ON A DISTINCTION BETWEEN LATE-MAGMATIC AND POST-MAGMATIC REPLACEMENT REACTIONS

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ABSTRACT. The kinds and habits of the minerals involved having failed to provide reliable criteria for discriminating between late- and post-magmatic replacements, it is suggested that more attention should be paid to the distribution of the products of these replacements through the rock mass. If a replacement reaction occurred while the magmatic residue was still homogeneously distributed through the mass, the amount of replacement mineral formed would be roughly proportional to the amount of original mineral available and probably would not vary inversely with the quantity of the latter surviving the reaction. If the reaction occurred after separation of magmatic residues from solid rock was well underway. the amount of replacement mineral would be essentially independent of the amount of original mineral but would vary inversely with that part of the original mineral surviving the reaction. On this basis it is shown that evidence gained from a sample consisting of 21 specimens offers reasonable assurance that muscovite pseudomorphously replacing plagioclase in the granite of Barre, Vermont, is late-magmatic rather than post-magmatic or hydrothermal.

SOME QUESTIONS OF TERMINOLOGY

THE descriptive terminology of end-stage reactions has been developed and refined to such an extent as to render it nearly worthless for an argument of this type. Each descriptive term has many connotations and each natural phenomenon may be described by any of several terms. On the other hand, the genetic terminology that enjoyed such great vogue in recent years is so abstract as to be inapplicable in most practical situations.

An argument that is to be carried through with small samples—a characteristic unfortunately shared by most geological disputes—requires some *a priori* hypothesis or model, for with small samples all we can ever hope to do is determine the compatibility of the observations with the hypothesis. Now in general the only useful hypotheses are those which may be either confirmed or rejected by the observations they are created to explain, and to reach such hypotheses clear and unambiguous descriptive terminology is essential. The matter is of such importance I have thought it best to clutter up the literature with yet one more discussion of terms before getting down to business.

In this note little will be said about the state of the materials involved for the very good reason that I have never visited an active magma in its chamber. I am guilty of the assumption that there is a (granite) magma and that it consists of a mixture of crystals and liquid, for it is in this way that I have been able to make the most sense of the observations. This is perhaps partly a personal idiosyncrasy. The data are given in full in table 1, and those who find it easier, more useful, or more fashionable to think in terms of alkali-emanations, "clouds of ions," or wholesale metasomatism may make full use of them.

The reader is entitled, however, to some rationalization of the discrimination made here between late-magmatic, post-magmatic, and hydrothermal action. The magmatic residue that never separates from the crystallized portion of the magma may be mostly water and will likely be pretty hot, but so long as it shows no detectable tendency to concentrate within or escape from the magma chamber, remaining, so far as we can tell, disseminated through the rock, I regard it as part of the magma, and the products of reaction between it and the solid part of the magma as late-magmatic. If for some reason—any number may be imagined—there is a tendency for residual liquors to be expelled from some parts of the chamber and gather in others without formation (or preservation) of well-defined fractures, the distribution of the products of end-stage replacement reactions through the mass will be very different from that found for the magmatic case. It is possible, but unproved, that deuteric action belongs in this category. At any rate, magma in the sense of a homogeneous paste of solids and liquids has ceased to exist at this stage; for lack of a better name reactions occurring at this time are here called post-magmatic. Anticipating considerable objection, I have reserved the term "hydrothermal" for the products of reactions in which some at least of the reagents seem to have reached their present sites by means of fractures and openings in the rock. Certainly such fracture fillings may give rise to metasomatic replacement along their margins; but if there is no evidence that material has been introduced very little is gained by the assertion that it has. This amounts to no more than saying that metasomatic replacement of one common mineral by another common mineral is not of itself evidence of the introduction of hot waters of foreign origin.

All that is new in this note is based on the notion of pseudomorphous replacement. The Mu_1 values of table 1 report the muscovite in each slide occupying space that seems once to have been filled by plagioclase. For the most part the basis of the inference is quite clear, since muscovite crystals are usually much smaller than plagioclase crystals and commonly lie either entirely inside or entirely outside them. Not infrequently, however, large flakes of white mica are interbanded with biotite and these may continue without visible break into adjacent plagioclase. In the plagioclase they tend to form irregularly bounded poikilitic plates or vermicular intergrowths, and the few cases of really extensive replacement are almost all of this type. There is an element of judgment involved in deciding which parts of such a muscovite grain fall in Mu_1 and which in Mu_3. I believe that most petrographers would have made about the same decisions I did and that though this uncertainty in identification must contribute to the analytical error, and hence to the residual variance, its contribution is quite small. Probably more of the analytical error is traceable to the minute size of many of the muscovite flakes.

Finally, in arguments of this type purely petrographic considerations rarely lead to satisfactory materials balances or stoichiometric equations, and the present case is no exception. On the assumption that "muscovite" is really potash mica, or even if it is pyrophyllite, its replacement of sodic oligoclase must release a certain amount of soda, lime, and silica. The lime may have gone into carbonate, which is present in about the right amount. The fate of the silica and soda is unknown. If country rock outcrop were more abundant, it might be useful to look for them there, but every explanation of this particular replacement runs into the same difficulty. Whether the released materials end up in the country rock or in the ocean is of small moment in determining whether the replacement was late-magmatic, post-magmatic, or hydrothermal.

OUTLINE OF THE PROBLEM

All of us who still believe in magmas are required also to imagine the end stages of plutonic magma consolidation. On the assumption that the magma contains more water than the rock, we must suppose that a hydrous residue remains after

most of the magma has crystallized, that the residue—or some derivative of it—does finally leave the magma chamber, whether by boiling or filtration, and that immediately before and during the early stages of the separation it is widely disseminated through the mass.

Even conceptually, however, reactions taking place in a largely solidified magma with only a thin interstitial liquid can hardly be distinguished from those taking place after the magma as such has ceased to exist. In practical cases this distinction usually depends on the geologist who happens to be making it. Traditionally, attempts to provide some reasonably objective basis for it have centered on the kinds and habits of the minerals involved. The history of the subject has been excellently summarized by S. J. Shand (1944, 1948) who has managed to cut back the dense verbiage that had grown up over it. It is to be hoped that this operation will be repeated at frequent intervals, though it seems a little unfair to expect one man to do all our pruning for us. As Shand's latest discussion shows (1948, p. 158), the nub of the difficulty is that neither the kind nor the habit of a mineral leads to a grouping in which the classes "late-magmatic" and "post-magmatic" are mutually exclusive.

The criteria currently in use may be applied quite independently of the distribution of the allegedly late- or post-magmatic minerals through the rock, yet it is just this distribution that seems to offer the most direct entry to the problem. If a mineral occurs in about the same amount everywhere in a rock mass, it must be the product of magmatic action or of very thorough metamorphism or weathering. If these last two can be excluded, we have no choice but to regard it as magmatic. If, on the other hand, it occurs only, or primarily, in veins or fracture fillings, it is clearly hydrothermal (though neither the heat nor the water is *ipso facto* of magmatic or non-magmatic origin). We can distinguish yet a third case in which there may be a decided tendency toward local enrichment or depletion so that the mineral is sporadically and irregularly distributed through the mass yet is apparently not concentrated along fractures or veinlets. Where magmatic residues are expelled by filter-pressing, local concentrations must often precede the actual expulsion and might easily lead to the sparsity or virtual absence of

the products of end-stage reactions in some parts of the mass and their considerable enrichment in others. If sufficient modal data were available, it would be useful to inquire to what extent the distribution of minerals regarded on other grounds as deuteric is of this type.

In the absence of data it may at least be pointed out that two pre-hydrothermal stages could be distinguished in this fashion and that regardless of what name be applied to the second, or "sporadic" type, the first can hardly be considered other than late-magmatic. If the reactions involved in both cases are pseudomorphous replacements, it may be shown that very different relations would hold between the reaction pairs depending on the distribution of reagents through the rock during the reaction.

If we suppose first that conditions favoring a particular reaction terminate before there has been any significant differential concentration (in space) of magmatic residues, so that during the critical period the entire rock is exposed to their action, the amount of replacement product (R) formed will be directly proportional to the amount of original mineral (O) available. There will be positive correlation between O and R and the significance of the sample correlation may be tested by the usual nul hypothesis. The best estimate of the proportionality will be the coefficient of regression of R on O, but it is not likely to be a very good one unless the sample is rather large and the environment quite uniform.

If, on the other hand, the reaction does not get underway until the magmatic residues have begun to concentrate, the amount of R formed will be a function not of O[1] but of the time during which the O contained in some particular sample, whatever its amount, was exposed to materials capable of reacting with it to form R. Assuming an abundant supply of these, so that in any particular case the reaction *might* proceed to completion, R would be absent from some parts of the rock, present in some, and abundant in others, but its amount would be essentially independent of that of O. Under such circumstances there would have to be negative correlation between R and the quantity (O-R), the amount of original mineral surviving the reaction. In the next section some analy-

[1] Except in the sense that $R < O$. O is here taken as a major constituent abundant throughout the rock, while R is in general a minor constituent.

tical basis for these assertions is given and the succeeding section describes a practical illustration.

CORRELATION OF A SUM WITH ONE OF ITS PARTS

A better treatment of the relations described below through equation (4) may be found in either of two excellent elementary statistics texts (Snedecor, 1946; Yule, 1946). The discussion is included here so that the argument may be followed, if necessary, without outside reference.

Let x be the deviation of a single measurement from the group mean, $(X - \bar{x})$, n be the number of measurements, and represent different variables by subscripts. Then the standard deviation is $s = \sqrt{\frac{S(x^2)}{n-1}}$, and the product moment correlation coefficient is $r = \frac{S(x_1x_2)}{(n-1)s_1s_2}$, where large S signifies summation. If $X_3 = X_1 + X_2$, then by definition,

$$x_3 = x_1 + x_2. \tag{1}$$

Squaring, summing, and dividing each summed term by $n - 1$ gives

$$s_3^2 = s_1^2 + s_2^2 + 2r_{12}s_1s_2 \tag{2}$$

This is the familiar relation used in isolating errors in experimental techniques. Where successive steps may be presumed independent, if, for instance, step 1 is the taking and step 2 the titration of an aliquot, then $r_{12} = 0$ and the third term vanishes.

Further, by definition,

$$r_{13} = \frac{S(x_1x_3)}{(n-1)s_1s_3} = \frac{S(x_1^2) + S(x_1x_2)}{(n-1)s_1s_3} \tag{3}$$

and combining (2) and (3) gives

$$r_{13} = \sqrt{\frac{s_1 + r_{12}s_2}{s_1^2 + s_2^2 + 2r_{12}s_1s_2}} \tag{4}$$

which is the usual statement for the correlation of a sum (X_3) with one of its parts (X_1), as a function of the relation between the parts.

Finally, let X_1 be the amount of R (the replacement product of the preceding section), X_3 be the quantity of O (the original mineral prior to replacement), and X_2 be (O-R) (the amount of O surviving the replacement process). The two types of replacement reaction may then be stated as special cases of

equation (4), but first it will be helpful to restate the equation explicitly for r_{12}, thus:

$$r_{12} = r_{13}\left(\frac{s_3}{s_2}\right) - \frac{s_1}{s_2} \tag{5}$$

The late-magmatic reaction, in which the amount of replacement product is proportional to the amount of original mineral available for the reaction, is exemplified by $r_{13} \geqslant 0$, and in small samples r_{13} will be rejected by the nul hypothesis test unless it is in fact quite large. Negative values of r_{12} may occur only if $s_1 > r_{13}s_3$; there is no *a priori* reason why this may not be so, but it is not likely that negative values of r_{12} will often be significant. For 19 degrees of freedom, for instance, the .01 point for r is 0.58; correlations smaller than this will usually be rejected as insignificant. Using data from the next section as an example, $s_1 = 1.46$, $s_2 = 2.98$ and $s_3 = 3.59$. Entering equation (5) with these values yields $r_{12} = +0.21$, which offers no support to the suggestion that X_1 and X_2 are negatively correlated. By similar substitution it may be shown that significant values of $r_{13} > 0$ and $r_{12} < 0$ could not occur together in this case unless $s_1 \geqslant 3.52$, a value more than twice as large as that actually observed. I believe this is a fairly typical example and that in general if r_{13} is significantly positive r_{12} will not be significantly negative, though this is to be regarded as a likely rather than a necessary result.

In the second type of reaction, which does not start until the concentration of magmatic residues is well underway, the extent of replacement will be governed largely by the time during which any part of the rock is exposed to their action. R and O will be independent except for the mild restriction that $R \leqslant O$. (In the example described below, R is never more than a fourth of O. The restriction might be bothersome in the case of very extensive replacement, such as often occurs in the metamorphism of gabbroic rocks.)

From equation (5)

$$\lim_{r_{13} \to 0} r_{12} = -\frac{s_1}{s_2} \tag{6}$$

so that in this sporadic type of replacement there will be negative correlation between R and (O-R), and if we are confined to small samples we shall again require a rather high sample correlation before discarding the nul hypothesis. As a

correlary of equation (7), if $r_{13} = 0$, $s_1 \leqslant s_2$; but s_1 will probably be a good deal larger in relation to s_2 than in the previous case for the reason that X_1 will be entirely lacking in some parts of the rock and quite abundant in others. This enlargement of range will very likely increase sample variance and tend to generate rather large (negative) values of r_{12}.

These results may be summarized as follows:

Distribution Type	*Corr. of O with R*	*Corr. of (O-R) with R*
I. Homogenous (late-magmatic)	positive	large negative values unlikely
II. Sporadic (deuteric?)	negligible	large negative values likely

The mere fact that the sample statistics of two minerals fall in one of the groups shown in the table is of course no basis for inferring a replacement relation between them; but if the existence of a replacement relation may be inferred *on other grounds* the table offers a method of determining its type. Extra-statistical information is crucial for the reason that the sum of *any* set of paired values will show correlation with either or both members of the pair. In general, if $r_{12} = 0$, $r_{13} = \sqrt{\frac{s_1}{s_1^2 + s_2^2}}$, which is always positive. Mineral pairs having no relation whatever to each other will thus frequently appear to fall in type 1. The same would likely be true of sets of numbers drawn from a telephone book or from a table of random numbers.

Where there is no outside information about the relationship between two minerals, it is probably legitimate to dismiss correlation between either of them and their sum as a function of their variances. Where there is independent reason for supposing that the variables are related, however, it is quite as legitimate to regard their variances as functions of the covariance required by the hypothesis.

Although the part-whole correlation may easily lead the unwary astray, it offers a simple, direct approach to many problems and is implicit in many others. A high positive correlation between live- and dressed-weight of beef cattle, for instance, would be a matter of considerable importance to the operator of a slaughter house. It would continue to hold his interest even if it should be pointed out to him that in many

cases there was no correlation between dressed-weight and waste. In our case the live-weight is O, the dressed weight is (O-R), and the waste is R.

The convention that end-stage reactions must terminate before or begin after the concentration of magmatic residues gets underway is of course highly arbitrary and has been adopted only to provide entry to the problem. The opposite state of affairs is more likely to obtain, and the probable effect of this will be that in many small samples neither tendency will attain significance. If the reaction were chiefly confined to one period or the other, however, it would generate the appropriate variances and covariances. The size of sample required to detect the effect may be regarded as some gauge of its strength. The next section describes a case in which the late-magmatic character of the reaction appears to have been strong enough so that it may be detected with reasonable assurance even in a rather small sample.

RELATION OF MUSCOVITE AND PLAGIOCLASE IN THE GRANITE OF BARRE, VT.

The granite of Barre is characterized by a rather low quartz content and a considerable excess of plagioclase (sodic oligoclase) over potash feldspar (microcline). Biotite is the principal mafic constituent. Transparent accessories, chiefly apatite, sphene, and epidote, are quite common; opaque minerals are remarkably scarce. Muscovite[2] is abundant throughout, occurring as a pseudomorphous replacement of plagioclase or in close association with biotite. Almost every thin section contains a little carbonate, nearly all of which has apparently replaced plagioclase. Biotite is sometimes transformed to chlorite, which is then commonly rimmed by a minutely crystalline aggregate of very high index and birefringence, probably leucoxene. The Barre is a medium-fine granite; in Shand's classification it is a peraluminous soda granite and in the Johannsen system it would be called granodiorite. Table 1 shows the results of point-counter analysis of twenty-one thin sections. An area ¾″ by 1″ was measured on each slide and the number of points identified for each analysis is shown in the table. Before analysis the slides were etched with HF and stained with sodium cobaltinitrite in the fashion described by Keith (1939).

[2] "White mica" would be a better term if it were less clumsy. Identification has been made by the usual thin section methods which do not distinguish between muscovite, paragonite, and pyrophyllite.

TABLE 1

Point Counter Analysis of 21 Thin Sections of Barre, Vt., Granite

Quarry	Spec. #	Quartz	Microcline	Plagioclase	Biotite	Mu_1*	Mu_2*	Mu_3*	Total Muscovite	Carbonate	Opaque access.	Non-opaque access.	# points counted
I	6	26.6	18.2	38.6	6.3	7.3	0.4	0.8	8.5	0.9	0.1	0.8	1406
	7	31.2	17.6	32.4	9.3	7.1	0.2	0.7	8.0	1.0	0.2	0.3	1350
	8	31.6	17.3	35.2	9.1	4.0	0.0	0.5	4.5	0.1	0.1	2.1	1464
II	9	32.7	20.0	32.1	8.0	4.7	0.0	1.1	5.8	0.4	0.1	0.9	1491
	10	24.7	23.5	32.3	8.5	8.0	0.0	0.9	8.9	1.0	0.0	1.1	1358
	11	22.5	18.7	39.7	7.0	8.8	0.1	0.8	9.7	0.8	0.1	1.5	1415
	12	26.4	23.8	33.5	6.2	6.2	0.1	1.8	8.1	0.6	0.3	1.1	1446
III	14	29.2	21.1	33.9	6.4	7.2	0.0	1.0	8.2	0.5	0.2	0.5	1294
	15	20.8	23.8	38.8	7.9	5.8	0.3	0.8	6.9	0.3	0.1	1.4	1459
	16	30.8	17.7	32.6	9.4	8.0	0.1	0.2	8.3	0.6	0.2	0.4	1341
IV	17	25.1	18.8	36.1	9.4	8.6	0.2	0.6	9.4	0.7	0.1	0.4	1450
	18	24.8	19.7	35.8	9.6	6.8	0.3	1.2	8.3	0.8	0.3	0.7	1433
	20	28.0	15.4	38.3	7.5	8.0	0.1	1.0	9.1	1.1	0.0	0.6	1466
	21	29.0	18.8	33.0	9.1	7.0	0.2	0.9	8.1	0.9	0.2	0.9	1475
V	22	27.4	24.8	36.6	0.2	8.8	0.1	0.9	9.8	0.6	0.1	0.5	1486
	23	25.8	21.2	32.6	7.1	10.3	0.1	0.8	11.2	1.4	0.4	0.3	1427
	24	25.4	20.4	30.3	16.0	6.0	0.4	0.4	6.8	0.4	0.1	0.6	1429
	25	27.9	17.6	37.6	6.3	8.4	0.2	0.7	9.3	0.6	0.1	0.6	1281
	26	28.6	18.5	33.5	7.7	7.7	0.4	1.0	9.1	1.5	0.3	0.8	1480
	27	24.3	18.3	35.9	11.1	7.3	0.2	0.5	8.0	1.4	0.5	0.5	1521
	28	27.9	12.5	40.4	8.7	7.0	0.2	0.7	7.9	1.6	0.4	0.6	1375
Mean		27.2	19.4	35.2	8.1	7.3	0.2	0.8	8.3	0.8	0.2	0.8	1421

* Mu_1 = Muscovite in Plagioclase, Mu_2 = Muscovite in microcline, Mu_3 = other Muscovite, mostly with biotite.

Location of Specimens

I Wells Lamson; 6 from West part of quarry, 7 and 8 from East part, current working.

II Wetmore Morse; 9 from #5 derrick, 10 from #12 derrick, 11 from #6 derrick, 12 from #13 derrick.

III Smith Granite Co; 14 from upper works, near Wetmore Morse, 15 from main central working face, 16 from Southwest part of quarry ("Barre medium-dark").

IV J. K. Pirie Estate Quarry; 17 from Southwest corner of quarry, 18 from center portion of quarry, 20 from Northeast key in floor of quarry, 21 from Northwest floor of quarry.

V Rock of Ages Corp. Quarry; 22 from Gazeley Pit, 23 from main quarry near derrick #10, 24 from black knot in grout near derrick #10 ("Barre dark"), 25 from #9 derrick, 26 from first derrick between office and observation booth, 27 from #3 service derrick, 28 from #5 derrick.

As in most of the finer grained granites of New England there is a tendency for potash feldspar—here exclusively microcline—to mantle plagioclase, but only very rarely is there evidence that these mantles have developed at the expense of plagioclase. Rather, early formed plagioclase crystals, often markedly euhedral, seem to have served as nuclei for the later crystallization of microcline. Many of the microcline crystals lack plagioclase cores and many of the plagioclase crystals show only incomplete microcline rims or none at all, so that probably the formation of microcline began well before that of plagioclase had been completed. Except in the true "dark Barre" (analysis number 25 in table 1), which is now very scarce and seems never to have been abundant, biotite appears to be an early-formed mineral developing before, or at any rate independently of, feldspar.

Muscovite on the other hand conspicuously replaces plagioclase. Commonly it forms plates and lamellae along cleavages. These may spread and interlock, yielding a complex aggregate, or they may coalesce into large poikilitic single crystals. Muscovite sharply interbanded with biotite may spread irregularly into adjacent plagioclase crystals, forming a crude halo about the biotite where it abuts on plagioclase. Really extensive replacements are generally of this type. In such cases the muscovite may be in either poikilitic or vermicular intergrowths with the plagioclase. A little muscovite seems to have been introduced with quartz in minute fractures, and here it often displays toward quartz the same poikilitic habit elsewhere shown with plagioclase. I have never been able to follow one of these veinlets more than a few millimeters and do not believe they account for more than a very small part of the muscovite or quartz contained in the rock. In many thin sections they do not occur at all.

From what has been said it seems fair to regard the great bulk of muscovite as almost certainly pre-hydrothermal and it remains only to decide whether it formed before or after significant separation of magmatic residues from crystalline material in the magma chamber; whether, in the terminology of the first section of this note, muscovite is to be classed as late-magmatic or post-magmatic. As far as I know there is no test that may be applied to *all* of the muscovite. Table 1 shows, however, that about 90 per cent of the Barre mus-

covite occurs as a pseudomorphous replacement of plagioclase, and for this material the method of the preceding section is available.

The original plagioclase available for the reaction (O of section 1) may be reconstructed by summing plagioclase, carbonate, and Mu_1 of table 1. The quantity of O surviving the replacement reaction (O-R) is the sum of plagioclase and carbonate. R of section 1, the replacement mineral, is Mu_1 of table 1. In summary form, the terminology is as follows:

Section 2	*Section 3*	*Section 4*
R	X_1	Mu_1
(O–R)	X_2	(Pl + C)
O	$X_3 = X_1 + X_2$	(Pl + C + Mu_1)

The relevant values are drawn together in table 2 and shown graphically in figure 1. The correlation of R with O, or r_{13}, is + 0.58. The correlation of (O-R) with R, or r_{12}, is + 0.21. The case thus falls in the first group of section 3 (homogeneous or late-magmatic); r_{13}^2 or 33.5 per cent of the sample variance of muscovite occurring as pseudomorphous replacement of plagioclase is compatible with the hypothesis that the replacement reaction occurred before extensive segregation of magmatic residues from crystalline material in the magma chamber.

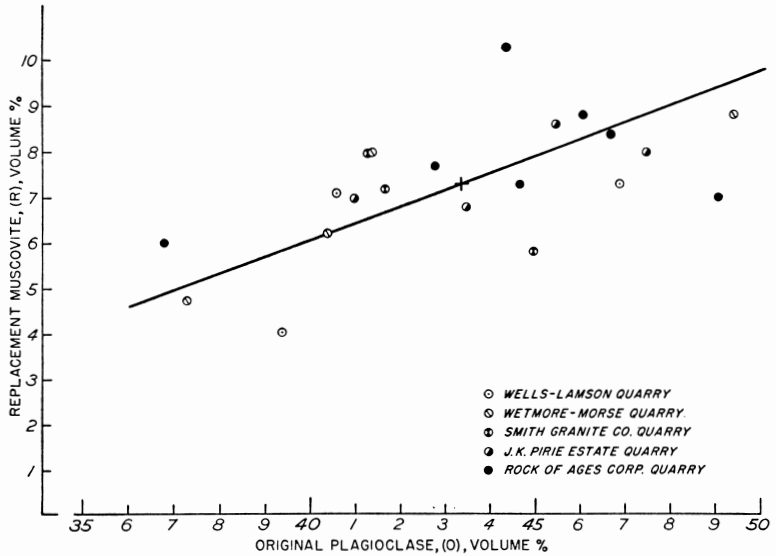

Fig. 1. Replacement muscovite as a function of original plagioclase in the Barre granite (data from Table 1).

TABLE 2

Values of R, O and O-R from Table 1

Specimen No.	O ($Mu_1 + Pl + Carb.$)	R (Mu_1)	O–R (Pl+ Carb.)
6	46.8	7.3	39.5
7	40.5	7.1	33.4
8	39.3	4.0	35.3
9	37.2	4.7	32.5
10	41.3	8.0	33.3
11	49.3	8.8	40.5
12	40.3	6.2	34.1
14	41.6	7.2	34.4
15	44.9	5.8	39.1
16	41.2	8.0	33.2
17	45.4	8.6	36.8
18	43.4	6.8	36.6
20	47.4	8.0	39.4
21	40.9	7.0	33.9
22	46.0	8.8	37.2
23	44.3	10.3	34.0
24	36.7	6.0	30.7
25	46.6	8.4	38.2
26	42.7	7.7	35.0
27	44.6	7.3	37.3
28	49.0	7.0	42.0
$\bar{x}$	43.3	7.3	36.0
s	3.59	1.46	2.98

The residual variance is of course far too large to be ignored, but the interpretation placed upon it will depend on the detail of the hypothesis being tested. If we are prepared to accept as magmatic only that part of the replacement accounted for by a *single* linear function of O, then the residual variance contains only two components, experimental error and post-magmatic or non-magmatic influences tending to localize the replacement process. This would imply that the regression coefficient of R on O, $b_{13} = r_{13}\frac{s_3}{s_1}$, is an estimate of a single constant supposed to hold for the entire mass and that r_{13} itself is an estimate of 1.

While this position is perhaps logically tenable it seems a little impractical. For a single constituent we usually regard the sample mean and standard deviation as estimates of population parameters themselves subject to variation. We do not suppose, for instance, that the Barre granite everywhere carries exactly the same amount of plagioclase and muscovite. In the same way we should be willing to grant that b_{13} is an

estimate of a ratio which varies somewhat *in the parent* quite independently of how we go about taking or measuring the sample. It follows that r_{13} will in general be less than 1 even in the absence of systematic effects tending to destroy the correlation. Residual variance on this construction must include not only experimental error and the influence of non-magmatic factors, but also random and possibly systematic variations in the parent value of b_{13} such as are not opposed to the hypothesis that $\rho > 0$.

Proper analysis of the residual variance is thus a complex matter concerning which a sample as small as that shown in table 1 provides very little relevant information. Variations in the regression coefficient from place to place in the mass—whether random or not—would materially reduce the value of r_{13} found in a sample taken without regard to them. Such variations would almost inevitably result from variations in the duration of the late-magmatic stage from place to place. And it is certainly an over-simplification to suppose that the time during which the conversion of O to R might occur was everywhere exactly the same, even in the absence of a physical separation of crystallized material and magmatic residues. My own hunch is that much of the residual variance is introduced by local variations of this type, and hence not necessarily opposed to the hypothesis that the muscovite of the Barre granite is of late-magmatic vintage. This is pure speculation however; the problem could be solved by means of a considerably larger sample taken so that reasonably reliable estimates of r and b could be reached for different parts of the mass. A further study of this sort would surely be worthwhile.

CONCLUSIONS

The distribution of the products of pseudomorphous replacements in a rock mass will depend on the distribution of magmatic residues through the mass at the time of the reaction. If the reaction occurs before these residues have been expelled from some parts of the chamber and concentrated in others, the amount of replacement mineral (O) formed will be roughly proportional to the amount of original mineral available for the reaction (R). There will be positive correlation between O and R and it is not likely that correlation between O and (O-R), the amount of original mineral surviv-

ing the reaction, will be significantly negative. Proportionality between O and R, as expressed in the regression coefficient of R on O, will no doubt vary from place to place even under these conditions, but it should always be positive. In a sample taken without regard to such variations the proper test is thus not whether the parent correlation might be perfect but whether it might be larger than zero.

If the reaction does not occur until there has been extensive separation of liquid residue from crystallized material, however, the amount of R will be essentially independent of O, and the quantities R and (O-R) will be negatively correlated.

It is proposed here that if the products of pseudomorphous replacements are distributed through the rock according to the first case they be termed late-magmatic, that if they come under the second they be called post-magmatic, and that the term hydrothermal be reserved for cases in which some at least of the reagents have reached their present sites *via* fractures in the rock.

On this basis it is shown that the relation between plagioclase and muscovite pseudomorphously replacing it in the Barre granite is conformable with the first, or late-magmatic, reaction type. The correlation is high enough to be significant in a probability sense but low enough to leave much of the variation unexplained. From a sample large enough to permit estimates of regression and correlation coefficients for different portions of the Barre mass it would be possible to determine how much of this residual variance is to be attributed to post-magmatic and hydrothermal effects and how much to variations not opposed to the hypothesis that the reaction is late-magmatic.

References

Keith, M. L., 1939. Selective staining to facilitate Rosiwal analysis. Am. Mineralogist, vol. 24, pp. 561-571.

Shand, S. J., 1944. The terminology of late-magmatic and post-magmatic processes. Jour. Geology, vol. 52, pp. 342-350.

———, 1948. Eruptive Rocks. 3d ed., New York, Wiley.

Snedecor, G. W., 1946. Statistical Methods, 4th ed. Ames: Iowa State College Press.

Yule, G. Y., and Kendall, M. G., 1946. Introduction to the theory of statistics, 13 ed., London, Charles Griffin & Co.

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ERRATA

In the article by F. Chayes "On a Distinction Between Late-Magmatic and Post-Magmatic Replacement Reactions," printed in the January issue, page 27, equation (4) should read

$$r_{13} = \frac{s_1 + r_{12}s_2}{\sqrt{(s_1^2 + s_2^2 + 2r_{12}s_1s_2)}}$$

and page 29, equation in the middle of the page should read

$$r_{13} = \frac{s_1}{\sqrt{(s_1^2 + s_2^2)}}$$