Measurement and distribution of zircons in some granitic rocks of magmatic origin.

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Summary. Morphological characters of zircons in concentrates have been studied by measurement of length along the *c*-axis and breadth along the a_1- or a_2-axis of 200 doubly terminated crystals for each sample. The sample is represented graphically by a line fitted mathematically to a scatter plot of the measurements. This line, the *reduced major axis*, is visualized as a growth trend, and samples are described and compared statistically.

From a careful study of zircons in a tonalite it is concluded that zircon crystallized over a short range before crystallization of the main constituent minerals.

The distribution of zircon in a batholith of magmatic origin has also been studied. The batholith grades from a core of granodiorite to a mantle of tonalite, but the zircons are uniform throughout. Small bodies of granodiorite and quartz monzonite have sharp contacts against the main batholithic rocks, and zircon samples from these intrusives differ from one another and from those of the batholith. It is concluded that the batholith represents a single intrusion which differentiated after emplacement, and that the later intrusives each crystallized under different conditions.

MORPHOLOGICAL characters of zircons in rocks have been studied for some fifty years, and results of these investigations have been applied to various petrogenetic problems. The work on zircons in igneous rocks has been reviewed by J. C. Reed,[1] G. Hoppe,[2] and A. Poldervaart.[3] These reviews show the need for more rigid control in laboratory techniques and for better means of comparison of zircon data obtained from different rocks. The present study is an attempt to improve graphic methods of representing zircon data, to test laboratory procedures used in preparing zircon concentrates, to determine the

[1] Amer. Min., 1937, vol. 22, p. 73 [M.A. 7–188].
[2] Geologica, 1951, Reihe 9, 114 pp. [M.A. 12–32].
[3] Amer. Jour. Sci., 1956, vol. 254, p. 521.

distribution of zircons in the mineral fabric of a tonalite, and to determine the distribution of zircons in a magmatic pluton.

This investigation is restricted to calc-alkaline rocks of magmatic origin. That zircon has crystallized before the main constituent minerals in such rocks is indicated by earlier work,[1] and established anew in the present study. The dimensions of each zircon crystal have been determined by measurement of length along the c-axis and of breadth along the a_1- or a_2-axis. It is assumed that dimensions along the a_1-axis equal those along the a_2-axis, a relationship which has been verified repeatedly for zircons in these rocks. Only doubly terminated crystals have been measured. Elongation is defined as the ratio of length to breadth (l/b), and size as their geometric mean ($\sqrt{lb}$).

Fundamental ideas in these studies are based on the concept of early formation and short range of crystallization of zircon in calc-alkaline rocks of magmatic origin. The sizes and elongations of a sample of self-nucleated, free-growing crystals depend on their physico-chemical environment: specifically, on such factors as chemical composition, rate of undercooling, viscosity of melt, and surface tension of crystals against melt.[2] Physico-chemical conditions may be expected to be nearly uniform throughout a magmatic pluton shortly after its emplacement and before the crystallization of the main constituent minerals, and this environmental uniformity is likely to be reflected in a uniformity of zircon samples from all parts of the intrusive (except perhaps from chilled borders). Major changes in environment during zircon crystallization are unlikely in view of the short range of crystallization of this mineral. Shortly after the onset of crystallization there is probably a wide range of elongations among small zircon crystals; growth results in wide ranges of both size and elongation, but competition between free-growing crystals ultimately produces relatively narrow ranges of preferred sizes and elongations. Zircons in a slowly cooled calc-alkaline rock of magmatic origin may therefore be expected to show simple monomodal frequency distributions (normal or skewed) of size and elongation. Although there are probably larger and smaller crystals present in the rock than are recovered in the zircon concentrate, their proportions are generally small and the zircons of the rock are to a close approximation represented by the concentrate.

If validated by the results, these ideas suggest numerous applications

[1] A. Poldervaart, loc. cit., p. 546.

[2] W. Eitel, The Physical Chemistry of the Silicates, 1954, Chicago Univ. Press, p. 569.

of zircon studies to petrogenetic problems. Physico-chemical conditions are probably not the same in two separate intrusions, even if they are almost contemporaneous and of similar magma type, and once crystallized, zircons are not likely to show the effects of subsequent magmatic differentiation. Thus zircon studies may be used to distinguish connected from disconnected intrusives, to trace differentiates of the same magma, and to separate them from differentiates of other magmas. They might also be used to advantage in establishing mixing of magmas,[1] or to test immiscibility in magmas.[2] The particular value of these studies is that they provide 'tracers' to the earliest magmatic conditions. In H. H. Read's[3] Granite Series, autochthonous granites are distinguished from parautochthonous and intrusive granites; the latter may be magmatic or migmatitic. In migmatitic intrusives the initial presence of residual solid phases and a partial melt may be reflected in the distribution of two or more distinct types of zircons throughout the body. Such a pluton is now being investigated by these methods.

Procedures.

Methods of graphic representation. The problem of graphic representation of length and breadth measurements has not been solved satisfactorily in earlier work. F. Smithson[4] has defined a sample field of zircons by plotting lengths and breadths as points on a scatter diagram; he also employed frequency curves of length, breadth, elongation (l/b), or size ($\sqrt{lb}$) constructed from histogram data using a moving average method. Subsequent workers have adopted these methods of representing their data.

In preparing scatter diagrams of length–breadth measurements of doubly terminated zircons separated from granitic rocks of magmatic origin, the authors have found that each sample field shows a linear distribution or trend, which can be generalized by a straight line. Taking advantage of existing procedures we have made extensive use of a line fitted mathematically to each scatter plot, and have further characterized each sample by appropriate statistical measures. At least four different lines can be fitted mathematically to such a scatter diagram;[5] regression of length on breadth, regression of breadth on length, a line

[1] For example, E. S. Larsen *et al.*, Amer. Min., 1938, vol. 23, p. 255 [M.A. **7**–178].

[2] N. Holgate. Jour. Geol., Chicago, 1954, vol. 62, p. 439 [M.A. **12**–537].

[3] Trans. Geol. Soc. South Africa, 1951, vol. 54, Annex, 27 pp.; Geol. Soc. Amer., Spec. Paper 62, 1955, p. 409.

[4] Geol. Mag., 1939, vol. 76, p. 351.

[5] J. Imbrie, Bull. Amer. Mus. Nat. Hist., 1956, vol. 108, art. 2, p. 230.

called the major axis, and a line called the reduced major axis. Of these we have chosen the reduced major axis as best representing the data. Regression methods are not as suitable because a regression line, being designed to indicate the most probable value of one variable for a given value of the other, does not exhibit the relation of the two variables in an unbiased manner. The major axis would really be the optimum estimate, since the errors in length and breadth (when both are expressed in mm.) will be the same; but the difference from the reduced major axis is likely to be far less than the variation imported from preparative techniques, etc., and the reduced major axis for a bivariate population is far easier to compute. The writers believe that the reduced major axis of a scatter plot of length and breadth measurements comes nearest to an expression of a trend of zircon growth in a particular environment. A dynamic concept is thus introduced.

The theory of the reduced major axis as a fitted line has been developed by K. A. Kermack and J. B. S. Haldane[1] and has been used by palaeontologists to describe growth trends of invertebrate fossils. Imbrie has given a lucid exposition of the method and the calculations involved in its use. The authors have found the method excellent when applied to zircons in calc-alkaline rocks of magmatic origin, though certain aspects of zircons in other types of rocks are better illustrated by frequency curves or contoured scatter diagrams. For the sake of brevity the abbreviation RMA is used in this paper for the *reduced major axis of a scatter plot of length and breadth measurements of a zircon sample.*

Kermack and Haldane and Imbrie have treated their data logarithmically because organic growth trends are usually curved on arithmetic plots. Various tests on data for zircons indicate an approximately linear variation of length and breadth on scatter diagrams with arithmetic coordinates; logarithmic transformations are therefore not essential. In such cases it is the choice of sample properties to be illustrated that largely determines arithmetic or logarithmic treatment of data. The writers have used the former treatment because it shows the variation of length and breadth of crystals more directly than logarithmic treatment, and because the RMA is employed in this study as a graphic means for comparison of samples.

Computations necessary for the RMA can be conveniently performed on a correlation form of the type developed by P. S. Burnham.[2] The necessary statistics are: number of crystals measured, N; mean length,

[1] *Biometrika*, 1950, vol. 37, p. 30.

[2] J. Imbrie, loc. cit., p. 244.

$\bar{x}$; mean breadth, $\bar{y}$; standard deviation of length,[1] s_x; standard deviation of breadth, s_y; coefficient of correlation, r; and coefficient of relative dispersion about the reduced major axis, Dd. The fitted line is drawn through the plotted point $(\bar{x}, \bar{y})$ at a slope $a = s_y/s_x$ with standard error, $\hat{\sigma}_a$. These statistics are defined as follows:

Mean of x, $\bar{x} = \Sigma(x)/N$, expresses the central value of the x observations. Mean of y, $\bar{y}$, is determined analogously.

Standard deviation of x, $s_x = \sqrt{\{\Sigma(x-\bar{x})^2/N\}}$, is a measure of absolute variation within the sample. Standard deviation of y, s_y, is determined analogously.

Correlation coefficient, $r = \Sigma(x-\bar{x})(y-\bar{y})/\sqrt{\{\Sigma(x-\bar{x})^2\Sigma(y-\bar{y})^2\}}$, is a measure of closeness of the relationship between the two variables. If $r = \pm 1$, correlation is perfect; if $r = 0$, correlation is absent.

Coefficient of relative dispersion about the reduced major axis, as defined by Imbrie,[2] $Dd = 100\sqrt{\{2(1-r)(s_x^2+s_y^2)/(\bar{x}^2+\bar{y}^2)\}}$, expresses (per cent.) the relative scatter of points about the RMA.

Slope, $a = s_y/s_x$, is the tangent of the angle at which the fitted line is drawn through the point $(\bar{x}, \bar{y})$.

Standard error of slope, $\hat{\sigma}_a = a\sqrt{\{(1-r^2)/(N-2)\}}$, is a measure of the reliability of the slope of the sample as an estimate of the slope of the actual population; the smaller the value of the standard error the more reliable the estimate.

A zircon sample can thus be defined by the statistics: mean length and breadth, standard deviation of length and breadth, slope and standard error of slope of the RMA, and coefficients of correlation and relative dispersion about the RMA. In addition, a length may be assigned to each RMA as a graphic means of indicating the observed range of sizes within the sample. The writers have found this a useful graphic measure of these essential data for comparing samples even though no formal mathematical use has been made of it. In this study the end points of each RMA have been determined arbitrarily by graphically eliminating on the correlation form the extreme $2\frac{1}{2}$ % each of the smallest and largest crystals. It is felt that, by excluding these extremes of variability, the length of the RMA has greater significance as a graphic sample measure. Wherever possible 200 or more zircons have been measured to obtain a statistically large sample.

Differences between samples may be evident upon visual comparison

[1] More precisely, s_x is the standard deviation (in x) of the sample, as distinct from the unknown σ_x, the standard deviation (in x) of the total population, and $\dot{\sigma}_x$, the best estimate of σ_x; $\sigma_x = s_x\{\sqrt{N}/(N-1)\}$.

[2] Loc. cit., p. 241.

of RMAs. If this is not the case, final judgement of similarity or dissimilarity should be based on objective procedures for determining significant differences. Although arithmetic frequency curves of length, size, or elongation of zircon samples are usually skewed, in large samples ($N = 200$) the lack of normality causes negligible error and statistical tests may be applied with confidence in comparing RMAs of different samples.[1]

The simple z-test is used here; a test based upon the assumption that the two samples being compared were drawn from the same population (null hypothesis). The test allows us to ascertain the probability that a difference as great as that observed might occur because of chance factors arising from random sampling; i.e. a conclusion concerning the reasonableness of the original assumption.

In this study the RMA represents a linear trend of zircon growth of which the essential elements are slope and position. Procedures for comparing these elements for pairs of RMAs are given below.

Comparison of slope. First calculate z for the two slopes:

$$z = (a_1 - a_2)/\sqrt{(\hat{\sigma}^2_{a_1} + \hat{\sigma}^2_{a_2})};$$

then from a table[2] of z determine the probability P that the observed difference is due to chance alone. For a large sample when z is numerically greater than 1·96, the probability is 0·05 or less; that is, the difference between slopes can be due to chance alone five or less times out of one hundred. This has arbitrarily been chosen here as the level of confidence at which differences are considered statistically significant; i.e. when P is numerically less than 0·05 ($z > 1{\cdot}96$) differences are considered real. Further experience may necessitate revision of this level of confidence.

Comparison of position. If the slopes tested are significantly different no further tests are necessary. When slope differences are not significant a positional comparison can be made[3] that tests the hypothesis that, for a value $x = x_0$, the true growth trends coincide; i.e. that $y_1 - y_2 = 0$ when $x_1 = x_2 = x_0$. This test is valid only when slope differences are not statistically significant. Calculate z for the two positions:

$$z = \{x_0(a_1 - a_2) + b_1 - b_2\}/\sqrt{\{\hat{\sigma}^2_{a_1}(x_0 - \bar{x}_1)^2 + \hat{\sigma}^2_{a_2}(x_0 - \bar{x}_2)^2}$$

where x_0 is arbitrarily chosen $\geqslant \bar{x}_1$ and $\bar{x}_2$, and $b = y$-intercept

[1] Prof. Howard Levene, Columbia University, 1956, personal communication.

[2] Values of z are tabulated in most statistical texts. If N is large (e.g. 200) z may be regarded as equivalent to t, and t tables may be used instead.

[3] J. Imbrie, loc. cit., p. 237.

calculated from the form $y = ax+b$. As before, if z is numerically greater than 1·96, the difference in position is taken to be significant.

Comparison of joint means. If desired, the positional differences between means of length and breadth may be tested using the following formulae in which x and y are interchangeable. Calculate the standard error of the mean, $\hat{\sigma}_{\bar{x}}$ or $\hat{\sigma}_{\bar{y}}$, for the two samples: $\hat{\sigma}_{\bar{x}} = \hat{\sigma}_x/\sqrt{(N)}$. Next, calculate z for the two sample means: $z = (\bar{x}_1-\bar{x}_2)/\sqrt{(\hat{\sigma}^2_{\bar{x}_1}+\hat{\sigma}^2_{\bar{x}_2})}$. As before, if z is numerically greater than 1·96, the difference in position of the means is taken to be significant.

Preparation and measurement of zircon samples. Procedures followed in this laboratory have been described by A. Poldervaart.[1] The following study was conducted to test and improve these methods.

Three samples of hand-specimen size were taken from a large block of friable, coarse-grained tonalite (LL–13–W) from the Kaniksu batholith, Idaho–Washington. One sample was treated for four days on a steambath with HF and H_2SO_4 (1:1) with repeated renewal of the acid mixture. This only partly dissolved the rock. The residue was washed, separated on bromoform, and the total heavy residue (about 500 zircons) mounted on a single slide. The second sample was crushed in a disk-grinder at a coarse setting, such that two-thirds of the crushed sample did not pass through a 20-mesh U.S. Standard sieve (0·84 mm. opening). The third sample was crushed at the finest setting of the grinder; all the crushed material passed through a 60-mesh U.S. Standard sieve (0·25 mm. opening). The crushed samples were individually separated with bromoform, followed by removal of magnetic minerals with a Frantz isodynamic separator, and the residues were further purified by settling with bromoform, followed by settling with Clerici solution. The concentrates were reduced in size by a cone-and-quarter technique suggested by C. O. Hutton.[2] Portions of about 2000 to 3000 zircons each were mounted on single slides, two portions being taken for each concentrate. Concentrates of practically pure zircon were obtained. Recovery was smallest from the sample treated with acid, while about four times as much zircon was obtained from the finely crushed sample as from the coarsely crushed sample.

Two hundred doubly terminated crystals were measured for each mount at a high magnification (×270), using an ocular micrometer. Only those zircons visible in the microscope field at equally spaced intervals along equally spaced traverses distributed over the entire slide

[1] Amer. Jour. Sci., 1955, vol. 253, p. 435.

[2] Bull. Geol. Soc. Amer., 1950, vol. 61, p. 643.

were measured. A Chayes point counter was used for this purpose, and the measurements were made a second time for a single slide of each concentrate obtained from the crushed samples.

The results of these measurements are shown in fig. 1 and table I. The

TABLE I. Statistical parameters of zircon samples for tonalite LL-13-W. (Under *Sample* read HF as acid separation, CC as coarse crush, and FC as fine crush; CC–1(1) as coarse crush, first slide, first measurement, CC–1(2) as coarse crush, first slide, second measurement, and CC–2 as coarse crush, second slide. Column B is the number of singly terminated, apparently broken zircons counted during measurement of each sample.)

Sample	B	a	$\hat{\sigma}_a$	$\bar{x}$(mm.)	$\bar{y}$(mm.)	s_x (mm.)	s_y (mm.)	r	Dd
HF	48	0·4183	0·0268	0·1140	0·0427	0·0455	0·0190	0·7139	29·9
CC–1(1)	64	0·3730	0·0245	0·1076	0·0379	0·0376	0·0140	0·6445	28·9
CC–1(2)	49	0·3701	0·0216	0·1099	0·0387	0·0335	0·0124	0·5629	29·7
CC–2	72	0·4034	0·0245	0·1081	0·0406	0·0383	0·0154	0·6261	30·9
FC–1(1)	56	0·4139	0·0267	0·1026	0·0357	0·0280	0·0116	0·4385	27·3
FC–1(2)	55	0·3940	0·0256	0·1030	0·0365	0·0321	0·0127	0·5258	30·8
FC–2	58	0·3595	0·0238	0·1155	0·0419	0·0373	0·0134	0·5836	29·4

differences between the joint means and the slopes of RMAs resulting from two measurements of the same slides are near the limit of accuracy for measuring single crystals; the differences between joint means and slopes of RMAs resulting from cone-and-quarter techniques are as much as ten times this amount, as are the differences resulting from different zircon-liberating techniques. Some statistical comparisons are given below in which z_a, $z_{\bar{x}}$, and $z_{\bar{y}}$ are z values calculated for slope, mean length, and mean breadth. The sample symbols are the same as in table I.

FC–(1)–FC–1(2):	z_a 0·56	$z_{\bar{x}}$ 0·13	$z_{\bar{y}}$ 0·20	CC–1(1)–FC–1(1):	z_a 1·23	$z_{\bar{x}}$ 0·54	$z_{\bar{y}}$ 1·71
CC–1(1)–CC–1(2):	0·10	0·64	0·62	HF–CC–1(2):	1·62	1·02	2·48
FC–1(1)—FC–2;	1·63	3·98	4·91	HF–FC–1(1):	0·13	3·08	4·41
CC–1(1)–CC–2:	1·01	0·13	1·80	HF–FC–2:	2·02	0·36	0·47

These tests indicate the magnitudes of error attributable to statistical sampling errors and the liberating and sampling techniques used, and emphasize the need for rigid standardization of methods for liberating and concentrating zircons from rocks in studies of this type. Mounting the entire zircon crop on as many slides as necessary and sampling of all the slides by spaced microscope traverses is desirable for consistent results, instead of the cone-and-quarter technique of sampling concentrates.

The extent of zircon breakage during crushing has been a major cause for concern in this work, and broken crystals are present in all the

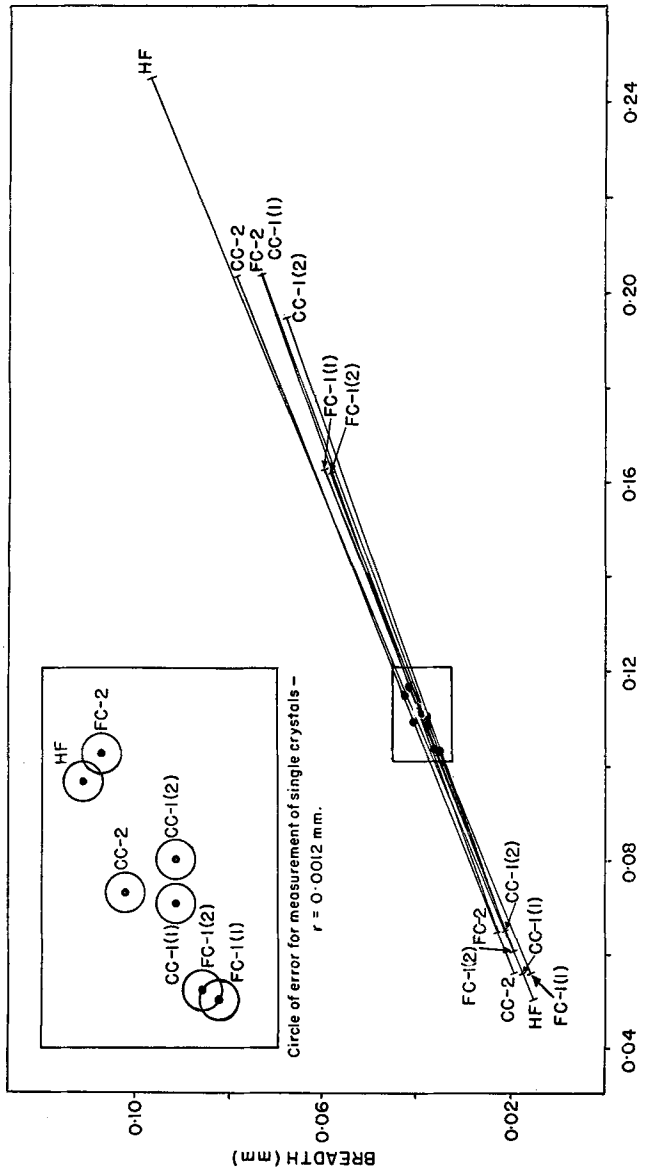

FIG. 1. RMAs for tonalite LL-13-W. For explanation of the term RMA see text.

concentrates; sometimes in relatively high proportions. It is therefore significant that in measuring 200 doubly terminated zircons liberated by acid treatment without crushing, forty-eight singly terminated, apparently broken crystals were encountered. The data in table I show no evidence of severe breakage of zircons due to crushing of rock samples, even when fine crushing is used. Apparently broken zircons in a rock may result from imperfect crystallization, or from breakage due to partial alteration and differential expansion of the main constituent minerals.

Rock crushing probably causes significant breakage among the largest zircons of high elongation, but normally such crystals are few in number. Fine crushing liberates three to four times as many zircons as coarse crushing, although the proportion of broken crystals is not significantly different in the two cases (table I). Fine crushing apparently assures more uniform results than coarse crushing by release of larger and more representative portions of the zircon sample at the expense of relatively few larger crystals. For those rare rocks having a preponderance of large zircons fine crushing should not be used.

It is also best to process all the crushed material that passes through a 60-mesh U.S. Standard sieve without removal of the fine dust by washing; separation of the finest material is facilitated by centrifuging. After removal of the magnetic minerals, final concentration of zircon crops by heavy liquids should be done without filter paper. Separations at this stage can be done in small tube-shaped vials, allowing the concentrate to settle and then floating the light minerals off; washing of the concentrates can be done in the vials, which also serve for storage until the concentrates are mounted.

Distribution of zircon in a tonalite.

The early formation and the short range of crystallization of zircon in magmatic calc-alkaline rocks are critical assumptions made in applying results of zircon studies to petrogenetic problems. The work reported here was undertaken to test these assumptions. The rock used, a tonalite (LL–11–I) from the Kaniksu batholith, Idaho-Washington, was selected because in it zircon is unusually abundant, and because evidence presented by J. L. Gillson[1] indicates that the opposite of the above assumptions holds for this batholith. The chemical analysis and mode of this rock are given in table II, the mode being based on three thin sections and 2000 points obtained by traversing the sections at regularly spaced intervals

[1] Amer. Min., 1925, vol. 10, p. 187.

with a Chayes point counter. Agreement between analysis and mode is poor, and calculations from the analysis indicate about 4 % less quartz and 4 % more chlorite than are found modally; the discrepancies may be due to silica deficiency in plagioclase, presence of magnesium in the muscovite, and errors in the analysis and mode.

TABLE II. Chemical analysis and mode of tonalite LL-11-I, together with zircon and zirconium abundance in the main minerals. (1000 zircons were counted by point-counter traverses of which 82 were found athwart grain boundaries, while the remainder were included as shown below. Silicate analysis by Dr. H. B. Wiik, Helsinki, Finland. Spectrographic data by Dr. Karl Turekian, Yale University, New Haven, Connecticut, U.S.A.)

	%		*Mode* %	*Zircons counted*	*Relative abundance zircons (by volume)*	*Spectrographic abundance zirconium (ppm)*
SiO_2	65·83	Quartz	30·8	368	12	< 100
TiO_2	0·55	Plagioclase	48·3	312	6	≈ 100
Al_2O_3	16·98	Orthoclase	1·7	29	16	≈ 100
Fe_2O_3	0·64	Hornblende	0·6	nil		
FeO	2·86	Biotite	10·0	166	18	> 200
MnO	0·07	Muscovite	3·4	43	13	> 200
MgO	1·16	Magnetite	0·6	nil	n.d.	> 200
CaO	4·17	Epidote	3·3	nil	—	—
Na_2O	3·90	Chlorite	0·8	nil	—	—
K_2O	1·76	Apatite	0·5	nil	n.d.	n.d.
P_2O_5	0·26	Total	100·0			
H_2O^+	0·98					
H_2O^-	0·07					
CO_2	nil					
Total	99·23					

Thin-section studies. Thin-section studies of zircon are generally of limited use because of the small number of zircons present in each thin section, the minute size of the crystals, their random orientation, and the difficulties experienced in their recognition as inclusions in various host minerals. Observations regarding the shapes of zircons are unreliable when based on thin-section work.[1]

The unusual abundance of zircon in the tonalite sample is shown by the presence of 800 to 1000 zircons in a single thin section. Many of the crystals are minute, often less than 0·001 mm. in breadth. Three thin sections were traversed at equally spaced intervals, noting zircon crystals in relation to the host minerals quartz, plagioclase, orthoclase, biotite, and muscovite. Observations on 1000 zircons are included in table II

[1] A. Poldervaart, Amer. Jour. Sci., 1956, vol. 254, p. 529.

without regard to their sizes and shapes. Relative abundance of zircons in the various host minerals is calculated by dividing the number of enclosed zircons by the volume per cent. of the host mineral, and may be compared with zirconium abundance determined spectrographically for pure fractions of the main constituent minerals. Too great a reliance should not be placed either on the thin-section observations or on the spectrographic data.

Thin-section observations show, however, that zircons are enclosed in all the non-opaque minerals; magnetite was found to contain more than 200 parts per million of zirconium (like biotite and muscovite).

TABLE III. Sequence of crystallization of main minerals in tonalite LL-11-I.

Apatite contains numerous minute zircons and occasional larger zircon crystals themselves contain minute zircons as inclusions. In addition there are zircons between crystals of the constituent minerals. In traversing the thin sections one gets the impression that zircons sometimes tend to be distributed in clusters, with proportionately large barren areas between clusters; no further work was done to confirm this impression.

The order of crystallization as determined from thin sections is shown in table III. The observations indicate that zircon was the first mineral to crystallize, but they do not warrant a conclusion concerning its range of crystallization. Evidently zircon crystals were present in the residual magmas throughout the magmatic consolidation sequence.

The distribution of zircon crystals in the mineral fabric of a magmatic rock is the overall result of a number of factors: time and range of crystallization of zircon relative to that of other constituent minerals, nucleation and rate of seeding of nuclei of zircon in the magma, nucleation of other constituent minerals on zircon crystals, and enclosure of zircons through growth and mutual interference of other constituent minerals. It has been suggested by Poldervaart[1] that minerals such as apatite, magnetite, biotite, and muscovite may nucleate on zircon

[1] Loc. cit., p. 547.

crystals with more facility than do felspars or quartz. Present observations tend to support this, but more detailed studies are required fully to ascertain the distribution of zircon crystals in a rock.

Studies of concentrates. The tonalite was crushed approximately to grain size, and pure fractions of quartz, plagioclase, orthoclase, biotite, muscovite, magnetite, and apatite were separated. Zircon was separated from apatite by solution of apatite in hot concentrated HCl, while the other mineral fractions were carefully crushed and processed with heavy liquids and a Frantz magnetic separator. Zircons in each concentrate were measured with results given in fig. 2 and table IV; included are data for a sample of the tonalite processed in its entirety.

TABLE IV. Statistical parameters of zircon samples for tonalite LL-11-I and its main constituent minerals, together with comparisons of RMA slopes of the constituent minerals with that of the tonalite.

Sample	N	a	σ_a	$\bar{x}$ (mm.)	$\bar{y}$ (mm.)	s_x (mm.)	s_y (mm.)	r	Dd	z_a
Tonalite	200	0·3343	0·0196	0·1017	0·0338	0·0365	0·0122	0·5572	33·8	—
Biotite	100	0·3415	0·0224	0·0986	0·0322	0·0396	0·0135	0·7575	28·1	0·241
Muscovite	100	0·3549	0·0308	0·0828	0·0293	0·0263	0·0093	0·5165	31·4	0·564
Orthoclase	66	0·3506	0·0316	0·0951	0·0321	0·0338	0·0118	0·6790	27·8	0·438
Plagioclase	100	0·3814	0·0283	0·0869	0·0283	0·0357	0·0136	0·6682	34·0	1·31
Quartz	50	0·4767	0·0312	0·0771	0·0270	0·0228	0·0109	0·8870	14·7	3·88
Magnetite	100	0·4216	0·0246	0·0723	0·0255	0·0293	0·0124	0·8133	25·4	2·78
Apatite	200	0·2873	0·0171	0·0214	0·0049	0·0113	0·0032	0·5386	51·3	1·81

In fig. 2 the RMA for the entire tonalite, if extended, passes nearly through the origin, indicating that the zircons are self-nucleated; i.e. they have not themselves nucleated on other minerals. The joint means of the RMAs from the different mineral fractions lie on or near the RMA of the tonalite, but the slopes do not all coincide with that of the tonalite. Statistical comparisons of these data are also shown in table IV where slopes of RMAs for the pure mineral fractions are compared with that of the rock. RMA slopes for quartz and magnetite are significantly different from the RMA slope of the tonalite, while apatite is a borderline case. RMA slopes for biotite, muscovite, orthoclase, and plagioclase are not significantly different from the RMA slope of the tonalite or from one another. Of this group of four mineral fractions the positions of muscovite and biotite differ most from one another, but a z-test indicates no significant difference in position between them.

Since the RMA slopes of quartz, magnetite, and apatite are significantly different from the RMA slope of the rock, statistical tests cannot be applied to test the analogous positional differences. But the positional differences are visibly not greater than that between the RMAs of

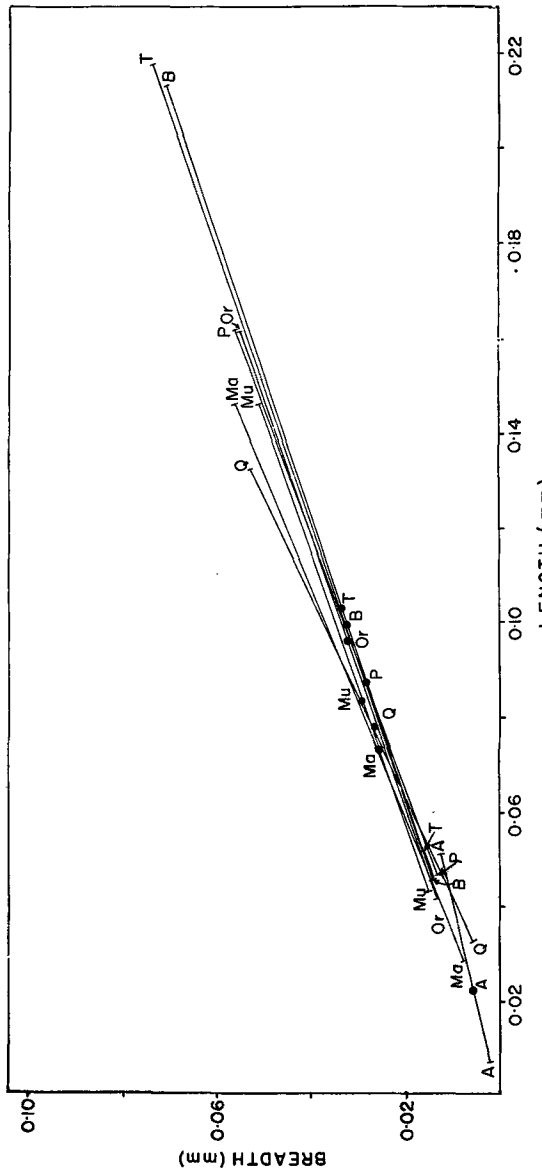

FIG. 2. RMAs for tonalite LL-11-I and its main constituent minerals.

muscovite and the rock: hence it is assumed that there are no significant positional differences between the RMAs of the mineral fractions and the RMA of the tonalite. The joint means all fall close to the RMA for the rock. There is clearly a difference in average size between samples, but not in average shape.

Differences in RMA slopes for quartz and magnetite are probably attributable to crushing. Quartz and magnetite have no well-developed cleavage, and quartz and zircon are of equivalent hardness, with magnetite not much different; crushing of quartz and magnetite is therefore likely to cause breakage, especially of elongated zircons, and most zircons, broken or unbroken, are likely to remain enclosed in the host mineral. This interpretation is fully supported by the results: although equal amounts of quartz and plagioclase were used for the preparation of the zircon concentrates, and thin-section studies indicate that these minerals enclose equivalent numbers of zircons (table II), only 50 zircons were recovered from the quartz, while 150–200 zircons were obtained from the plagioclase. Further, examination of the crushed quartz after zircon separation shows that many broken and unbroken zircons have remained enclosed in the quartz particles.

Thus it seems that the lower elongations and smaller sizes of zircons recovered from quartz and magnetite as compared with those obtained from minerals with good cleavage is an effect of crushing. It is apparent from fig. 2 that the combined effect of zircons separated from main constituent minerals with good cleavage, in which release of zircons upon crushing is high, masks that of quartz, in which release of zircons upon crushing is low. Well-developed cleavage in the main constituent minerals clearly plays an important role in the liberation of zircon without serious breakage.

Earlier it was concluded (table III) that zircon and apatite overlap in crystallization, because not only does apatite include numerous minute zircons, but a few large zircons partly enclose apatite crystals. Since zircons included in apatite are always small (fig. 2) and abundant it appears that the zircon population was still immature and actively growing at the onset of apatite crystallization, and further, that apatite may have nucleated on minute zircons. Magnetite began to crystallize after apatite and before plagioclase, but the mean size of the zircons contained in magnetite (fig. 2) indicates that the zircon population was nearly or quite full-grown. Hence it is concluded that zircon was the earliest mineral to crystallize, and that its range of crystallization was brief.

Distribution of zircon in a batholith.

The Bald Mountain batholith, Oregon, provides an ideal example of the uniformity of zircons throughout a magmatic pluton, and also yields examples of the lack of uniformity of zircons in different magmatic bodies. W. H. Taubeneck[1] has made an unusually detailed study of the batholith and his field and laboratory observations leave no doubt that it is a magmatic intrusive. The main phases are a mantle of tonalite

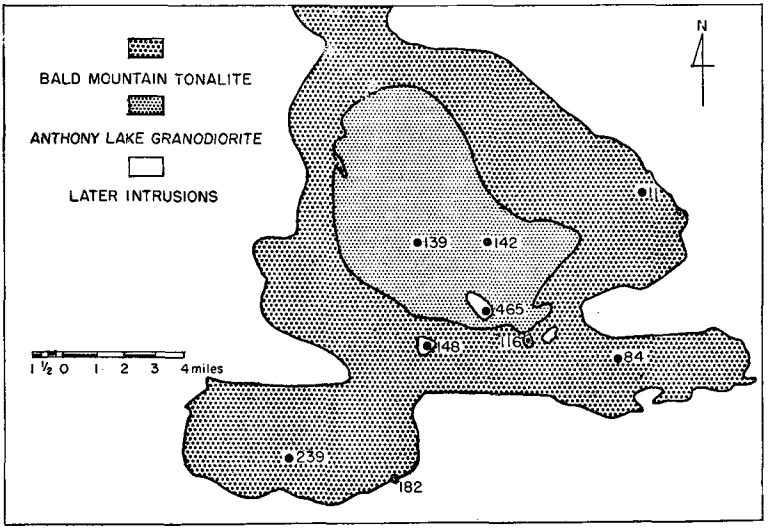

FIG. 3. Sketch-map of Bald Mountain batholith, Oregon.

that grades continuously into a core of granodiorite. Fig. 3 is a sketch-map in which a boundary between core and mantle has been arbitrarily drawn at a modal content of K-felspar of about 6 %. Small intrusives of granodiorite and quartz monzonite are found within the batholith and have sharp contacts against the main batholithic rocks.

Zircons from six main batholithic rocks (4 tonalites and 2 granodiorites) and from each of three later intrusives were separated and measured by Taubeneck. The samples are geographically widely separated (max. 15 miles; fig. 3), differ in altitude by as much as 2000 feet, and differ in petrographic type. The authors have calculated RMAs for these samples, and the results are shown in fig. 4 and table V.

Fig. 4 shows that the RMAs for the six main batholithic rocks are

[1] Bull. Geol. Soc. Amer., 1957, vol. 68, p. 181.

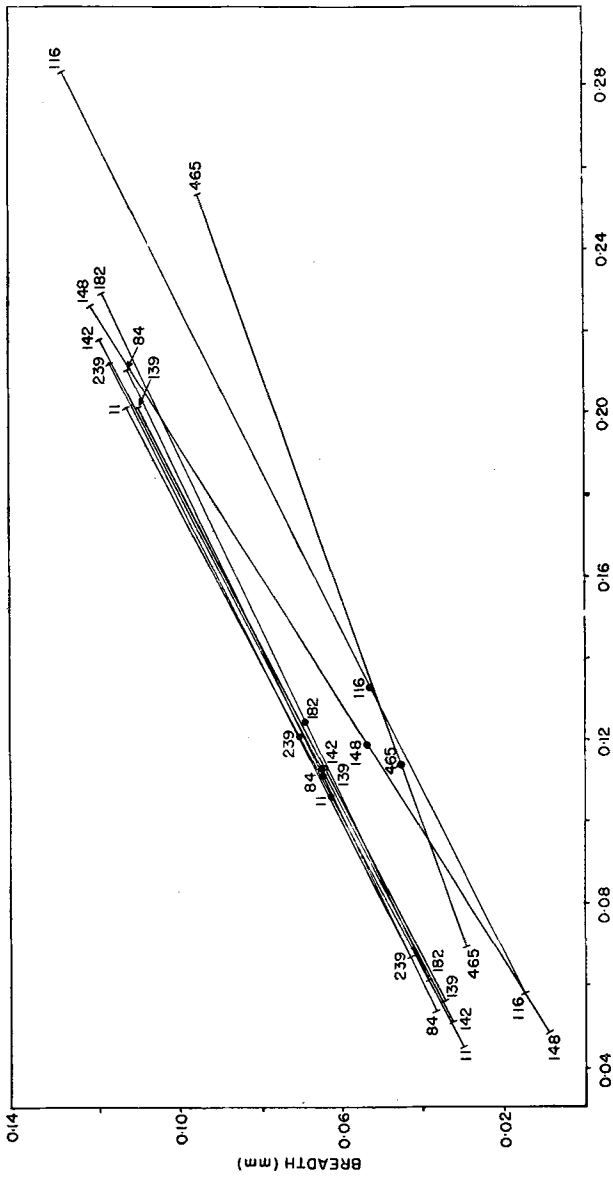

FIG. 4. RMAs for rocks of Bald Mountain batholith, Oregon.

similar, while the RMAs for the three later intrusives are different. Of the six similar RMAs, samples 11 and 182 differ most in slope, but a test of slopes shows this difference to be insignificant ($z_a = 1{\cdot}88$). A positional test between samples 11 and 182 also shows no significant difference ($z_p = 0{\cdot}83$). All the main batholithic samples may therefore be considered to have been drawn from a single population of zircons, and a mean growth trend may be calculated to represent this population (MGT; table V).

TABLE V. Statistical parameters of zircon samples for rocks of Bald Mountain batholith, Oregon. (300 zircons were measured in each sample. Samples 11, 84, 182, and 239 are tonalites and 139 and 142 are granodiorites, all from the main batholithic series; the mean growth trend for these six samples is given against *MGT*. Samples 116 and 148 are later granodiorite intrusives, and sample 465 is a late quartz monzonite intrusive.)

Sample	a	σ_a	$\bar{x}$ (mm.)	$\bar{y}$ (mm.)	s_x (mm.)	s_y (mm.)	r	*Dd*
11	0·5332	0·0214	0·1059	0·0625	0·0388	0·0207	0·7187	26·8
84	0·4954	0·0205	0·1109	0·0640	0·0414	0·0203	0·6984	27·8
182	0·4793	0·0191	0·1242	0·0690	0·0434	0·0208	0·7233	24·8
239	0·5098	0·0159	0·1202	0·0702	0·0382	0·0195	0·8403	17·4
139	0·5230	0·0224	0·1128	0·0640	0·0406	0·0213	0·6704	28·7
142	0·5188	0·0192	0·1129	0·0646	0·0433	0·0230	0·7672	26·2
MGT	*0·5097*	*0·0199*	*0·1145*	*0·0657*	*0·0411*	*0·0209*	*0·7364*	*25·3*
116	0·5070	0·0244	0·1326	0·0528	0·0562	0·0285	0·5529	41·8
148	0·6401	0·0233	0·1184	0·0535	0·0506	0·0234	0·7768	28·7
465	0·3567	0·0179	0·1139	0·0451	0·0464	0·0165	0·4937	40·4

Although zircon shapes are not significantly different in these samples, fig. 4 shows considerable variation in size of zircon crystals. The smallest and largest joint means of zircons are from the tonalite mantle, while the two granodiorites from the core have zircons of intermediate sizes. There is no complete assurance that these size differences are real and not due to variations resulting from laboratory procedures in separation, sampling, and measurement of the crystals, but, assuming that the differences are real, the following explanation may account for the observed size variation: G. C. Kennedy[1] has argued that water concentrations are likely to vary over short distances near the margins of a batholith; higher water concentrations are likely to promote growth of zircon crystals through lowering of the viscosity of the magma, while lower water concentrations probably have the opposite effect; hence considerable variations in size of zircons may be expected in the marginal portions of the batholith, while in the central portions variations in size of zircons from one rock sample to the next are likely to be negligible.

[1] Geol. Soc. Amer., Spec. Paper 62, 1955, p. 489.

It is evident from fig. 4 that each of the three later intrusives has zircons of a different character. Tests of RMA slope difference give the following results: 116–148, z_a 3·93; 116–465, z_a 4·97; 148–465, z_a 9·63. Of this group only sample 116 is similar in RMA slope to the mean growth trend of the main batholithic rocks. A positional comparison yields a z_p value of 9·88, showing the difference to be significant. These results emphasize not only that zircons from the same magmatic intrusive are alike, but also that zircons from different magmatic bodies are different.

It is concluded from these observations that the Bald Mountain batholith was formed by a single magmatic intrusion. After this had crystallized there were three further pulses of magmatic activity which formed separate bodies within the batholith. The three later intrusions are not differentiates of the same magma that produced the main batholith, but are distinct from that magma and represent three disconnected magmas that cooled individually. If one accepts the concept of large magmatic reservoirs at depth that are maintained for several hundreds, perhaps thousands, of years, it is still possible to argue that the main batholithic magma and the three later magmas may all have originated at different times from the same reservoir; the authors admit but do not favour this possibility.

Discussion.

For some time, students of petrogenetic problems connected with calc-alkaline plutons have felt the need for a method that might yield clues to early conditions in these bodies. Recognition that there are granites and granites and the development of the concept of a Granite Series by H. H. Read[1] have accentuated this need. Several workers in this field have turned to studies of the morphological characters of zircons in these rocks as a possible source of information on early conditions in granitic plutons. Much of the earlier work on zircons has been of a reconnaissance nature; it has served to crystallize fundamental ideas in this work and has opened the way toward more detailed and specific studies, while at the same time certain conclusions have emerged that are of importance to the application of these studies to petrogenesis.

Basic assumptions in this type of work are: that the morphological characters of zircons are controlled by the physico-chemical environment in which they crystallized; that zircon crystallizes so early and its range

[1] Trans. Geol. Soc. South Africa, 1951, vol. 54, Annex; and Geol. Soc. Amer., Spec. Paper 62, 1955, p. 409.

of crystallization is so short that normally there is no appreciable change in environment during its crystallization; that similar environments produce similar zircons, while different environments produce significantly different zircons; that although growth results in a wide range of sizes and habits of zircons, competition between crystals growing in the same environment will produce a relatively narrow range of favoured sizes and habits, which will be of high frequency and can thus be used to characterize the sample; finally, that the narrow range of preferred sizes and habits are normally included in the zircons concentrated from a rock, and these zircon samples are therefore representative of the zircon population in the rock (effects of possible procedural bias can be reduced by use of bivariate rather than univariate analyses).[1]

These assumptions are largely warranted by earlier zircon studies and are further confirmed in this paper. The earlier work also shows clearly that these assumptions do not all apply to all igneous rocks; the physico-chemical environment may change rapidly during the final stages of magmatic consolidation, and zircon is frequently of late crystallization in basaltic and in sodic peralkaline rocks.[2] Environment may change rapidly even during the earliest stages of crystallization, for example in volcanic centres or in the flat roof zones of batholiths emplaced high in the crust. We do not know whether zircon samples would be similar or dissimilar in different parts of such intrusives; these are examples yet to be studied. According to H. H. Read[3] and others, intrusive granitic plutons may be migmatitic or magmatic; if they are migmatitic, zircons in these rocks are likely to be of more than one type, reflecting their crystallization from the partial melt, as well as their crystallization in the residual solid phases. Zircons of autochthonous and parautochthonous members of the Granite Series should also be studied.

Studies of the morphological characters of zircons can be focused on the habits or on the dimensions of crystals. Y. Karakida[4] has published an excellent study of zircon habits in two granitic plutons. The authors have chosen to study dimensions of crystals because this best suits the purpose of this restricted investigation and is more easily expressed numerically and controlled statistically. In different cases, other methods of zircon study may be more suitable; for example, the development of outgrowths and overgrowths on zircons of autochthonous granites[5] is

[1] J. Imbrie, loc. cit., p. 223. [2] A. Poldervaart, loc. cit., p. 522.
[3] Loc. cit., 1951, p. 21. [4] Jour. Geol. Soc. Japan, 1954, vol. 60, p. 517.
[5] F. D. Eckelmann and A. Poldervaart, Bull. Geol. Soc. Amer., 1955, vol. 66, p. 947.

best studied in zircon samples from series of rocks by counts of crystals that do and do not show these features than by measurement of lengths and breadths of crystals only.

In this study, unusual precautions have been taken in the separation, sampling, and measurement of zircons. Such a procedure is proper since this is a pilot study; it is also necessitated by the high sensitivity of the method of the reduced major axis and by rigid statistical comparisons made between RMAs of different samples. The method of the reduced major axis is not a panacea, but if care is taken in laboratory procedures it offers an elegant and rigidly controlled means of expressing and comparing the data. As a method of bivariate analysis it also involves a dynamic concept of relative growth and focuses on growth pattern, rather than static morphological characters. For reconnaissance types of zircon studies, visual comparison of elongation, length, and breadth frequency curves, or of contoured scatter diagrams, probably remains the easiest method of approach. For more detailed studies of specific rocks it will be necessary to augment comparison of RMAs with other means of graphic representation (frequency curves and contoured scatter diagrams) and other data (tabulated counts and observations) to bring out and trace specific morphological characters of zircons.

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