[AMERICAN JOURNAL OF SCIENCE, VOL. 275, JUNE, 1975, P. 683-691]

AGE OF THE GRANULITE-FACIES METAMORPHISM OF THE WILMINGTON COMPLEX, DELAWARE-PENNSYLVANIA PIEDMONT

B. GRAUERT* and M. E. WAGNER**

ABSTRACT. U–Pb isotopic analyses on zircon fractions from the granulite-facies "banded gneiss" (Ward, 1959) of the Wilmington Complex yield a well-defined discordia on a concordia diagram. The data points plot very close to the lower concordia intercept of the discordia at 441 m.y., with the smallest size fraction being concordant within analytical error. The high upper intercept age of about 1500 m.y. points to presence of an inherited Precambrian zircon component.

We interpret the age of about 440 m.y. as indicating the time of the granulite-facies metamorphism. The estimated error due to possible later disturbances of the U–Pb systems is less than plus 10 percent (440 + 40 m.y.). From all available geochronologic data, the result is the most direct evidence for the existence of a regional *Taconic metamorphism* in the Piedmont of Pennsylvania, Delaware, and Maryland.

Cathode luminescence patterns of polished zircon mounts reveal a remarkable internal heterogeneity of the grains and suggest a complex history for the Wilmington Complex: (1) Euhedral, partly resorbed cores showing internal zoning represent a pre-granulite-facies period of zircon growth and may be correlated with a volcanic-magmatic or anatectic stage of the rock. (2) The final stage is characterized by the growth of typically rounded zircon grains and is correlated with the granulite-facies metamorphism.

INTRODUCTION

In recent years, U–Pb isotopic studies on zircon populations of granulites (Köppel, 1971, 1974; Grauert, Crawford, and Wagner, 1973) have shown that zircon is suited to date granulite-facies metamorphisms: the U–Pb "clocks" of inherited older zircon components appear to be better reset under granulite-facies conditions than during amphibolite-facies metamorphism.

In the Wilmington crystalline complex, which lies in the northern Piedmont and extends from southeastern Pennsylvania into northern Delaware, granulite-facies metamorphism was supposed to be the result of the "Appalachian Revolution" (Ward, 1959). Ward's supposition was based essentially on structural considerations and tentative lithostratigraphic correlations. A geochronologic test seemed of twofold interest: (1) because the northern end of the Wilmington Complex is only about 8 km distant from another granulite-facies area in the "Baltimore Gneiss" of the West Chester Prong (Wagner, ms; Wagner and Crawford, 1975), where extrapolated zircon ages point to a metamorphic period between 980 and about 1100 m.y. (Tilton and others, 1960; Grauert, Crawford, and Wagner, 1973), and (2) because up to now no geochronologic data have been published that could directly prove the existence and importance of Taconic metamorphism in the Maryland, Delaware, and Pennsylvania Piedmont.

GEOLOGICAL SETTING

According to Ward (1959), the crystalline Wilmington Complex consists of "banded gneiss", granite (Arden granite), amphibolite, and gab-

* Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D.C. 20015. Present address: Institut für Kristallographie und Petrographie, Eidgenössische Technische Hochschule, Sonneggstr. 5, CH-8006 Zürich, Switzerland
** Department of Geology, University of Pennsylvania, Philadelphia, Pa. 19174

bro, the banded gneiss being the major rock type and comprising more than half the presently exposed rocks (Ward, 1959, pl. 1). The banded gneiss, from which the analyzed zircon population was separated, is a dark-colored, massive rock composed of alternating mafic and felsic bands. Their average modal compositions are given in table 1. Ward (1959, p. 1453) discusses four possibilities for the origin of the banded gneiss: "(1) a (hypabyssal) stratiform gabbroic body, (2) a series of sedimentary rocks, (3) a series of basaltic lavas or tuffs, and (4) a plutonic gabbro body." Sedimentary origin, however, he considers wholly inadequate and is inclined to suggest a volcanic origin because this would simplify some regional relationships. The felsic portion of the gneiss is interpreted as having formed by metasomatic replacement of mafic rock, but Ward states that "during this process the felsic material, in many places, became sufficiently mobile to appear truly igneous."

Southwick (1969, p. 51) points out that greenschist-facies and amphibolite-facies metavolcanic rocks in Harford County (James Run gneiss of Southwick and Fisher, 1967) and Cecil County, northeastern Maryland, that are more or less on strike with the Wilmington Complex, have closely comparable bedding characteristics and chemical compositions. He considers it likely that all these rocks have more or less the same age and represent a variably metamorphosed marine volcanic sequence. Also Higgins (1972, p. 1020) regards the layered rocks of the Wilmington Complex as correlative with the metavolcanics of his James Run Formation in Cecil County, which he defines as including all the closely associated, approximately contemporaneous metavolcanics, metavolcanoclastics, metamorphosed epiclastic rocks, and small plutons and masses of hypabyssal intrusives that crop out near the Fall Line in the eastern and northeastern Maryland Piedmont (Higgins, 1972, p. 1001).

Tilton, Doe, and Hopson (1970) analyzed two zircon samples from the James Run gneiss. Assuming loss of lead by continuous diffusion as the only cause for the discordant U–Pb data, they obtained an age of 550 m.y. Also Higgins and others (1971) concluded from their zircon data that the James Run Formation is in part Cambrian; however, more recent analyses have led these authors to consider a Cambrian age too high, be-

TABLE 1

Average modal composition of the "banded gneiss" and of sample WIL-453

	Mafic bands*	Felsic bands*	WIL-453
Plagioclase	45.5	47.3	43.1
Quartz	5.6	36.6	44.6
Hornblende	25.2	0.8	0.8
Hypersthene	15.1	8	8.0
Augite	5.4	0.1	0.2
Biotite	1	5.7	1.0
Magnetite	2	2	2.3
Total	99.8	100.5	100.0

* After Ward (1959, table 6)

cause the data seem to indicate the presence of inherited lead in old seed crystals (Higgins, written commun. 1974).

On the west, north, and northeast the Wilmington Complex is bordered by rocks of the Glenarm Series (Wissahickon Formation), and the whole southeastern edge is covered by Coastal Plain sediments. The metamorphic zones are disposed roughly concentrically about the granulitic Arden granite (Ward, 1959), but the metamorphic grade decreases markedly to the southwest. Some of this decrease, at least, is due to retrogressive metamorphism (Higgins, written commun. 1974). In the Wissahickon Formation immediately north and northeast of the complex, the metamorphic grade increases toward the Wilmington Complex. The adjacent schists show almandine-sillimanite subfacies of the amphibolite facies (Wyckoff, 1952).

ZIRCON

The zircon sample was separated from a very fresh, blasted block of felsic material of the banded gneiss, roughly from the center of the region of highest metamorphic grade. The exact location is a road cut of a driveway at Talley Road (Wilmington North quadrangle, Delaware-Pennsylvania, $^{44}02^{750}$ N/$^{4}54^{250}$ E, 1000-m grid). The modal composition of the medium-grained, massive rock is indicated in table 1.

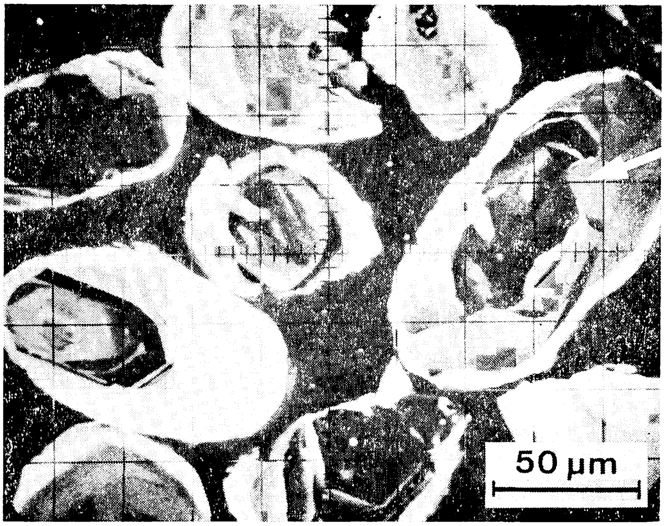
The zircon yield was relatively low: about 1 g from 35 kg of rock. Similar low yield has also been reported by Tilton, Doe, and Hopson (1970, p. 432) for the James Run gneiss, and the same has been found by Higgins (written commun., 1974) for other metavolcanics of the James Run Formation.

The size of the grains is generally less than 80 microns. The clear, brilliant zircons are rounded, oval, or irregularly shaped; crystal faces, if present, are poorly developed. About 1 percent of the coarser grains display short simple prisms. The population appears fairly homogeneous with respect to color, which is a very pale pink, and shows morphologic similarities to zircon described from other granulite terranes, such as the Baltimore Gneiss of the West Chester Prong (Grauert, Crawford, and Wagner, 1973), the Lewisian of the Outer Hebrides (Pidgeon and Aftalion, 1972), the Ivrea Zone of the Alps (Köppel, 1974), and the Kola peninsula (Bibikova and others, 1973).

A study of the cathode luminescence patterns on polished grain mounts (pl. 1) revealed a remarkable internal heterogeneity with respect to the distribution of heavy elements (uranium, thorium, lead). These inhomogeneities are not apparent under the microscope by means of either transmitted or reflected light. The patterns may be interpreted as reflecting a multistage zircon growth; they are indirect indicators for a presumably complex history of the rocks:

(1) Fairly large cores in many grains display a repeated zoning and point to a magmatic or anatectic stage of the rock during which euhedral crystal growth was possible. Consequently, the majority of these cores appear to represent an earlier stage of zircon formation in the same rock rather than an inherited detrital component; however, from the isotopic

PLATE 1



Photograph showing the cathode luminescence of polished zircon grains of sample WIL-453-4. The patterns reflect the relative distribution of heavy elements such as uranium, thorium, and lead (light: low concentration of heavy elements; dark: high concentration).

data below, it is most likely that the euhedral cores, on their part, contain some optically unrecognizable relicts of much older zircon. (2) A second stage is characterized by corrosion phenomena: many of the cores show embayed shapes (see arrow, pl. 1) with pits that cut across the euhedral zoning. (3) During a "final" stage — possibly intermitted by periods of corrosion — the typically rounded zircon grains of granulite-facies rocks were formed.

As similar cathode luminescence patterns have also been observed on zircon of other granulite areas (Grauert, unpub. data, 1974), one may reasonably correlate stage three (and possibly stage two) with the granulite-facies metamorphism. Stage one, however, may belong to the volcanic-magmatic phase or to an anatectic phase in the course of the progressive metamorphism.

ANALYTICAL PROCEDURE

Zircon separation and mass spectrometric techniques are essentially the same as previously described (Grauert, Hänny, and Soptrajanova, 1973). The dissolution of zircon and the extraction of uranium and lead followed the method developed by Krogh (1973). Aliquots of all zircon fractions were spiked with the same combined ^{208}Pb-^{235}U tracer. Common-lead contaminations during the analyses were on the order of 0.5 to 2.0 ng. The analytical results are listed in table 2.

DISCUSSION OF THE RESULTS

The analytical data are plotted on a concordia diagram (fig. 1). The data points of the four size fractions fall remarkably well on a straight line with a lower intersection with the concordia curve at 441 m.y. The ages of the smallest size fraction may be considered concordant within analytical error. Patterns like that shown on figure 1 are characteristic for zircon populations that contain significantly older, inherited zircon components. They have been found for paragneisses (Grauert and Arnold, 1968; Pidgeon, Köppel, and Grünenfelder, 1970) as well as orthogneisses (Grauert and Arnold, 1968; Gulson and Krogh, 1973; Grauert and Hofmann, 1973). Unfortunately, they do not allow a decision as to whether the rocks are of igneous or sedimentary origin. Grauert and Hofmann (1973) and Grauert, Hänny, and Soptrajanova (1974) found examples where the position of data points close to the lower concordia intercept of the best-fit lines is largely due to mixing of young, newly grown zircon with a much older inherited component. We therefore conclude, in accordance with the cathode luminescence pattern, that the data in figure 1 are primarily the result of zircon new-growth and overgrowth (in addition to possible lead loss) rather then a mere resetting of U–Pb "clocks" of an old Precambrian zircon population. As the morphology of the zircon grains is similar to the typical morphology of zircon

TABLE 2
U–Pb analytical data

Sample no.	Sieve fraction in μm	Concentrations: Uranium ppm	Concentrations: Radiogenic lead ppm	Atomic ratios observed*: $^{206}Pb/^{204}Pb$	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{206}Pb$
WIL-453-1	<30	372	28.2	5120	0.05868	0.19205
WIL-453-2	30-40	347	26.4	4373	0.05948	0.18739
WIL-453-3	40-65	305	23.9	1826	0.06534	0.19447
WIL-453-4	>65	273	21.4	1586	0.06733	0.18947

Sample no.	Atomic ratios calculated**: $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	Apparent ages in m.y.†: $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
WIL-453-1	0.07102	0.5469	0.05585	442.3	443.0	446.3
WIL-453-2	0.07144	0.5533	0.05617	444.8	447.1	459.5
WIL-453-3	0.07298	0.5767	0.05731	454.0	462.3	504.0
WIL-453-4	0.07435	0.5968	0.05821	462.3	475.2	538.0

* The internal precision of the ratio measurements expressed in two standard deviations of the mean (= two standard errors) is:
$^{207}Pb/^{206}Pb$: better than ± 0.03%
$^{208}Pb/^{206}Pb$: better than ± 0.03%
$^{206}Pb/^{204}Pb$: better than ± 2%

** Isotopic composition of common lead used for the corrections:
$^{206}Pb/^{204}Pb$: 18.0, $^{207}Pb/^{204}Pb$: 15.5, $^{208}Pb/^{204}Pb$: 37.0

Analytical uncertainties assigned:
$^{206}Pb/^{238}U$: ± 0.5%, $^{207}Pb/^{235}U$: ± 1.0%, $^{207}Pb/^{206}Pb$: ± 0.5%

† Constants used for the age calculations:
$\lambda^{238}U = 1.5513 \times 10^{-10}\ y^{-1}$ (Jaffey and others, 1971)
$\lambda^{235}U = 9.8485 \times 10^{-10}\ y^{-1}$ (Jaffey and others, 1971)
$^{238}U/^{235}U = 137.88$ (Shields, personal commun.)

from other granulite areas, it seems reasonable to interpret the lower intersection age of the discordia as indicating the time of the granulite-facies metamorphism. The age of 441 m.y. agrees well with the age of 430 to 440 m.y. suggested for the Ordovician-Silurian boundary (Holmes symposium, 1964). Thus, the granulite-facies metamorphism is likely to be ascribed to the Taconic orogeny.

There remains, however, the question of whether secondary, post-Taconic "events" have disturbed and influenced the U–Pb systems of the zircons in a way such that on the concordia diagram the original discordant pattern was rotated and shifted toward younger ages. There is ample evidence from geochronologic data (Wetherill and others, 1966; Grauert, 1973) and structural analyses (Higgins, 1973; Amenta, 1974) for the existence of an Acadian metamorphism for the Maryland and Pennsylvania Piedmont about 330 to 350 m.y. ago. Also recent weathering of the rocks may have had some influence (Stern, Goldich, and Newell, 1966); however, because of the freshness of the rock and the low uranium concentration of the zircon (which means low radiation damage), the existence of a significant lead loss by weathering can be excluded. We consider also negligible lead loss by continuous diffusion (Tilton, 1960; Wasserburg, 1963), based on observations on zircon from the Baltimore

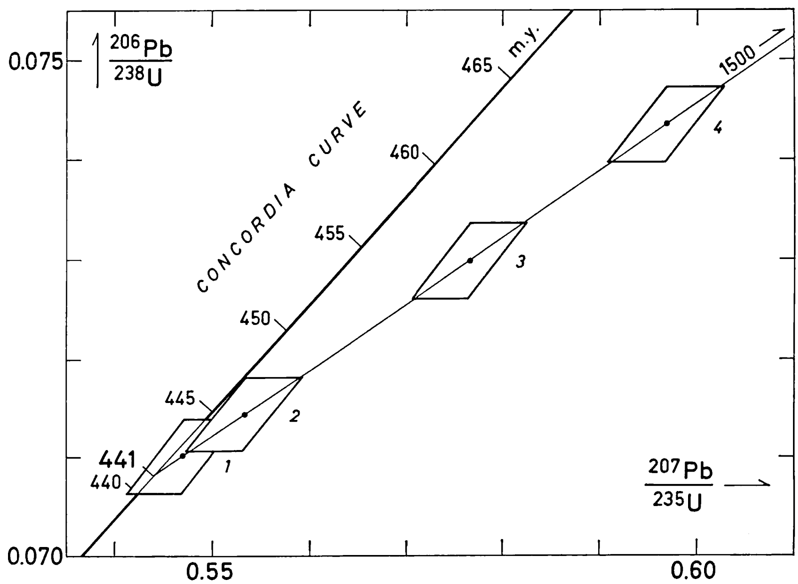


Fig. 1. Concordia diagram showing the data points of four size fractions of zircon sample WIL-453. The parallelograms represent the analytical uncertainty including the uncertainty of the common-lead correction. The numbers in italics refer to the data in table 2.

Gneiss (Grauert, 1974) and the low diffusion coefficients of lead in zircon as experimentally determined by Shestakov (1972).

From a comparison with the isotopic data for similar clear, uranium-poor zircon of granulite-facies rocks from the Baltimore Gneiss of the West Chester Prong (Grauert, Crawford, and Wagner, 1973), we can make an estimate of the maximal effect of a possible episodic disturbance of the U–Pb systems during an Acadian event. As similar types of zircon from the West Chester Prong are about 10 to 30 percent discordant with respect to a chord between 450 and 1050 m.y. on a concordia diagram, we suppose that the maximal Acadian influence on the zircon of the Wilmington Complex is on the same order of magnitude. This means that the granulite-facies metamorphism is not older than 480 m.y.

From all available geochronologic data, the present result is the most direct evidence for the existence of a Taconic metamorphism in the Piedmont of Pennsylvania, Delaware, and Maryland. The euhedral cores in the zircon grains as well as preliminary results of Rb–Sr whole-rock analyses of the Arden granite by Foland (personal commun., 1974), which yield an isochron of about 505 m.y., point to a complex history for the Wilmington Complex. We regard the granulite-facies metamorphism as a final stage of regional dehydration, presumably preceded by a more or less extended metamorphic period that may have led locally to the formation of anatectic melts.

As to the upper intercept age of about 1500 m.y., an interpretation should be postponed until detailed zircon data on less metamorphic rocks are available. Because of the extreme extrapolation, the error of this age is rather large. In addition, it is possible that the inherited zircon is a composite of about 1 b.y. old and much older components.

ACKNOWLEDGMENTS

The isotopic analyses were performed at the Department of Terrestrial Magnetism, Washington, D.C., and the cathode luminescence study was made at the Institute for Crystallography and Petrography, Zürich. B. G. acknowledges a Carnegie Institution fellowship. We wish to thank Mr. K. D. Burrhus and Dr. S. R. Hart, who took care for the high performance of the mass spectrometer, and Dr. Maria L. Crawford, who kindly made some helpful comments on an earlier version of the manuscript. Drs. M. W. Higgins and B. O'Connor reviewed the manuscript; their comments and valuable suggestions are gratefully acknowledged.

REFERENCES

Amenta, R. V., 1974, Multiple deformation and metamorphism from structural analysis in the eastern Pennsylvania Piedmont: Geol. Soc. America Bull., v. 85, p. 1647-1660.

Bibikova, E. V., Tugarinov, A. I., Gracheva, T. V., and Konstantinova, M. V., 1973, The age of the granulites of the Kola peninsula: Geokhimiya, p. 664-675.

Grauert, Borwin, 1973, U–Pb isotopic studies of zircons from the Gunpowder granite, Baltimore County, Maryland: Carnegie Inst. Washington Year Book, v. 72, p. 288-290.

———— 1974, U–Pb systematics in heterogeneous zircon populations from the Precambrian basement of the Maryland Piedmont: Earth Planetary Sci. Letters, v. 23, p. 238-248.

Grauert, Borwin, and Arnold, A., 1968, Deutung diskordanter Zirkonalter der Silvrettadecke und des Gotthardmassivs (Schweizer Alpen): Contr. Mineralogy Petrology, v. 20, p. 34-56.

Grauert, Borwin, Crawford, M. L., and Wagner, M. E., 1973, U–Pb isotopic analyses of zircons from granulite and amphibolite-facies rocks of the West Chester Prong and the Avondale Anticline, southeastern Pennsylvania: Carnegie Inst. Washington Year Book, v. 72, p. 290-293.

Grauert, Borwin, Hänny, R., and Soptrajanova, G., 1973, Age and origin of detrital zircons from the pre-Permian basements of the Bohemian Massif and the Alps: Contr. Mineralogy Petrology, v. 40, p. 105-130.

——— 1974, Geochronology of a polymetamorphic and anatectic gneiss region: the Moldanubicum of the area LamDeggendorf, eastern Bavaria, Germany: Contr. Mineralogy Petrology, v. 45, p. 37-63.

Grauert, Borwin, and Hofmann, Albrecht, 1973, Old radiogenic lead components in zircons from the Idaho Batholith and its metasedimentary aureole: Carnegie Inst. Washington Year Book, v. 72, p. 297-299.

Gulson, B. L., and Krogh, T. E., 1973, Old lead components in the young Bergell massif, south-east Swiss Alps: Contr. Mineralogy Petrology, v. 40, p. 239-252.

Higgins, M. W., 1972, Age, origin, regional relations, and nonmenclature of the Glenarm Series, central Appalachian Piedmont: a reinterpretation: Geol. Soc. America Bull., v. 83, p. 989-1026.

——— 1973, Superimposition of folding in the northeastern Maryland Piedmont and its bearing on the history and tectonics of the central Appalachians: Am. Jour. Sci., v. 273-A (Cooper v.), p. 150-195.

Higgins, M. W., Sinha, A. K., Tilton, G. R., and Kirk, W. S., 1971, Correlation of metavolcanic rocks in the Maryland, Delaware, and Virginia Piedmont [abs.]: Geol. Soc. America Abs. with Programs, v. 3, no. 5, p. 320.

Jaffey, A. H., Flynn, K. F., Glendenin, L. E., Bentley, W. C., and Essling, A. M., 1971, Precision measurement of half-lives and specific activities of ^{235}U and ^{238}U: Phys. Rev. C, v. 4, no. 5, p. 1889-1906.

Köppel, V., 1971, U–Pb mineral ages from the crust-mantle transition and the Ivrea and Ceneri Zones, Southern Alps, Italy [abs.]: Annales Soc. Géol. Belgique, v. 94, p. 118.

——— 1974, Isotopic U–Pb ages of monazites and zircons from the crust-mantle transition and adjacent units of the Ivrea and Ceneri Zones (Southern Alps, Italy): Contr. Mineralogy Petrology, v. 43, p. 55-70.

Krogh, T. E., 1973, A low-contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determinations: Geochim. et Cosmochim. Acta, v. 37, p. 485-494.

Pidgeon, R. T., and Aftalion, M., 1972, The geochronological significance of discordant U–Pb ages of oval-shaped zircons from a Lewisian gneiss from Harris, Outer Hebrides: Earth Planetary Sci. Letters, v. 17, p. 269-274.

Pidgeon, R. T., Köppel, V., and Grünenfelder, M., 1970, U–Pb isotopic relationships in zircon suites from a para- and ortho-gneiss from the Ceneri Zone, southern Switzerland: Contr. Mineralogy Petrology, v. 23, p. 1-11.

Shestakov, G. I., 1972, Diffusion of lead in monazite, zircon, sphene, and apatite: Geokhimiya, p. 1197-1204.

Southwick, D. L., 1969, Crystalline rocks of Harford County, *in* The Geology of Harford County, Maryland: Baltimore, Maryland Geol. Survey, p. 1-76.

Southwick, D. L., and Fisher, G. W., 1967, Revision of stratigraphic nomenclature of the Glenarm Series in Maryland: Baltimore, Maryland Geol. Survey Rept. Inv., no. 6, 19 p.

Stern, T. W., Goldich, S. S., and Newell, M. F., 1966, Effects of weathering on the U–Pb ages of zircon from the Morton gneiss, Minnesota: Earth Planetary Sci. Letters, v. 1, p. 369-371.

Tilton, G. R., 1960, Volume diffusion as a mechanism for discordant lead ages: Jour. Geophys. Research, v. 65, p. 2933-2945.

Tilton, G. R., Doe, B. R., and Hopson, C. A., 1970, Zircon age measurements in the Maryland Piedmont, with special reference to Baltimore Gneiss problems, *in* Fisher, G. W., and others, eds., Studies of Appalachian geology—central and southern: New York, Interscience, p. 429-434.

Tilton, G. R., Wetherill, G. W., Davis, G. L., and Bass, M. N., 1960, 1000-million-year-old minerals from the eastern United States and Canada: Jour. Geophys. Research, v. 65, p. 4173-4179.

Wagner, M. E., ms, 1972, Metamorphism of the Precambrian Baltimore Gneiss in southeastern Pennsylvania: Ph.D. thesis, Bryn Mawr College, Bryn Mawr, Pa.

Wagner, M. E., and Crawford, M. L., 1975, Polymetamorphism of the Precambrian Baltimore Gneiss in southeastern Pennsylvania: Am. Jour. Sci., v. 275, p. 653-682.

Ward, R. F., 1959, Petrology and metamorphism of the Wilmington Complex, Delaware, Pennsylvania, and Maryland: Geol. Soc. America Bull., v. 70, p. 1425-1458.

Wasserburg, G. J., 1963, Diffusion processes in lead-uranium systems: Jour. Geophys. Research, v. 68, p. 4823-4846.

Wetherill, G. W., Davis, G. L., and Lee-Hu, C., 1968, Rb-Sr measurements on whole rocks and separated minerals from the Baltimore Gneiss, Maryland: Geol. Soc. America Bull., v. 79, p. 757-762.

Wetherill, G. W., Tilton, G. R., Davis, G. L., Hart, S. R., and Hopson, C. A., 1966, Age measurements in the Maryland Piedmont: Jour. Geophys. Research, v. 71, p. 2139-2155.

Wyckoff, D., 1952, Metamorphic facies in the Wissahickon schist near Philadelphia, Pennsylvania: Geol. Soc. America Bull., v. 63, p. 25-58.