RESORBED FELDSPAR IN A BASALT FLOW*

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Introduction

During a study of feldspar twins in a thick flow of basalt, an interesting occurrence of partly assimilated feldspar of the fundamental composition of andesine was noted. The distribution and physical characters of these included crystals were studied because of their relation to twin-origin. These characters will be described, and an attempt will be made to interpret their significance.

It is hoped to show that the basalt had sufficient heat to resorb the andesine, thus producing skeleton and honeycombed remnants. Before all the feldspar had been assimilated, however, temperature had dropped to the point where the normal crystallization of the basalt began. The skeletons were filled and surrounded by bytownite in crystallographic continuity. The outer borders of the newly crystallized feldspar show gradational zoning.

Description of Basalt

The basalt in which the andesine occurs is known as the Cape Spencer flow, 556 feet thick. It is the thickest of a series of five Triassic flows which form the headland of Cape d'Or, Nova Scotia, and which have been named the North Mountain basalt. The flows have been described by Powers and Lane (1916), from drill cores, to show evidence of magmatic differentiation in effusive rocks. Later work by Lund (1930), based on the same cores, gave further evidence of differentiation in the Cape Spencer flow. A brief résumé of their work is given here.

The basalt is composed of four chief constituents—feldspar, 34–59%; pyroxene, 32–48%; magnetite and glass, 2–30%. The present study indicates that quartz occurs in the central third of the flow, and becomes important near the center. Chlorite, limonite, hematite, zeolites and olivine are minor constituents. Feldspar content is highest between the 136 and 248 foot depths. Pyroxene increases from the top downward. Magnetite and glass are highest in the top 100 feet.

It has been concluded by Lund (1930, p. 562) that pyroxene has settled during cooling, and that feldspar has concentrated near the center. Some of it may have risen. During cooling there has been enrichment of soda in the liquid fraction, and the feldspar of lowest anorthite content occurs near the 248 foot depth. The highest anorthite content occurs near the base.

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Method of Study

The basalt was studied from drill core A, which Professor Lane kindly sent to the University of Wisconsin some years ago. The thin sections which were used were in some cases the same as those used by Lund, but in other cases new sections were taken at intervals corresponding to those listed in his paper. The numbers and depths of these sections are given in Table 1.

Table 1

Section no.	Depth below flow top	No. of determinations of composition
A-13	36 feet	3
A-14	61	4
A-15	86	9
A-15a	86	2
A-17	136	11
A-19a	188	7
A-20	248	29
A-22a	288	10
A-25	361	12
A-28	436	6
A-31	511	14
A-34	561	5

All determinations were made from sections mounted on a Bausch and Lomb universal stage, and were incidental to a study of twin laws. One unit of a feldspar was oriented in such position that the optic symmetry planes were in the cardinal positions—one horizontal, the second vertical and north-south, the third vertical and east-west. From this recorded position the feldspar was rotated until a twin composition face, or cleavage, was vertical and north-south. The pole of this face was plotted on a stereographic net whose three diameters represented the three vibration directions: α, β, and γ. This was then superposed on the Fedorov-Nikitin stereograms, which give composition of the feldspar and identity of the cleavage or composition face. Accuracy is believed to be $\pm 2\%$ An.

Description of Feldspar

Variation in grain size of the feldspar is considerable. Excluding phenocrysts, which become important in the lower half of the flow, size is least at the top, reaches a maximum through the third quarter, and becomes intermediate near the bottom. The phenocrysts increase in abundance from the first third downward. The groundmass feldspar is generally tabular parallel to 010. A small percentage is elongate in the direction 001, and others are nearly equidimensional. The phenocrysts are equidimensional in small part, but they are generally elongated about $2\frac{1}{2}:1$ in the direction 010.

The feldspar of the basalt is almost exclusively plagioclase of intermediate to calcic composition. No potash feldspar was identified. Since the chemical analyses show less than 1% K_2O, the potash is probably in solid solution with the plagioclase. The normal plagioclase ranges in composition from An_{35} to An_{85}, although it is rare for any crystal to be entirely below An_{55}. Variation in a single crystal embraces the entire range. Variations within the sections are indicated in Table 2. It is believed that the higher figure is very nearly the maximum in all cases, although the lower figure is not always the minimum. The minimum composition occurs in the lower central portion of the flow. The maximum is very nearly the same in all sections, except at the top.

TABLE 2

Slide no.	Depth below flow top	Composition range	
		Normal feldspar	Cores
A-13	36 feet	58–69% An	40% An
A-14	61	59–78	30–38
A-15, A-15a	86	40–70	35–38
A-17	136	51–80	37–38
A-19a	188	56–80	
A-20	248	40–85	
A-22a	288	35–75	
A-25	361	40–85	
A-28	436	55–81	
A-31	511	60–80	
A-34	561	62–80	

As suggested above, zoning is important in all the feldspars, excluding the cores. Two types of zoning occur—an early "line zoning" (oscillatory), and a later "gradational zoning." The line zoning is due to extremely fine bands of slightly different and alternating composition. Alternating variation of composition is probably within the limit of error of the method used, ±2% An, although the outer layers become progressively more sodic. Line zoning is limited to feldspar above An_{70}, so that it is most noticeable in the more calcic phenocrysts. It occurs, also, only in the inner portions of these crystals. The innermost lines enclose perfectly euhedral crystals. In some cases later lines indicate that two crystals have come together along crystal faces and have then grown as a single unit. Twin lamellae are crossed by these lines with but slight change in direction. In some cases the form changes from one twin to the next, although delineated by the same line. In other words, the twins grew as twins.

It has been indicated that line zoning is confined to the more calcic feldspar. Gradational zoning, however, occurs universally, from the tiniest visible crystal to the largest phenocryst. It is extremely marked in the larger crystals and is generally confined to the outer third or quarter of the units. Table 3 gives some examples of range of composition within single crystals. The minimum composition is not always known because of difficulty in orienting narrow units.

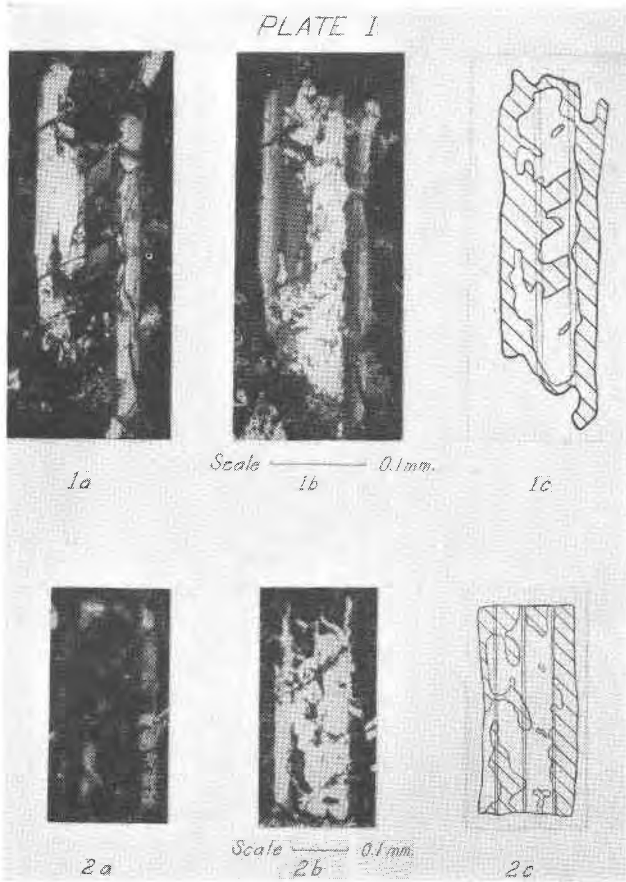
TABLE 3

Specimen no.	Range in composition	Specimen no.	Range in composition
A-14 (26)	78-59% An	A-22a (35)	61-35% An
A-15a (54)	70-40	A-25 (5)	60-40
A-17 (50)	80-56	A-25 (42)	83-52
A-19a (1)	70-56		

CORED FELDSPAR

It has been necessary to describe the feldspar in some detail in order to develop a background for description and interpretation of the partly assimilated andesine, which is the main thesis of this paper. The andesine occurs in sections of the upper 175 feet of the flow. It decreases in abundance from the top downward. In sections A-13 and A-14 the larger part of the feldspar contains some of the included material, while in section A-17 only a few of the larger phenocrysts have small core remnants.

The old feldspar is irregular in outline and is abundantly dotted with elongate cavities filled with bytownite or magnetite. Plate I illustrates two typical specimens from section A-14. If the bytownite were destroyed the core would consist of a ragged-edged, honeycombed structure with little semblance of feldspar form. The trend of destruction of the andesine is sometimes well defined and may be in the planes 010, 001, 100 or a brachydone. Apparently, unless fractures were present, the direction of easiest solution or replacement was in the planes of the chief crystallographic forms assumed by feldspar.



1. Specimen A-14 (26), under crossed nicols. 1*a* shows calcic border lighted. 1*b* shows andesine core lighted. Both line and gradational zoning can be seen in outer feldspar. 1*c* is a diagram which illustrates the ragged, honeycombed structure of the core (unruled), position of twin lamellae, and calcic border feldspar (ruled).

2. Specimen A-14 (42), under crossed nicols. Figures correspond to those of No 1.

The composition of the cores varies within a narrow range, about An_{30-40}, and the majority of this feldspar is An_{35-38} (Table 2). Excluding the newly crystallized borders, no zoning is present. The cavities in the andesine are filled with feldspar of high anorthite content, indicating that they were filled at the time the phenocrysts were being formed. Where the cores are small, the new feldspar exhibits line zoning in the interior, which gives way to gradational zoning in the borders. If the core is excluded, zoning and composition variation in the new feldspar is exactly comparable to the phenocrysts which occur throughout the flow. Evidence indicates that growth tended to produce euhedral form. The cavities and irregularities were filled in first. Later the crystals were enlarged in the regular manner.

The twins of the andesine are not markedly different from those of the feldspar of the basalt. There is a tendency, however, for the units to be broader and less numerous. Specimen A-14 (26) (Plate I-1) is composed of three Carlsbad units. Two narrow albite units are on either side of the central Carlsbad. These are in albite relation to the central unit. As indicated by the diagram accompanying the photograph, the new feldspar has crystallized in continuity with the twin structure of the older andesine. Specimen A-14 (42) (Plate I-2) shows only albite lamellae. Here, also, the new feldspar preserves the twin fabric of the old.

Composition of specimen A-14 (26) is An_{30} for the core, while the new material drops from An_{78} near the center to An_{59} near the border. In specimen A-14 (42) the core is An_{38} and the outer part An_{62}. As in other determinations, the lowest value of the border cannot always be determined by the method used. The photograph of specimen A-14 (26) illustrates both line and gradational zoning in the outer feldspar. Composition data of other crystals are given in Table 4.

TABLE 4

Specimen no.	Composition range	
	Core	Exterior
A-13 (3)	40% An	58% An
A-14 (32)	35	63
A-15 (9)	36	60
A-15 (10)	38	60
A-15 (11)	35	64
A-15a (54)	38	70–40
A-17 (49)	38	71–58
A-17 (50)	37	80–56

DISCUSSION OF FELDSPAR HISTORY

The Ab:An ratio of the basaltic magma was probably between Ab_{40}-An_{60} and $Ab_{35}An_{65}$, as suggested by the composition range of the feldspar of the quickly cooled upper surface of the flow, section A-13. This is in agreement with Bowen's (1928, p. 141) statement that "the most calcic composition of the total plagioclase of a uniformly fine-grained or aphanitic, basaltic rock appears to be about Ab_1An_2."

Evidence has been given to indicate that feldspar crystallization has occurred through a considerable time range. The first feldspar which crystallized from the basaltic magma has the composition An_{80-85}. This separated while much of the basalt was yet liquid, as shown by perfect euhedral form of the central zones of the phenocrysts. The line zoning, due to slight alternation of composition, suggests that these crystals formed while there was considerable movement of the basalt, or probably before the flow came to final rest. Thus, possibly slightly varying temperatures may have been experienced during their early growth. The early formed, high anorthite crystals showed a slight tendency to settle, which is expressed by their increasing abundance in the lower portions of the flow.

As cooling continued, the remaining liquid became progressively enriched in soda. The outer borders of all the feldspars were formed from this more salic material. The feldspar of lowest anorthite content occurs on the borders of those crystals just below the center of the flow, together with interstitial quartz (refer to Table 1). This suggests that the final liquid phase was last present there. Solidification progressed inward from the top and the bottom. Temperatures were slightly higher in the lower central portion of the flow during the later stages of cooling. Differentiation in the plagioclase series is, thus, well exhibited.

It has been indicated that the andesine cores of the feldspars in the upper portion of the basalt were present as crystals before the phenocrysts began to form, since they are filled and surrounded by the high calcic feldspar which first crystallized from the basaltic liquid. Furthermore, they were partly destroyed by resorbtion before any feldspar had crystallized from the magma, as indicated by their honeycomb structure. It is possible that there may have been some direct replacement in the solid phase, but inasmuch as line zoning occurs in the newer feldspar of these assimilated units, it would seem that the cavities existed, as such, at some time. This is in agreement with principles discussed by Bowen (1928, pp. 199–201), wherein he states that, "inclusions can become part of the liquid only when they have a composition toward which the composition of the liquid can vary by spontaneous differentiation." The quantity of included material is small, and it is probable that its effect on the gross composition of the basalt was not great.

The structure and twin fabric of the cores have apparently been followed and rebuilt by the later feldspar. It is possible that the cores were recrystallized during and after the addition of the feldspar from the basalt. In this case, they may have assumed the twin pattern of the border. In view of the slightly different twin pattern of the cored crystals to that of the normal feldspar of the basalt, it is believed that the former is the more plausible explanation. It is believed that the addition of calcic feldspar in and around the core protected it from further attack by the magma. There was probably not enough heat to form a melt after the bytownite had begun to crystallize.

The source of the andesine is unknown. There is no normal feldspar of the basalt which has the composition or character of the andesine. Feldspar of this composition occurs only in the outer zones of crystals well within the flow and of later origin. The fact that it was already present in crystal form when the calcic phenocrysts of the basalt first began to crystallize suggests that it was picked up by stoping before or during extrusion of the magma. Apparently the process of resorbtion was a slow one. The interval of time between acquisition of the andesine and initiation of crystallization of the feldspar normal to the basalt must have been a short one. In other words, there could not have been much excess of heat when the andesine was included.

The partly resorbed feldspar occurs within the upper 175 feet of the flow and increases in abundance upward. Both the proportion of cored to uncored, and of core to total of each unit increase toward the top. It is believed that evidence is sufficient to conclude that these crystals rose while the basalt was yet largely fluid. With the exception of this cored feldspar, and possibly some of the early large phenocrysts, it is believed there was little tendency for the feldspar crystals to migrate either upward or downward.

Summary

The feldspar of a thick, normal basalt has been described, as a background for description and discussion of partly resorbed andesine which occurs in the upper portion of the flow. The following conclusions have been reached.

(1) A basaltic magma has picked up andesine, source unknown, which has the composition An_{30-40}. The magma has partly resorbed the included feldspar—some was probably entirely resorbed—and has furnished the more calcic material which fills and surrounds the ragged and honeycombed structures in crystallographic continuity.

(2) Early crystallized plagioclase, An_{70-80}, shows line zoning, due to slight oscillation in composition. This is surrounded by gradationally zoned material which drops to as low as An_{35} near the center of the flow. Thus, differentiation in the plagioclase series is well exhibited. The normative feldspar probably lies in the range An_{60-65}.

(3) Early formed phenocrysts are largely bytownite and have shown

a tendency to settle toward the bottom. Cored feldspar which occurs within the top 175 feet of the flow shows definite evidence of having risen. There was probably little or no differential movement of the remaining feldspar.

Acknowledgments

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