Feldspars that become progressively more calcic from the center to the border are rare in the San Juan lavas.

Oscillatory

Homma subdivides oscillatory zoning into 15 types. Most of his types are present in the San Juan lavas. Probably the commonest type, and the type that shows the most conspicuous oscillatory zoning, is Homma's wavy-oscillatory-even, in which the variations are similar to sine curves with little change in average composition from center to border. One crystal shows 30 rather even oscillations. The maximum difference in composition between different zones is seldom over 10 per cent anorthite. Commonly there are one or more very thin layers that are much more calcic than the others. Oscillatory zoning appears to be most common and well developed in the andesitic rocks and in feldspars with compositions ranging between An_{35} and An_{50}. It was not found in bytownite.

Calcic Cores (multiple promoted)

Feldspars of this type, with calcic cores which have sharp boundaries in contact with the more sodic outer part, are common but are not easily distinguished from feldspars with gradational zoning. The calcic cores are usually rounded and irregularly embayed as a result of resorption before the outer sodic zone was deposited. In some crystals only a skeleton of the original calcic core is left. Of the seventy rocks examined that contain plagioclase phenocrysts, eight show conspicuously this type of zoning with differences between the core and outer shell of from 11 to 31 per cent in anorthite content. Many of the other rocks show a less conspicuous zoning of this type.

Figure 15*a* shows a feldspar of this type from the Los Pinos andesite (Con. a) of Green Ridge in the Conejos quadrangle. In the diagram to the right of the photograph, the composition of the zoned feldspar is plotted from the center to the border of the crystal according to Homma.[33] The core of this crystal is composed of a fine irregular mixture of two feldspars of very different compositions. The more sodic one occurs in patches and is replacing the more calcic portion. The diagram showing change in composition is diagrammatic for the core as the intergrowths are too fine to show on the scale used. Only a few of the plagioclase phenocrysts of this rock show calcic cores.

Sodic Cores (multiple retarded)

These feldspars have sodic cores and sharply separated more calcic outer zones. The less complex of these show a clear core of sodic composition with a rounded or embayed outline; a clouded intermediate zone, whose outer border is likewise rounded or embayed; and an outer zone that is clear and calcic in composition. The intermediate clouded layer in some crystals extinguishes approximately with the core, in others, approximately with the outer zone, and in some crystals it gives a moderate extinction with either the core or the border and a slight extinction with the other. This cloudy zone is a very fine intimate mixture of the groundmass, the core, and the border feldspars.

Illustrations of this type of zoning are shown in figures 15*b* and 16. Figure 15*b* represents a feldspar in a quartz basalt from a flow in the Santa Fe formation in Santa Clara Creek, near Espanola, New Mexico. Nearly all the phenocrysts of this rock show somewhat similar zoning. In this crystal the core is clear; the clouded zone contains some groundmass, and abundant patches sufficiently large to give clear extinctions that are a little more calcic than the core. Some less distinct patches are present that have nearly the composition of the outer rim. Figure 16 shows three feldspar crystals from the Antone quartz basalt of Cerro Ortez, New Mexico (NM 213). Nearly all the plagioclase phenocrysts of the rock show similar zoning. The rock has a few large grains of sanidine. In 16*a* the clouded zone is a mixture of groundmass and a feldspar of composition near that of the core, but some approaches that of the calcic

[33] *Loc. cit.*

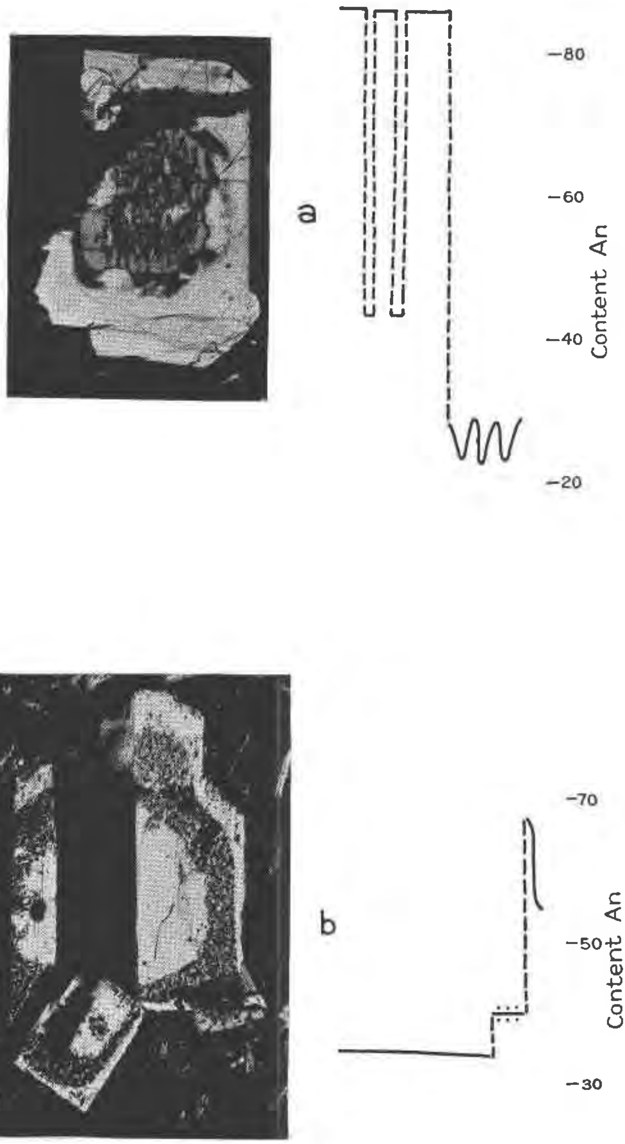

FIG. 15. Zoning in plagioclase. Photographs ×55, plots ×110.
(a) Los Pinos andesite. Shows calcic cores partly replaced by more sodic feldspar.
(b) Quartz basalt. Shows sodic cores.

part of the outer border. In 16*b* the clouded zone is made up chiefly of a feldspar more calcic than the core. In 16*c* the mottled central area is composed of a coarse mixture of groundmass, clear plagioclase like that of the calcic inner part of the clear border, and some thin layers next to the groundmass that are more sodic.

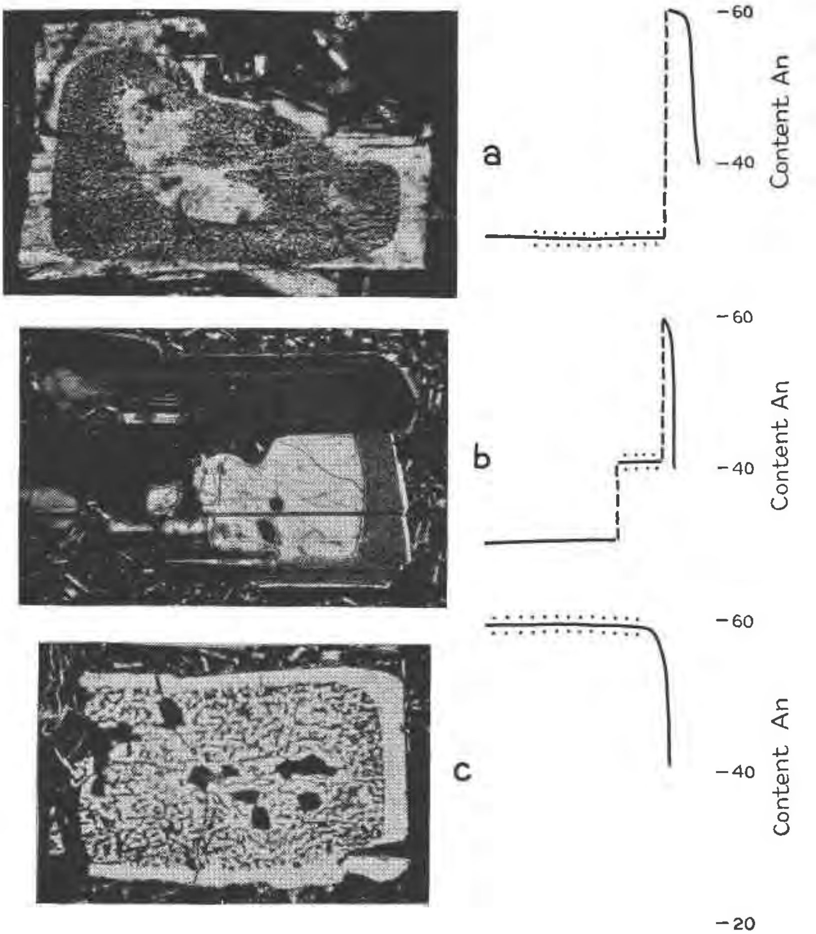

FIG. 16. Zoned plagioclase from Antone quartz basalt. Photographs and plots, ×60.

Feldspars with this type of zoning, with differences in anorthite content of the two zones ranging from 12 to 30 per cent were found in seven of the seventy rocks included in this study. They are especially common in the quartz basalts but were found likewise in some andesitic rocks.

Some of the phenocrysts show a multiple structure with two or more sharp breaks, usually with resorption. One such phenocryst from the Conejos andesite (Con 320) is shown in figure 17. It contains a small central area of An_{60}; around this is a broad band with oscillatory zoning averaging An_{46}; next is a rather narrow band with some zoning and composition of An_{33}. The outline of this latter zone is rounded by resorption. Outside this is a rather narrow zone that grades from An_{56}, near the inner portion, to An_{45} at its border. The four main zones are all rather sharply bounded.

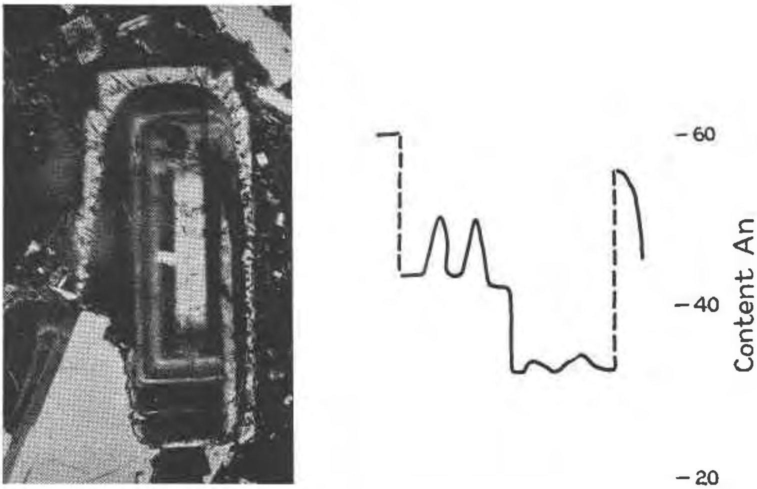

FIG. 17. Zoned plagioclase from Conejos andesite. Photograph ×70, plot ×175.

Two Types of Feldspar

Fifteen per cent of the San Juan lavas, varying from andesites to rhyolites, show two distinct types of feldspar phenocrysts. A good example is the obsidian from No Agua volcano, New Mexico. This glass has only a half per cent of feldsparphenocrysts, about a millimeter across, of which approximately 95 per cent are albite-oligoclase (An_{11}) and 5 per cent oligoclase-andesine (An_{30}). The two are in separate crystals and both show slight zoning. A Piedra quartz latite (Lag 1221) has some crystals of An_{29} and a smaller number of An_{46}. Both show moderate zoning. Conejos andesite (Con 591) has some feldspar with thin albite twin lamellae, very fine recurrent zoning without much change in composition, averaging An_{62}; also another feldspar with broad albite lamellae, large cores of An_{28} and wide borders of An_{41}. Some phenocrysts of this latter type contain remnants of a core of An_{36} enclosed in the An_{28}. A

Fisher quartz latite (Lag 2137) with phenocrysts of sanidine up to 30 millimeters long, and smaller ones of plagioclase, quartz, biotite, and hornblende, has two kinds of plagioclase phenocrysts. Some have moderate zoning (± 5 per cent anorthite) and average An_{55}; others have broad gradational zoning with cores of An_{40} and wide borders of An_{20}. Also a layer of sodic plagioclase encloses the rounded and resorbed sanidine crystals.

Feldspars near andesine in composition show more prominent zoning, especially of the oscillatory and complex types, than do those of more sodic or calcic types. Quartz latites commonly have broken crystals of oligoclase which have the normal type of zoning without much change in composition, except where calcic cores are found.

Chemical Analyses

F. A. Gonyer has made complete analyses of four plagioclases from the San Juan lavas and partial analyses of five others. These are listed in Table 5. All of the analyzed feldspars showed some zoning. None of the analyses shows an appreciable deficiency in SiO_2 compared with the theoretical composition, but those of NM 3004 and SC xx show an excess of 2.4 per cent SiO_2, and NM 3 has an excess of 4.6 per cent.

All the plagioclases contain appreciable amounts of K_2O; the amount is low in the calcic members but increases with the soda content. In terms of orthoclase, the calcic labradorites have about 1 part of orthoclase to 18 parts of albite plus orthoclase, whereas the andesines have from 1 part to 5, to 1 part to 10, averaging about 1 part to 7; the oligoclase-andesines have 1 part to 9; and the albite-oligoclase has only 1 part to 14.

In the table the analyses and the composition of the feldspar calculated from them are followed by the average anorthite content of the plagioclases and the range of the zoned feldspar, as determined by the immersion method on part of the same powder used in the analyses. The check with the chemical analyses is surprisingly close; in only one case was the deviation as much as 4 per cent, although the minerals were zoned and the averages had to be estimated. Determinations in thin sections using the following methods: (1) Carlsbad and albite twins, (2) normal to (010) and (001), (3) parallel to (010), (4) maximum extinction, and others, checked nearly as closely.

TABLE 5. ANALYSES OF PLAGIOCLASES

	1	2	3	4	5	6	7	8	9
SiO_2		53.18			59.07		59.20		65.81
Al_2O_3		28.81			25.33		24.55		20.86
Fe_2O_3		1.15			0.26		1.40		0.65
FeO									n. d.
MgO		none					0.14		none
CaO	13.02	12.01	9.15	6.01	8.60	6.71	7.09	5.31	2.19
Na_2O	3.65	4.11	5.30	6.86	6.24	6.01	5.97	6.69	8.98
K_2O	0.22	0.32	1.03	1.22	0.91	2.12	1.76	1.14	1.12
H_2O+		0.29			none		0.30		0.15
		99.87			100.41		100.41		99.76
Composition in weight per cent calculated from analyses to 100% feldspar									
Or	1	2	6+	8−	$5\frac{1}{2}$	$12\frac{1}{2}$	11	8	7
Ab	32	36	$46\frac{1}{2}$	61	52+	53	$52\frac{1}{2}$	63	$81\frac{1}{2}$
An	67	62	$47\frac{1}{2}$	31+	42+	$34\frac{1}{2}$	$36\frac{1}{2}$	29	$11\frac{1}{2}$
Anorthite content from optical properties									
Anorthite average	69	60	47	28	40	35	40	27	$10\frac{1}{2}$
Anorthite range	72	61	50	41	38	39	26	17	
	64	57	40	19	42	29	52	40	

1. Plagioclase from the groundmass of the Antone Peak basalt (NM 5) from Buffalo Butte, N. Mex. The rock has no plagioclase phenocrysts.
2. Plagioclase from the groundmass of the Hinsdale basalt (NM 402), railroad cut near Servilleta Plaga, N. Mex. The rock has no plagioclase phenocrysts.
3. Plagioclase phenocrysts from Sheep Mountain andesite (SV 9) from Summitville quadrangle.
4. Plagioclase phenocrysts from Alboroto quartz latite (Up 413), Uncompahgre quadrangle.
5. Plagioclase phenocrysts from Los Pinos latite-andesite, Conejos quandrangle, north of Green Ridge and near Goat Ranch.
6. Plagioclase phenocrysts from Alboroto latite (DN 2017), Del Norte quadrangle. Quarry 4 miles southeast of Del Norte.
7. Plagioclase phenocrysts from Piedra quartz latite (SC xx glass base analyzed), eastern part of San Cristobal quadrangle, near road north of Rio Grande and north of mouth of Spring Creek.
8. Plagioclase phenocrysts from Alboroto tridymite rhyolite (Up 3027). Uncompahgre quadrangle, east of Pine Creek, along road to Pine Creek Mesa.
9. Plagioclase phenocrysts from Hinsdale obsidian of No Agua volcano (NM 3) just east of No Agua, N. Mex. The rock has about $\frac{1}{2}$ per cent of plagioclase phenocrysts, about 1 millimeter across and no other phenocrysts. 95 per cent of the plagioclase is of the type analyzed, with $\alpha=1.534$, $\beta=1.539$, $\gamma=1.542$, and 5 per cent has $\alpha=1.543$, $\beta=1.547$, $\gamma=1.551$ and has the composition An_{30}. Neither type shows much zoning and no crystals of intermediate composition were found.

Statistical Study

Relation between Composition of Rock and its Plagioclase

A statistical study of the plagioclase phenocrysts, plotted against different characteristics of the rocks in which they occur, has been made, and some of these plots are reproduced in this paper. Plagioclase phenocrysts from 70 analyzed rocks are included in the plots.

In figure 18 the anorthite content of the phenocrysts is plotted against the composition of the rocks (rhyolite to basalt) in which they occur; and in figure 19 the composition of the anorthite content of the phenocrysts is plotted against that of the groundmasses.[34]

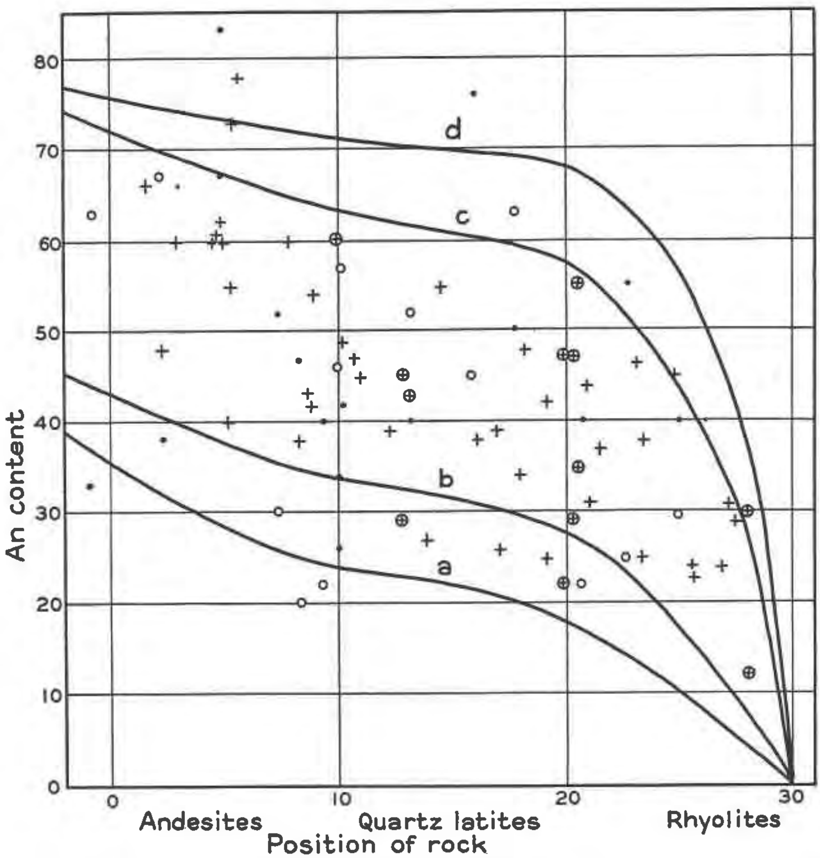

Fig. 18. The anorthite content of the plagioclase phenocrysts plotted against the compositions of the rocks in which they occur

[34] The groundmasses were calculated from rock analyses and the phenocrysts by Rosiwal determinations.

The crosses represent phenocrysts with ordinary zoning; the dots represent the cores, and the circles the outer shells of feldspars with sharp breaks, and resorption between the cores and the outer rims; the circled crosses represent one of two different feldspars in a rock. Where one of these has cores it is represented by a dot and a circle.

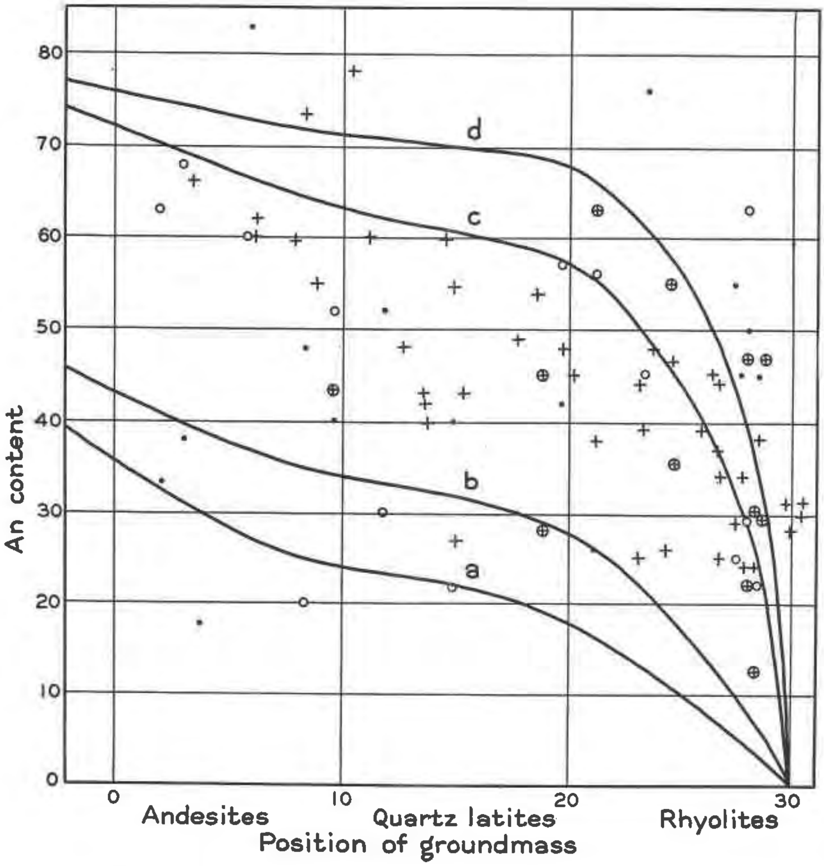

FIG. 19. The anorthite content of the plagioclase phenocrysts plotted against the compositions of the groundmasses. Conventions as in figure 18.

In these figures, the lower curve (*a*) represents the anorthite content of the normative feldspar $\left(\frac{\text{an}}{\text{or}+\text{ab}+\text{an}}\right)$ of the rock or groundmass; the second curve (*b*) represents the normative anorthite of the plagioclase $\left(\frac{\text{an}}{\text{ab}+\text{an}}\right)$; the third curve (*c*) represents the plagioclase in equilibrium with a liquid which has the anorthite content of this feldspar (curve *d*), as shown by Bowen's[35] equilibrium diagram for the plagioclases (adding the or to the ab); the upper curve (*d*) represents the feldspar in equilibrium with a liquid with the anorthite content of the plagioclase (curve *b*).

Figure 20 is plotted in the same way as figure 18, but only those plagioclases were plotted that were believed from the thin-section study to have crystallized from the liquid which solidified to form the rock of which they are a part.

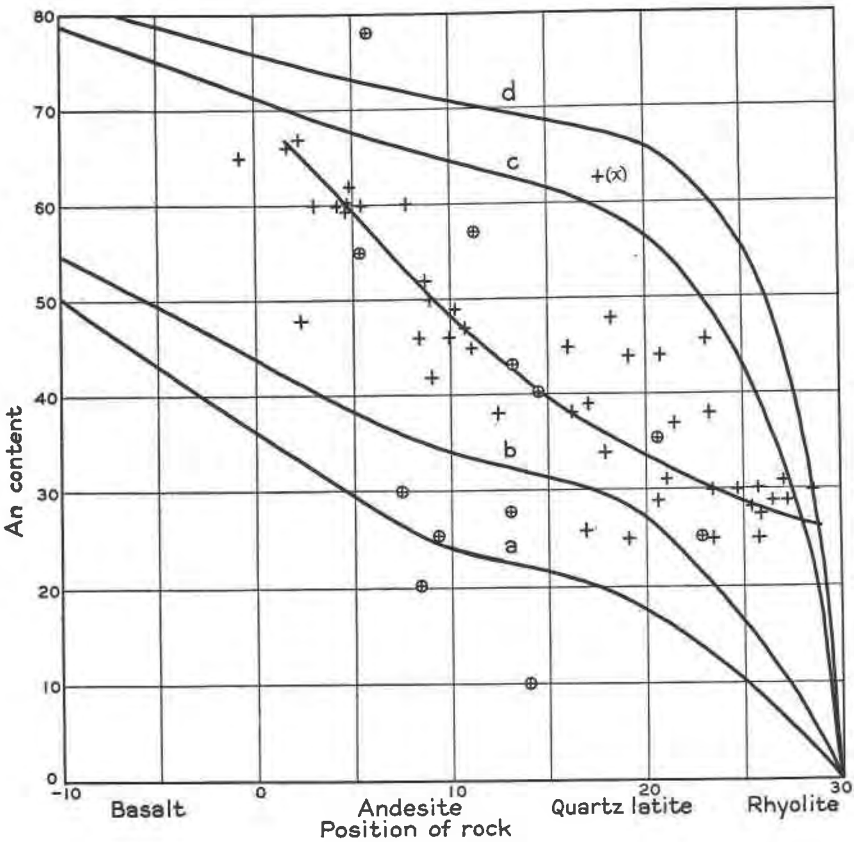

FIG. 20. Plagioclase phenocrysts that appear to have crystallized from the melt that solidified to form the rock in which they are now found, plotted against the composition of that rock. The circled crosses are less reliable than the crosses.

[35] Bowen, N. L., The melting phenomena of the plagioclase feldspars; *Am. Jour. Sc.*, vol. **35,** p. 583, 1913.

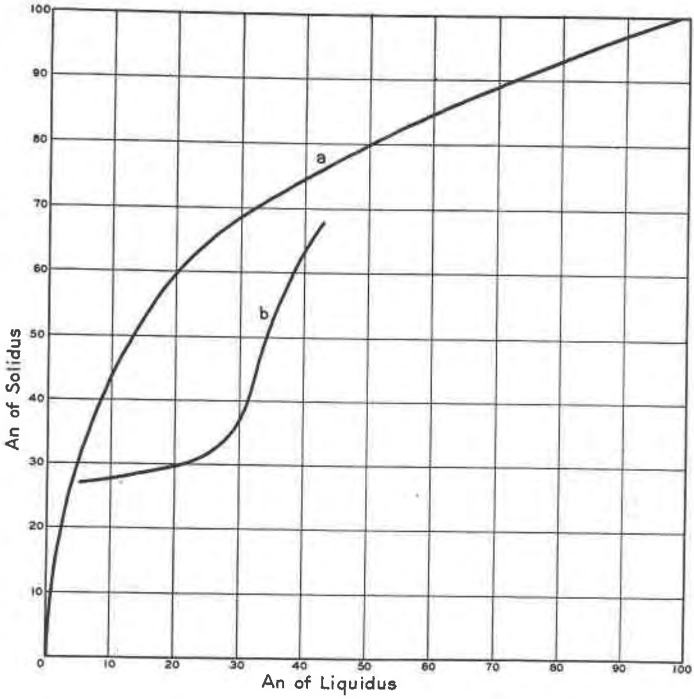

FIG. 21. Plagioclase in equilibrium with melts of various compositions. Curve *a* is constructed from the melting curves of Bowen, curve *b*, from the data of the San Juan lavas (figure 20).

Figure 21 is a plot showing the plagioclase in equilibrium with melts of all proportions of Ab and An, according to the equilibrium diagram (curve *a*), and according to the curve of crystallization for the San Juan lavas as shown in figure 20 (curve *b*). In figures 22 and 23 the anorthite contents of the plagioclase phenocrysts are plotted against the anorthite contents of the normative plagioclases and feldspars, respectively, of the rocks in which they occur. Figure 24 shows the relation between the anorthite content of plagioclase phenocrysts and the anorthite content of the normative plagioclase of the groundmasses, and figure 25 the relation of anorthite content of phenocrysts to the anorthite in the total normative feldspars of the groundmasses. In the last four figures, the diagonal line represents the anorthite content of the feldspars of the rock or the groundmasses, and the curve represents the anorthite content of the feldspar in equilibrium with a liquid of the composition of the normative feldspar.

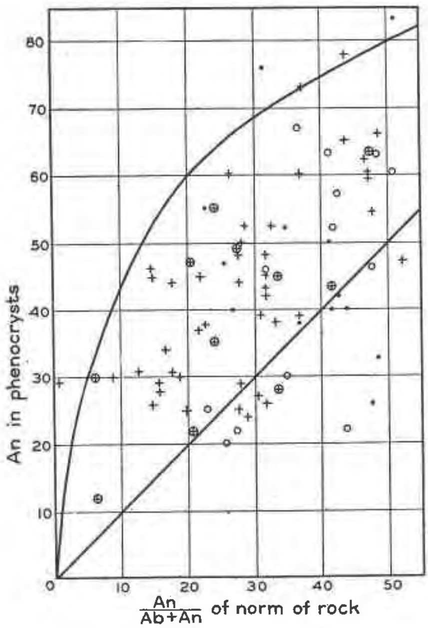

FIG. 22

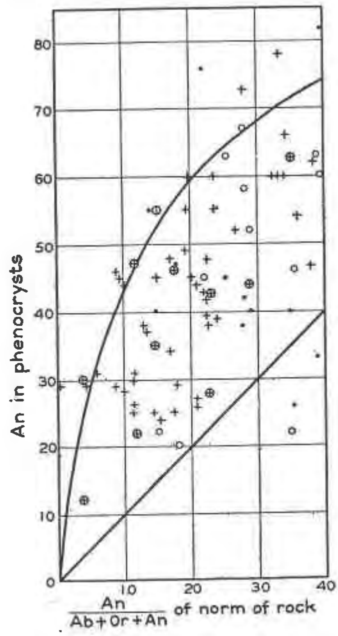

FIG. 23

FIG. 22. Anorthite content of plagioclase phenocrysts plotted against anorthite content of normative plagioclase (an/an+ab) of the rocks in which they occur. Conventions as in figure 18.

FIG. 23. Anorthite content of plagioclase phenocrysts plotted against anorthite content of the normative feldspar (an/an+ab+or) of the rocks in which they occur. Conventions as in figure 18.

The plots show that the plagioclase phenocrysts range from An_{11} to An_{83}, but by far the greater part are between An_{22} and An_{67}. About half of the rocks, whose normative feldspar has less than 13 per cent An, carry plagioclase phenocrysts, but nearly all the rocks with more calcic normative feldspar have them, excepting the basaltic types.

No satisfactory curve can be drawn to show the relation between the composition of the plagioclase phenocrysts and the composition of the rock, or the groundmass, or the anorthite content of the feldspar of the rock or groundmass. For all such curves the rocks or groundmasses of about the same compositions have phenocrysts that vary from 30 to 50 per cent or more in anorthite content.

In figure 20 that portion of the plagioclase phenocrysts that appear to have crystallized from the magma of the rock in which they were finally frozen is plotted against the composition of the rock, and in this plot there is sufficient clustering of points to justify drawing a curve. The point that deviates most (marked x) represents a rock that has 1.4 per

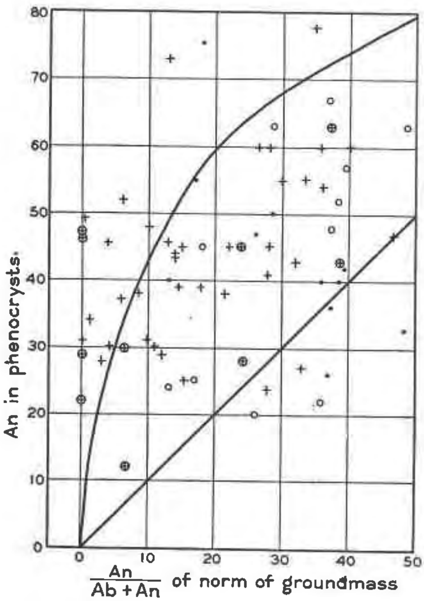

FIG. 24

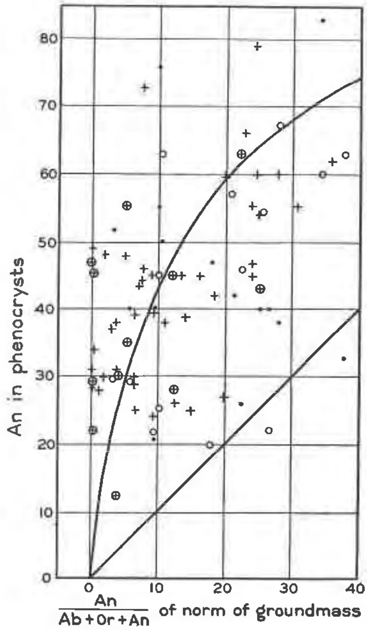

FIG. 25

FIG. 24. Anorthite content of plagioclase phenocrysts plotted against the anorthite content of the normative plagioclase (an/an+or) of the groundmasses of the rocks in which they occur. Conventions as in figure 18.

FIG. 25. Anorthite content of plagioclase phenocrysts plotted against the anorthite content of the normative feldspar (an/an+ab+or) of the groundmasses of the rocks in which they occur. Conventions as in figure 18.

cent less Na_2O than other rocks of about the same composition and is therefore abnormal. The feldspars used in figure 20 were plotted against the composition of the plagioclase and of the total feldspar of the rock in which they are found. They fall in a broad zone but yield a poorer curve than that shown in figure 20.

Points are clustered at the extreme rhyolite end, at about 24 to 30 per cent of anorthite, and this appears to be the lowest anorthite content of phenocrysts that is present in appreciable amounts. The extreme outer zone of many of the plagioclases is more sodic but this portion is present only in very small amount, as the total percentage of plagioclase phenocrysts in these rocks is less than ten.

In most of the plots nearly all the phenocrysts fall between the curves of the anorthite content of the normative feldspar (or plagioclase) of the rock or groundmass, and of the feldspar in equilibrium with a liquid of that composition. The curve for the plagioclase phenocrysts in equilibrium with the groundmass feldspar, obtained by plotting phenocrysts against anorthite content or total feldspar of the groundmass (Fig. 19), comes nearer to fitting the plotted points than any other.

The relation between the composition of the rocks and groundmasses, and the proportion and composition of the plagioclase phenocrysts is shown in Table 6.

TABLE 6. COMPOSITION AND AMOUNT OF PLAGIOCLASE PHENOCRYSTS IN ROCKS AND GROUNDMASSES OF DIFFERENT COMPOSITION

Rocks		Number of rocks		Per cent of plagioclase phenocrysts		Composition of plagioclase phenocrysts	
		lacking plagioclase phenocrysts	carrying plagioclase phenocrysts	Range	Average	Range An.	Average An.
Basalts	−10 to −5	4	1	0 to 2	1	—	70
	−5 to 0	0	2	2 to 3	2	42 to 63	54
Andesites	0 to 5	2	9	0 to 40	11	35 to 82	60
Quartz Latites	5 to 10	0	13	1 to 38	17	20 to 78	49
	10 to 15	0	11	1 to 33	16	22 to 64	43
	15 to 20	0	10	17 to 30	26	25 to 63	39
Rhyolites	20 to 25	0	14	3 to 27	14	22 to 55	38
	25 to 30	3	7	0 to 16	5	12 to 31	27
Groundmasses	−10 to −5	1	1	0 to 1	1	—	70
	− 5 to 0	3	1	0 to 2	1	—	65
	0 to 5	2	3	0 to 22	5	30 to 66	63
	5 to 10	0	7	2 to 23	6	20 to 82	63
	10 to 15	0	10	1 to 38	15	30 to 78	50
	15 to 20	0	9	8 to 28	20	22 to 60	45
	20 to 25	0	13	4 to 39	19	25 to 63	43
	25 to 30	3	21	0 to 31	14	11 to 62	35
	30 to 35	0	2	4 to 8	6	30 to 31	31

The proportion of plagioclase phenocrysts is low in the basalts, high in the andesites and quartz latites, and low in the siliceous rhyolites. Compared with the composition of the groundmasses, the plagioclase phenocrysts are low in amount where the groundmass is basaltic, rather low where andesitic, high where it has the composition of quartz latite and less siliceous rhyolite, and low where it is highly siliceous.

The average composition of the plagioclase phenocrysts changes progressively from An_{70} in the basalts to An_{27} in the siliceous rhyolites. Many of the siliceous rhyolites and basalts lack plagioclase phenocrysts.

As a further study of the plagioclase in the rhyolitic rocks, forty-four such rocks from six of the formations were studied. Most of these rocks were not analyzed, but their compositions were determined with the microscope. The rocks varied from rhyolites to quartz latites near the rhyolites. No quartz latites near the andesites were used. Five of the rocks contained plagioclase phenocrysts that were strongly zoned or were of two kinds, and these rocks were disregarded. Table 7 gives the data on the feldspar of these rocks.

TABLE 7. DATA ON PLAGIOCLASE PHENOCRYSTS IN RHYOLITIC ROCKS

Per cent of sanidine in feldspar phenocrysts	Number and kind of rocks	Anorthite content of plagioclase phenocrysts	
		Range	Average
100	3 rhyolites	—	—
99 to 66	7 rhyolites	29 to 33	30
	2 rhyolites	—	7[a]
66 to 33	4 rhyolites	24 to 35	27
	1 rhyolite-latite		34
33 to 1	3 quartz latites	25 to 35	30
	5 rhyolite-latites	25 to 47	36
0	1 quartz latite		40
	5 rhyolite-latites	29 to 50	40
	7 rhyolites	24 to 45	33

[a] One of these is a Willow Creek rhyolite from near the mines at Creede. It is somewhat altered and may have been albitized.

This table confirms the conclusion, drawn from the smaller amount of data obtained from the analyzed rocks, that in the extreme rhyolites, and especially in the rocks with much more abundant phenocrysts of sanidine than of plagioclase, the plagioclase has the composition An_{30}. Most of these rocks have less than 10 per cent of phenocrysts and less than 2 per cent of plagioclase. They have less than 1.2 per cent of CaO and only a few per cent of normative anorthite. To this group belong the rocks called "cavernous rhyolite" in the field. They are present in, and form an appreciable part of, all three of the rhyolitic members of the Potosi series and form widespread, thick flows. In many places they are at the base of the rhyolitic formations and filled in the valleys and other irregularities of the surfaces on which the formations spread.

Plagioclase in Relation to Other Phenocrysts

Table 8 shows the result of taking into consideration the phenocrysts associated with the plagioclase.

TABLE 8. RELATION BETWEEN PHENOCRYSTS IN LAVAS AND CHARACTER OF PLAGIOCLASE

Phenocrysts	No. of rocks	No. with multiple zoning		No. with two plagioclases	Average composition of plagioclase phenocrysts	Remarks
		(calcic cores)	(sodic cores)			
Olivine (no quartz)	4				Calcic	Plagioclase phenocrysts absent in most.
Olivine+ quartz	5	2	2		Outer zone mostly calcic	
Pyroxene ±biotite	2	1			Average	
Pyroxene +hornblende ±biotite	17	1	3	2	Calcic	
Pyroxene +biotite	9	1			Average	
Hornblende +biotite	6	1		3	Sodic	
Biotite	13	3		2	Average to sodic	
Quartz and orthoclase	12		1	3	Average to sodic	Plagioclase phenocrysts absent in some.
Orthoclase ± quartz	17	1	1	5	Average	Plagioclase phenocrysts absent in some.

Amount and Composition of Plagioclase

Table 9 shows the relation between the amount and composition of the plagioclase phenocrysts in the lavas. The plot shows that calcic andesine is the most abundant and that plagioclase phenocrysts less calcic than An_{20} are very rare, while those more calcic than An_{70} are in small number.

The rocks of the Antone andesite and Hinsdale andesite-basalt, which are basaltic in habit, are very low in plagioclase phenocrysts, but the rocks of the other formations have varying amounts and none are especially high or low.

TABLE 9. RELATION BETWEEN AMOUNT AND COMPOSITION OF PLAGIOCLASE PHENOCRYSTS

Composition	Number of rocks	Per cent of plagioclase phenocrysts	
		Range	Average
An_{10} to An_{20}	1	—	$\frac{1}{2}$
An_{20} to An_{30}	17	tr to 27	10
An_{30} to An_{40}	13	1 to 30	13
An_{40} to An_{50}	25	1 to 33	13
An_{50} to An_{60}	10	1 to 40	15
An_{60} to An_{70}	9	1 to 22	7
An_{70} to An_{80}	3	10 to 23	17
An_{80} to An_{90}	1	—	4

CRYSTALLIZATION OF PLAGIOCLASE IN ROCKS

Our most detailed knowledge of the crystallization of the plagioclase in rocks is based on Bowen's study of their melting phenomena.[36] The other constituents present in the rocks will modify Bowen's curves by an unknown amount. We know that they lower the temperature of crystallization by several hundred degrees. The potash feldspar in rocks may have an especially important influence as it enters into the plagioclase crystals in moderate amount. Likewise, the sanidine crystals take into solution a large amount (up to 50 per cent) of soda feldspar and a small amount of lime feldspar. In the basalts and andesites the amount of potash feldspar in the rocks is small, and much of it enters into solid solution in the plagioclase. This may have much the same effect on the crystallization of the feldspar as increasing the soda content in the rock. At the rhyolite end nearly all the soda enters the sanidine in solid solution, and this appears to have a large influence on the crystallization of the feldspar.

[36] Bowen, N. L., The melting phenomena of the plagioclase feldspars; *Am. Jour. Sci.*, 4th series, vol. **35**, pp. 577–599, 1913.

Figure 21 (curve *b*) shows approximately the anorthite content of plagioclases that crystallize from rocks in the ordinary lime-alkali series of the San Juan area. These feldspars are much lower in anorthite than the feldspars that would crystallize from melts with the same albite-anorthite ratio according to the plagioclase equilibrium diagram, even if we add all of the potash to the soda. The presence of mineralizers and other constituents, therefore, seems to have a large influence in reducing the anorthite content of the phenocrysts.

Plagioclase phenocrysts with less than 20 per cent of anorthite are very rare in the San Juan rocks (only 1 in 70 rocks) although those with 20 to 25 per cent anorthite are fairly abundant. Phenocrysts with 20 per cent of anorthite would, according to the melting curves of the plagioclase, crystallize from a melt with only about 2 per cent of anorthite. In the San Juan lavas plagioclase appears to have crystallized until the composition of the crystallizing plagioclase was as sodic as An_{25} and the melt was very low in anorthite. Beyond that stage plagioclase ceased to crystallize or crystallized in very small amount, and the sanidine, which began its crystallization somewhat before this, took into solid solution practically all of the material of feldspar composition that remained in the melt. Indeed, there is a strong suggestion that there is a reaction relation between oligoclase and sanidine.

Another explanation for the apparent absence of very sodic plagioclase phenocrysts is that the amount of plagioclase crystallizing in this range is very small.

Explanation of the Variations in the Plagioclase

Uniform Crystals

The uniform phenocrysts are nearly all near bytownite and are in basaltic rocks. Such crystals rarely show oscillatory or irregular zoning. A possible explanation for this is that diffusion in both the liquid and solid phases is more rapid in the calcic rocks, and hence the phenocrysts tend nearly to reach equilibrium in such rocks. Another possibility is that these calcic phenocrysts crystallized slowly from a calcic melt and settled into the magma which finally crystallized into the present rock. This is suggested by the fact that these uniform calcic phenocrysts are unusually calcic for the rocks in which they are found and they commonly have a thin layer that is much more sodic. Moreover, from the nature of the diagram for feldspar equilibrium, crystals precipitating from a calcic liquid change more slowly on crystallization of the liquid than do those crystallizing from a sodic liquid, as shown in figure 26. Such crystals should have large cores with little change in composition, followed by intermediate zones that change rapidly in composition, and finally an outer shell of very sodic feldspar. In phenocrysts, crystallization has not proceeded to completion and a greater or lesser portion of the outer zones, shown on figure 26, would be missing.

The uniform composition of the plagioclase of some granular rocks is probably explained by slow crystallization with complete reaction and equilibrium, whereas the uniform composition of the groundmass plagioclase in the porphyritic rocks is explained by rapid crystallization without equilibrium.

Normal Zoning

The simplest case of normal zoning with calcic cores grading into more sodic borders is easily explained as the result of progressive crystallization without reaction, and both the liquid and the material crystallizing become more sodic as crystallization proceeded. Starting with the plagioclase equilibrium diagram, curves have been constructed to indicate the course of crystallization under such conditions that the precipitation of zoned crystals takes place so that at all times the liquid is in equilibrium with the outer shell of the crystals, but without reaction between the liquid and crystals. Such curves for the following initial liquids and crystals are shown in figure 26. Curves 1 to 5 were constructed from the curves of the plagioclase equilibrium diagram, assuming that the feldspar was precipitated in equilibrium with the melt and that there was no reaction. The anorthite content of the outer zone of the crystals is plotted against the weight per cent of the part that is crystalline.

	Anorthite content of initial liquid	Anorthite content of first feldspar to precipitate
Curve 1	85	95
2	72	90
3	46	80
4	20	60
5	7	40

For the conditions postulated for curve 1, the first crystals to form have the composition of An_{95}. On cooling, precipitation is rapid and the change in composition of the feldspar is slow. When the outer rim has a composition of An_{80}, 85 per cent of the original melt is crystalline. From here on, crystallization becomes gradually slower and the change in composition of the precipitating feldspar becomes very rapid, so that when it has the composition An_5, 96 per cent of the original melt is crystalline. On further cooling, precipitation of highly sodic feldspar

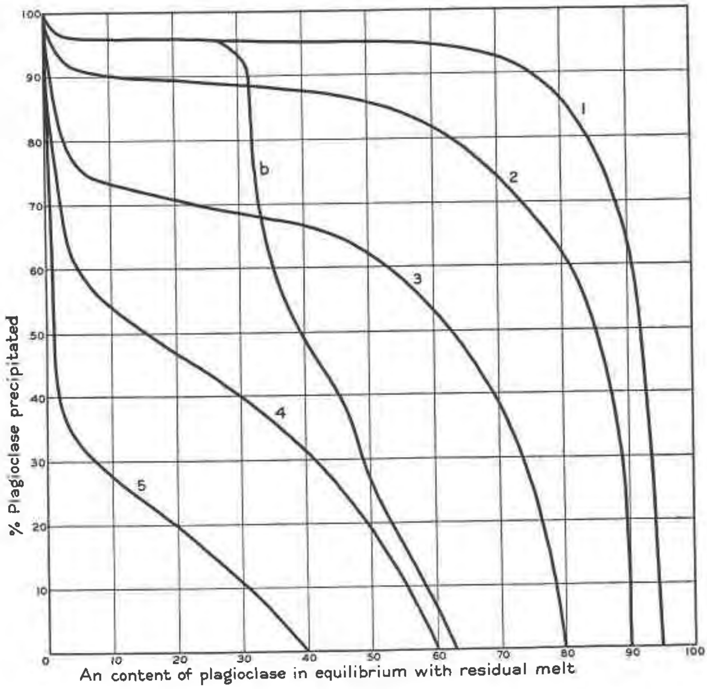

FIG. 26. Precipitation curves for progressively zoned plagioclases.

proceeds more rapidly and with less change in composition. Curves 2, 3, 4 and 5 are simply parts of curve 1 with enlarged vertical scale. Where crystallization takes place according to curve 5, the first crystals to precipitate have the composition of An_{40}. On cooling, precipitation takes place with moderate rapidity and moderate change in composition, until the precipitating crystals have about the composition An_5, when 34 per cent of the original liquid is crystalline. Here a fairly sharp break appears in the curve, and on further cooling precipitation is very rapid and the change in composition slow.

If a zoned plagioclase was formed according to curve 1, it should have a large core with only moderate change in anorthite content until the composition An_{80} is reached. At about that composition a rapid change should begin and the band including the range An_{80} to An_5 should be narrow. At about An_5 another rather abrupt change should take place and an outer zone more sodic than An_5 should be rather broad. In case the initial melt was lower in anorthite than for curve 1, the inner core would be smaller and the outer zones correspondingly larger, and if the first feldspar was more sodic than An_{80}, the rather uniform inner core would be lacking. If a more sodic melt was used, the sodic border would become increasingly larger in amount.

Curve *b* of figure 26 represents the crystallization of a melt of composition An_{40} according to the curve of crystallization of the San Juan lavas shown in figure 20. In this curve the change in composition is more regular and less marked than in those drawn from the melting curves of plagioclase.

Figure 27 shows more clearly the kind of zoning that would result from such types of crystallization. In this figure the compositions of the different plagioclases are plotted against the distance from the center of the crystal. These curves may explain the fact that the very calcic plagioclase phenocrysts commonly show little zoning except for a narrow border of very sodic feldspar.

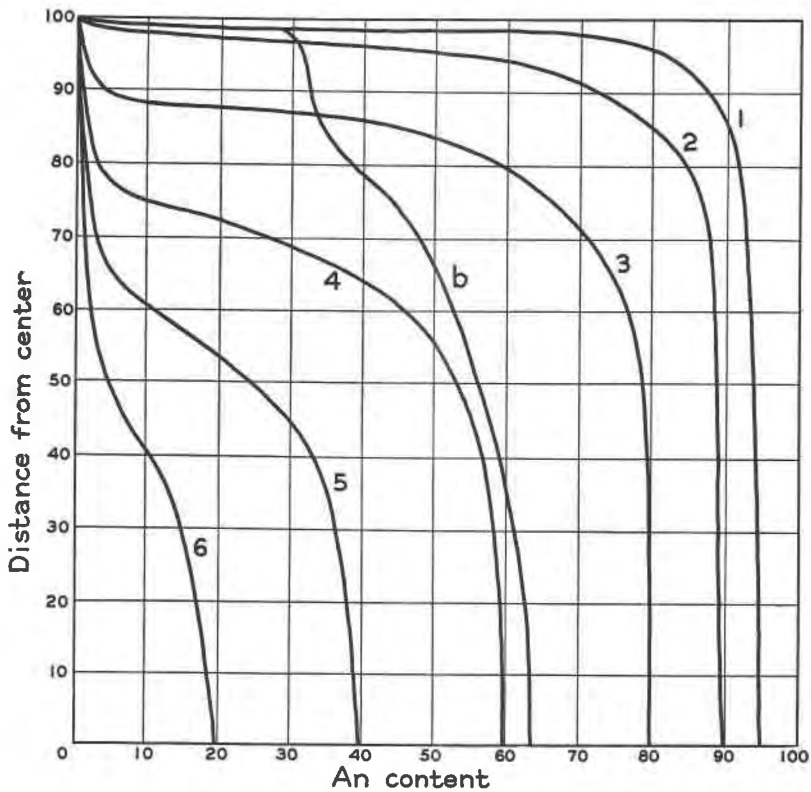

FIG. 27. Theoretical distribution of zones in plagioclases.

Curve *b* is drawn for the crystallization of a magma with 40 per cent of anorthite in the plagioclase, from the data for the San Juan lavas as shown on curve *b* of figure 26.

Among the plagioclase phenocrysts of the San Juan lavas few show zoning even approximately resembling that shown in figure 27. In addition to the progressive zoning, many of the phenocrysts show more or less recurrent zoning, others show sharp boundaries between zones, and still others have very calcic cores. Few of these phenocrysts show as wide a variation in composition as is indicated in figure 27 and few show the sodic borders. This lack of sodic borders is to be expected in liquids that did not complete their crystallization, but in a number of the San Juan lavas the anorthite molecule was almost completely removed from the groundmass as shown in figure 25. The zoning is much more like that shown on curve *b* of figure 27. These facts tend to confirm this curve.

Oscillatory Zoning

Homma[37] has classified a great many types of oscillatory zoning. In a single rock the type of oscillation varies more or less but usually within moderate limits.

For a general discussion of the subject of oscillatory zoning in the plagioclases and for references to the literature the reader is referred to the excellent paper by Hills.[38]

The explanation of regular oscillatory zones with as many as 80 repetitions requires some sort of rhythmic precipitation and Hills' theory seems very satisfactory. He thinks that crystallization starts under conditions of equilibrium. As it proceeds, by slow diffusion, the liquid next the crystal and the outer shell of the crystal itself become enriched in soda and correspondingly the liquid beyond is enriched in lime and supersaturated. Crystallization may now become slow, or may even cease, and diffusion will enrich the liquid next the crystal in lime and crystallization of an anorthite-rich zone may follow. This may be repeated again and again.

Some of the irregular oscillations are probably due to other causes, such as a change in the liquid in which the crystals are immersed by movement of the crystal, or by mixing of two magmas, or by change in conditions such as loss of mineralizers, or by movement through convection currents.[39]

[37] Homma, F., The classification of the zonal structure of plagioclase; *Mem. College Sci., Kyoto Imp. Univ.*, ser. B., vol. **11**, pp. 135–155, 1936.

[38] Hills, E. S., Reverse and oscillatory zoning in plagioclase feldspar; *Geol. Mag.*, vol. **73,** pp. 49–56, 1936.

Phemister, J., Zoning in plagioclase feldspar; *Mineral. Mag.*, vol. **23,** pp. 541–555, 1934.

[39] Homma, F., The method and the principle of delineating the composition-variation curve of a zoned plagioclase with an example: *Mem. College of Science, Kyoto Imp. Univ.*, ser. B., vol. **12,** no. 1, pp. 39–40, 1936.

Calcic and Sodic Cores

The calcic cores, where present, have in some specimens rounded outlines with long arm-like embayments; in others only a skeleton of the calcic core remains. They are sharply separated from the more sodic border (Fig. 15*a* and 17). Their general appearance suggests a solution remnant but the long projecting arms and the skeleton forms all oriented with the host are indications that they are replacement remnants.

In the crystals with sodic cores, the core is of clear sodic feldspar, surrounded by a layer that is clouded and made up of a fine-textured mixture of groundmass, feldspar near that of the core in composition, and feldspar near that of the outer zone. The outer zone is clear and calcic. The boundary between the clouded zone and the clear outer part of the crystal is sharp and rounded (see Figs. 15*b* and 16). The boundary between the clouded zone and the clear core is rounded and sharp but some prongs of the clouded zone project into the clear portion. It seems evident that a feldspar that was much too sodic to be in equilibrium with the magma was partly dissolved and later penetrated by the liquid and partly replaced by a fine aggregate—the cloudy zone.

The calcic cores have as much as 40 per cent more anorthite than the bordering feldspar, and the sodic cores as much as 30 per cent less. They clearly did not crystallize from the magmas which deposited the outer zones. They may have crystallized in the lower or upper parts of a layered magma and floated or settled into another part of the magma. This implies that the calcic cores have densities less than those of the siliceous magmas into which they floated, and that the sodic cores have densities greater than those of the liquids into which they settled. It is doubtful if either is true, and one excludes the other.

It is more likely that the calcic cores are due to contamination of a silicic magma by basaltic material, and the sodic cores are due to contamination of a relatively calcic magma by more sodic material. The contaminating material that it furnished to the cores of the plagioclase might have been a partly crystallized liquid or a rock. The fact that many basaltic rocks which have feldspars with sodic cores have phenocrysts of quartz, sanidine, or other unexpected minerals indicates this.

Two Feldspars in One Rock

The two feldspars differ by as much as 30 per cent in anorthite con-

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Homma, F., Über das Ergebnis von Messungen an zonaren Plagioklasen aus Andesiten mit Hilfe des Universaldrehtisches: *Schweiz. Min. Petr. Mitt.*, **12**, pp. 345–351, 1932.

Rittmann, A., Geologie der Island Ischia: *Zeits. Vulkanologie*, vol. **6**, pp. 208–210, 1930.

Kozu, S., and Watanabe, S., The zonal structure of plagioclase phenocrysts in pumice ejected from Komagake in 1929: *Proc. Imp. Acad. Japan*, vol. **8**, pp. 379–382, 1932.

tent and they differ in habit and kind of zoning as well. In some rocks one of the feldspars appears to be high in soda for such rocks, in others low in soda. These two feldspars in one rock seem to require much the same explanation as do the feldspars with sodic or calcic cores. One of the feldspars must have come from a contaminating rock or magma.

Origin of the Phenocrysts

Review of Evidence that Crystals are Foreign

Many facts listed below lead to the conclusion that some of the phenocrysts in the San Juan lava did not crystallize from the magmas in which they were erupted and that they are in a sense foreign crystals. Yet with few exceptions many of the rock analyses fall on a very uniform variation diagram which is essentially that of the average of the rocks from rhyolite to basalt, as calculated by Daly. Indeed, for most of the rocks, if one of the major variable oxides, SiO_2, total iron, MgO, CaO, or K_2O is known, a fair analysis of the rock can be written.

1. The average of the plagioclase phenocrysts in the silicic rhyolites is An_{28}, that in pyroxene andesites is An_{60}, and for intermediate rocks they range between these values. However, in rocks with about the same composition the plagioclase phenocrysts vary 25 to 40 per cent, or more, in anorthite content. In fact, plots comparing the anorthite content of the plagioclase phenocrysts and the composition of the rocks or of the groundmasses, and plots of the anorthite content of the normative plagioclase of the rock or of the groundmass, and the normative feldspar (or+ab+an) of the rock or the groundmass, show a very wide scattering of points. They show a surprisingly small relation between composition of plagioclase phenocrysts and composition of the rock or groundmass (Figs. 18 to 25).

2. The character of the zoning in many of the feldspars and the presence of highly calcic cores in over 10 per cent of the rocks, and of highly sodic cores in 10 per cent show that there was some addition of foreign crystals.

3. Two different kinds of plagioclase phenocrysts are present in about 15 per cent of the rocks.

4. Rocks with two kinds of plagioclase phenocrysts or with very sodic or calcic cores are commonly, though not always, found in rocks that contain other unexpected phenocrysts—such as quartz or orthoclase in basaltic rocks, rounded sanidine with outer layers of oligoclase, etc.

5. As shown in a former section of this series of papers, the pyroxene phenocrysts[40] show no systematic variation in iron content in rocks rang-

[40] *Am. Mineral.*, vol. **21**, pp. 695–699, 1936.

ing from rhyolite to pyroxene andesite. Pyroxenes that have crystallized from siliceous rocks should be richer in iron than those crystallized from a pyroxene andesite.

6. Among the San Juan lavas it is not uncommon to find two lavas, or groups of lavas, with essentially the same composition but with different phenocrysts. This is illustrated by the quartz latites of the three rhyolitic members of the Potosi volcanic series. The Treasure Mountain rocks carry phenocrysts of andesine, biotite and augite; those of the Alboroto have quartz, orthoclase, oligoclase, biotite, hornblende, and sphene; and those of the Piedra have quartz, orthoclase, andesine, biotite, hornblende, augite and sphene. The quartz latites of each of the three formations have the same range in composition. Why are the phenocrysts so consistently different in these three formations? Combined with other evidence, the best explanation is that many of the phenocrysts are foreign to the rocks in which they are now present.

The foreign crystals might have come from a different part of the magma chamber by floating, sinking, convection currents, or in some other way. They might be due to the mixing of two magmas, either or both of which had suspended crystals, or they might be undissolved remnants from a rock, more or less completely solidified, that had been dissolved or reacted on by the magma.

Accumulated by Sinking or Floating

Probably a part of these foreign crystals floated or sank into their present position. However, not all of the erratic crystals can be accounted for in that way. If a layered magma be assumed, or one that changes progressively from top to bottom, it is necessary to have the lighter rhyolitic magma above the heavier basaltic magma. Since the feldspars with calcic cores ranging from An_{40} to An_{83} are in the rhyolitic and intermediate rocks, it would be necessary, if gravity separation were the cause of the movement of the crystals, to have crystals of labradorite, or even of bytownite and probably pyroxene, float from a basaltic liquid into a rhyolitic liquid. It seems reasonably certain that such crystals have a greater density than rhyolitic magmas.

Likewise, the feldspars with sodic cores ranging from An_{26} to An_{50} are in the basaltic and intermediate rocks. In some rocks they are associated with either sanidine or quartz or both. The sodic plagioclase, sanidine and quartz must have crystallized from rather siliceous magmas and they are no doubt too low in density to have sunk into andesitic and basaltic magmas.

Where two types of feldspar phenocrysts are present in a rock, one does not grade into the other. If one crystallized in place and the other reached its position by movement due to gravity, the movement probably took place in a magma chamber that had two distinct layers of different compositions, for if the magma changed gradually we should not find such distinct crystals. The same difficulty in density relations would be present as in the crystals with calcic or sodic cores; and the two types of plagioclase, as well as the plagioclases with cores, are believed not to have accumulated by gravity. They differ from the calcic and sodic cores chiefly in that they are not resorbed to any great extent and are not bordered by feldspar of very different composition. This is probably due to the fact that the magma was erupted shortly after the phenocrysts were added.

In rocks with one type of plagioclase and no conspicuous cores, many of the phenocrysts are foreign to the rock, since in rocks of essentially the same composition there is a large range in the composition of the plagioclase phenocrysts. For instance, in rocks in which the normative plagioclase of the groundmass (Fig. 23) is about An_{27}, some have phenocrysts less calcic than the groundmass (An_{24}) and others as calcic as An_{60}. If the plagioclase crystallizing from this liquid was An_{60}, the more sodic plagioclase might have settled by gravity from a less calcic liquid above. A liquid of this type with much quartz and orthoclase, some water and only a moderate amount of FeO and MgO might have a lower specific gravity than the crystals, but it is doubtful if such crystals of oligoclase would settle into a liquid of the composition of pyroxene andesite.

Reaction with Wall Rock

Bowen[41] has discussed the reaction of magmas on inclusions. If a magma includes a crystalline rock more siliceous than the magma, the inclusion will be dissolved if the magma has sufficient superheat, but, if not, the inclusion will be dissolved with precipitation of crystals that are in equilibrium with the modified magma. The basalt (NM 213) from Cerro Ortez, near Tres Piedras, illustrates this point. This rock contains 7% of olivine phenocrysts, 1% of pyroxene, 2% of plagioclase, and less than 1% each of quartz and sanidine. The groundmass is made up of abundant small plates of laboradorite and pyroxene grains in a submicroscopic matrix.

The quartz and sanidine are much resorbed. The plagioclase phenocrysts have clear cores of An_{42}, surrounded by a cloudy zone made up of a mixture of groundmass, An_{42} and An_{63}, and an outer clear zone of An_{63}

[41] Bowen, N. L., The behavior of inclusions in igneous magmas: *Jour. Geology*, vol. **30**, pp. 513–567, 1922.

——— *The evolution of the igneous rocks*, Princeton University Press, pp. 175–223. **1928.**

(Fig. 16). The plates of the groundmass have cores near An_{60} and more sodic borders. The sodic feldspar of the cores and the sanidine and quartz are, no doubt, crystal remnants from the partial solution of a quartz latite or granodiorite. The plagioclase appears to have been dissolved at first to the rounded boundary outside of the clouded zone. During this stage there may have been superheat. Then the magma penetrated the outer shell of the rounded grain and dissolved part of the crystal and precipitated a feldspar in equilibrium with the liquid. This formed the mixed clouded zone. The outer zone then grew by precipitation and protected the core from further reaction. That this outer zone was in equilibrium with the melt is indicated by the fact that it has nearly the same composition as the cores of the groundmass plagioclase. The amount of foreign material that was required to furnish the foreign crystals need not have been great. In other rocks more was needed. The effect of this added material would have been to change the rock toward a rhyolite. The mixed rock would fit the equilibrium diagram since, except at the extreme siliceous end, the curves for the various oxides, excepting Al_2O_3, are nearly straight lines.

If a rock less siliceous than the magma is reacted on, the results are much as in the preceding case, but it will take a greater amount of superheat to bring about complete solution and without superheat a greater proportion of crystals would be precipitated.

Mixing of Two Magmas

The mixing of two magmas of different compositions, either or both of which carried phenocrysts, would give much the same effect as reaction on included fragments, but the heat and solution effects would be simpler. If the magma that carried the chief phenocrysts was present in small amount, the phenocrysts would be farther from equilibrium with the liquid than if a large amount of the magma had carried the phenocrysts.

The probability of mixing two magmas is increased by the intimate and erratic association of rhyolitic and basaltic or andesitic rocks in the area. There are local basaltic horizons interlayered with nearly all of the rhyolitic members and there are local rhyolitic rocks in some of the andesitic members. The Treasure Mountain quartz latite illustrates these relations. It is a regularly layered formation made up chiefly of rhyolitic flows and tuff beds. It is over 1,000 feet thick in the Summitville quadrangle and has four discontinuous thin lenses of dark pyroxene andesite interbedded with it. Both rhyolites and dark pyroxene andesitic lavas must have been erupted periodically from the same vent or from vents very close together. Williams[42] has described alternate eruptions of rhyolitic and basaltic rocks from the Newberry craters of Oregon.

Conclusions

The conclusion seems inevitable that many if not most of the plagioclase phenocrysts in the San Juan lavas did not crystallize from a magma of the composition of the lavas in which they are found. Some of the crystals that crystallized in the extruded lava may have originated by settling or floating from a higher or lower layer of magma of different composition, but most of them are not believed to have accumulated in this way, but rather by the mixing of two partly crystallized magmas, or by the reaction on solidified rock.

Some of the other phenocrysts were accumulated in the same way; probably all of the quartz phenocrysts in the quartz basalts are foreign. In an earlier part of this series of papers[43] it was stated "that quartz crystallized from the basalt magma as well as did the olivine," but the conclusion that many of the phenocrysts of sanidine and plagioclase associated with the quartz basalts are foreign, leads to the conclusion that the quartz also is foreign.

The sanidine phenocrysts in the basaltic rocks, the rapakivi-like sanidine, associated with quartz phenocrysts in some of the Fisher andesite-latites are almost certainly foreign, and probably some of the quartz and sanidine phenocrysts in the quartz latites are likewise foreign.

The pyroxenes in the siliceous rocks are essentially the same as the pyroxene phenocrysts in the andesites, and it seems probable that they are foreign, since if they crystallized from siliceous rocks they would be richer in iron.

Another conclusion, contrary to the authors' former conceptions, is that there must have been some means to mix thoroughly large bodies of magmas before eruption. The uniformity of large bodies of magma that have foreign phenocrysts makes this seem inevitable. Some of these flows are very large and even great groups of flows are quite uniform. This statement as to the uniformity of flows is based on estimates of composition in the field and laboratory. A thorough and more quantitative study of some of the flows is desirable.

Detailed studies of the crystallization of magmas after the method of

[42] Williams, Howel, Newberry volcano of central Oregon: *Bull. Geol. Soc. Am.*, vol. **46,** pp. 300–302, 1935.

[43] *Am. Mineral.*, vol. **21,** p. 685, 1936.

Vogt are highly desirable and should yield important results to supplement the equilibrium diagrams worked out in the Geophysical Laboratory. They should help to bridge the wide gap between the equilibrium diagrams and the igneous rocks. In making such studies, great care must be taken to be certain that the rock studied has neither lost nor gained phenocrysts. One favorable place for such studies is in dikes and other small intrusive bodies where the course of crystallization can be followed from the chilled borders to the center of the bodies.