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ZIRCONS FROM PRECAMBRIAN GNEISS, SOUTHERN BIGHORN MOUNTAINS, WYOMING[1]

R. J. MALCUIT[2] AND R. A. HEIMLICH, *Department of Geology, Kent State University, Kent, Ohio 44242*

ABSTRACT

Studies of textural relationships, color, internal features, and morphology of zircons in four samples of gneiss from the southern Bighorn Mountains indicate that two distinct generations of zircon are present. Older dark-colored, strongly zoned, inclusion-bearing, commonly subrounded zircons are mantled, partly or completely, by younger colorless, unzoned or weakly zoned, largely inclusion-free, subhedral zircon of high clarity. The younger colorless zircon is also represented by subordinate amounts of discrete core-free crystals which occur along with the dark zircons in several samples.

The morphologic characteristics of the dark, pre-metamorphic zircons, from two of the samples in which these zircons exhibit little or no later alteration effects, tentatively suggest a sedimentary parentage for the gneiss. The modes of occurrence and character of the colorless zircon suggest formation by solution of the older zircon, under alkaline conditions, and redeposition during the episode of metamorphism represented by the gneiss.

INTRODUCTION

With the exception of some preliminary data regarding a single sample of granitic rock (Heimlich and Banks, 1968), no study of zircons has ever been published pertaining to the extensive Precambrian terrain exposed in the Bighorn Mountains. The study reported here was initiated as a pilot program in conjunction with a petrogenic (Heimlich, 1969; Heimlich, in press; Heimlich, Nelson, and Malcuit, in press) and radiometric age (Heimlich and Banks, 1968; Condie and Heimlich, 1969) study of the gneiss exposed in the southern portion of the Bighorn Mountains (Fig. 1). The zircons are of particular interest in terms of their bearing on the parentage of the gneiss and its metamorphic-metasomatic evolution. Furthermore, their mode of occurrence is critical to the interpretation of Pb/U ages obtained for the gneiss.

SAMPLE PREPARATION

Because the material was to be used for radiometric age study as well as for morphologic analysis, large representative samples of the gneiss approximating 25 kg. each were collected at four separate localities within the southern gneiss terrain (Fig. 1). The samples were processed by repeated grinding and

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[1] Contribution No. 66, Department of Geology, Kent State University, Kent, Ohio.

[2] Present address: Department of Geology, Michigan State University, East Lansing, Michigan 48823.

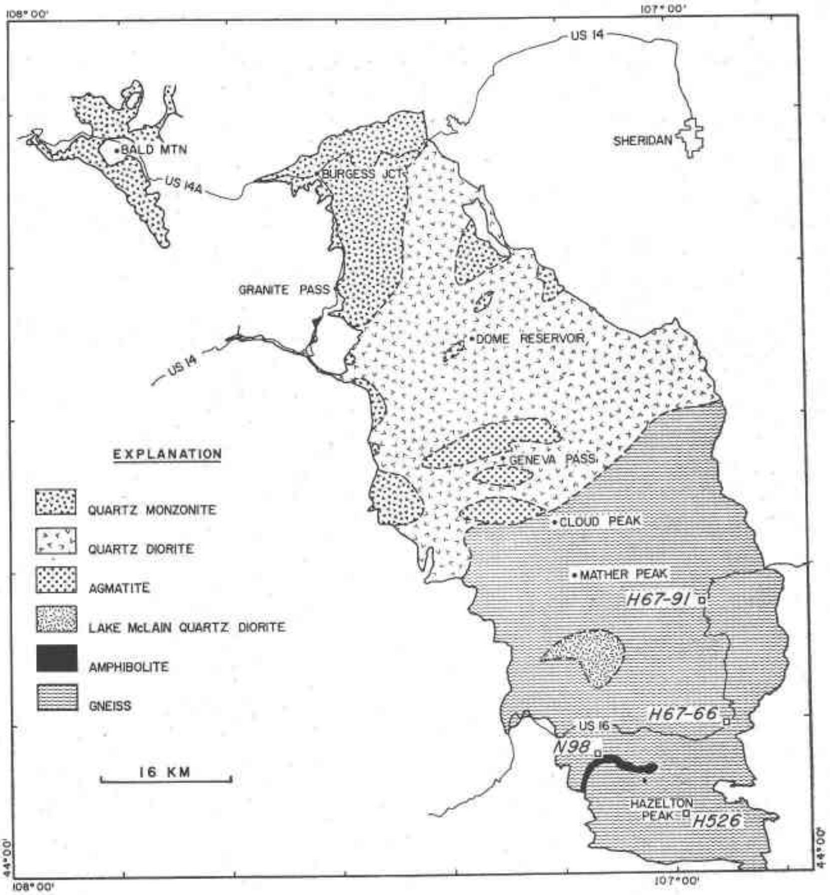

FIG. 1. Reconnaissance geologic map of the Bighorn Mountains showing zircon sample locations.

sieving until all powder passed through a 60-mesh sieve. The powder was then run over a Wilfley shaking table, resulting in a concentrate of 1.5 to 2.5 kg. of heavy minerals. This concentrate was then washed in acetone, dried, and passed along a horseshoe magnet. Samples were than subjected to heavy liquid (tetrabromoethane) separation, magnetic separation (Frantz isodynamic separator), a second heavy liquid (methylene iodide) separation, and a second magnetic separation.

The final zircon concentrate was boiled in concentrated nitric acid at 250° F. for approximately one hour, washed in acetone, and dried. Using disposable, nylon-mesh sieves, each zircon sample was separated into three size fractions (+200 mesh, 200–285 mesh, and −285 mesh). A representative split from each fraction was then mounted on slides using Aroclor ($n = 1.65$) as the mounting medium.

DATA COLLECTION

The slides were studied under 250x magnification using an ocular micrometer, mechanical stage for point counting, and both transmitted and reflected light. Data were recorded only for those grains, any part of which appeared under the cross-hairs along the traverse. The dimensions and other characteristics of 100 unbroken crystals per slide (300 per zircon sample) were observed and recorded along equally-spaced traverses. For two of the samples which contain two distinct groups of zircons, additional counts of 220–225 grains from the less abundant group were made as well. Data were recorded for the main crystals, cores within the main crystals, partial overgrowths, and outgrowths.

For purposes of this study we consider the main crystal to be that body defined by the outermost complete shell, whether the shell is clear, colored, zoned, or unzoned. A core is that portion of a zircon crystal which can be distinguished as a separate entity under 250x magnification, in transmitted and/or reflected light, and which may or may not be in optical continuity with the enclosing zircon shell. For highly zoned grains, a subjective decision must be made as to whether or not a slight break in zoning is evidence for the delimitation of a core. We believe that a break in zoning, accompanied by a color change, is significant in establishing a core-shell relationship. Although individual examples of this may be subject to dispute, our general conclusions would not be altered by using more restrictive criteria.

CHARACTER OF THE GNEISS

The gneiss terrain of the southern Bighorn Mountains encompasses an area of some 1400 sq. km. Although thin amphibolite bodies are scattered throughout the terrain and typical metasedimentary units are common in one area (Palmquist, 1965), the terrain is dominated by a monotonous assemblage of foliated, quartzofeldspathic rocks which are remarkably uniform in mineral composition. The common gneiss consists of plagioclase, quartz, and biotite for the most part. Hornblende and microcline are significant minerals locally. The rocks were metamorphosed under conditions of the lower amphibolite facies. For a more detailed description of the gneiss and its mineralogy the reader is referred to papers by Osterwald (1959) and by Heimlich, Nelson, and Malcuit (in press).

The gneiss samples used in this study are typical of the common gneiss in the area. Detailed modes of the samples are given in Table 1. All samples have low hornblende and microcline contents and the percentage of biotite in them reflects the common range for this mineral throughout the terrain. The samples are weakly to well-foliated. All are equigranular except H67-91 which contains a few scattered plagioclase augen. Both H67-66 and H67-91 are characterized by the presence of irregular, discordant and concordant aplitic, white, quartz-feldspar bodies which are 3mm to 15cm thick.

On the basis of preliminary chemical data, Heimlich (in press) con-

Table 1. Modal analyses of gneiss samples.

Sample	N98	H526	H67-66	H67-91
Plagioclase	62.0	60.3	54.1	60.0
Quartz	25.7	21.3	24.6	31.1
Biotite	10.0	15.8	19.2	7.3
Hornblende	0.0	0.5	0.0	0.0
Microcline	1.5	0.6	0.2	0.5
Epidote	0.2	1.2	tr	0.1
Muscovite	tr	tr	0.1	tr
Apatite	0.2	0.1	0.2	0.4
Allanite	0.1	tr	0.0	0.0
Sphene	tr	0.1	0.2	0.0
Zircon	0.1	tr	0.2	tr
Chlorite	tr	tr	0.2	0.0
Opaque Accessories	0.2	0.1	0.8	0.6

cluded that likely parent rocks for the gneiss are graywacke, felsic plutonic rocks (such as adamellite, granodiorite, or tonalite), or the volcanic equivalents of these igneous rocks. Osterwald (1959) indicated that the gneiss was derived substantially from a felsic volcanic sequence that contained some sedimentary material.

CHARACTERISTICS OF THE ZIRCON SUITES

Physical characteristics of zircons from each of the four samples are summarized in Table 2. The data are based on a count of 300 unbroken grains of any type encountered under the microscope cross-hair intersection. Representative zircons, as well as some of the less common types, are pictured in Figure 3. As the study progressed, it became obvious that the pre-metamorphic characteristics of the zircons in sample N98 are more prominently displayed than in the other three samples. Later alteration of the zircons and the presence of a second generation of zircon in these samples have, to some extent, obscured their primary character. The second-generation zircon is present in the form of clear overgrowths on darker grains and as discrete clear crystals which lack cores. Their nature will be discussed in a later section.

Table 2. Characteristics of the zircon suites.

Sample	Color	Zoning	Euhedrism and Rounding	Termination Type[2]				Inclusions	Partial Overgrowths and Outgrowths	Complete Overgrowths	Clear, Core-free Crystals
				1	2	3	P				
N98[1]	pale yellow-green; purple; medium to dark brown	strong - 90 moderate - 7 unzoned - 3	euhedral - 5 subrounded - 90 rounded - 5	20	30	45	5	34	25	0	0
H526	pale yellow-green; purple; brown; colorless	strong - 80 moderate - 10 unzoned - 10	euhedral - 15 subrounded - 80 rounded - 5	5	0	90	5	59	19	8	2
H67-66	purple; medium to dark brown; colorless	strong in cores; moderate to weak in shells	euhedral - 16 subhedral - 64 anhedral - 20	0	0	100	0	46	33	67	30
H67-91	purple; medium to dark brown; colorless	strong in cores; moderate to weak in shells	euhedral - 10 subhedral - 70 anhedral - 20	0	0	100	0	35	6	61	28

[1] All statistical data, other than for termination type, are given as percentage of total sample of 300 grains studied.

[2] Termination types 1, 2, and 3 refer to those pictured in Fig. 2; P=basal pinacoid form. Percentages are based on total number of grains possessing distinct terminal faces.

The common dark zircon crystals are typically purple or some shade of brown. Smaller grains are generally lighter shades than are the larger grains which may be so dark that they are essentially opaque. Zoning is a distinctive feature of many of the dark crystals (Fig. 3). Strong, hairline zoning dominates the crystals in samples N98 and H526 and is confined to the dark cores in zircons from the other two samples.

Some 85–95 percent of the dark zircons in samples N98 and H526 are either rounded (possessing no original terminal crystal faces, with or without prism faces in tact) or subrounded (retaining at least portions of the terminal faces). Roughly a quarter to a third of samples H67-66 and H67-91 consist of the clear zircons in addition to the darker variety present almost exclusively as cores within clear zircon overgrowths. The euhedrism-rounding data in Table 2 pertain to both types of grains. In both samples 80 percent of the overgrown zircons and the clear crystals are characterized by euhedral or subhedral form, the remaining 20 percent being anhedral. For the euhedral and subhedral crystals in all four samples, the more complex of the three common zircon termination types (Fig. 2) dominates each of the samples.

Although a detailed analysis of inclusions was not attempted, several kinds were distinguished. Some of the inclusions are typically irregular, opaque bodies (Fig. 3G and L). Other opaque or translucent

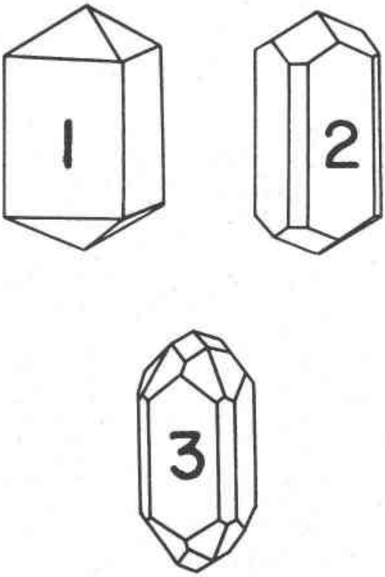

FIG. 2. Common types of zircon form combinations (from Berry and Mason, 1959).

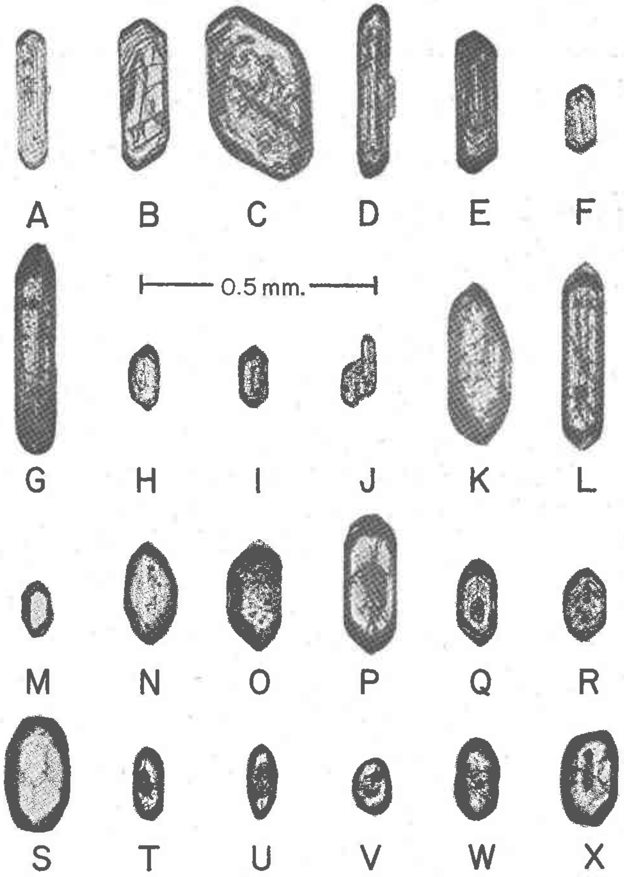

Fig. 3. Types of zircon crystals in the gneiss.
A–F, sample N98; A, E, and F, typical.
G–L, sample H526; G, I, K, and L, typical.
M–R, sample H67-66; all typical.
S–X, sample H67-91; S, T, U, V, and X, typical.
A, C, and F, strong hairline zoning.
H, K, Q, and R, moderate zoning.
P, weak zoning near core-shell contact.
E, H, P, Q, T, U, and V, crystals containing zircon cores.
E, multiple core (3 stages).
B and C, transparent inclusions.
C, G, L, N, and R, opaque inclusions.
X, oriented opaque uraninite/thorite (?) inclusions.
W, microfaults.
J, composite grain.
O, clear partial overgrowth at grain terminus.
D, outgrowth.
M, N, and S, typical clear, core-free crystals.
P, Q, T, U, and V, clear shells enclosing dark cores.

cubes and prisms (Fig. 3X) are probably thorite and uraninite. A third group are transparent, prismatic, and acicular crystals of apatite and rutile (Fig. 3B and C). A final group consists of irregular, transparent, colorless to light brown, fluid inclusions (Fig. 3N). Inclusions characterize at least a third of the zircons in each sample. They are largely confined to the dark zircons and the dark cores although some occur near core-overgrowth interfaces (and these are primarily fluid inclusions). In all samples zircons from the +200 size fraction contain the most inclusions.

As Table 2 shows, three of the zircon suites, but particularly H67-66 and H67-91, contain crystals which possess complete overgrowths. All the suites include crystals characterized by partial overgrowths and/or outgrowths. The overgrowth and outgrowth material appears to be the same clear zircon which also occurs as discrete, core-free crystals in three of the samples. Its character will be discussed in a later section.

Data pertaining to zircon crystal widths, lengths, and elongation (length/width) are presented in Figure 4. Means and standard deviations of the data are summarized in Table 3. The present discussion centers on the main crystals in each sample.

Of the dimensional parameters, the width of crystals varies far less than their length. Although mean widths of zircons in the four suites fall in the narrow range 0.05–0.07mm., widths vary more among zircons in samples N98 and H526 than in the other two samples. Width frequency curves for the former two samples are similar in shape as are those for the latter two samples, but the two pairs of curves differ as would be expected. Samples H67-66 and H67-91 contain a significant number of the clear, core-free zircons and an appreciable number of dark zircons possessing complete overgrowths (Table 2).

Among the four suites, zircon crystal lengths fall in the range 0.11–0.16mm. and show a distinct grouping relative to the two pairs of suites as discussed above. Zircons in samples N98 and H526 are typically longer than those in the other two samples. Statistics regarding crystal lengths in samples H67-66 and H67-91 are affected, in part, by the presence of the characteristically shorter, clear zircons in these samples. Their influence is shown in the bimodal plots of zircon lengths for samples H67-66 and H67-91 (Fig. 4B). Length-frequency plots for samples N98 and H526 show considerable scatter compared with those for the other two samples.

Similarly, elongation (length/width) of the crystals in samples N98 and H526 is more variable than that for crystals in the other two samples (Fig. 4C). Mean elongation ranges from slightly less than 3 to slightly below 2. Although values for mean elongation tend to be

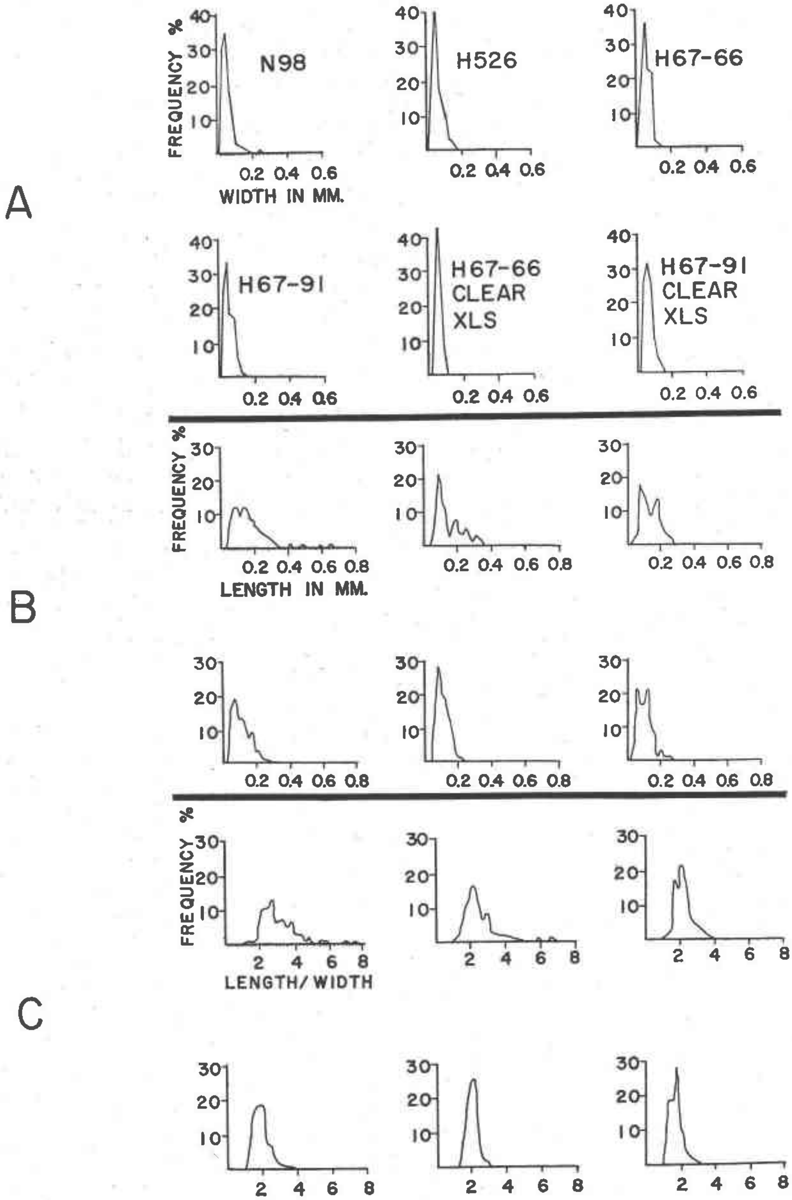

FIG. 4. Width (A), length (B), and elongation (C) frequency diagrams for main crystals and clear, core-free crystals.

Table 3. Dimensional data for the zircon suites.

Sample Number	Number of Crystals	Mean Length	Mean Width	Standard Deviation of Length	Standard Deviation of Width	Mean Elongation	Standard Deviation of Elongation	Correlation Coefficient
MAIN CRYSTALS								
N98	300	0.1579	0.0534	0.0818	0.0282	2.9273	0.8217	-0.4427
H526	300	0.1440	0.0654	0.0734	0.0280	2.3240	0.7211	0.0000
H67-66	300	0.1252	0.0613	0.0500	0.0218	2.1147	0.4319	+0.1990
H67-91	300	0.1134	0.0593	0.0543	0.0235	1.9267	0.4407	-0.1815
CORES								
N98	153	0.0971	0.0320	0.0506	0.0218	4.0033	2.3319	+0.0001
H526	150	0.0865	0.0425	0.0460	0.0257	2.7740	1.8843	+0.2795
H67-66	199	0.0778	0.0416	0.0405	0.0216	2.1613	1.2578	+0.0151
H67-91	218	0.0651	0.0318	0.0408	0.0228	2.7206	1.6282	+0.0080
CLEAR, CORE-FREE CRYSTALS								
H67-66	220	0.1005	0.0542	0.0337	0.0191	1.9162	0.3238	+0.0407
H67-91	225	0.0961	0.0593	0.0405	0.0235	1.6933	0.3721	-0.0028

grouped in like fashion to those for mean width and mean length, there is less closeness between zircons from samples N98 and H526. However zircons from both these samples are clearly more elongate than those from samples H67-66 and H67-91.

ZIRCON CORES

A significant number of grains within each zircon suite contain cores (Table 3). Although most of the cores are single entities, some are actually multiple cores which most commonly consist of two units.

Cores are characteristically dark-colored in shades of brown. Few purple cores were noted. Many are strongly zoned. Some contain inclusions. Most cores are subrounded (Fig. 3P) or subhedral (Fig. 3Q); euhedral and anhedral cores occur as well.

As Table 3 shows, the mean length and mean width of the cores are consistently shorter than those parameters for the main crystals (including core-free crystals). Mean elongation, which ranges from 4 to slightly above 2, is highly variable among the samples but generally greater than that of the main crystals. The standard deviation of elongation for the cores is much greater than that of the main crystals.

CLEAR ZIRCON CRYSTALS

As indicated earlier, the zircon suites (particularly H526, H67-66, and H67-91) contain light-colored, clear zircon in addition to the darker variety. The mode of occurrence of this lighter material is similar to that in granitic gneiss from the Beartooth Mountains (Poldervaart and Eckelmann, 1955; Eckelmann and Poldervaart, 1957; Harris, 1959; Nunes and Tilton, 1971) as well as that in cataclastically deformed granitic rocks of the Boulder Creek batholith in Colorado (Phair, Stern, and Gottfried, 1971). In samples H67-66 and H67-91 and, to a much lesser extent, in sample H526 the light-colored zircon is represented, in part, by discrete crystals. In the same samples it occurs as complete overgrowths on dark-colored zircons. Additionally, partial overgrowths and outgrowths of clear zircon occur in all the samples. The percentage distribution of the three modes of occurrence is given in Table 2.

The clear crystals are typically colorless or pale shades (Table 4). Some are slightly pleochroic and many have a shadowy appearance when viewed in transmitted light using one nicol prism. Some exhibit undulatory extinction. Almost all lack zoning and inclusions. Where present, inclusions are mainly fluid inclusions.

Most of the clear grains are multi-faceted (Fig. 3N and S), football-

Table 4. Characteristics of the clear, core-free zircon crystals from samples H67-66 and H67-91.

Color	Colorless; pale yellow-green; pale brown; gray.
Pleochroism	Pale yellow-green to slightly darker hue.
Shadowy Appearance	Common.
Undulatory Extinction	Exhibited by several crystals.
Birefringence	Very high.
Zoning	Commonly lacking; weak to moderate in several crystals.
Inclusions	Uncommon; small fluid inclusions main type; larger inclusions rare.
Habit	Anhedral to euhedral; majority subhedral; euhedrism percentages similar to those in Table 2. Type 3 terminations prominent.

shaped (Fig. 3N and U) crystals which are commonly subhedral. In sample H67-66 the majority (51 percent) occur in the −285 size fraction whereas in sample H67-91 the majority (48 percent) occur in the +200 fraction. Figure 4 illustrates the dimensional differences between the clear zircons and the total suites. Mean length, width, and elongation of the clear zircons may be compared with the same parameters for the total suites and the dark cores in Table 3. Mean elongation of the clear zircon crystals ranges from 1.7 to 1.9, the lowest for the three groups of zircons for which data are presented in the table. Standard deviation of the elongation for these crystals is also lowest among the three groups.

The distinction between the light-colored and the dark-colored zircons stands out in Figure 5 which is a plot of their reduced major axes. The figure is based on data for the light-colored zircons from the only two samples which contain significant numbers of them as well as data for the total zircon suites from each sample. When the RMA's for total samples H67-66 and H67-91 are replotted after data for the clear zircons are deleted, the following changes occur: 1) both axes are shifted downward closer to the axis for sample H526, 2) the slope of both axes is flattened slightly, 3) the lengths of the axes for both samples are increased slightly, and 4) the point for mean length versus mean width plots slightly lower for sample H67-91 while that for sample H67-66 is almost superimposed on the comparable point

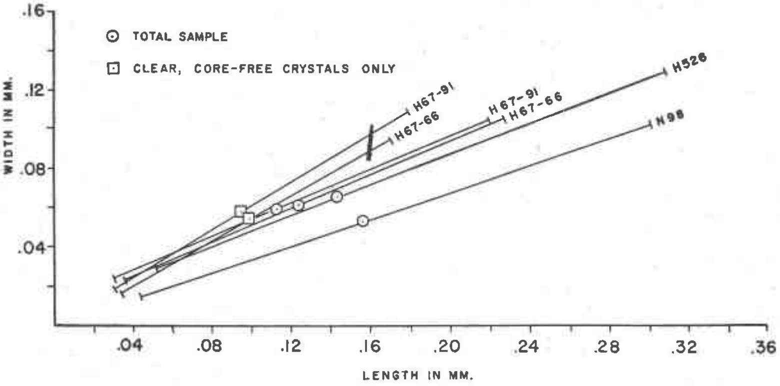

FIG. 5. Reduced major axes for main crystals and clear, core-free crystals.

for sample H526. Thus the RMA plots shown in Figure 5, or their modification as discussed above, indicate that the clear zircon crystals constitute a distinctly separate group. Their RMA's have a steeper slope and shorter length than those for the total samples (or the dark zircons only). Furthermore, their mean lengths and widths are closely grouped and they plot to the left of those for the total samples (or the dark zircons only).

CLEAR ZIRCON OUTGROWTHS AND OVERGROWTHS

As indicated earlier, clear zircon occurs also as partial or complete overgrowths or as outgrowths typically on darker zircons. However, the relationships are complex and, in a few cases, clear zircon appears to be overgrown on clear zircon cores. Additionally clear partial overgrowths and outgrowths have formed on clear complete overgrowths locally. The interrelationships account for the high frequency of the three modes of occurrence of clear zircon in samples H67-66 and H67-91, as shown in Table 2. They appear to represent stages in the growth continuum of the clear zircon.

Aside from the obvious color differences, overgrowths may be distinguished from cores by the common lack of inclusions and general weakness of zoning in the former. Highly birefringent overgrowths enclose less birefringent, metamict cores. Fractured cores are commonly enclosed in clear zircon lacking fractures, although the reverse is true locally (Fig. 3P). In some grains the long axis of the overgrowth is not parallel to that of the subhedral core on which it occurs (Fig. 3T). Finally, the boundary between the core and the overgrowth may be highly irregular, characterized by convex-inward surfaces locally or by dangling splinters of zoned core zircon which protrude into the overgrowth.

The volume of outgrowth and overgrowth zircon, in relation to that of the core grain, ranges widely in the four zircon suites. At the one extreme is the very small amount of clear zircon present as a terminal overgrowth (Fig. 3, O) or prism outgrowth on a dark grain. The other extreme is represented by thick complete overgrowths which tend to dwarf the core grain (Figs. 3P and T). Such shells, which are generally thickest at core terminations, are relatively common in samples H67-66 and H67-91. However, in general the typical relationship is that in which the overgrowth is volumetrically subsidiary to the core.

Origin of the Clear Zircon

From the foregoing discussion it is clear that the gneiss contains at least two distinct generations of zircon. Older dark-colored, strongly zoned, inclusion-bearing, subrounded zircons are mantled, partly or completely, by younger colorless, unzoned or weakly zoned, largely inclusion-free, subhedral zircon of high clarity, and locally interspersed with discrete core-free crystals of the same younger zircon. In most respects the clear crystals possess properties identical to those of the clear overgrowths and outgrowths, suggesting that both occurrences represent the crystallization of zircon during a time interval which post dates the time of formation of the darker zircons. In granitic gneiss from the Beartooth Mountains, dark zircon cores are at least 3140 m.y. old whereas light-colored zircon overgrowths are on the order of 2750 m.y. old (Nunes and Tilton, 1971). Preliminary radiometric age data (Banks, personal communication) for sample H67-91 suggest that a similar age relationship may exist between the two generations of zircon in the Bighorn Mountains gneiss.

As is true of the gneiss in the Beartooth Mountains and meta-igneous rocks of the Boulder Creek batholith (Phair, Stern, and Gottfried, 1971), the second-generation clear zircon in the Bighorns gneiss evolved during the metamorphic event represented by the gneiss. Some of the clear, core-free crystals, in particular, possess a shadowy appearance under one nicol and undulatory extinction. Some of them lack coincidence of their length with their *c*-axis. These features suggest growth under stress. Furthermore, the morphologic characteristics of the clear overgrowths are similar in many details to those in the Beartooth Mountains gneiss interpreted by Poldervaart and Eckelmann (1955) and Eckelmann and Poldervaart (1957) as growth phenomena occurring during regional metamorphism and metasomatism.

With respect to formation of clear zircon in the Bighorn Mountains, experimental data are pertinent. It is well documented that zircon is unstable under alkaline conditions. Maurice (1949), in a series of experiments, found that zircon crystallized readily and was stable in acid solutions, but that zircon and associated zircono-silicates had very limited stability in alkaline solutions. His experimental results are supported in principle by Blumenthal (1958). More recently Dietrich (1968) found that addition of small amounts of $Na_2Si_2O_5$ or NaF to zirconia-bearing mixtures suppressed the crystallization of zircon. Observations by Carroll (1953) and by Coleman and Erd (1961) also suggest that zircon is unstable under moderately alkaline conditions.

This information is of interest in the Bighorn Mountains because alkaline conditions existed locally during the metamorphism which produced the gneiss. The three samples which contain clear zircon, and particularly samples H67-66 and H67-91 in which it is abundant, are characterized by the presence of irregular, white aplitic quartz-feldspar bodies which analyze high in soda and silica relative to the gneiss. These bodies record the passage of aqueous, alkaline fluids through the rocks during their metamorphism. Evidence of their aqueous character is found in the prevalence of biotite and the common sericitization of plagioclase in the gneiss. Although zirconia may have been introduced by such fluids, there is no need to call upon a new supply from outside the system. As Phair, Stern, and Gottfried (1971) postulate, the clear zircon may represent the results of solution and redeposition of the dark, metamict zircon on or near the same crystals from which it was dissolved. The solution process would begin as the alkaline fluids passed through the rock. Deposition would occur ultimately as the chemical environment became less alkaline due to reaction of the fluids with the rock. In some cases the clear zircon was redeposited as an overgrowth on the dark, metamict zircon whereas, in others, it developed discrete core-free crystals.

The prevalent zoned, metamict zircons in the gneiss were readily amenable to solution in the presence of aqueous, alkaline fluids (Poldervaart, 1956; Marshall, 1968). Many core-overgrowth boundaries in these zircons exhibit the kind of irregularities one would expect if solution of the core exteriors had taken place. Interestingly, as pointed out earlier, the dark cores within overgrown grains (in samples H67-66 and H67-91) are typically smaller than the dark grains lacking such overgrowths (in sample N98 and H526). Many of the former may well have been reduced in size by the solution process described above. On the other hand, many such cores lack obvious evidence of

Table 5. Diagnostic characteristics of zircons from igneous and sedimentary rocks, and comparative data for zircons from Bighorns gneiss.

CRITERION	REFERENCE	PARENTAGE		N98	H526	H67-66	H67-91
		IGNEOUS	SEDIMENTARY	DARK CRYSTALS		DARK CORES	
Mean Elongation Ratio	Poldervaart (1955)	Commonly >2	Commonly <2	2.9	2.3	2.2	2.7
Rounding Index (%)	Eckelmann and Kulp (1956)	Low	High	95	85	76[1]	88[1]
Percent of Euhedral Crystals	Poldervaart (1955, 1956)	High	Very Low	5	15	24	12
Coincidence of Crystal Length with C-axis (%)	Murthy and Siddiquie (1964)	Common	Moderately Common	100	97	100	100

[1] Includes a small percentage of angular, broken grains.

solution, and we must conclude that the process(es) leading to the formation of the clear zircon operated erratically and selectively in these rocks.

PROVENANCE OF THE DARK ZIRCONS

The character of the dark zircon crystals and, to some extent, the dark cores within overgrown zircons are of interest in terms of providing data regarding the parentage of the gneiss. Assembled in Table 5 are four provenance criteria and comparative data from the four samples used in this study. Data for the dark cores in samples H67-66 and H67-91 are included primarily for the sake of completeness. Relative to provenance, we believe that data for these two samples must be interpreted with caution because the present morphology of the core zircons may have been determined substantially by the chemical solution process referred to above.

Although there are exceptions, it is generally statistically true that zircons which crystallized from magma have mean elongation ratios greater than 2 (Poldervaart, 1955). In contrast, those that have undergone subsequent transport or repeated reworking in the sedimentary cycle have mean elongation ratios less than 2 because of rounding and breakage (Poldervaart, 1955). However, there are exceptions to this generalization as well. For example, in a study of heavy detrital minerals in sands and gravels from many localities in New Zealand, Hutton (1950) found that zircons in one locality had elongation ratios of 3 and even 4. Rather than being distinctly below

2, elongation ratios of detrital zircons from the other New Zealand localities were approximately 2, or on the border line. With respect to the Bighorn samples, dark zircons from all the suites have mean elongation ratios either slightly or distinctly above 2 (Table 5). Although the dark cores in samples H67-66 and H67-91 and a few of the dark zircons in sample H526 were undoubtedly altered, we see no reason why solution activity should have changed their elongation ratio significantly. Thus, on the basis of this single criterion, the gneiss might be interpreted as being of igneous parentage.

Precisely the opposite must be concluded relative to the rounding index which is expressed as the percentage of crystals showing any sign of rounding (Eckelmann and Kulp, 1956). Samples N98 and H526 have extremely high indices (Table 5) typical of detrital zircons. Dark cores in the other two samples also have very high rounding indices. However, much of the rounding of the cores may well be the result of solution related to generation of the clear zircon.

Antipathetically related to the rounding index is the percentage of angular, euhedral crystals in each suite. Although there are some major variations here, as Poldervaart (1955, 1956) points out, suites of igneous zircons are characteristically dominated by euhedral crystals whereas detrital zircon suites usually contain relatively low percentages of them. The low percentages of sharply-bounded, euhedral zircons in these samples suggest clearly a sedimentary parentage for the gneiss. Again we must add that the relatively small number of euhedral core zircons in samples H67-66 and H67-91 may be the result of solution rather than detrital transport.

With respect to the fourth criterion, it is reasonable that, during sedimentary transport, some elongate zircons will tend to break at angles other than 90° to their long axis, leading to the formation of rounded segments whose long axis does not coincide with the *c*-axis (extinction position) of the original crystal. The number of grains showing this phenomenon would depend upon transport longevity and the degree of elongation possessed by the original crystals. Murthy and Siddiquie (1964) found that well-rounded zircons from some Indian metasedimentary rocks possess angles between their long axis and *c*-axis in the range 13–21°. Igneous zircons which have not been transported in the sedimentary cycle should exhibit a coincidence of crystal length and *c*-axis. This is true for zircons in all of the suites except H526 which contains a small percentage lacking such coincidence (angle between crystal length and *c*-axis is 4–14°).

Thus when data for the dark zircons in the four suites are compared against the criteria listed in Table 5, it appears that a totally unequivocal interpretation of parentage for the gneiss cannot be made. Yet relative to the important criteria, rounding index and percent of euhedral crystals, the samples tentatively suggest derivation of the Bighorn gneiss from a sedimentary parent, presumably graywacke which the gneiss closely approximates chemically (Heimlich, in press). Graywacke is a particularly appealing parent rock, considering the commonly subrounded rather than rounded or well-rounded character of the zircons, their mean elongation ratios above 2, and their common coincidence of crystal length and *c*-axis. These characteristics would be expected in a sediment which had undergone minimal transport. The idea of sedimentary parentage is further supported by the extent of morphologic variability among the dark zircons in the samples.

SUMMARY

This study presents, for the first time, a quantitative description of zircons from the Precambrian gneiss terrain which underlies the southern half of the Bighorn Mountains. The results of the study indicate that two generations of zircon occur in these rocks.

The older generation consists of dark zircon crystals and dark cores within overgrown grains. These dark zircons are premetamorphic in origin and they relate to the source rocks from which the gneiss was derived. Their morphologic characteristics, particularly for zircons in two of the samples which exhibit little or no later alteration, tentatively suggest a sedimentary parent rock for the gneiss.

The younger generation of zircon consists of colorless, clear crystals and clear overgrowths on dark zircon cores. The character of this clear zircon suggests formation by solution of the older zircon and redeposition during the episode of metamorphism represented by the gneiss. The solution process was facilitated presumably by the presence of aqueous, alkaline fluids which circulated through the rock during metamorphism.

We must conclude that the question regarding gneiss parentage is not fully resolved on the basis of data accumulated for the four samples used in this study. A larger number of samples containing zircons lacking outgrowths, overgrowths, and other signs of later alteration must be examined. Such a study is presently underway.

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