SETTLING OF HEAVY MINERALS IN A GRANODIORITE DIKE AT BRADFORD, RHODE ISLAND

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ABSTRACT

A granodiorite dike at Bradford, Rhode Island, has a thickness of sixty-five feet, an east-west strike, and a dip of 28° south. The rock appears to be uniform, except for zones at the upper and lower contacts.

A two-foot zone at the upper contact is pegmatitic in texture, poor in heavy minerals, and rich in muscovite. It is explained as being due to hydrothermal action.

Heavy mineral separations of samples from different parts of the dike indicate that the proportion of heavy minerals increases systematically toward the base of the dike. This is also shown by thin-section studies of specimens from different parts of the dike, and by studies of a dark zone at the base of the dike. The systematic increase of heavy minerals toward the base seems to be due to crystal settling, for the following reasons. (1) The minerals which are concentrated toward the base are heavier than the magma of granodiorite. (2) These minerals crystallized early in the solidification of the rock. (3) In the dark zone at the base, the greatest concentrations of heavy minerals are in the small depressions, as might be expected from the settling of crystals on a slightly irregular floor. (4) An alternative origin by hydrothermal solutions is opposed by the fact that the variations extend through the body of the rock and that the main concentration is in the lower part of the dike.

The small size of the settled grains, with zircon as small as .10 by .03 mm. indicates a low viscosity of the magma.

INTRODUCTION

Studies of heavy minerals in a granodiorite dike at Bradford, Rhode Island (Niantic on the Charlestown sheet of the United States Geological Survey topographic map), were begun in part for the purpose of teaching students the technique of heavy mineral separation, and in part to see if there were any variations in the heavy minerals of what appears to be a very uniform rock mass.

The chief advantages of this dike for study are: (1) the apparent uniformity of the rock throughout the dike indicates that it is one simple intrusion; (2) quarrying operations at the Sullivan Quarry have exposed a great deal of fresh rock at various positions in the dike; and (3) the limited size makes possible a fairly complete study.

RELATIONSHIPS

This is one of several fine-grained dikes in the Westerly area (Dale, 1923 and Martin, 1925). The dike which is about a half-mile south of Bradford is approximately sixty-five feet thick, dips south about twenty-eight degrees, and strikes about east-west. It cuts sharply across the foliation of the Sterling granite gneiss, which stands almost vertical and strikes about east-west.

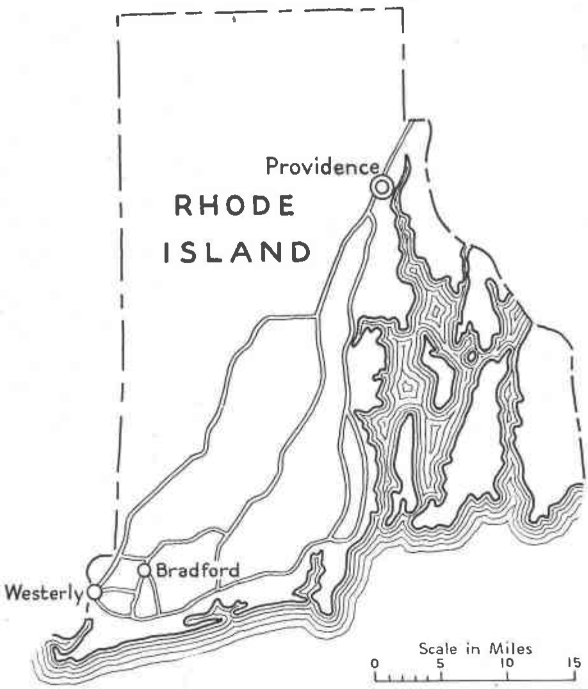

FIG. 1. Map showing location of Bradford.

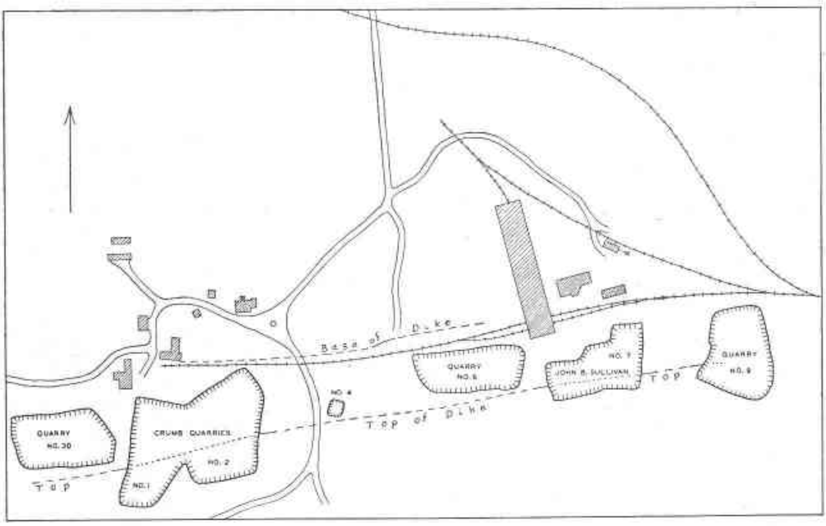

FIG. 2. Quarries in granodiorite dike at Bradford.

This dike is probably of post-Carboniferous age as it is petrographically similar to the granitic intrusions which cut the Carboniferous sedimentary rocks along the west shores of Narragansett Bay fifteen to twenty miles to the east and northeast of Bradford (Loughlin, 1910).

Methods of Study

The methods used for study of the variations within the dike were: (1) field observations, (2) thin-section studies for Rosiwal analysis and for determining the order of crystallization, and (3) heavy mineral studies. Only the methods of heavy mineral study need description.

Methods of heavy mineral separation.

In the heavy mineral separations a greater effort was made to obtain uniformity than extreme accuracy.

At first, samples of approximately 100 grams were crushed to pass a 40-mesh screen with openings of about 0.5 mm. (Taylor, 1937). The samples were washed to remove the fine dust. The heavy minerals were then separated with bromoform (specific gravity 2.82) in a centrifuge. There were almost no light minerals in the heavy portion, but a few biotite flakes remained in the light portion. At first, only 25 grams of the 100-gram sample were separated by individual students, but eventually the whole sample was used and the percentages given in Table 1 are from these totals. In some of the later samples only 25 to 40 grams were taken and the whole sample separated. The author performed part or all of the work on each sample.

Certain of the heavy mineral fractions were separated according to magnetic properties. The strongly magnetic portion was removed by a small "alnico" magnet. Further separation was accomplished by use of a Franz Isodynamic Separator. The heavy minerals were thus divided into strongly magnetic, moderately magnetic, and non-magnetic portions and the weight of each was determined.

The non-magnetic fraction was further studied to determine roughly the percentages of muscovite, apatite, sphene, and zircon. Small amounts of the fractions were immersed in an appropriate oil, random traverses of the field were made, and the length of the intercepts of the grains were taken as a volumetric measure of the percentages of the different minerals. The volumes were calculated to weight percentages. This method, obviously, does not give an accurate measure of the amounts of the different minerals present, but it probably gives comparable results. It should be noted that the percentages of the individual minerals in Table 1 are only estimated.

Field Observations

The rock of the dike is bluish-gray or gray in color. The texture is even grained with the crystals measuring one to three millimeters across. The constituents visible to the unaided eye are: feldspars, quartz, and biotite. The rock is widely known for its attractive appearance, both on polished and on hammered surfaces. With the exception of the lower and upper contact zones, the rock of the dike is remarkably uniform. Specimens from different parts of the dike match very well and only rarely does one see dark or light streaks in the blocks about the yard or in the quarry. No evidence of a chilled border is present.

The dike as exposed in the Sullivan Quarry is more uniform than are most of the dikes in the vicinity of Westerly. The upper contact, where exposed in the main working pit, is almost a plane surface. The lower

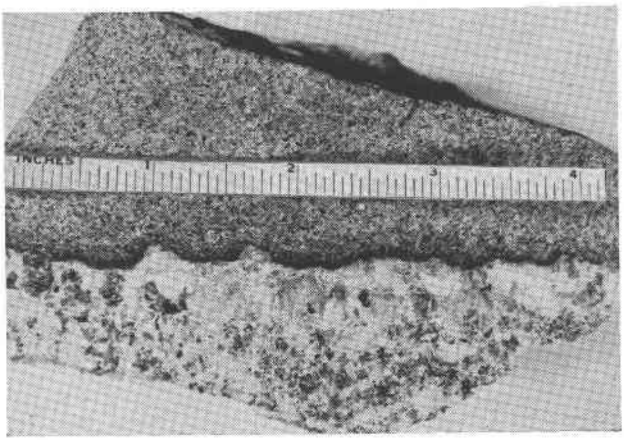

Fig. 3. Photograph of dark zone at base of dike.

contact, which is not well exposed in the Sullivan pit, but which is exposed at several places in the Crumb Quarry to the west, undulates with departures of two or three feet from a plane. This lower contact is very sharp and is marked by a dark zone of heavy minerals (See Fig. 3). The main dark zone is only an eighth to a quarter of an inch thick, but a transition zone, two to three inches thick, is streaky and somewhat darker than the ordinary granodiorite above. The Sterling granite gneiss, just below the contact, has a half-inch bleached zone which is poor in biotite, somewhat enriched in magnetite, and somewhat coarser in texture. At the upper contact of the dike is a zone two to four feet thick in which the granodiorite is pink, poor in dark minerals, somewhat richer in muscovite, coarser in texture, and somewhat pegmatitic.

Small pegmatites and aplite dikes are common here, especially in the enclosing Sterling granite gneiss.

Petrography

Main constituents.

The texture is irregular, with considerable variation in grain-size. The main constituent is oligoclase (An_{18-22}), which shows some zoning. The small variations in the composition of the plagioclase do not seem to be systematic with respect to the position within the dike. There is some tendency for the oligoclase to show crystal outlines. Carlsbad twins are common. The potash feldspar is microcline, some of which is perthitic. A few grains of it surround the oligoclase. Quartz is in part interstitial and seems to embay the feldspars as though partially replacing them. Biotite has a considerable tendency to be bounded by the base. Some grains appear to have crystallized early and some appear to have formed as later replacements of oligoclase. The β and γ indices range between 1.630 and 1.635, 2V is small, the optic sign is negative, and the pleochroism is in dark greenish brown and pale golden. No systematic variations in the optical properties were discovered. Some is altered to chlorite. Muscovite is uncommon, except in the upper contact zone. The order of crystallization appears to be: biotite, oligoclase, microcline, and quartz. The rock is a granodiorite, as is indicated by the modes of Table 2.

Accessory minerals.

The chief accessory minerals are listed below. In addition to these more abundant ones, there are a very few grains of pyrite and rutile.

Allanite

Allanite is present in a very few scattered crystals. It is yellowish-brown, pleochroic, and usually shows pronounced zoning. The indices of refraction vary between different crystals and within one crystal. Observed indices of refraction ranged from 1.63 to 1.68. The birefringence is about .010 to .015. The optic sign is negative and 2V is large. Crystals are commonly enclosed by early biotite, which has pleochroic haloes around the allanite. This relationship to the biotite and the euhedral form indicate that the allanite formed early. The lengths of measured crystals varied from .10 to .40 mm. and the widths from .03 to .22 mm.

Apatite

Apatite is present as tiny needles and as larger round grains. Certain of the grains are included in early biotite. Crystals in thin section measured .19×.09; .15×.10; 08×.02 mm.

Magnetite

Much of the magnetite is in irregular grains, but some grains show crystal boundaries. Textural relations are indeterminate, but they suggest that some of the magnetite formed early and some late. Some of this material shows leucoxenic alteration, so it is probably ilmenite. The largest grains measured .30 mm. in diameter.

Sphene

Sphene is present in irregular grains, and diamond-shaped or wedge-shaped crystals. Some crystals are enclosed by early biotite. The intermediate index of refraction, 1.896 $\pm$.002, indicates that it is sphene. A similar mineral in the enclosing Sterling granite gneiss has an intermediate index of 1.878$\pm$.002, which is nearer to that of keilhauite (Young 1938). The sphene of the granodiorite has many tiny inclusions, whereas the keilhauite is almost free of inclusions. The largest grains measured .24 mm. in diameter.

Zircon

Zircon is generally in good crystals, many of which are within pleochroic haloes in early biotite. Representative grains measured .21$\times$.03; .13$\times$.03 and .06$\times$.02 mm.

Order of crystallization of accessory minerals.

The textural relationships indicate that allanite, apatite, zircon, most of the biotite, and some of the sphene crystallized early. Some of the magnetite may also have formed early.

Results

The distribution of minerals in this dike is indicated by: (1) heavy mineral separations (total heavy mineral fractions and individual minerals), (2) thin-section studies, and (3) by a special thin-section study of material from the lower dark zone (21 in Table 2) obtained from the well-exposed base in the abandoned Crumb Quarry to the west of the main working pit.

Totals of heavy mineral fractions.

The most obvious feature, which first attacted attention in the course of the work, is that the lowest samples, and especially those nearest the base of the dike, have the largest percentages of heavy minerals. The series 1, 2, 3, and 4, show this especially well. There are a number of exceptions, as at 5 and 15. No satisfactory explanation for these has occurred to the writer, but a very few vague dark and light streaks have been seen in blocks about the yard. These erratic samples may have come from such a zone which was not noticed when the sampling was done. An apparent exception is 10, which appears to have too small a heavy mineral fraction. The sample was taken from a large block on a shelf at the west side of the quarry. At the time the sample was taken it was thought that the block had come from an adjacent wall. A re-examination showed, however, that it certainly did not come from that position and the conclusion is reached that it came from some location higher on the quarry wall. All other samples were taken from the walls of the quarry and not from loose blocks. Thus, the total heavy fractions show, with few exceptions, a systematic increase toward the lower contact of the dike.

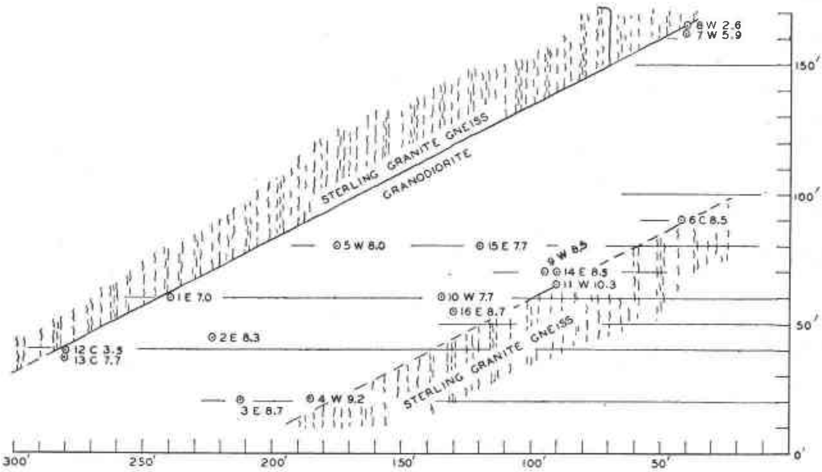

FIG. 4. Cross section of Bradford dike at Sullivan quarry. Numbers show positions of samples (1 to 16); whether from east wall (E), west wall (W), or center (C) of quarry; and per cent of heavy minerals. Distances and elevations in feet, but not referred to a known datum.

TABLE 1. HEAVY MINERALS

Sample No.	Weight of sample	Percentage by weight—heavier than bromoform (2.82)			Non-magnetic (amounts of individual minerals estimated)					
		Total	Strongly magnetic (magnetite)	Moderately magnetic (biotite & allanite)	Total	Muscovite	Zircon	Sphene	Apatite	Total excluding muscovite
1	30.87 g.	7.0	1.2	5.4	.39	.31	.01	.04	.03	.08
2	83.20 g.	8.3	1.3	6.3	.73	.47	.04	.19	.03	.26
3	69.44 g.	8.7	1.2	6.9	.67	.29	.05	.21	.12	.38
4	80.00 g.	9.2	1.2	7.3	.70	.49	.06	.04	.11	.21
5	125.48 g.	8.0								
6	81.12 g.	8.5								
7	25.00 g.	5.9								
8	25.00 g.	2.6								
9	100.00 g.	8.5								
10	100.00 g.	7.7								
11	32.75 g.	10.3	1.7	7.7	.93	.13	.09	.54	.17	.80
12	24.08 g.	3.5								
13	26.52 g.	7.7								
14	23.00 g.	8.5								
15	64.55 g.	7.7								
16	36.66 g.	8.7								

TABLE 2. MODES FROM THIN SECTIONS—PERCENTAGE BY VOLUME

Specimen No.	Microcline	Oligoclase	Quartz	Biotite	Muscovite	Magnetite	Accessories excluding allanite	Allanite
1	23	39	31	6		1		
2	25	41	27	5	1		1	
3	28	44	19	8			1	
4	27	45	19	8			1	
12	37	37	25	1				
13	27	42	25	5			1	
21	22	33	10	15		15	1	4

Individual minerals.

Allanite is not readily found in the heavy fractions and is too scattered to show systematically in thin sections, but is greatly concentrated in the dark zone at the base, as shown by thin section 21.

Apatite shows some concentration in the bottom dark zone and some in the lower heavy fractions, as shown in Table 1.

Biotite shows an increase toward the base by all of these observations.

Because of its high specific gravity, magnetite might be expected to be concentrated most by settling, but it shows only slight variations in the heavy fractions of Table 1. It shows a strong concentration in the bottom dark zone, however (see 21 of Table 2). These results indicate that some of the magnetite is concentrated toward the base and some is not, which agrees with the textural evidence that some formed early and some late. The presence of a number of magnetite grains in the Sterling granite gneiss just below the lower contact of the dike indicates that some of it may have a hydrothermal origin.

Muscovite, from observations in the quarry, appears to be concentrated along the bleached zone at the upper contact. It probably has a hydrothermal origin. Its distribution is irregular in thin sections and in the heavy fractions. There is very little of it in the lower dark zone.

Sphene is somewhat concentrated in the lower heavy fractions of Table 1, but shows some unsystematic variation. It is definitely more abundant in the bottom dark zone.

Zircon shows a regular and systematic abundance in the lower heavy fractions of Table 1 and is concentrated in the bottom dark zone.

A study of the modes of Table 2 shows that there is also a systematic variation of the main constituents. The most definite variations are the increase of plagioclase and the decrease of quartz toward the base. The determination of quartz is probably the most reliable and it is the most systematic.

Explanation

The pegmatitic texture, the bleaching, and the concentration of muscovite in the zone at the upper contact appear to have been caused by pegmatitic or hydrothermal solutions which traveled upward along the contact. Some of the magnetite in the Sterling granite gneiss at the lower contact, and in the lower dark zone, may also have been caused by hydrothermal solutions.

The other variations appear to have been caused by crystal settling, for the reasons given below.

(1) The minerals which are concentrated toward the base are heavy minerals. The mean specific gravities as given in the *Handbook of Physical Constants* (Birch and others 1942) are: allanite 3.5, apatite 3.2, biotite 2.9, magnetite 5.1, sphene 3.5 (from Dana's *Textbook of Mineralogy*, as it is not listed in the *Handbook*), and zircon 4.4. The specific gravity of the granodiorite ranges from 2.64 to 2.67, and the magma must have had a lower specific gravity. It is apparent from this that the settled minerals had considerably greater specific gravities than the granodiorite magma.

(2) The minerals which are concentrated toward the base are minerals which generally form early in igneous rocks. Allanite, apatite, zircon, most of the biotite and some of the sphene have textural relations which indicate that they were formed early in this rock.

(3) In the dark zone at the base, the greatest concentrations of heavy minerals are in the small depressions, as is to be expected from the settling of crystals on a slightly irregular floor. This is shown even in a hand specimen (see Fig. 3). The crystals lie in this lower zone as though they had settled there.

(4) The following evidence opposes the alternative origin by hydrothermal solutions. The variations extend throughout the body of the rock where there is no accompanying evidence of hydrothermal action. The main concentration is at the base, whereas hydrothermal action would ordinarily be at the top. The upper bleached and pegmatitic zone shows that the main hydrothermal action was at the top in this dike.

The size of the crystals of heavy minerals might be expected to increase toward the base, but no such increase was observed either in thin section or in the heavy fractions. This may be due to the fact that most of these minerals are too scarce for adequate observation in thin section and that the larger grains are more likely to be broken during crushing.

A further conclusion from these results is that the viscosity of this magma was very low. The sinking of zircon crystals as small as .10 by .03 mm. is only possible in a liquid of considerable fluidity.

Acknowledgments

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