THE ROSIWAL METHOD AND THE MODAL DETERMINATION OF ROCKS

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INTRODUCTION

The present laudable tendency to introduce more quantitative data into petrographic papers makes it desirable to consider critically our quantitative methods, with a view to determining their probable accuracy, the sources of errors in the results, the ways of avoiding errors, and the best methods to secure a required degree of accuracy. Grout (19) discussed the precautions that must be taken in sampling rocks for chemical analyses, and it is the purpose of this paper to point out those that are equally necessary in sampling rocks for micrometric mineral analyses.

REVIEW OF THE LITERATURE

A number of papers have appeared in the geologic literature since the time of Delesse and Sorby expounding various quantitative methods for the determination of the relative proportions of the mineral constituents in a rock. The first attempts of Delesse (1, 2) involved only tracings of a polished rock surface and so were purely macroscopic. Microscopic methods of measurement were introduced by Sorby (3, p. 21). Two types of quantitative microscopic measurement are in common use at the present time —one areal, the other linear. Johannsen (12) advocates an areal method which makes use of a camera lucida and a planimeter. Lincoln (9) has also used a planimeter to measure areas either on a camera lucida drawing, on a photomicrograph, or on the surface of the rock itself. Thomson (18) has sought to obtain greater accuracy by projecting the image of a thin section upon a blackboard with a lantern and carrying out areal or linear measurements on this enlarged projection.

The linear method of Rosiwal (5) has been simplified by the introduction of recording micrometers for the automatic integration of the measurements—first that of Shand (10) and later those of Wentworth (16) and Hunt (17). Although the fundamental premise of Rosiwal (5, p. 146) that linear (and areal) measurements are directly proportional to the volumes of the

minerals measured, regardless of the shape of the individual grains, was challenged by Julien (6) and by Williams (8), it has been satisfactorily defended by Lincoln and Rietz (9) and by Johannsen (12).

With respect to the inherent accuracy of the Rosiwal method, its author pointed out (5, p. 148) that the accuracy is directly proportional to the length of traverse measured and inversely proportional to the grain size of the rock, and that to obtain a measurement accurate to 1 per cent, assuming the greatest possible uniformity of distribution and grain size for the mineral constituents of a rock, the total length of traverse must be at least 100 times the grain size. Lincoln and Rietz (9) hold that this minimum length of traverse is altogether insufficient to reduce the probable error to 1 per cent; and they present formulae derived from the laws of probability and of random sampling for the determination of the probable error in any particular case. When they work through their formulae with a concrete example, they find that the traverse must cross 3,283 mineral grains to insure an error of less than 1 per cent for a granite from Maine. This excessively large figure results from the high degree of probability on which they insist and the geometrical rate at which the necessary number of measurements increases as it approaches the required standard of 1.0 per cent.

Thomson (17) has attacked the problem of the accuracy of these measurements from a more practical standpoint. His experiments on polished sections of synthetic mixtures of pyrite and magnetite in known proportions give average deviations from these proportions of about 1 per cent for linear measurements. The maximum deviation is 3 per cent. The number of grains dealt with is only that contained in an ordinary polished section. On the basis of nearly 100 measurements he concludes that the linear method of Rosiwal is sound and easily capable of an accuracy within 1 or 2 per cent for each constituent and that the areal methods are slightly less accurate.

Holmes (13, p. 317) finds the linear method to be accurate within about 1 per cent for an artificial test field designed especially to check the measurements. The results of a number of Rosiwal determinations tabulated by Johannsen and Stephenson (11) indicate errors of the same order of magnitude, reaching a few per cent as a maximum. Without presenting any experimental

data, Grout (19) states that the accuracy of a Rosiwal determination may be within 1 per cent for a rock with grains less than 1 millimeter in diameter, but that for coarse-grained rocks the errors may rise to 20 per cent. Stewart (20) reports differences between two sets of measurements on the same thin section of less than 1 per cent for any constituent, but his differences for two separate thin sections of the same rock amount to as much as 6 per cent.

Two Types of Error in Micrometric Analyses

In any consideration of the accuracy of micrometric analyses, it is important to keep in mind that there are two distinct types of error which may enter into the results: (1) errors caused by failure of the measuring process to give an adequate representation of the thin section to which it is applied and (2) errors due to failure of the thin section to provide a proper sample of the rock from which it is cut. The possible errors arising from these two sources have rarely been distinguished as such in the literature.

Accuracy of Measurements of a Given Thin Section

The errors arising from the measuring process itself will be considered first. In view of the results of the writers cited above and the further experimental results presented below, there seems to be no doubt that the ordinary methods of measurement can be made to yield analyses of a given thin section which will be accurate within roughly 1 per cent for each constituent mineral. Yet attention should be drawn to certain possible errors resulting from the inherent limitations of thin sections as a basis for measurements and from the mechanical limitations of the measuring process.

In the first place, an error may be introduced because the measurements are not made strictly on a single plane, such as the upper surface of the thin section. In the case of opaque minerals, minerals with strong color or high relief, and minerals in very small grains, there is a systematic tendency to over-estimate the amount present by including in the measured intercepts more than actually lies at the upper surface. If the maximum intercept in the thickness of the thin section (0.03 to 0.04 mm.) is recorded, the error would be about 3 per cent of the measured value for intercepts averaging 1 millimeter. For smaller intercepts the error would be greater.

In the second place, it is often tacitly assumed that the investigator is able to determine accurately every grain which is needed for his measurements. Several factors combine to make difficult the elimination of personal errors. The common recording micrometers raise the thin section so far above the level of the microscope stage that the light coming to it from below is seriously cut down, and interference figures are not available to check doubtful grains. Hence, even an experienced worker will frequently find grains of questionable identity. Then since the whole process of measurement is tedious whatever the method employed, eye strain and fatigue combine to invite error. Only the greatest watchfulness and patience in measuring the intercepts and not a little ingenuity in identifying border-line grains will prevent errors from creeping in.

Accuracy of Sampling of a Rock by a Thin Section

Of greater difficulty and importance than the problem of obtaining an accurate measurement of a single thin section is the question of how accurately a thin section samples a rock. Discussions of the Rosiwal method commonly begin with the assumption that the rock is well mixed. Certain it is that many rocks, particularly coarse-grained rocks, are not well mixed on the scale represented by a thin section. The grains of one mineral often tend to be segregated locally into clusters or glomeroporphyritic aggregates. Still more serious in the problem of sampling any considerable body of rock is the frequency with which rocks show pronounced local variations in the relative proportions of their constituent minerals, or even in the assemblage of minerals present.

In the case of moderately coarse-grained rocks, there is the additional difficulty that even though the rock may be well mixed, there may not be enough grains cut by the thin section to provide a satisfactory sample of the rock as a whole. If only a few score or a few hundred grains appear within the thin section, as is frequently the case, the addition or subtraction of one or two grains of a particular mineral at the margin will have an appreciable effect upon the results. The tearing out of grains in the grinding of the thin section is still more serious, because it has a definite tendency to affect relatively resistant minerals, such as hornblende or magnetite, or the coarse phenocrysts in a porphyry. At times it may be possible to estimate from the shape of the holes

the character of the grains thus lost and to allow for them accordingly, but this is not ordinarily true.

Experimental Data

The results of a number of careful Rosiwal determinations made on thin sections of different types of rocks are given below to illustrate the principles just discussed.

Rocks from the San Luis Rey Quadrangle, California: The first two rocks are a granodiorite and a gabbro from the Peninsular Range batholith in the San Luis Rey quadrangle, California. These are ordinary plutonic rocks of moderately coarse grain. The average grain size is slightly more than 1 sq. mm., the few largest grains in each rock reaching an area of 3 to 4 sq. mm. Because of the grain size, an unusually large thin section of each rock was obtained for purposes of measurement. These large sections were subdivided by ruled lines into upper and lower halves, each with an area about equivalent to that of an average thin section, 200 to 300 sq. mm. Two independent sets of measurements and computations were carried out on each half of each section. The results of the successive determinations on the same areas give an indication of the accuracy of the measurements, while a comparison of the two halves of each section shows the amount of variation in composition within a very small area of the rock. As additional evidence bearing on the problem of sampling, there are also presented results of similar measurements upon other thin sections of ordinary size cut from duplicate specimens of the same two rocks. The duplicate specimens come from the same outcrops and from within a few feet of the location of the other specimens.

The measurements were made with a modified Wentworth type recording micrometer (Hunt, 17). The results are given in volume percentages for these rocks, just as they were measured. The stated averages are based directly on the total micrometer readings and are not simply averages of the figures in the preceding columns. The figures for the size of the sections represent the actual area available for measurement exclusive of holes and irregularities. They were obtained by multiplying the average length of the sections by the average length of the individual traverses.

I. *Woodson Mountain granodiorite, San Luis Rey quadrangle, California* (SLR 596).

This rock is a quartz-rich granodiorite which appears in the field to be uniform in composition and grain size. The two thin sections were cut from apparently identical specimens from the same outcrop. The tabulated potash feldspar includes both microcline and microperthite. No orthoclase was observed.

Size of large section: 450 sq. mm.
Size of ordinary section: 300 sq. mm.

	1st Measurement	2nd Measurement	Weighted Average	
	Upper Half of Large Section			
No. traverses	15	10	25	
Total length	176 mm.	100 mm.	276 mm.	
Quartz	39.3%	38.9%	39.1%	
Potash feldspar	23.5	23.6	23.5	
Plagioclase	33.5	35.1	34.2	
Biotite	2.9	2.4	2.7	
Hornblende	0.6	0.0	0.4	
	Lower Half of Large Section			
No. traverses	15	10	25	
Total length	217 mm.	138 mm.	355 mm.	
Quartz	44.4	45.0	44.6	
Potash feldspar	25.8	25.5	25.7	
Plagioclase	26.9	26.8	26.9	
Biotite	1.1	1.0	1.1	
Hornblende	1.7	1.6	1.7	
	Whole Large Section			Ordinary Section
No. traverses	30	20	50	14
Total length	393 mm.	238 mm.	631 mm.	254 mm.
Quartz	42.1	42.4	42.2	46.7
Potash feldspar	24.8	24.7	24.8	27.0
Plagioclase	29.9	30.3	30.0	21.6
Biotite	1.9	1.6	1.8	4.0
Hornblende	1.2	1.0	1.1	0.8

II. *San Marcos gabbro, San Luis Rey quadrangle, California* (SLR 218).

This is a hypersthene gabbro which was known to show local variations in the extent to which the pyroxenes were replaced by hornblende. But the hand specimens represented by the two thin

sections were taken from the same apparently uniform outcrop and were believed to be as similar as any two specimens of this variable rock. Examination of the thin sections revealed at once marked differences in the proportion of hornblende, as well as the presence of small amounts of quartz and biotite in the smaller section.

Size of large section: 550 sq. mm.
Size of ordinary section: 350 sq. mm.

	1st Measurement	2nd Measurement	Weighted Average	
	Upper Half of Large Section			
No. traverses	18	15	33	
Total length	298 mm.	229 mm.	527 mm.	
Plagioclase	58.6%	59.0%	58.8%	
Pyroxene	29.2	27.2	28.3	
Hornblende	3.2	4.5	3.8	
(Total pyrobole)	(32.4)	(31.7)	(32.1)	
Iron ore	8.9	9.3	9.1	
	Lower Half of Large Section			
No. traverses	18	15	33	
Total length	298 mm.	228 mm.	526 mm.	
Plagioclase	65.6	65.8	65.7	
Pyroxene	19.7	20.5	20.0	
Hornblende	7.3	5.8	6.6	
(Total pyrobole)	(27.0)	(26.3)	(26.6)	
Iron ore	7.4	7.8	7.6	
	Whole Large Section			Ordinary Section
No. traverses	36	30	66	15
Total length	596 mm.	457 mm.	1053 mm.	268 mm.
Plagioclase	62.1	62.4	62.2	73.9
Pyroxene	24.5	23.8	24.2	2.3
Hornblende	5.2	5.2	5.2	18.1
(Total pyrobole)	(29.7)	(29.0)	(29.4)	(20.4)
Iron ore	8.1	8.6	8.3	3.3
Quartz	0.0	0.0	0.0	1.5
Biotite	0.0	0.0	0.0	0.8

To test the personal error in measuring the constituents in a single thin section, the large thin section of this gabbro was given to five students for measurement. The students had already made

one Rosiwal measurement. One of the measurements differed from the other four by several per cent for both the feldspar and the pyroboles. The range for the constituents and the averages and maximum errors both for all five measurements and for the best four are given below:

	Minimum		Maximum		Average		Maximum error		Measurement by authors
	of 5	of 4	of 5	of 4	of 5	of 4	of 5	of 4	
Plagioclase	59%	61%	63%	63%	61½%	62%	2½%	1%	62.2%
Pyroboles	28½	28½	32½	30½	30	29½	2½	1	29.4
Magnetite	8	8	9	9	8½	8½	½	½	8.3

These data show that with favorable material the constituents in a thin section can easily be measured with a probable error of 1 per cent.

ROCKS FROM IRON HILL, COLORADO: Another group of rocks from the Iron Hill alkaline stock in southwestern Colorado affords an opportunity to compare the results of Rosiwal determinations with those of actual separations of the minerals by heavy liquids. The heavy liquid determinations were made on part of the powder used for chemical analyses of the same rocks. They were checked step by step with the microscope and should be accurate to within about 1 per cent. The results of these separations correspond closely with the chemical analyses. The rocks were especially favorable for heavy liquid separations, but they were rather unfavorable for Rosiwal determinations, since some of them are coarse-grained and some are megascopically variable in mineral composition. To make the results from the separations directly comparable with those from the thin sections, the latter are all stated in weight per cents.

I. *Pyroxenite, Iron Hill, Colorado* (U 1199).

This pyroxenite with a grain size of about 1 mm. appears uniform in the outcrop and in the hand specimen. Four thin sections which were measured with the recording micrometer show surprising variations among themselves and fail to agree closely with the heavy liquid determination or the chemical analysis. The thin sections and the powder used for the analysis and for the heavy liquid separation came from a single block of apparently uniform rock a foot on a side.

Section	1	2	3	4	Weighted Average	Heavy Liquid
Size, sq. mm.	320	200	300	250	1070	
Pyroxene	50%	83%	59%	86%	67%	76%
Apatite	13	3	12	1	7	1
Iron Ore	23	14	29	18	27	17
Perofskite	14					6
Biotite	—	tr	—	—		tr

II. *Shonkinite, Iron Hill, Colorado* (U 2138).

This rock is composed of feldspar crystals up to 40 mm. across, which enclose poikilitically millimeter-sized pyroxene grains. Considering the coarseness of the texture, the agreement of the results given below is very satisfactory. Rosiwal determinations on three thin sections check within 5 per cent of the average, and the latter average checks to within 3 per cent with the heavy liquid analysis.

Section	1	2	3	Weighted Average	Heavy Liquid
Size, sq. mm.	360	420	360	1140	
Altered nepheline / Orthoclase	28%	22%	28%	26%	29%
Pyroxene	56	65	59	60	61
Apatite	10	4	8	7	5
Titanite	6	8	4	6	5
Calcite	—	1	1	1	1

III. *Melteigite, Iron Hill, Colorado* (U 1877).

This melteigite is a rock of uniform character with a grain size of about 1 mm. The measurements on two thin sections show variations of 5 per cent from the average. This average agrees with the results of the heavy liquid analysis within 2 per cent.

Section	1	2	Weighted Average	Heavy Liquid
Size, sq. mm.	300	480	780	
Pyroxene	70%	79%	75%	77%
Nepheline	26	18	21	19
Apatite	3	3	3	4
Magnetite	—	tr	tr	tr

IV. *Pyroxene Melteigite, Iron Hill, Colorado* (U 1132).

Since this rock contains grains up to 10 mm. across and is megascopically variable in composition, it is unfavorable for quantitative determinations. The measurements on two thin sections show wide variations, and yet their average checks to within 3 per cent with the results of the heavy liquid separation.

Section	1	2	Weighted Average	Heavy Liquid
Size, sq. mm.	225	320	545	
Nepheline	37%	18%	26%	29%
Apatite	4	4	4	4
Pyroxene	30	38	35	38
Garnet	19	38	28	25
Iron Ore	9	tr	5	2
Phlogopite	4	1	2	1
Calcite	tr	1	tr	1

Discussion of Results

It is apparent from an examination of the data for the rocks from the San Luis Rey quadrangle that two independent determinations on the same thin section or the same part of a thin section check very closely. The maximum deviation of the percentage of any constituent from the weighted average of all the measurements for that constituent is 1.1 per cent. The average deviation of all the figures from the weighted averages is only 0.2 per cent. Because they are based on only two determinations, the deviations from the weighted averages may be less significant than the actual differences between the two sets of measurements. But the maximum difference between two corresponding figures is 2.0 per cent, and the figures in question are those for the pyroxene in the gabbro. The reason for this discrepancy is that the hornblende is replacing the pyroxene so irregularly and on such a small scale in this thin section, that it is difficult to measure the proper intercepts of the two minerals with the recording micrometer. If the sums of the pyroxene and hornblende are considered throughout, this difference is only 0.7 per cent.

In marked contrast to these close correspondences are the discrepancies between the figures for the two halves of each section and for the large and ordinary sections of each rock. Here the differences reach 8.4 per cent for the plagioclase of the granodiorite,

21.9 per cent for the pyroxene of the gabbro. The change from predominant plagioclase to predominant potash feldspar in the smaller granodiorite section would throw the rock into a different pigeonhole in the classification. Yet the granodiorite appears to be uniform. Close examination of the ordinary thin section shows the different composition of the latter to be due to the presence of a cluster of quartz grains with an unusually high proportion of potash feldspar. It would be necessary to examine a number of additional thin sections before it would be possible to say how common such clusters are or what should be considered the average mineral composition of the rock as a whole. Here is an important problem in sampling.

The gabbro may be considered an extreme example of the variations which are sometimes found in rock specimens collected from a single outcrop, even when they present a similar appearance megascopically. It was not possible to estimate accurately from the hand specimen the relative proportions of pyroxene and amphibole in the rock. A field worker collecting specimens from what looks to be, for this gabbro, a remarkably uniform outcrop would easily be misled into concluding that a single thin section would suffice to sample the outcrop. Yet it is probable that the thin sections now available still fail to cover the range of variation at this place.

For the Iron Hill rocks different thin sections cut from a single block of rock about one foot on a side yielded Rosiwal determinations that varied among themselves by as much as 20 per cent for some of the constituents, and not uncommonly as much as 10 per cent. The averaged results from two to four large thin sections should give satisfactory data for an ordinary rock. Yet in this case the averages are found to differ from the more reliable determinations by heavy liquid separations by as much as 9 per cent. Many of the averages are in error by several per cent.

The tabulated data with regard to the number and total length of the traverses measured on the San Luis Rey sections throw some light upon the question of how many intercepts it is necessary to measure, in order to secure an adequate representation of the mineral composition of a thin section. The number of traverses upon each area of the size of an ordinary thin section varied from 10 to 36, and the total length of these traverses from 100 to 298 mm. The traverses were all made in the same direction across the

sections and were spaced at distances of about 1 mm. The degree of correspondence of the results from two independent measurements on the same sections and a theoretical consideration of the problem lead to the conclusion that 10 to 20 traverses across a thin section, spaced about a millimeter apart, will sample that thin section regardless of the grain size. If the maximum grain size is less than 1 mm., even fewer traverses will suffice. Unless the thin section offers some special difficulties to accurate measurement, such as have been indicated above, the results should be correct within 1 per cent for the minerals present in the thin section.

Conclusions

The preceding data and discussion lead to the following conclusions:

(1) The mineral constituents of a thin section can be measured by the Rosiwal method with an error of only about 1 per cent, provided ordinary care and pains are taken. Greater accuracy cannot easily be attained, nor is it necessary or desirable in view of the much larger error which is likely to be introduced through failure of a thin section to sample a rock mass or even a hand specimen.

(2) For an accuracy of about 1 per cent in a Rosiwal determination of a thin section, a satisfactory technique is to make fifteen traverses about a millimeter apart across the section. The traverses should be transverse to any fluidal banding or other linear structure which the rock may show. For rocks with a grain size less than one millimeter fewer traverses will be necessary.

(3) Failure of a thin section to sample a hand specimen or rock outcrop introduces a much larger error than that of the Rosiwal measurement on a thin section. In the experience of the authors, Rosiwal determinations on two or more thin sections from the same hand specimen or small outcrop or even on the two halves of a single large thin section commonly differ by from 2 to 10 per cent for the major constituents, and in some rocks they may differ much more.

(4) For an accuracy of about 1 per cent in a Rosiwal determination of a rock in which the constituents are perfectly mixed, the thin section or surface on which the measurements are made must have an area at least 100 times that of the largest grains that are present to the extent of 1 per cent of the rock. In practice the errors will still often be greater than 1 per cent.

(5) To insure an accuracy of 1 per cent in the measurements for a rock as a whole, determinations should be made on at least two thin sections to test the mixing of the rock. The number of thin sections required to sample a given rock must then be determined by a consideration of the grain size and the uniformity of the rock.

(6) Errors in the measurement of a single thin section increase with decrease in size of grain, because of (1) the exaggeration of the cumulative error from the surface boundary estimation of the opaque minerals, etc., and (2) the increased difficulty in the recognition of the mineral grains. On the other hand, the difficulties of proper sampling increase directly with the grain size, because of (1) the limited number of grains in a thin section, (2) the greater likelihood of improper mixing, and (3) the greater danger of a systematic tearing out of grains in coarse-grained rocks or rocks with coarse phenocrysts. The most favorable rock for measurement is one in which the minerals are uniformly distributed and the grains about 1 mm. across. An ordinary thin section of such a rock will show about 250 grains, and the intercepts will be long enough to measure satisfactorily.

(7) Rosiwal analyses should not be expressed closer than the nearest per cent, except for the minor constituents, without a specific justification of the accuracy for the particular case.

(8) The danger of basing far-reaching conclusions on a few Rosiwal determinations of specimens from widely scattered outcrops is evident. Even if the thin sections used for this purpose are selected with care from a much larger number, as representative of the rock under consideration, there is no assurance that the proportions of the minerals in any one thin section are within less than several per cent of the correct average for the rock mass as a whole.

Bibliography

1. Delesse, A., Procédé méchanique pour déterminer la composition des roches, (extrait): *Compt. Rend. Acad. Sci.*, Paris, vol. **25**, pp. 544–545, 1847.
2. Delesse, A., Procédé méchanique pour déterminer la composition des roches: *Annales des Mines, Series IV*, vol. **13**, pp. 379–388, 1848.
3. Sorby, H. C., On Slaty Cleavage as exhibited in the Devonian Limestones of Devonshire: *Phil. Mag., 4th Series*, vol. **11**, pp. 20–37, esp. p. 21, 1856.
4. Sollas, W. J., Contributions to a Knowledge of the Granites of Leinster: *Trans. Roy. Irish Acad.*, Dublin, vol. **29**, pp. 428–514, esp. p. 471 et seq., 1887–1892.
5. Rosiwall, A., Über geometrische Gesteinsanalysen: *Verh. der K. K. Geol. Reichanstalt*, Wein, pp. 143–175, **1898.**

6. Julien, A. A., Genesis of the Amphibole Schists and Serpentines of Manhattan Island, New York: *Bull. Geol. Soc. Amer.*, vol. **14,** pp. 460–468, 1903.
7. Hirschwald, J., Über ein neues Mikroskopmodell und ein Planimeter-Ocular zur geometrischen Gesteinsanalyse: *Centralbl. f. Min.*, etc., pp. 626–633, **1904.**
8. Williams, I. A., The Comparative Accuracy of the Methods for Determining the Percentages of the Several Components of an Igneous Rock: *Am. Geologist,* vol. **35,** pp. 34–46, 1905.
9. Lincoln, F. C., and Rietz, H. L., The Determination of the Relative Volumes of the Components of Rocks by Mensuration Methods: *Econ. Geol.* vol. **8,** pp. 120–139, 1913.
10. Shand, S. J., A Recording Micrometer for Geometrical Rock Analysis: *Jour. Geology,* vol. **24,** pp. 394–404, 1916.
11. Johannsen, A., and Stevenson, E. A., On the Accuracy of the Rosiwal Method for the Determination of the Minerals in a Rock: *Jour. Geology,* vol. **27,** pp. 212–220, 1919.
12. Johannsen, A., A Planimeter Method for the Determination of the Percentage Compositions of Rocks: *Jour. Geology,* vol. **27,** pp. 276–285, 1919.
13. Holmes, A., *Petrographic Methods and Calculations,* London, Thomas Murby, pp. 310–322, **1921.**
14. Richardson, W. A., A Simplification of the Rosiwal Method of Micrometric Analysis: *Mineral. Mag.*, vol. **19,** pp. 314–315, 1922.
15. Richardson, W. A., A Micrometric Study of the St. Austell Granite, Cornwall: *Quart. Jour. Geol. Soc. London,* vol. **79,** pp. 546–576, 1923.
16. Wentworth, C. K., An Improved Recording Micrometer for Rock Analysis: *Jour. Geology,* vol. **31,** pp. 228–232, 1923.
17. Hunt, W. F., An Improved Wentworth Recording Micrometer: *Am. Mineral.*, vol. **9,** pp. 190–193, 1924.
18. Thomson, E., Quantitative Microscopic Analysis: *Jour. Geology,* vol. **38,** pp. 193–222, 1930.
19. Grout, F. F., Rock Sampling for Chemical Analysis: *Am. Jour. Sc.*, vol. **24,** pp. 394–404, 1932.
20. Stewart, D., The Petrography of Some Antarctic Rocks: *Am. Mineral.*, vol. **19,** pp. 150–160, 1934.