STATISTICAL STUDY OF ZIRCON POPULATIONS FROM IGNEOUS AND METAMORPHIC ROCKS IN THE MARTINSVILLE WEST QUADRANGLE, VIRGINIA

by

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ABSTRACT

The Martinsville West quadrangle, located in the southwestern Piedmont of Virginia, is underlain by polymetamorphic paragneisses and schists that have been intruded by a semi-concordant plutonic complex composed of mafic and felsic rocks. Zircon concentrates were made from saprolites of the major lithologic units and zircon morphology was described. Statistical comparisons of zircon populations were made using the reduced major axis method, which mathematically fits a line through a scatter diagram of length and breadth measurements. To accelerate this work a computer program was written and is presented.

The data shows moderate to poor correlation among populations from the same lithologic unit. In contrast many correlations exist between populations of zircons from rocks of different composition and origin. Visually, populations from igneous rocks contain both igneous and meta-detrital grains with overgrowths. The zircon populations in

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igneous rocks appear to be contaminated by detrital zircons, probably from the country rock surrounding the igneous intrusions. The data and techniques presented in this study should be useful in studying zircon morphology. Rocks containing multiple populations of zircons should be used with caution for radiometric age dating because metadetrital zircons as contaminants will increase the age determined.

INTRODUCTION

The Martinsville West 7.5-minute quadrangle is located in the southwestern Piedmont of Virginia, about 20 miles east of the Blue Ridge (Figure 1). The geology of the quadrangle was mapped by Conley and Toewe (1968). The rocks of the area are contained within the Smith River allochthon, a synformal structure that is surrounded by, and structurally verlies rocks of Grenville and younger Precambrian age of the lue Ridge and Sauratown Mountains anticlinoria (Conley and lenika, 1973).

The oldest rocks in the allochthon are of metasedimentary origin. They consist of the Bassett formation, a locally migmatitic biotite paragneiss that, at or near its top, contains amphibolite and amphibole paragneisses and the overlying Fork Mountain formation, predominantly a high-alumina mica paraschist containing quartzite interlayers (Conley and Henika, 1973). These metasedimentary rocks were intruded by a semiconcordant multi-injection igneous body, which, in the vicinity of its contact, has converted metasedimentary rocks into gneissic hornfels (Conley and Henika, 1973). The rocks composing this plutonic complex are divided into a felsic unit, the Leatherwood Granite and a mafic unit, the Rich Acres formation. The Leatherwood is composed predominantly of porphyritic granite but includes quartz monzonite and may grade into alaskitic dikes and sills. The Rich Acres (as redefined by Conley and Henika, 1973) is composed of rocks ranging in composition from gabbro to diorite and in the Martinsville West quadrangle contains much norite. Age relationships among the various lithologic units are obscure. The gabbro seems to be the oldest unit in the sequence. The porphyritic Leatherwood occurs as thin discontinuous sheets at the top of the pluton. Alaskite and pegmatite dikes and sills cut the gabbro, the granite, and country rock surrounding the pluton. Crosscutting relationships between the norite and the Leatherwood Granite have been observed in the southwestern part of the quadrangle (Conley and Toewe, 1968) suggesting that the norite is younger than the Leatherwood.

OBJECTIVES

The radioactivity clocks of detrital zircons are rarely reset when they are incorporated in igneous rocks (Gastil and others, 1967). For this reason the determination of the presence of metadetrital grains in an igneous population is particularly important to Pb-U age dating as ages determined from such mixed populations would be older than the time of crystallization of the igneous rock. Detrital and metadetrital grains as contaminants in igneous populations also cause problems in comparing statistical growth trends among various igneous populations.

A preliminary study of zircons was completed before zircon samples were submitted for radiometric age dating by Pb-U analyses (Conley and Henika, 1973) and these preliminary results were used in selecting samples for dating. The dates received from the samples were of Grenville age (1,020 m.y. old) and much older than the Paleozoic age originally proposed by Conley and Toewe (1968) for these rocks. A computer program was devised for mathematically comparing various zircon populations and a more detailed study was undertaken to see if contamination by older detrital zircons could be a factor in producing such an old date.

The objectives of this study were to determine if an igneous or detrital-metamorphic genesis could be determined for zircon populations collected from the various rock types in the quadrangle and, if possible, to determine the presence of relic detrital-metamorphic zircons in the igneous populations. An attempt was made to see if rocks of the same lithologic type from different parts of the igneous complex could be correlated with each other, and comparisons were made to see if relationships could be established among the various igneous and metamorphic lithologic units in the quadrangle.

SAMPLE COLLECTING AND ZIRCON CONCENTRATION

Ten samples were collected for this study (Figure 2): five from the Leatherwood Granite (R-3380*, R-3383, R-3386, R-3387, and R-3389); one from the Rich acres formation (R-3382); two from the Bassett formation, one a layered biotite paragneiss (R-3381) and the other a migmatitic biotite paragneiss (R-3385; two samples of pegmatite, one a coarse-grained inequigranular pegmatite cutting amphibolite in the Bassett formation (R-3384) and the other an equigranular alaskitic pegmatite cutting the Rich Acres formation (R-3388). In the present study, zircons were extracted from either saprolite or partially decomposed rock, as good results have been obtained from a study of zircons extracted from saprolites (Drummond, 1962 and personal communication). Saprolite and weathered rock have advantages as a source for zircons because they can be rapidly processed and thus zircon concentrates made from rocks that contain few zircons. Breakage of zircon crystals, an inherent problem in crushing fresh rock (Larsen and Poldervaart, 1957) is completely eliminated when a decomposed source rock is used. Zircons are resistant to chemical weathering (Poldervaart, 1955; Carroll, 1953; and Goldich, 1938). Zircons with rounded terminations are attributed by Carroll (1953) to weathering, but also occur in metamorphic rocks as detrital grains with metamorphic

*Numbers preceded by "R" are Virginia Division of Mineral Resources repository numbers for rock samples.

overgrowths (Poldervaart and Eckleman, 1955).

Approximately 20 pounds of either decomposed rock or saprolite were initially collected from each locality. The biotite paragneiss of the Bassett formation and the diorite of the Rich Acres formation each required the processing of up to 150 pounds of sample to obtain two grams of zircon concentrate. To insure against possible contamination, the samples were collected as deep as possible in the weathered rock. Clay seams, quartz veins, and (except where the pegmatites themselves were the object of the sampling) pegmatites were excluded from samples being collected. The samples were air dried and crushed lightly. Clays were removed by using settling tubes. A danger in this method is that the smaller sized zircons, especially in the -300 mesh fraction, where clay minerals are principally concentrated, can be lost by being held in suspension by the clay and floated off in the muddy slurry thus created. For that reason the samples were sieved producing a -150 + 300 mesh fraction that contains most of the zircons and a -300 mesh fraction containing a few zircons and almost all the clay. For each of these fractions settling tubes were filled with water, the samples were added, stirred and allowed to stand until the sand and most of the silt had settled out. Then the water containing clay in suspension was decanted. Caution was used not to disturb the settled fraction. This process probably saved most of the small zircons. After removal of the clays, the two size fractions were further concentrated by panning. The making of a rough concentrate by using settling tubes and panning is considered justified (even if some of the very small zircons were lost) considering the large amount of sample that had to be processed to obtain concentrates from the Rich Acres and Bassett formations and the very slight effect on the final results of the loss of the very small zircons. This is shown by a controlled experiment performed by Hall and Eckelman (1961) who found that two samples from the same rock, one in which these two fractions had been partially lost during routine concentration and the other in which, by recycling overflow, recovery was almost complete: both when plotted using reduced major axis method had identical slopes.

An almost pure zircon concentrate was made using procedures described by Larsen and Poldervaart (1957) and Drummond (1962). An exception was that micas were removed by electrostatic attraction prior to further concentration in heavy liquid as they tend to remain suspended in the heavy liquids and interfere with settling of heavy minerals. A piece of lucite, electrostatically charged by being rubbed briskly with a felt blackboard eraser, was passed over the sample several times, so that most of the mica was removed. The samples were then further concentrated using 1,1,2, 2-tetrabromoethane heavy liquid. After heavy liquid separation, an almost pure zircon concentrate was made.

First magnetite was removed with a hand magnet. The slightly magnetic fraction was removed using the Frantz isodynamic separator at progressively higher field strengths. The nonmagnetic residue, composed mostly of zircons but containing small amounts of quartz, feldspar, and mica, was digested first in concentrated HCl then in HF until all that remained was zircons and silica jell formed from digestion of silicate minerals. Dilute H_2SO_4 was added to take the silica jell into solution, the liquid was decanted, the zircons were caught on filter paper, dried, and mounted on glass slides with Lakeside 70 thermoplastic cement. In some cases, the entire crop of zircons was mounted on glass slides, but in most cases the samples were split and only part of each sample was mounted.

DATA COLLECTION

After each zircon population was mounted, equal-spaced traverses were made across each slide using a mechanical stage equipped for point counting. Each doubly terminated zircon crystal that fell under the cross hairs of the microscope, as the mechanical stage was advanced, was measured for length and breadth using an ocular micrometer at a magnification of 400x until 200 grains had been measured. This number of grains was measured because Poldervaart and von Backstrom (1950) have shown measurement of any number of grains in excess of 200 crystals does not significantly alter the results. In addition, in measuring a zircon population of this magnitude Greenwood and Greenwood (1970) have found operator error to be insignificant. As length and breadth measurements were taken, a visual inspection was made of each grain to determine if it showed rounded terminations by overgrowth and distortion of prism faces by overgrowth. Also metamict grains, grains with inclusions, and grains with phantom growth lines were noted.

STATISTICAL METHODS USED IN TREATMENT OF DATA

The reduced major axis method used to analyze data in this report was developed by Kermack and Haldane (1950) to show growth trends in invertebrate fossils. The method is described in detail by Imbrie (1956). One of the first and most complete discussions of its applications in studying zircons in a suite of igneous rocks is by Larsen and Poldervaart (1957).

In fitting a line to a set of data where error is known to be distributed in both x and y components, the reduced major axis has certain unique advantages. Regression analysis, widely employed as the method of "least squares," has the disadvantage of assigning all error to either the x or the y component; whereas, in reality it is shared by both. The assumption of dependence and independence is never warrented in natural systems. The major axis, a line that minimizes the sum of the squares of the perpendicular distances from each point to the desired line, seems intutively reasonable. Unfortunately, its slope changes with the unit of measurement. The reduced major axis minimizes the sum of the areas of the triangles formed by lines drawn from each point to the desired line and parallel with the x and y axes. Of all the above methods, it emerges as the best available statistical method for analyzing data that follows a linear trend. This line offers the following advantages: (1) it does not assume the error resides in only one of the two variables, a significant factor in analyzing scattered data; (2) it does not change with change in scale; and (3) it is simple to compute.

The basic formulas for the computation of the reduced major axis are:

$$a = \frac{\sigma_y}{\sigma_x}$$

$$\sigma_a = a\sqrt{\frac{1-r^2}{N}}$$

$$b = \bar{y} - \bar{x}a$$

$$Dd = 100\sqrt{\frac{2\ (1-r)\ (\sigma_x^2 + \sigma_y^2)}{\bar{x}^2 + \bar{y}^2}}$$

where

a = growth ratio or slope

b = initial growth index, or intercept

σ_a = standard error of a

Dd = coefficient of relative dispersion about the reduced major axis

N = number of crystals measured

$\bar{x}$ = mean length of crystals

$\bar{y}$ = mean breadth of crystals

σ_x = standard deviation of x (length)

σ_y = standard deviation of y (breadth)

r = Pearson correlation coefficient

The last six terms listed are all standard statistical measurements found in many texts.

The problem now arises that, given two or more axes, what is the probability that their differences in slope are real and not due to chance in sampling. This can be calculated from the formula:

$$z = \frac{a_1 - a_2}{\sqrt{\sigma_{a_1}^2 + \sigma_{a_2}^2}}$$

For large sample populations ($N \geq 200$), if the absolute value of z is greater than 1.96, the probability that the difference in slope arose by chance is less than 0.05. If the absolute value of z is greater than 2.58 the corresponding probability is 0.01. Normally if the probability is less than 0.05 ($z>1.96$) the hypothesis of equal slopes is rejected, and the observed difference is considered statistically significant. In this case, the position of the lines has little meaning. If however, the probability is greater than 0.05 ($z \leq 1.96$), the hypothesis of identical slopes is normally accepted, and a test is made for the significance of positional differences.

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

As above, if z is greater than 1.96, the difference is taken to be significant at the 5 per cent level. If z is less than or equal to 1.96, the observed difference will generally not be accepted as significant. In our calculations we set $x_o = 10$ for normal data and $x_o = 1$ for log data.

Several measurements related to the morphology of zircon crystals are included in the output from the computer program presented in this paper. They are as follows:

Elongation $= \frac{\bar{x}}{\bar{y}}$

Size $= \sqrt{\bar{x}\bar{y}}$

Average Diameter $= \frac{\bar{x} + \bar{y}}{2}$

Scatter diagrams of size versus elongation for the 10 populations in this study show marked differences. Some populations like R-3381 and R-3389 are very uniform, tight populations; other like R-3383 and R-3385 are very dispersed and show subpopulations of elongated zircons or very large zircons (see dispersion column in Tables 1 and 2 and Figures 5 and 6). This nonuniformity in the individual populations is interesting as far as the geologic history of the sample goes, but renders the sample of little or no value as far as age dating and comparison of reduced major axes is concerned.

In the present study, many procedures were tried to eliminate oversize or highly elongate zircons and thus "enhance" the dominant population and show the underlying relationships among rock types. The only procedure found of benefit was eliminating elongated zircons (for example length to breath ratio >4.0). This clarified many relationships, but clouded others. In the end, all of these elimination and selection procedures were discarded because they were judged to be too subjective and not applicable to a universal zircon analysis program.

Statistical results, using all of the data in its normal and log-transformed form, are presented in Tables 1 and 2. Z-tests for comparing slope and position were calculated for all populations at a confidence level equal to or greater than 95 percent ($z>1.96$). The results are presented in Table 3.

STATISTICAL PACKAGES AND THE ANALYSIS OF ZIRCON MORPHOLOGY

Most large computer centers have access to collections of statistical programs that can be run by persons without programming knowledge and minimal computer experience. A flexible collection of statistical routines, the BMD Biomedical Computer Programs edited by W. J. Dixon (1971) and developed by the University of California, was used in this study.

These statistical packages are ideally suited to many types of geologic data reduction and analysis. In this case, the analysis of zircon shapes and sizes is especially amenable to them. Two BMD programs were used in this study for that purpose. The first (BMD05D) produces histograms of zircon length, breadth, elongation ratio, size, and average diameter. This was done by feeding in raw length and breadth values for each zircon. By request, the program automatically does the proper transgeneration on these two variables to calculate elongation ratio, size, and average diameter. Next the program scales these five variables and outputs histograms of the variables. This is the first step used in zircon analysis. By visual inspection of these histograms, some idea can be obtained as to whether each population is homogeneous (normally distributed) or composed of several subpopulations (skewed, overlapping, or multiple distributions).

A second BMD program (BMD02D) is used to produce scatter diagrams of zircon length verses breadth and size verses elongation ratio. Additionally, this program gives sums, means, standard deviations, and correlation among all the variables and has the ability to select or eliminate cases depending on the criterion which the user specifies. Figures 3 through 8 show a representative output from these programs. Histograms and scatter diagrams of length, breadth, elongation, and size are presented for a normal distribution, R-3381, and a multipopulated distribution, R-3383.

REDUCED MAJOR AXIS COMPUTER PROGRAM

The FORTRAN computer program presented in the appendix of this report calculates reduced major axes through sets of zircon length-breadth data. These axes are then compared with one another using the null hypothesis to determine if statistical difference or statistical identity exist among the sets of data at the 95 percent confidence level.

The program was developed by the second author of this paper to aid in the reduction of large quantities of petrographic data to significant statistical parameters which are more directly comparable. Specifically, this program was used to reduce zircon length and breadth data to the two parameters, slope and intercept by fitting a reduced major axis through the scattered points. In turn, these parameters were statistically compared for different zircon populations to determine into which geologic grouping each zircon population falls. It is thus possible to differentiate populations of dissimilar geologic origin from populations of similar geologic origin.

This program is not limited to petrographic problems, but is applicable to any study where bivariate analysis can help characterize differences and similarities between samples.

Program Description

The reduced major axis program is written in FORTRAN IV for a Control Data Corporation 6400 computer. It has an estimated core storage requirement of 16,900 words. Up to 300 points can be used to determine any axis and up to 50 axes can be computed and compared on any run. Compilation time for this program is approximately 3 seconds and execution time for 20 axes of 200 points each is also approximately 3 seconds.

Program Output

1. If requested, the input zircon length and breadth data is listed in tabular form.
2. For each zircon population the following parameters are recorded: mean length and breadth, standard deviation of length and breadth, correlation between length and breadth, slope and intercept of the axis, standard error of the slope, dispersion, elongation, size, and average diameter.
3. All of the computed axes are compared by the z test for

significant differences in slope and position. The resultant z values are printed in two tables and zircon populations which show no significant differences are grouped together and listed.

VISUAL OBSERVATIONS OF THE VARIOUS ZIRCON POPULATIONS

Visual inspection was found to be the easiest method for indicating the genesis of individual zircon grains, whether detrital with metamorphic overgrowths or igneous. Therefore, mixed populations could be recognized by this method. From visual inspection it becomes apparent that each zircon concentrate in this study has its own individual characteristics.

Bassett Formation

Sample number R-3381, biotite paragneiss, contains very few zircons, but those present produce a very uniform population of stubby, smoked, purple grains that may show phantom growth lines and a rounded form. A small number of grains are barrel shaped and have euhedral overgrowths on rounded grains and multiple terminations typical of detrital zircons (Poldervaart, 1955). Gastil and others (1967) have found that metadetrital grains only refacet at near melting conditions, suggesting that the rock was formed at high metamorphic grade. This is further suggested by pelitic rocks in the vicinity that contain sillimanite, suggesting upper amphibolite facies metamorphism.

Sample number R-3385, biotite paragneiss containing a large amount of migmatite bands, has two populations. One population consists of grains with large rounded centers and euhedral overgrowths producing stubby barrel-shaped zircons. Aggregate grains are common. The second population is composed of euhedral forms typical of plutonic intrusive rocks (Poldervaart, 1956). Many are clear euhedral grains, many of which have a euhedral nucleus and phantom growth lines.

Rich Acres Formation

R-3382 from the Rich Acres formation contains a population composed of two types of grains, those that are smoky to metamict and those that are almost opaque malacons. At high magnification, all crystals are euhedral but may be distorted by curved overgrowths. The zircons are presumed to be of igneous origin; however, if rounded detrital nuclei were present, they probably would be obscured by the metamict nature of these grains.

Leatherwood Granite

The description of the individual populations in the Leatherwood Granite are as follows:

R-3380—very uniform population, for the most part composed of perfectly formed euhedral grains; almost all of the grains show multiple metamict phantom growth lines; grains are smoky to lavender and generally contain a euhedral metamict nucleus. These zircons contain fewer inclusions than the rest of the populations observed. Inclusions might be present but obscured by the metamict-smoky nature of the grains.

R-3383—two populations, one composed of clear, elongate grains, generally terminated by 111 faces and may show phantom growth lines. The second population is metamict and may contain large round nuclei with overgrowths. The side prisms and pyramidal faces are distorted by overgrowths and are curved around the rounded nuclei producing stubby, rounded, barrel-shaped grains.

R-3386—two populations; the first is composed of clear to slightly purple, euhedral crystals that may contain metamict centers and phantom overgrowths, although these are the exception rather than the rule. The second population is composed of grains with large rounded metamict centers and distorted, but euhedral overgrowths.

R-3387—contains three types of grains; metamict crystals having distorted curved boundaries on both prisms and pyramidal faces; euhedral, clear crystals; and euhedral crystals with numerous metamict phantom growth lines.

R-3389—uniform population, a large number of grains are smoky to metamict, metamict phantom growth lines are common, prisms and pyramidal faces are distorted by overgrowths, and multiple phantoms indicate that the zircons were originally elongate but by successive additions of overgrowth layers became more stubbly in outline.

Pegmatites

R-3384—pegmatite dike cutting the Bassett formation: two populations; the major population is composed of small, elongate, euhedral, clear grains that may show phantom growth lines and generally have complex terminations consisting of a combination of 111 and 311 prisms. The minor population is composed of larger metamict stubby grains showing polyterminations and overgrowths on large rounded nuclei.

R-3388—equigranular alaskitic pegmatite cutting Rich Acres formation; two populations, one composed of elongate to extremely elongate, clear to metamict, euhedral grains; many are terminated by 331 prism faces and many show phantom growth lines. The other population is composed of metamict grains that show corrosion of side prisms.

Discussion of Zircon Populations

Previous workers (Poldervaart, 1956; Larsen and Poldervaart, 1957) have found that zircons, especially in felsic rocks, crystallize before other constituent minerals. Contrary to this, Silver and Deutsch (1963, p. 756) have found that zircons begin to crystallize early in a melt and grow over much of the crystallization history of the parent rock. If the latter is correct, it might account for some of the variations found in the separate Leatherwood populations. This might also explain the often observed phantom overgrowths, distortion of side prisms, and an elongate euhedral nuclei contained in stubby crystals. Additionally, contamination by detrital grains incorporated in the magma from the country rock could also cause variations in populations.

SLOPE AND POSITION

The groupings resulting from z-test for slope and position of the raw- and log-transformed data are presented in Table 3. The z-test, using log data for significant differences in slope and position, indicates that the ten zircon populations can be placed into four groups in which all individuals of a group correlate with each other within the prescribed limits of probability. The raw data is poorer in defining and separating different rock units from each other than the log-transformed data. This is because small anomalous subpopulations of zircons exist within some of the samples, especially those which are extremely elongated. These anomalous subpopulations exert a relatively larger influence on the raw data than they do on the logarithmically transformed data. Thus, the transformed data more realistically portrays the essential character of the modal population of zircons from the various rock units.

Of the five zircon concentrates from the Leatherwood Granite, all correlate with each other within one grouping for both slope and position, except for sample R-3383, which is clearly anomalous.

The zircon populations from diorite of the Rich Acres formation (R-3382), biotite paragneiss (R-3381) from the Bassett formation, and migmatitic paragneiss (R-3385) from the Bassett formation all correlate by both slope and position with four of the five zircons concentrates from the Leatherwood Granite (R-3380, R-3386, R-3387, and R-3389). However, none of these three samples correlate with each other (Table 3).

Unlike plutons studied by Larsen and Poldervaart (1957), Alper and Poldervaart (1957), and Taubernack (1957), variations do occur in the zircon populations collected in the Leatherwood Granite. Although any individual will correlate with more than one individual from the rest of the granite, not all individuals will correlate with each other, and some correlate with units outside the igneous complex.

The two populations from the pegmatite (R-3384) and alaskite pegmatite (R-3388) correlate with each other and with the one anomalous sample (R-3383) from the Leatherwood Granite. Additionally, the pegmatite (R-3384) shows the most ambiguous relationships of all the samples collected when compared in all of its possible groupings. Not only does it correlate with the alaskite but also with all of

Leatherwood Granite samples and the diorite of the Rich Acres formation.

ELONGATION RATIOS

Populations of detrital zircons in sedimentary rocks (Poldervaart, 1955, p. 441) and metadetrital zircons in metamorphic rocks (Eckelmann and Kulp, 1956; Gastil and others, 1967) have elongation ratios that do not generally exceed 2.0. All zircon populations studied with the exception of sample number R-3381 (biotite paragneiss from the Bassett formation) exceed the 2.0 threshold established for detrital grains (Tables 1 and 2). The next lowest elongation ratio is from a zircon population extracted from sample R-3385, migmatitic paragneiss from the Bassett formation. The other populations range from 2.4 to 3.1. Only one population (R-3383) from the Leatherwood Granite has a elongation ratio that exceeds 3.0. The rest range between 2.4 and 2.7. This suggests that all but one population (R-3381, biotite paragneiss from the Bassett formation) contain enough zircons of igneous origin to exceed the 2.0 detrital-metadetrital threshold.

CONCLUSION

Because of the resistance of zircons to weathering the use of saprolite instead of hard rock as a source of zircons for statistical studies makes possible collection of samples from any area desired instead of only areas where unweathered rock occur. This is a great boon in the southeastern Piedmont where a thick mantle of saprolite covers most of the area and outcrops of rock are rare.

The use of settling tubes and a gold pan is the quickest and easiest method for removing clay and rapidly concentrating heavy minerals. Concentrates can be made from rocks containing so few zircons that quantities of material can be processed that would be prohibitive if this material had to be crushed to a particle size small enough to liberate zircons. When using saprolites (especially saprolites with high clay content), the danger exists that zircons in the -300 mesh fraction can be lost by being held in suspension by clay and floated off during separation. This was partially avoided by putting the sample in suspension in water, allowing the sand and silt to settle out and then decanting off the clay fraction before panning. In addition, Hall and Ecklemann (1961) have shown that the loss of the extremly large and extremely small zircons of a population does not substanitally modify the statistical results when using the reduced major-axis method of comparing length and breadth.

Visual inspection of the morphology of individual zircons within each sample was found to be the easiest method of detecting the presence of detrital grains and mixed populations. The reduced major-axis method is considered the best statistical tool for comparing zircon populations

(Larsen and Poldervaart, 1957, p. 547). However, present work indicates that it should not be used alone, as serious misinterpretations of the data could result, especially in the study of rocks with complex histories or that might contain mixed populations of both metadetrital and igneous zircons. The reduced major-axis method and other common statistical measures such as mean, standard deviation, and correlation are based on the hypothesis that data follow a normal distribtuion. If this assumption is false, as it is in the case of mixed populations of metadetrital and igneous zircons (compare Figures 7 and 8) and other skewed or poly-modal distributions, the statistical calculations break down and have no meaning or predictive value. Length-breadth ratios indicate whether the major part of a populations is of igneous or metadetrital origin. The computer program greatly reduces the amount of time required to mathematically treat the data. This, combined with the use of saprolite instead of hard rock, greatly reduces the time and labor required to study zircon morphology and statistically compare populations.

Table 3 shows that there is overall poor correlation and that there is about as much correlation among different rock types as between individuals of the same rock type. Sample R-3381, Bassett formation, biotite paragneiss, will not correlate with the other sample of Bassett migmatitic biotite paragneiss (R-3385). However, both samples R-3385 and R-3381 correlate with all but one population from the Leatherwood Granite. In addition, the one sample of diorite from the Rich Acres formation(R-3382), will correlate with all populations from the Leatherwood Granite. Of the five samples of Leatherwood Granite, sample R-3383 will not correlate with all of the others. However, the two pegmatite samples, R-3384 and R-3388, will only correlate with each other and with sample R-3383.

From visual inspection it is apparent that the two populations from the Bassett paragneiss as well as the igneous rocks contain metadetrital grains. In addition, paragneisses from the Bassett formation also seem to contain igneous zircons and statistically correlate with populations from the Leatherwood Granite. The presence of mixed populations of metadetrital and igneous zircons in varying porportions is the primary cause of the general lack of correlation among populations from the Leatherwood Granite. The general correlation among most populations in the Leatherwood Granite and the Rich Acres formation might suggest that igneous zircons from each population were from the same parent magma. The lack of correlation of Leatherwood Granite sample R-3383 with Leatherwood samples R-3380, R-3386, R-3387, and R-3389 and its correlation with the two pegmatites might further suggest a continued growth of zircons in volatile differentiates after growth had ceased in more normal granite.

Elongation ratios suggest that all the populations with the exception of sample R-3381 (Bassett biotite paragneiss) are of igneous origin whereas visual inspection would suggest that most of these "igneous" populations are composed in part of metadetrital grains. This suggests either that the number of metadetrital grains were not enough to influence the statistical average or the unlikely circumstance that the detrital zircons only acted as nucleation sites for the igneous overgrowths and did not affect length and breadth of the igneous overgrowths.

A study of zircons such as this is extremely helpful in determining the origin of rocks that have had a complex history. It would seem that such an in depth study would be absolutely essential before trying to interprete radiometeric dates derived from zircons. Considering the amount of detrital zircons from most of the populations studied, it is not surprising that age dates of 1,020 million years (Conley and Henika, 1973, p. 22) could be obtained from rocks thought to be of Paleozoic age (Conley and Toewe, 1968).

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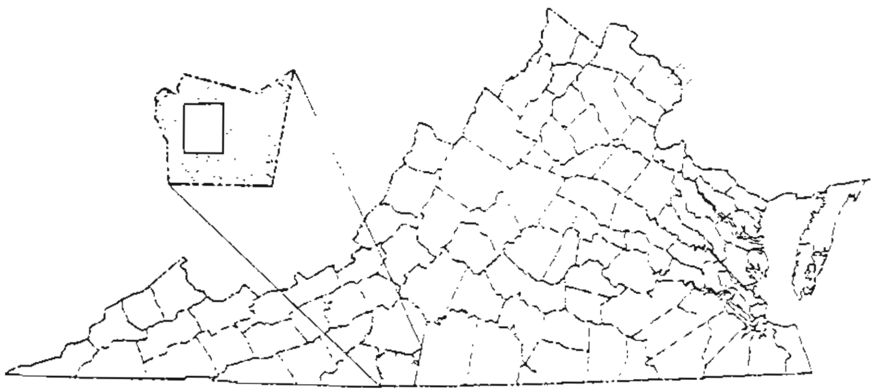

Figure 1. Index map showing locations of study area (Martinsville West quadrangle, Virginia).

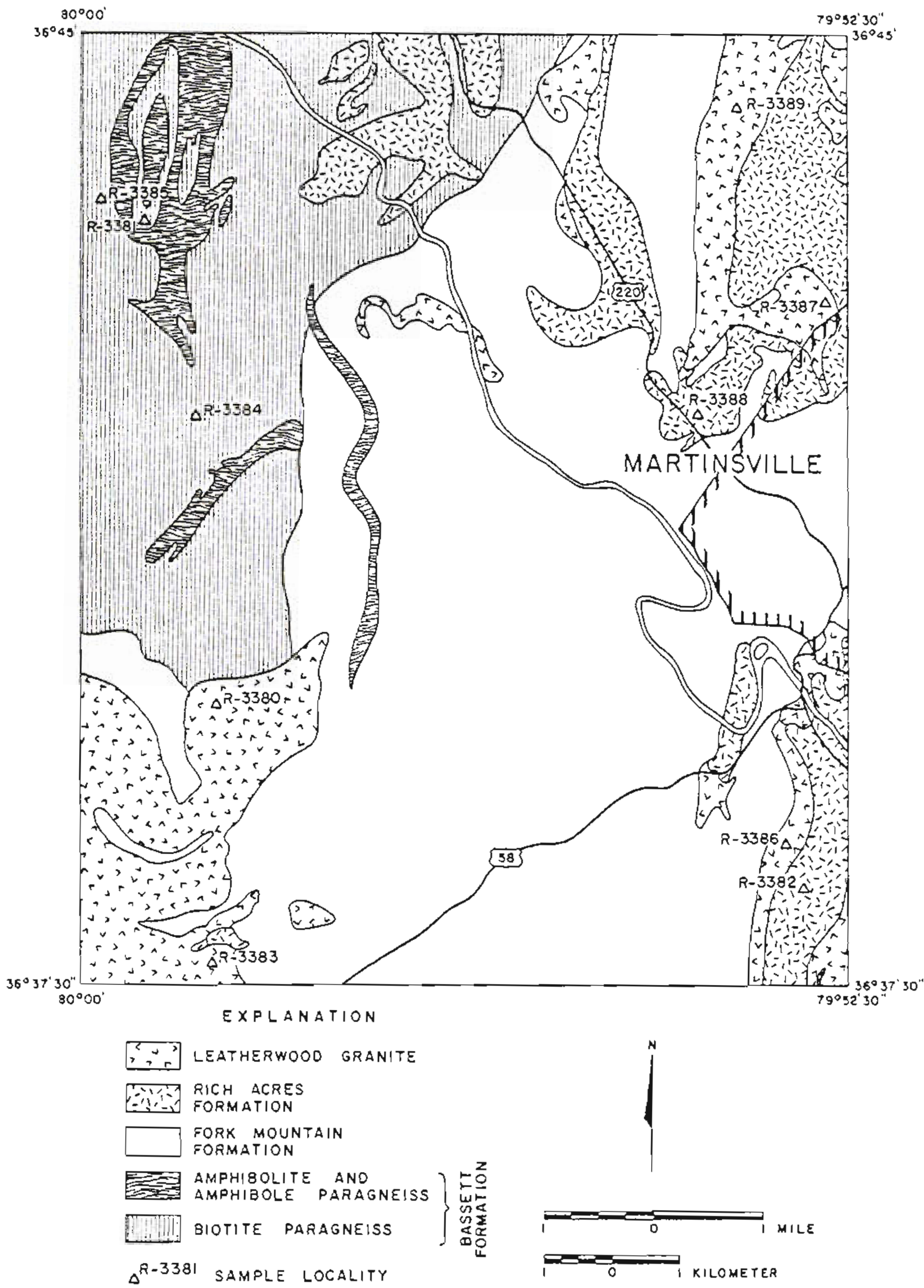

Figure 2. Geologic map of Martinsville West quadrangle, Virginia showing sample localities.

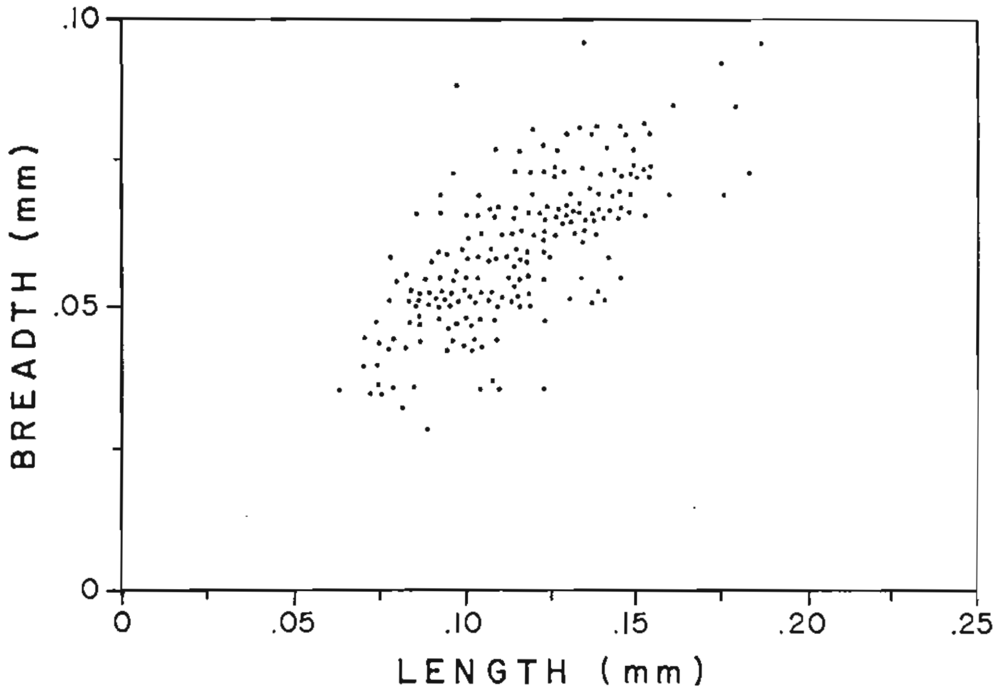

Figure 3. Scatter diagram of length versus breadth for sample R-3381.

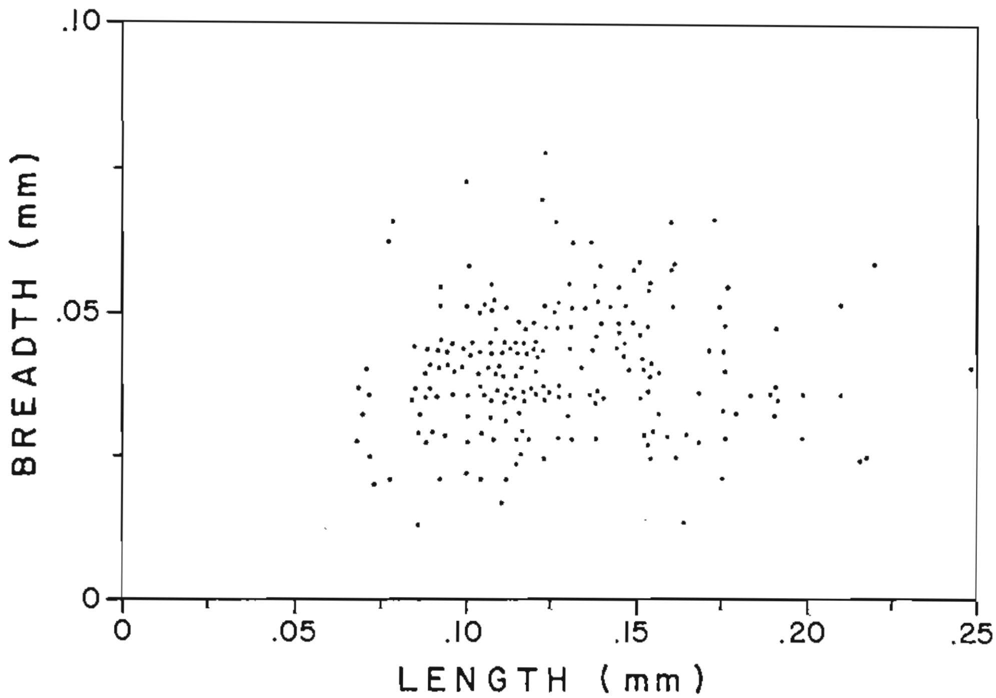

Figure 4. Scatter diagram of length versus breadth for sample R-3383.

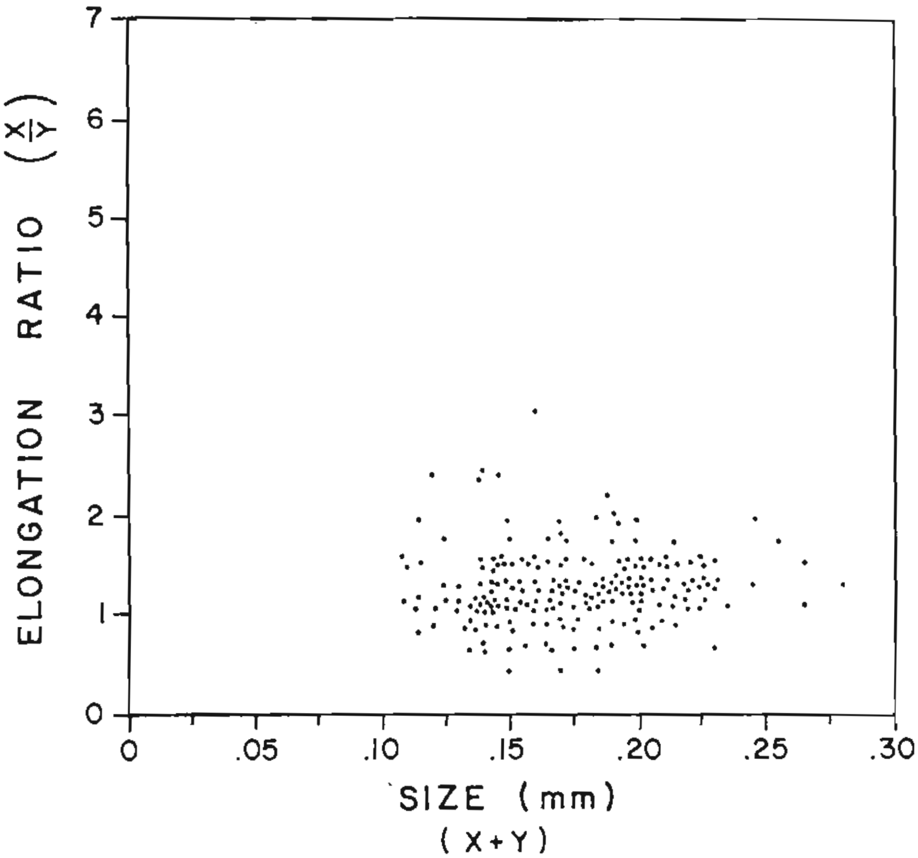

Figure 5. Scatter diagram of size versus elongation for sample R-3381.

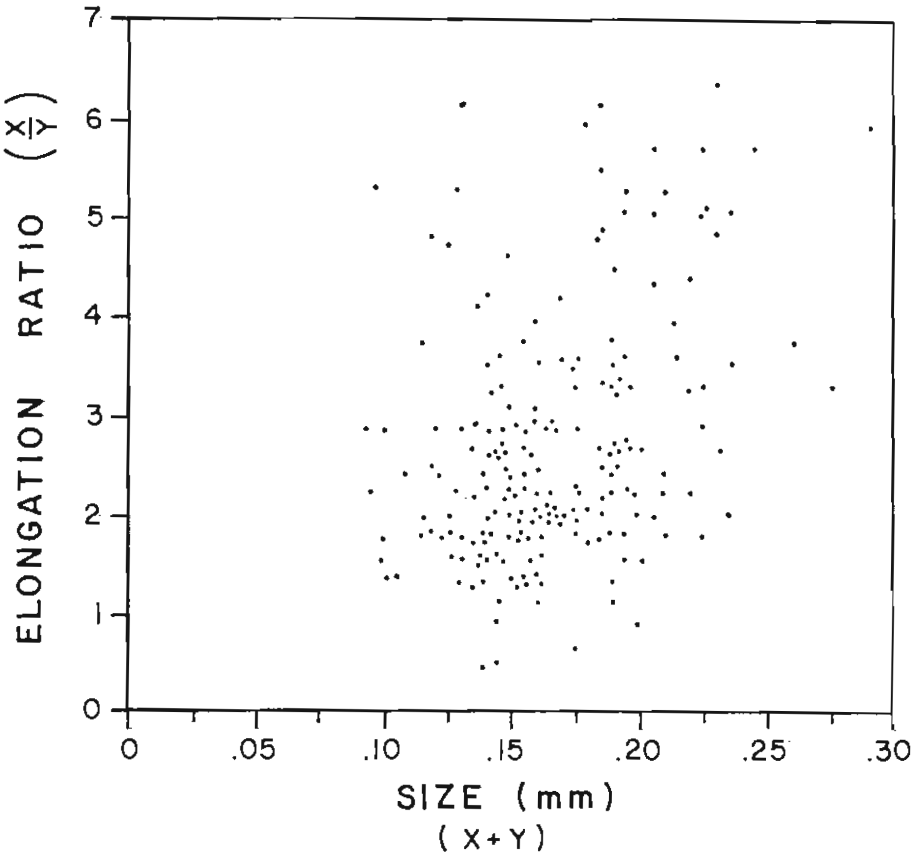

Figure 6. Scatter diagram of size versus elongation for sample R-3383.

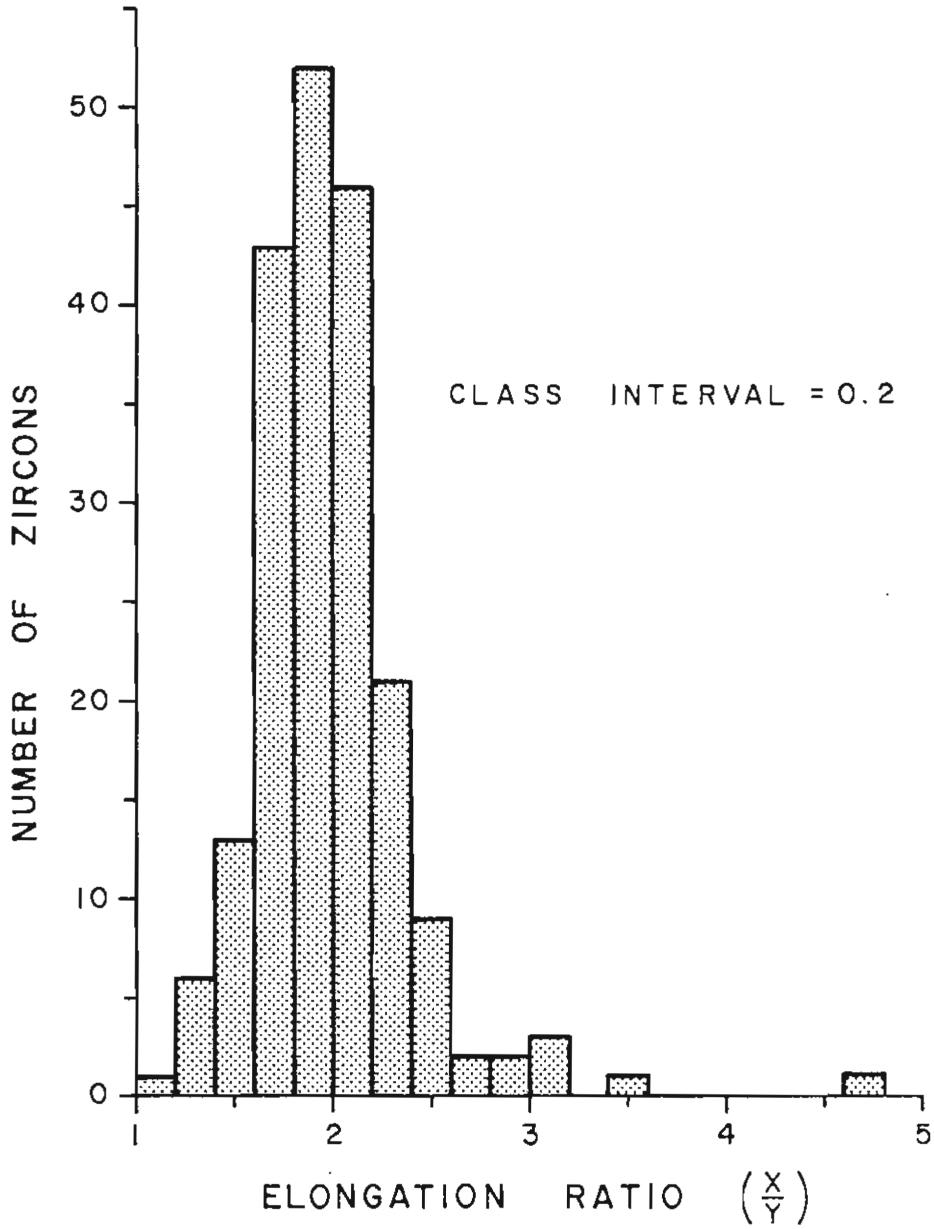

Figure 7. Histogram of elongation ratios for sample R-3381.

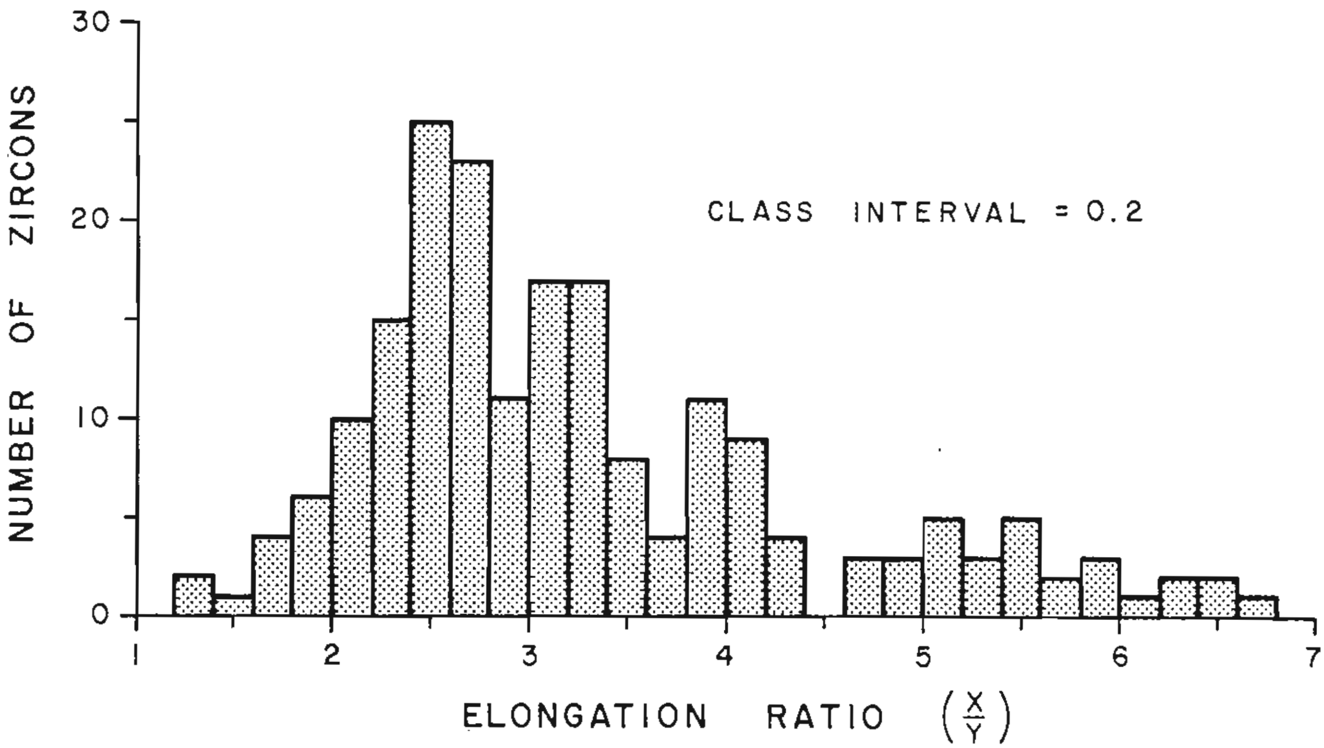

Figure 8. Histogram of elongation ratios for sample R-3383.

Table 1.—Statistical analysis of raw data for zircon populations collected from the Martinsville West quadrangle, Virginia.

SAMPLE	N	MEAN(X) *	MEAN(Y) *	STD DEV (X) *	STD DEV (Y) *	CORRELATION (R)	SLOPE (A)	INTERCEPT (B) *
R-3380	200	50.680	18.495	11.363	4.099	.337	.361	.212
R-3381	200	46.450	23.960	9.781	5.178	.711	.529	-.630
R-3382	200	52.675	20.645	11.489	4.451	.501	.387	.239
R-3383	200	50.975	16.330	13.245	4.401	.084	.332	-.607
R-3384	200	56.755	22.765	16.538	7.703	.675	.466	-3.670
R-3385	200	31.965	13.405	14.781	5.703	.779	.386	1.072
R-3386	200	47.810	19.905	11.224	4.700	.644	.419	-.113
R-3387	199	47.809	18.809	11.914	4.480	.688	.376	.829
R-3388	200	46.730	17.380	13.113	5.962	.607	.455	-3.866
R-3389	200	49.715	20.565	10.437	4.513	.648	.432	-.931

SAMPLE	STD ERROR -SLOPE	DISPERSION (DD)	ELONGATION	SIZE *	AVE DIAMETER *
R-3380	.0241	25.781	2.740	30.616	34.588
R-3381	.0265	16.101	1.939	33.361	35.205
R-3382	.0238	21.766	2.551	32.977	36.660
R-3383	.0235	35.296	3.122	28.852	33.653
R-3384	.0244	24.004	2.493	35.945	39.760
R-3385	.0172	30.367	2.385	20.700	22.685
R-3386	.0228	19.831	2.402	30.849	33.858
R-3387	.0194	19.557	2.542	29.987	33.309
R-3388	.0257	25.609	2.689	28.499	32.055
R-3389	.0234	17.742	2.417	31.975	35.140

* Values in mm × .0025

Table 2.—Statistical analysis of log transformed data for zircon populations collected from the Martinsville West quadrangle, Virginia.

SAMPLE	N	MEAN(X)	MEAN(Y)	STD DEV (X)	STD DEV (Y)	CORRELATION (R)	SLOPE (A)	INTERCEPT (B)
R-3380	200	1.693	1.256	.103	.100	.322	.973	-.391
R-3381	200	1.657	1.369	.093	.097	.705	1.050	-.371
R-3382	200	1.712	1.304	.093	.097	.485	1.040	-.475
R-3383	200	1.693	1.196	.110	.123	.118	1.118	-.696
R-3384	200	1.736	1.335	.126	.139	.669	1.101	-.576
R-3385	200	1.463	1.093	.189	.169	.734	.898	-.220
R-3386	200	1.668	1.288	.100	.099	.631	.986	-.357
R-3387	199	1.667	1.262	.104	.103	.700	.985	-.379
R-3388	200	1.653	1.215	.121	.148	.588	1.232	-.821
R-3389	200	1.687	1.303	.093	.096	.651	1.028	-.431

SAMPLE	STD ERROR -SLOPE	DISPERSION (DO)	ELONGATION	SIZE	AVE DIAMETER
R-3380	.0654	7.912	2.737	29.830	33.691
R-3381	.0529	4.801	1.942	32.595	34.407
R-3382	.0646	6.328	2.554	32.211	35.816
R-3383	.0789	10.596	3.140	27.852	32.535
R-3384	.0581	6.968	2.519	34.304	38.031
R-3385	.0433	10.124	2.343	18.961	20.704
R-3386	.0544	5.739	2.400	30.043	32.969
R-3387	.0501	5.423	2.538	29.144	32.362
R-3388	.0708	8.463	2.741	27.168	30.694
R-3389	.0548	5.154	2.422	31.243	34.348

Table 3

Significant groups by slope and position

Log Data

R-3383 Δ	R-3380 Δ	R-3380 Δ	R-3380 Δ
R-3384 *	R-3385 †	R-3381 †	R-3382 o
R-3388 *	R-3386 Δ	R-3386 Δ	R-3384 *
	R-3387 Δ	R-3387 Δ	R-3386 Δ
	R-3389 Δ	R-3389 Δ	R-3387 Δ
			R-3389 Δ

Raw Data

R-3381 †	R-3384 *	R-3380 Δ	R-3380 Δ	R-3382 o
	R-3388 *	R-3383 o	R-3382 o	R-3385 †
		R-3383 Δ	R-3385 †	R-3386 Δ
		R-3387 Δ	R-3386 Δ	R-3387 Δ
			R-3387 Δ	R-3389 Δ

Δ granite, Leatherwood
o diorite, Rich Acres
† paragneiss, Bassett
* pegmatite

APPENDIX

FORTRAN COMPUTER PROGRAM FOR CALCULATING AND COMPARING REDUCED MAJOR AXES

OPERATING INSTRUCTIONS

DECK SET-UP

1. Job Card
2. System Control Cards
3. FORTRAN Source Deck for RMAXIS Program
4. Data Input Cards

DATA INPUT

1. Title Card

Column	Format	Entry
1-70	7A10	Name of project—any combination of alphanumeric characters
71-72	I2	Number of axes to be calculated right justified
73	I1	INPUT (enter 0 or 1) If 0, length and breadth data entered as input. If 1, means and standard deviations entered as input
74	I1	LIST (enter 0 or 1) If 0, lists length and breadth data. If 1, no listing
75	I1	LOG (enter 0 or 1) If 0, calculates data in its normal form. If 1, calculates data in a log base 10 transformed form
76-80*	F5.0	Zircon length at which position of reduced major axes are to be compared

2. Data Cards

If INPUT = 0

Column	Format	Entry
1-10	A10	Name or number of axis being
11-20	A10	Designation of lc coordiante (for example Length (mm))
21-30	A10	Designation of y coordiante (for example Breadth (mm))
31-33	I3	N — the number of zircons measured for the axis being computed, right justified
1-5*	F5.0	Length of first zircon
6-10*	F5.0	Breadth of first zircon
11-15*	F5.0	Length of second zircon
16-20*	F5.0	Breadth of second zircon
21-25*	F5.0	Length of third zircon
26-30*	F5.0	Breadth of third zircon

*Decimal point must be entered with these numbers.

Entries continue in this format across all 80 columns of the card and cards continue in the same fashion until the Nth zircon measurement is reached. At that point if another axis is to be computed, start again with the first Data Card. Keep repeating this process until all data is entered. When the last data for the study has been entered, the program input is complete. If further studies are to be processed on the same run, start again with the Title Card and repeat the entire procedure.

If INPUT = 1

Column	Format	Entry
1-10	A10	Name or number of axis being computed
11-20*	F10.0	Mean zircon length
21-30*	F10.0	Mean zircon breadth
31-40*	F10.0	Standard deviation length
41-50*	F10.0	Standard deviation breadth
51-60*	F10.0	Correlation of length and breadth
61-63	I3	N—the number of zircons measured for the axis being computed, right justified

One card of this format is required for each axis to be computed. The program input is complete when the data for the last axis is entered.

*Decimal point must be entered with these numbers.

```
      PROGRAM RMAXIS(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      CIMENSION X(300), Y(300), ABC(7), N(50), XM(50), YM(50), SDX(50),
     1SDY(50), R(50), ELONG(50), SIZE(50), ADIA(50), A(50), B(50), SE(50
     2), DD(50), ZS(50,50), ZP(50,50)
      COMMON NSAM,SAMPLE(50)
C
C     READ INPUT DATA
C
10    INPUT=LIST=LOG=0
      READ (5,190) (ABC(K),K=1,7),NSAM,INPUT,LIST,LOG,XO
      IF (EOF(5)) 170,20
20    WRITE (6,280)
      IF (LIST.EQ.1.OR.INPUT.EQ.1) GO TO 30
      WRITE (5,200) (ABC(K),K=1,7),NSAM
      WRITE (6,210)
30    DO 120 I=1,NSAM
      IF (INPUT) 40,40,100
40    READ (5,220) SAMPLE(I),XOES,YOES,N(I)
      M=N(I)
      READ (5,230) (X(J),Y(J),J=1,M)
      IF (LIST.EQ.1) GO TO 50
      WRITE (5,250) SAMPLE(I)
      WRITE (6,260) (XOES,YOES,K=1,5)
      WRITE (6,270) (X(K),Y(K),K=1,M)
      WRITE (6,280)
50    IF (LOG.EQ.0) GO TO 70
      DO 60 J=1,M
      X(J)=ALOG10(X(J))
60    Y(J)=ALOG10(Y(J))
C
C     CALCULATION OF MEAN,STANDARD DEVIATION, AND CORRELATION
C
70    SX=SY=DX=DY=SIGMA=0
      DO 80 J=1,M
      SX=SX+X(J)
80    SY=SY+Y(J)
      XM(I)=SX/M
      YM(I)=SY/M
      DO 90 J=1,M
      DX=DX+(X(J)-XM(I))**2
      DY=DY+(Y(J)-YM(I))**2
90    SIGMA=SIGMA+(X(J)-XM(I))*(Y(J)-YM(I))
      SDX(I)=SQRT(DX/(M-1))
      SDY(I)=SQRT(DY/(M-1))
      R(I)=SIGMA/((M-1)*SDX(I)*SDY(I))
      IF (INPUT.EQ.0) GO TO 110
100   READ (5,240) SAMPLE(I),XM(I),YM(I),SDX(I),SDY(I),R(I),N(I)
      M=N(I)
C
C     CALCULATION OF REDUCED MAJOR AXIS
C
110   A(I)=SDY(I)/SDX(I)
      B(I)=YM(I)-(A(I)*XM(I))
      SE(I)=A(I)*SQRT((1.0-R(I)**2)/(M-2))
      DD(I)=100.*SQRT((2.0*(1.0-R(I))*(SDX(I)**2+SDY(I)**2))/(XM(I)**2+Y
     1M(I)**2))
      ELONG(I)=XM(I)/YM(I)
```

```
          SIZE(I)=SQRT(XM(I)*YM(I))
          ADIA(I)=(XM(I)+YM(I))/2.0
          IF (LOG.EQ.0) GO TO 120
          TX=10**XM(I)
          TY=10**YM(I)
          ELONG(I)=TX/TY
          SIZE(I)=SQRT(TX*TY)
          ADIA(I)=(TX+TY)/2.0
  120     CONTINUE
          WRITE (6,200) (ABC(K),K=1,7),NSAM
          IF (LOG.EQ.1) WRITE (6,180)
          WRITE (6,210)
          WRITE (6,290)
          WRITE (6,300)
          DO 130 K=1,NSAM
  130     WRITE (6,310) SAMPLE(K),N(K),XM(K),YM(K),SDX(K),SDY(K),R(K),A(K),B
         1(K)
          WRITE (6,320)
          WRITE (6,330)
          WRITE (6,340)
          DO 140 K=1,NSAM
  140     WRITE (6,350) SAMPLE(K),SE(K),DD(K),ELONG(K),SIZE(K),ADIA(K)
          WRITE (6,280)
C
C         Z TEST FOR COMPARING SLOPE AND POSITION OF REDUCED MAJOR AXES
C
          DO 160 I=1,NSAM
          DO 160 J=1,NSAM
          IF (I.NE.J) GO TO 150
          ZS(I,J)=ZP(I,J)=0
          GO TO 150
  150     ZS(I,J)=(A(I)-A(J))/SQRT(SE(I)**2+SE(J)**2)
          ZP(I,J)=(XO*(A(I)-A(J))+(B(I)-B(J)))/SQRT((SE(I)**2*(XO-XM(I))**2)
         1+(SE(J)**2*(XO-XM(J))**2))
  160     CONTINUE
          WRITE (6,360)
          CALL ZTEST (ZS)
          WRITE (6,370)
          CALL ZLIST (ZS)
          WRITE (6,380) XO
          CALL ZTEST (ZP)
          WRITE (6,390)
          CALL ZLIST (ZP)
          GO TO 10
  170     STOP
C
C
C
  180     FORMAT (1H ,50X,*LOG TRANSFORMED OATA*)
  190     FORMAT (7A10,I2,3I1,F5.0)
  200     FORMAT (1H ,24X,7A10,/,47X,*NUMBER OF SAMPLES =*,I4//)
  210     FORMAT (1H ,60(2H* )//)
  220     FORMAT (3A10,I3)
  230     FORMAT (16F5.0)
  240     FORMAT (A10,5F10.0,I3)
  250     FORMAT (1H ,54X,A10)
  260     FORMAT (1H ,10(A10,2X))
```

```
      270   FORMAT (1H ,10(F7.3,5X))                                             A 115
      280   FORMAT (1H1)                                                          A 116
      290   FORMAT (1H ,*SAMPLE*,10X,*N*,6X,*MEAN(X)*,8X,*MEAN(Y)*,8X,*STD DEV   A 117
           1*,8X,*STD DEV*,4X,*CORRELATION*,10X,*SLOPE*,6X,*INTERCEPT*)          A 118
      300   FORMAT (1H ,55X,*(X)*,12X,*(Y)*,10X,*(R)*,15X,*(A)*,10X,*(B)*/)      A 119
      310   FORMAT (1H ,A10,I7,3X,6(F10.3,5X),F10.3)                              A 120
      320   FORMAT (//////////)                                                   A 121
      330   FORMAT (1H ,*SAMPLE*,15X,*STD ERROR*,8X,*DISPERSION*,8X,*ELONGATIO   A 122
           1N*,14X,*SIZE*,6X,*AVE DIAMETER*)                                      A 123
      340   FORMAT (1H ,22X,*-SLOPE*,13X,*(OD)*/)                                 A 124
      350   FORMAT (1H ,A10,13X,F7.4,6X,F12.3,3(8X,F10.3))                        A 125
      360   FORMAT (1H ,39X,*Z TEST FOR SIGNIFICANT DIFFERENCE IN SLOPE*/////)   A 126
      370   FORMAT (1H ,30X,*SIGNIFICANT GROUPS FOR SLOPE AT 95% CONFIDENCE LE   A 127
           1VEL (Z≤1.96)*/////)                                                   A 128
      380   FORMAT (1H ,30X,*Z TEST FOR SIGNIFICANT DIFFERENCE IN POSITION AT    A 129
           1X=*,F6.2/////)                                                        A 130
      390   FORMAT (1H ,28X,*SIGNIFICANT GROUPS FOR POSITION AT 95% CONFIDENCE   A 131
           1 LEVEL (Z≤1.96)*/////)                                                A 132
            END                                                                   A 133-
```

41000B CM STORAGE USED   1.341 SECONDS

```
      SUBROUTINE ZTEST (Z)
      DIMENSION Z(50,50)
      COMMON NSAM,SAMPLE(50)
      L=LL=0
   10 L=LL+1
      LL=L+9
      IF (LL.GT.NSAM) LL=NSAM
      WRITE (6,30) (SAMPLE(K),K=L,LL)
      DO 20 I=1,NSAM
   20 WRITE (6,40) SAMPLE(I),(Z(I,J),J=L,LL)
      WRITE (6,50)
      IF (LL.LT.NSAM) GO TO 10
      WRITE (6,60)
      RETURN
C
C
C
   30 FORMAT (1H ,14X,10A10)
   40 FORMAT (1H ,A10,10F10.2)
   50 FORMAT (////)
   60 FORMAT (1H1)
      END
```

41000B CM STORAGE USED .127 SECONDS

```
      SUBROUTINE ZLIST (Z)
      DIMENSION Z(50,50), NT(50), MARK(50), SWITCH(50)
      COMMON NSAM,SAMPLE(50)
      DO 10 I=1,NSAM
      NT(I)=0
      SWITCH(I)=SAMPLE(I)
      DO 10 J=1,NSAM
      IF (ABS(Z(I,J)).LE.1.96) Z(I,J)=1.0
      IF (ABS(Z(I,J)).GT.1.96) Z(I,J)=0.0
   10 NT(I)=NT(I)+Z(I,J)
      KEEP=NSAM+1
      NP=0
      DO 30 I=1,NSAM
      DO 30 J=1,NSAM
      IF (NT(J).NE.I) GO TO 30
      NP=NP+1
      HOLD=SWITCH(NP)
      SWITCH(NP)=SWITCH(J)
      SWITCH(J)=HOLD
      NK=NT(NP)
      NT(NP)=NT(J)
      NT(J)=NK
      DO 20 K=1,NSAM
      Z(K,KEEP)=Z(K,NP)
      Z(K,NP)=Z(K,J)
   20 Z(K,J)=Z(K,KEEP)
   30 CONTINUE
      DO 40 I=1,NSAM
      DO 40 J=1,NSAM
      IF (SAMPLE(I).EQ.SWITCH(J)) MARK(J)=I
   40 CONTINUE
      DO 90 I=1,NSAM
      DO 90 J=1,NSAM
      JJ=MARK(J)
      IF (Z(JJ,I)) 90,90,50
   50 DO 70 K=1,NSAM
      TEST=Z(K,I)-0.5
      IF (TEST) 70,70,60
   60 IF (Z(K,J)) 80,80,70
   70 CONTINUE
      Z(JJ,I)=2.0
      GO TO 90
   80 Z(JJ,I)=0.5
   90 CONTINUE
      BLANK=10H
      DO 110 I=1,NSAM
      DO 110 J=1,NSAM
      IF (Z(J,I).EQ.2.0) GO TO 100
      Z(J,I)=BLANK
      GO TO 110
  100 Z(J,I)=SAMPLE(J)
  110 CONTINUE
      DO 120 I=1,NSAM
      NS=0
      DO 120 J=1,NSAM
      IF (Z(J,I).EQ.BLANK) GO TO 120
      NS=NS+1
```

```
                  Z(NS,I)=Z(J,I)
                  IF (NS.NE.J) Z(J,I)=BLANK
          120     CONTINUE
                  DO 150 I=1,NSAM
                  L=I+1
                  DO 150 J=L,NSAM
                  DO 130 K=1,NSAM
                  IF (Z(K,I).NE.Z(K,J)) GO TO 150
          130     CONTINUE
                  DO 140 K=1,NSAM
          140     Z(K,J)=BLANK
          150     CONTINUE
                  L=0
                  DO 160 I=1,NSAM
                  IF (Z(1,I).EQ.BLANK) GO TO 160
                  L=L+1
                  WRITE (5,170) L,(Z(J,I),J=1,NSAM)
          160     CONTINUE
                  WRITE (5,180)
                  RETURN
         C
         C
         C
          170     FORMAT (1H ,*GROUP NO. *,I2,* =    *,10A10/,4(17X,10A10/))
          180     FORMAT (1H1)
                  END
```

410008 CM STORAGE USED .673 SECONDS