THE DISTRIBUTION OF HEAVY ACCESSORY MINERALS IN A LACCOLITH.

E. C. DAPPLES.

ABSTRACT. The heavy accessory minerals in the Mt. Wheatstone laccolith were separated from aggregate samples collected at five localities on the mountain slope. Samples were crushed by hand, sieved into sizes of 100-200 mesh and -200 mesh, and the heavy minerals were separated by centrifugation in tetrabromoethane. The heavy minerals were mounted on slides and the relative percentages of zircon, apatite, and sphene determined by count. The relative percentage of error in laboratory procedure is large and extremely variable. Relative percentage of error for the entire samples, including both errors due to sampling and laboratory procedure, average 22.8 for sphene, 89.7 for zircon, and 38.7 for apatite. The probable relative percentage of field error is determined as 16.2 for sphene, 55.7 for zircon, and 25.1 for apatite. Variation in the percentage of field error indicates that zircon, sphene, and apatite are not uniformly distributed throughout the igneous body.

INTRODUCTION.

CORRELATION of igneous rock bodies by means of the similarity in the percentage occurrence of contained heavy accessory minerals is dependent upon the basic assumption that such minerals are distributed in the same relative abundance throughout a body of igneous rock. Such distribution must maintain its percentage uniformity in instances where the igneous mass may differentiate into several distinct rock types. Therefore, the relative abundance of heavy accessory minerals should be identical in all bodies which have originated from the same parent magma. If such an assumption be accepted as valid, then the relative distribution of such minerals in a properly collected sample from an igneous rock body should vary from a similarly collected sample from the same body only as the result of errors accumulated by sampling and laboratory procedures. Errors resulting from improper sampling, which may cause wide variation in the apparent mineral distribution, have been demonstrated to exist, and certain laboratory procedures of crushing and separation have been shown to give results with a large probable error. (1, 2). If the magnitude of the field and laboratory errors could be determined, then the remaining variation in percentage mineral distribution, if present, should indicate the degree of uniformity of original

distribution of accessory minerals in the magma. In order to test the validity of the fundamental assumption of uniform distribution of accessory minerals in an igneous body, and to accumulate more data concerning the accuracy of the laboratory procedure now generally followed in heavy mineral analysis, samples were collected from a laccolith of seemingly uniform rock composition. The laccolith, Mt. Wheatstone, is a prominent peak of Tertiary age in the West Elk Mountains in central Colorado, and intrudes strata of upper Cretaceous and Eocene age.

ROCK DESCRIPTION.

From the lowest exposures to the peak of the mountain the igneous mass of the Mt. Wheatstone laccolith appears to be nearly uniform in composition and texture. The rock is a light gray to pink, rather coarse-grained quartz monzonite porphyry containing phenocrysts of quartz and orthoclase. Phenocrysts of orthoclase (sanidine) are frequently one to two inches in length and are generally remarkably euhedral in shape, whereas the quartz lacks any well developed form and occurs in small rounded particles which constitute about ten per cent of the rock. The groundmass is fine-grained and shows kaolinization resulting from some hydrothermal alteration. If the biotite content is high, the rock may also have a reddish color through development of hematite.

Microscopic examination indicates that approximately 25 per cent of the mineral constituents consist of euhedral crystals of andesine ($Ab_{68}An_{32}$) approximately 1 to 2 mm. long. Many crystals show pronounced zonal outlines and have cores which are somewhat more calcic than the borders. Biotite with well developed tabular outline is present as approximately ten per cent of the total mineral constituents. Hornblende occurs as long, acicular, and well terminated crystals composing 15 per cent of the rock. Most of the hornblende is fresh but occasional crystals show alteration to chlorite. Augite is present to the extent of about three per cent of the constituents and is usually observed as phenocrysts of euhedral outline. The groundmass of the remainder of the rock is a fine-grained aggregate of biotite, quartz, feldspar and stilbite.

FIELD AND LABORATORY PROCEDURE.

Approximately two pounds of large chips were collected at each of five outcrops, selected at random at various elevations

up the slope of Mt. Wheatstone (Table 1). Sampling was done following the procedure recommended by Grout (1), by collecting chips over an area of 100 square feet of outcrop. Each outcrop sampled was selected at random from a location which was at a higher elevation and also deeper within the igneous mass than the previously sampled outcrop. Chips collected at each outcrop constituted an aggregate sample which was designated by an "X" serial number.

TABLE 1.

Position of samples on slope of Mt. Wheatstone.

Sample No.	*Elevation*	*Height*
X1	9,000	0
X2	10,200	1,200
X3	11,000	2,000
X4	11,500	2,500
X5	12,100	3,100

Aggregate samples were crushed to one quarter of an inch in a jaw crusher and then reduced by hand in an iron mortar. The fines were frequently removed and sieved to assure maximum uniformity of size. Such a procedure is recommended by Tyler and Marsden (2) as a method producing the smallest variation in percentile mineral distribution during the crushing operation. Following crushing, each field sample was separated into two sizes, one consisting of material which passed through a 100 mesh screen but remained upon the 200 mesh screen, and another whose grain size passed through the 200 mesh screen. Each of the two sizes was then reduced in quantity on a Jones splitter until two samples of approximately ten grams each remained. After weighing, the magnetite and metallic iron were separated from each sample by a magnet of moderate strength, the metallic iron removed by dissolving in nitric acid and the non-magnetic samples weighed (Table 2). Samples containing the non-metallic minerals were then carefully washed to remove particles of clay dimensions, dried, and centrifuged in tetrabromoethane. The heavy minerals obtained by centrifugation were weighed (Table 2), split into small samples and mounted on slides. Two slides were made from each centrifuged sample and the mineral distribution determined by count. At least 400 grains were counted in each slide but in those slides in which there were floods of biotite and hornblende as many as 2,000 grains were counted (Tables 3 and 4).

TABLE 2.

Weight Percentage of Heavy Minerals.

Sample No.	Size	Wt. of Sample, grams	Wt. of Magnetics grams	Per cent Magnetics	Wt. of non-magnetics, grams	Per cent non-magnetics
X1-a	100-200	8.770	0.591	6.8	0.481	5.5
X1-b	100-200	8.650	.538	6.2	.640	7.4
X1-c	-200	6.160	.061	1.	.230	3.7
X1-d	-200	5.021	.121	2.4	.399	7.9
X2-a	100-200	6.930	.451	6.5	.350	5.1
X2-b	100-200	7.168	.442	6.2	.371	5.2
X2-c	-200	6.822	.348	5.1	.232	3.4
X2-d	-200	6.354	.339	5.3	.223	3.5
X3-a	100-200	4.632	.312	6.7	.313	6.7
X3-b	100-200	5.579	.401	7.2	.396	7.1
X3-c	-200	7.470	.157	2.1	.300	4.0
X3-d	-200	6.960	.249	3.6	.389	5.6
X4-a	100-200	10.637	.039	.4	.309	2.9
X4-b	100-200	10.658	.048	.4	.371	3.5
X4-c	-200	9.632	.183	1.9	.259	2.7
X4-d	-200	12.469	.319	2.5	.224	1.8
X5-a	100-200	6.840	.599	8.6	.280	4.1
X5-b	100-200	7.241	.633	8.7	.273	3.8
X5-c	-200	7.163	.473	6.6	.154	2.2
X5-d	-200	7.970	.740	9.3	.200	2.5
Relative per cent of error				38.5		24.5

DESCRIPTION OF MINERALS.

The heavy minerals in the igneous rock of Mt. Wheatstone are few in variety and consist of common minerals, factors which increased the accuracy of the mineral counts by eliminating errors in identification during the counting procedure. Epidote is present as transparent, greenish fragments resting on the basal cleavage and as translucent, granular crystal aggregates. Grains of the clear variety are rarely present and the predominant occurrence is the granular material. Biotite is found in two varieties, one consisting of clear fragments and another containing a network of inclusions of acicular crystals of rutile. Alteration to hematite was noted in many grains, the alteration apparently progressing chiefly along the boundaries between rutile inclusions and the biotite. The inclusion-free variety is the more abundant of the two forms of biotite in those samples collected about half way up the mountain, whereas the rutilated variety is preponderant in the samples from the top and bottom. Sphene occurs as clear,

angular fragments of highly irregular outlines and with conchoidal fracture surfaces. The optic angle is very small and approaches zero in some grains which results in a uniaxial interference figure. Most of the sphene, however, occurs as granular aggregates that show marked alteration to leucoxene. The granular sphene commonly shows abnormal blue interference colors. Hypersthene occurs as cleavage fragments of larger crystals and occasional grains are strongly pleochroic. Zircon is present as gray, doubly terminated crystals less than 1/100 mm. long. The faces of the bipyramidal terminations appear slightly rounded and consist of both first and second order forms. Usually the crystals are elongate with prism faces which are better developed than the bipyramids. Another habit rather rarely observed is as a geniculated twin crystal. Apatite is found as slightly elongate, tabular shaped, colorless crystals and as cleavage fragments of larger grains. The crystals usually have the hexagonal prism flattened and the ends terminated with second order bipyramids in combination with a basal pinacoid. Hornblende occurs as cleavage fragments of larger crystals. Ilmenite is abundant as small unaltered broken fragments. Identification of this mineral was doubtful in many instances in the -200 mesh size and errors of appreciable magnitude are present, therefore, in the percentage estimates.

ANALYSIS OF RESULTS.

The percentile distribution of the minerals described in the preceding paragraph is far from uniform between samples of different "X" series (Table 3). In some samples of the X4 series biotite constitutes more than 60 per cent of the total minerals and hornblende may exceed 40 per cent in samples of the same series. In other samples, as in those of the X1 series, hornblende may constitute less than one per cent of the heavy minerals. Such variations in the relative abundance of certain minerals are not apparent in the thin sections examined although certain hand specimens appear to contain more biotite than others. Sphene is also variable in distribution, particularly the granular variety altering to leucoxene. Leucoxene is abundant in series X1, X2 and X5 but low in series X3 and X4. Variation in the percentage of ilmenite is also pronounced. Zircon is conspicuous by its scarcity.

Although variations in percentage of minerals are pro-

TABLE 3.*

Percentage (by count) of Heavy Minerals.

Sample	clear epidote	altered epidote	total epidote	biotite	sphene altering to leucoxene	clear sphene	total sphene	hypersthene	zircon	apatite	hornblende	ilmenite	pyrite	total opaques
X1-a1	4.2	17.7	21.9	30.0	34.8	1.3	36.1	3.9	0.0	5.8	0.0	.9	.9	1.8
X1-a2	1.9	2.6	4.5	26.2	62.3	1.5	63.8	2.0	0.0	3.2	.1	0.0	0.0	0.0
X1-b1	1.8	3.1	4.9	43.0	43.0	1.3	44.3	2.9	.6	3.6	.2	.3	.2	.5
X1-b2	1.2	5.0	6.7	38.3	44.4	1.3	45.7	3.8	0.0	3.7	.5	1.3	.4	1.7
X1-c1	.3	0.0	0.3	6.2	3.6	11.1	14.7	.2	.7	8.5	.3	69.0	0.0	69.0
X1-c2	.2	.4	0.6	4.1	7.6	9.7	17.3	.4	1.0	5.5	.6	72.6	0.0	72.6
X1-d1	.3	.0	0.3	3.5	3.3	6.2	9.5	.6	1.0	11.8	.6	73.0	0.0	73.0
X1-d2	.3	.1	0.4	7.8	6.9	10.6	17.5	0.0	1.0	11.8	.5	61.0	0.0	61.0
X2-a1	.5	1.5	2.0	32.5	46.7	.7	47.4	10.2	.3	3.0	1.5	3.2	0.0	3.2
X2-a2	.6	.8	1.4	31.5	42.4	2.4	44.8	10.3	.3	4.3	1.9	5.0	.5	5.5
X2-b1	.1	3.0	3.1	45.0	38.1	.3	38.4	8.4	.1	3.1	.7	1.0	0.0	1.0
X2-b2	1.0	3.5	4.5	41.4	38.4	0.0	38.4	9.4	0.0	4.0	1.2	.5	.5	1.0
X2-c1	2.5	2.5	5.0	9.3	24.4	6.7	31.1	10.7	.2	19.9	1.1	16.8	5.6	22.4
X2-c2	3.2	1.6	4.8	9.9	23.6	6.3	29.9	10.7	2.6	27.7	1.0	11.1	2.0	13.1
X2-d1	1.5	1.5	3.0	8.2	36.6	5.8	42.4	10.5	3.1	23.5	1.3	7.2	0.5	7.7
X2-d2	1.6	2.4	4.0	8.0	42.1	7.8	49.9	8.0	1.5	20.7	.2	5.3	2.2	7.5
X3-a1	0.0	.2	0.2	54.7	5.3	1.1	6.4	1.8	0.0	2.5	34.0	0.0	0.2	0.2
X3-a2	0.0	0.0	0.0	54.7	2.6	1.8	4.4	2.2	0.0	3.7	34.9	0.0	0.0	0.0
X3-b1	0.0	0.0	0.0	64.8	3.1	.5	3.6	1.3	0.0	2.4	27.6	0.0	0.0	0.0
X3-b2	0.0	0.0	0.0	61.1	2.9	.5	3.4	.5	0.0	2.5	32.2	0.0	0.0	0.0
X3-c1	0.2	0.0	0.2	21.1	1.9	7.9	9.8	.3	1.6	9.5	27.2	30.2	0.0	30.2
X3-c2	0.2	0.0	0.2	14.7	5.0	3.8	8.8	1.0	1.8	18.1	40.2	15.3	0.0	15.3
X3-d1	0.2	0.0	0.2	17.6	1.8	4.8	6.6	.2	2.6	13.4	26.6	32.5	0.0	32.5
X3-d2	0.1	0.2	0.3	20.6	.7	7.1	7.8	.2	1.0	11.7	28.2	30.0	0.0	30.0
X4-a1	0.0	0.0	0.0	60.6	0.5	0.5	1.0	0.1	0.0	1.5	36.8	0.0	0.0	0.0
X4-a2	0.0	0.0	0.0	66.0	0.7	1.0	1.7	0.1	0.0	2.0	30.3	0.0	0.0	0.0
X4-b1	0.0	0.0	0.0	61.5	0.2	1.5	3.7	0.0	0.0	2.1	34.8	0.0	0.0	0.0
X4-b2	0.0	0.0	0.0	66.0	0.6	0.3	0.9	0.3	0.1	1.8	30.8	0.0	0.0	0.0
X4-c1	0.2	0.0	0.2	31.5	0.6	5.7	6.3	0.9	2.1	5.7	33.1	20.0	0.0	20.0
X4-c2	0.3	0.0	0.3	27.5	0.2	2.5	2.7	0.8	3.0	11.0	41.6	12.9	0.0	12.9
X4-d1	0.0	0.0	0.0	46.1	0.4	3.8	4.2	0.0	0.6	6.1	37.9	4.9	0.0	4.9
X4-d2	0.0	0.0	0.0	56.0	0.0	2.8	2.8	0.0	0.5	3.5	34.7	2.5	0.0	2.5
X5-a1	0.9	1.2	2.1	51.7	35.4	2.7	38.1	1.2	0.1	4.2	2.6	0.0	0.0	0.0
X5-a2	0.9	0.7	1.6	52.2	33.8	2.6	36.4	0.5	0.0	6.2	1.9	0.7	0.2	0.9
X5-b1	0.9	1.9	2.8	52.6	34.2	2.2	36.4	1.9	0.2	3.8	1.9	0.2	0.0	0.2
X5-b2	1.5	0.3	1.8	50.3	34.8	4.1	38.9	1.7	0.0	5.2	1.7	0.2	0.2	0.4
X5-c1	1.0	2.1	3.1	16.5	18.6	6.4	25.0	3.5	1.2	6.8	1.9	41.8	0.0	41.8
X5-c2	1.6	0.9	2.5	7.9	22.1	8.5	30.6	2.0	1.6	8.5	1.5	45.2	0.0	45.2
X5-d1	2.5	0.0	2.5	21.1	15.7	8.9	24.6	0.9	2.3	14.3	3.4	30.9	0.0	30.9
X5-d2	2.3	1.3	3.6	13.2	16.6	14.3	30.9	1.3	2.3	13.4	3.4	31.9	0.0	31.9

* Actually the figures are significant to one per cent but percentages have been carried out to 1/10 per cent to indicate the magnitude of abundance where only one or two grains of any mineral are present in the slide.

nounced between samples of the "X" series, marked differences in the percentile distribution of samples in any one series also exist, particularly between those samples of different grain size. Such differences may be the result of crushing large grains. For example, unaltered sphene is consistently more abundant in fractions less than 200 mesh than in those exceeding 200 mesh dimensions. Sphene grains observed in the slides of 100-200 mesh sizes are fragments which have been broken in crushing. Thus, crushing to smaller dimensions forms more particles and increases the percentage based on grain counts. Such is also true in the case of hornblende, although the variation in percentage is not as strongly pronounced. Conversely, biotite is consistently less abundant in the small size because it separates along its cleavage but tends to resist reduction transverse to the cleavage and so remains chiefly with the larger size. Zircon, which occurs chiefly in crystals less than 1/100 mm. in length, is more abundant in the fine size because it occurs as inclusions in feldspar and quartz and is released when such material is crushed to less than 200 mesh (Fig. 1a).

Three accessory minerals, sphene, zircon, and apatite, are considered critical since they are the only ones present in the rock which may be assumed to have crystallized directly from the magma. The relative percentage of these three minerals in the various field samples is important, therefore, in determining the magnitude of errors involved in the laboratory procedure and in indicating the degree of variation in accessory mineral distribution within the laccolith. The relative abundance of the three critical minerals is listed in Table 4 and the percentage of variation in any given field sample is indicated in Table 5. The relative percentages of error listed were obtained by calculating the standard deviation from the arithmetic mean of the percentile distribution of each of the three minerals, sphene, zircon, and apatite, in the 100-200 mesh size, the -200 mesh size, and for the entire sample. The standard deviation is multiplied by .6745 to obtain the probable error in any percentile, and the relative percentage of error is obtained by dividing the probable error by the arithmetic mean of the mineral percentages for any given size. The relative percentage of error in per cent mineral distribution is not constant in any one sample and the variation is particularly large in the case of zircon and nearly equally as great in the cases of the other two minerals. In the 100-200 mesh size the errors may

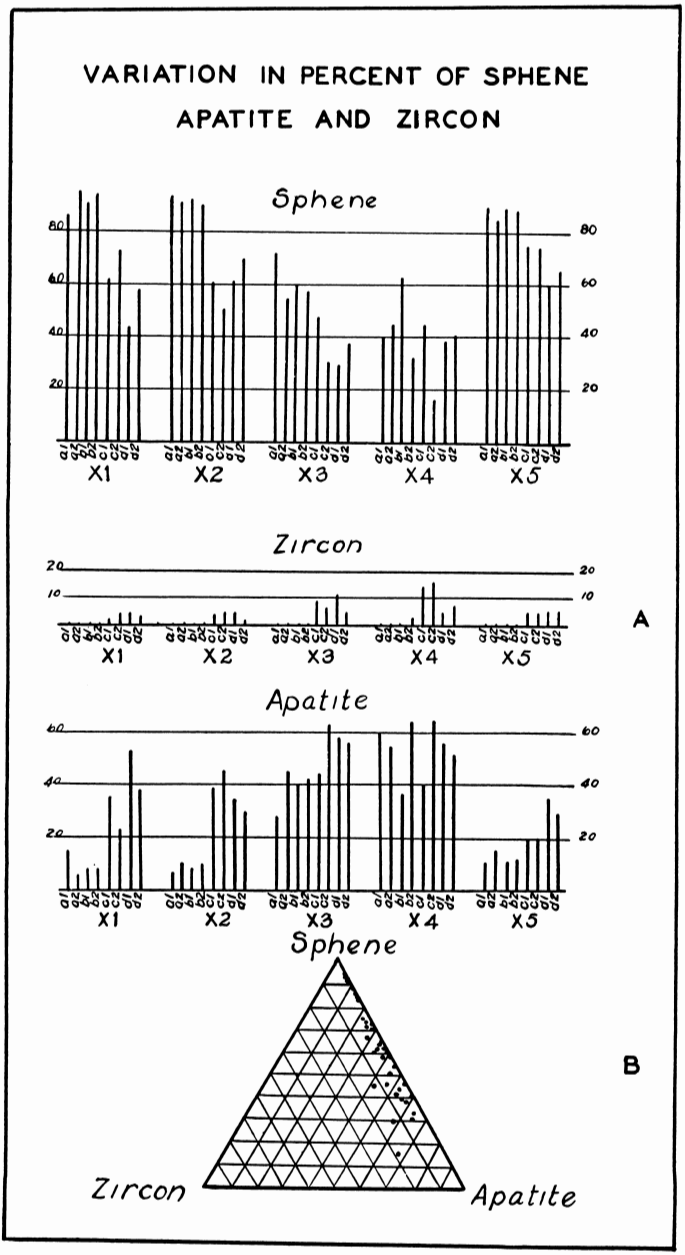

Fig. 1A—Variation in per cent of sphene, apatite, and zircon in individual field samples.

B—Variation in sphene, apatite, and zircon in all samples.

TABLE 4.

Relative Percentages of Sphene, Zircon, and Apatite.

Sample	*Sphene*	*Zircon*	*Apatite*
X1-a1	86.0	0.0	14.0
X1-a2	95.3	0.0	4.7
X1-b1	91.5	1.1	7.4
X1-b2	92.5	0.0	7.5
X1-c1	61.5	2.9	35.6
X1-c2	72.7	4.2	23.1
X1-d1	42.7	4.5	52.8
X1-d2	57.7	3.3	39.0
X2-a1	93.4	0.6	6.0
X2-a2	90.7	0.6	8.7
X2-b1	92.4	0.2	7.4
X2-b2	90.5	0.0	9.5
X2-c1	60.7	0.4	38.9
X2-c2	49.7	4.3	46.0
X2-d1	61.5	4.5	34.0
X2-d2	69.2	2.1	28.7
X3-a1	72.0	0.0	28.0
X3-a2	54.4	0.0	45.6
X3-b1	60.0	0.0	40.0
X3-b2	57.5	0.0	42.5
X3-c1	46.9	7.7	45.4
X3-c2	30.6	6.4	63.0
X3-d1	29.2	11.5	59.3
X3-d2	38.1	4.9	57.0
X4-a1	40.0	0.0	60.0
X4-a2	46.0	0.0	54.0
X4-b1	63.7	0.0	36.3
X4-b2	32.1	3.6	64.3
X4-c1	44.8	14.9	40.3
X4-c2	16.2	18.0	65.8
X4-d1	38.5	5.5	56.0
X4-d2	41.2	7.4	51.4
X5-a1	89.9	0.2	9.9
X5-a2	85.5	0.0	14.5
X5-b1	90.0	0.5	9.5
X5-b2	88.2	0.0	11.8
X5-c1	75.8	3.6	20.6
X5-c2	75.2	3.9	20.9
X5-d1	59.8	5.6	34.6
X5-d2	66.3	4.9	28.8

become so large as to make statements of mineral percentage in a sample an absurdity. The minimum percentage of error in the distribution of any single mineral appears in the -200 mesh size in an "X" series, yet even so the variations are very large. The relative percentage of error listed in Table 5 represents the expected variation in percentile distribution of any mineral in each of the selected sizes as the result of laboratory procedure alone, for each "X" series represents one field sample.

TABLE 5.

Relative Percentage of Error in Samples from the Same Field Series.

Field Series	Sample	Sphene			Zircon			Apatite		
	entire sample	100-200 mesh	-200 mesh	entire sample	100-200 mesh	-200 mesh	entire sample	100-200 mesh	-200 mesh
X1	16.4	2.5	12.3	60.6	107.	11.8	43.3	27.4	18.9
X2	14.6	0.9	7.8	71.6	50.	44.1	45.7	11.3	11.6
X3	19.6	7.4	13.1	74.2	0.	2.2	15.4	7.4	9.1
X4	20.9	17.2	21.4	70.6	117.	30.5	12.4	13.3	11.5
X5	9.2	1.4	6.5	65.5	92.	11.9	30.6	11.6	15.0
Arithmetic mean	16.1			68.5			29.5		

Hence, there can be no error due to field sampling between sizes of any one series. The total error resulting from both laboratory procedure and field collecting should be obtained from the variation in percentage between the "X" series for each of the three minerals, sphene, zircon, and apatite. The expected relative percentage of variation in the percentile distribution for all sizes and all samples was determined for each mineral. In the case of sphene the probable variation is 22.8 per cent of the arithmetic mean of the relative percentage of sphene to zircon and apatite; for zircon the probable variation is 89.7 per cent and apatite 38.7 per cent. Such figures indicate the total error in the distribution resulting from sampling and laboratory procedures. Krumbein (3) has shown that the errors due to field sampling and laboratory procedure may be separately determined by use of the following equation:

$$E = \sqrt{(e_1)^2 + (e_2)^2}$$

where E = total relative per cent error
e_1 = relative error due to field sampling
e_2 = relative error due to laboratory procedure

The total error, E, in the case of sphene is 22.8 per cent, the average laboratory error, e_2, is 16.1 (the arithmetic mean of the relative percentages of error of the entire samples, Table 5), and e_1 may be determined from the equation above as 16.2. For zircon the field error is determined as 57.8 per cent and for apatite 25.1 per cent would be the probable relative field error. Such figures indicate that the error in field sampling

is great despite the usage of samples consisting of aggregates of chips. The field error, however, does not appear to be merely the result of irregularities in sampling for the field error for zircon is not identical with that of sphene or apatite. Much of the variation in the magnitude of the field error, therefore, must be due to irregularities in distribution of the three critical accessory minerals throughout the Mt. Wheatstone laccolith. Such a conclusion directly contradicts the fundamental assumption upon which the study was based, namely that heavy accessory minerals are uniformly distributed throughout a crystallizing body.

CONCLUSIONS.

In the preceding paragraphs several observations appear particularly pertinent to the usage of heavy accessory minerals as aids in the correlation of igneous rock bodies. If the results obtained from the study of the minerals of the Mt. Wheatstone laccolith are representative of those obtained from other igneous masses, the magnitude of the errors involved in the laboratory procedure is sufficiently large to give mineral percentages which are not similar. Likewise, the error due to field sampling and variability in the distribution of heavy accessory minerals within the laccolith is observed to be very great. The total errors thus become so large that in many instances it is impossible to note more than slight similarity between the percentage of heavy minerals in samples from the same body. Obviously such a condition seriously limits the use of heavy mineral percentages as a means of correlation of igneous bodies. Nevertheless, percentage distribution of minerals seems to be of value if used within the limits of its error. For example, all samples of the Mt. Wheatstone laccolith are characterized by a low content of zircon whereas the apatite-sphene contents may be quite variable. The low zircon content is apparently characteristic not only of the Mt. Wheatstone mass but also of a similar body, Crested Butte, nearby (4). Field associations and rock composition indicate that Crested Butte and Mt. Wheatstone originated from the same parent body so that a low zircon content characterized the magma. Masses consistently low in zircon, therefore, could be distinguished from masses containing a high percentage of zircon.

Despite the variation in percentage of the mineral constituents the habits of the various minerals remain consistently the

same throughout the rock mass of Mt. Wheatstone. Zircon, for example, occurs always as grayish, stubby, or long slender crystals, and both types are terminated with bipyramidal faces whose surfaces appear slightly rounded. The persistence of occurrence of the same accessory minerals in the same habits is noteworthy and emphasizes the value of using peculiar habits, anomalous optical properties, characteristic colors and other like properties as a more reliable means than mineral percentages for correlation of igneous bodies.

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NORTHWESTERN UNIVERSITY,
EVANSTON, ILLINOIS.