MINERAL ISOGRADS IN SOUTHEASTERN PENNSYLVANIA

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"It is much to be desired that the zonal method of mapping, initiated by Barrow, should be confirmed and further elaborated by its application in other countries." Alfred Harker[1]

Abstract

The formations that have been grouped as the "Glenarm Series" consist of phyllites, schists and gneisses with subordinate amounts of quartzite and marble. Within this series, a general, though by no means regular, increase in intensity of metamorphism toward the east and south has long been recognized; several authors have published small-scale maps, some based on texture and some on mineral distribution but without definite mineral isograds.

The main feature of the present paper is a map (in two sections) of the area covered by the Philadelphia and Coatesville-West Chester Folios showing reported and observed occurrences of index minerals. In the argillaceous rocks the zonal arrangement: chlorite, biotite, garnet, staurolite, cyanite, sillimanite is in accord with observations in metamorphic areas in other parts of the world. The zones are somewhat crowded and show local overlapping. In the associated carbonate rocks, tremolite appears in the middle-grade zone and sparse pyroxene in the highest grade attained. Wollastonite and garnet have not been reported in the carbonate rocks.

Introduction

The distribution of metamorphic minerals in the Wissahickon and associated formations in the Piedmont region of southeastern Pennsylvania shows a zonal arrangement indicating increasing grade of metamorphism from northwest to southeast. Despite some overlapping of zones and a few local anomalies, the general arrangement of index minerals is the same as that observed in many other tracts of aluminous schists and gneisses.[2] The sequence with increasing grade of metamorphism is: chlorite, biotite, garnet, staurolite, cyanite, sillimanite.

The main purpose of this paper is to present maps showing the distribution of index minerals. Although the metamorphic problems of the region need much more study in the field as well as in the laboratory, the data now available may help to round out the broader picture of

[1] Harker, Alfred, Metamorphism. London, Methuen and Co. **(1932),** p. 187.

[2] Barth, T. F. W., Structural and petrologic studies in Duchess County, New York, Pt. II: *G. S. A. Bulletin,* **47,** 775–850 (1936).

Billings, M. P., Regional metamorphism of the Littleton-Moosilauke area, New Hampshire: *G. S. A. Bulletin,* **48,** 463–566 (1937).

References to earlier studies, mainly in Scotland and Scandinavia, will be found in Turner, Francis, Mineralogical and structural evolution of the metamorphic rocks: *G. S. A. Memoir* **30,** 35, 36 (1948); also Harker, Alfred, Metamorphism, London: Methuen and Co. Ltd. (1932), p. 188.

metamorphism in the Piedmont region and at the same time point to localities where further investigation is needed.

Location

The present study embraces an area of about 700 square miles in the extreme southeastern corner of Pennsylvania and includes most of the area covered by the U.S. Geological Survey's Coatesville-West Chester and Philadelphia folios (Fig. 1). It includes the southern half of Chester County, all of Delaware County and parts of Philadelphia and Montgomery Counties.

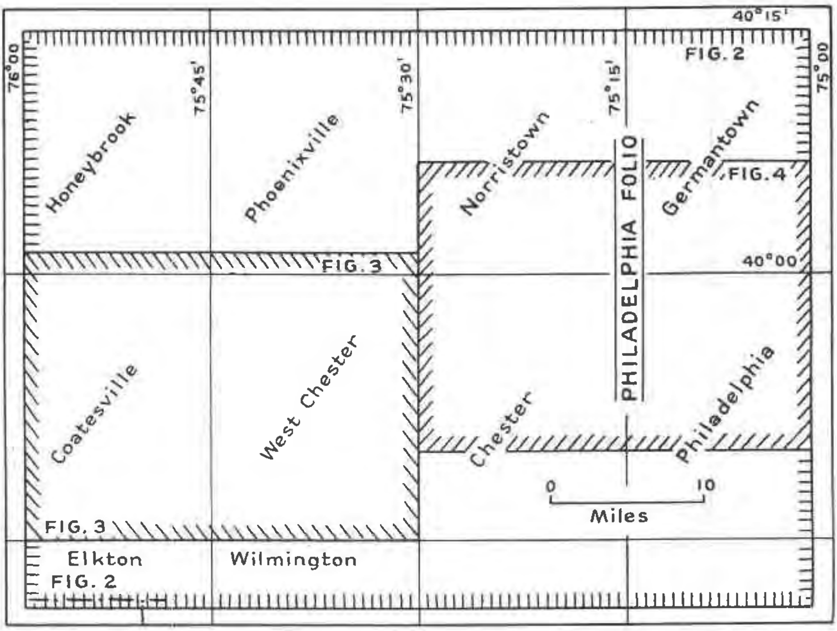

Fig. 1. Index Map to U.S.G.S. Quadrangles and to Figures 2, 3 and 4.

General Geology

Regional Setting

A glance at the geologic map of North America will show that the trend of Appalachian structure, though following a general northeasterly course from Georgia to New England, swings locally to a more easterly direction through Pennsylvania. Anyone making a traverse southerly across this trend would cross the Paleozoic rocks of the Appalachian province and enter a belt of formations of which some are unquestionably pre-Cambrian and others are of controversial age. The most southerly occurrence of undisputed Paleozoic rocks is a strip of Cambrian and Ordovician limestones[3] that finds topographic expression as a nearly straight valley forty miles long, the Chester Valley. (Fig. 2).

Age of Formations

With regard to the sequence and structure of the formations south of the valley, it is difficult to present a brief and simple statement, owing to differences of opinion. The oldest formation, the Baltimore gneiss, is unquestionably pre-Cambrian but the age of the overlying Glenarm series is controversial. Knopf and Jonas[4] regarded the Glenarm series as pre-Cambrian and in order to account for the fact that the Glenarm rocks apparently overlie the Ordovician limestones of the Chester Valley, postulated a fault-contact—the Martic overthrust. Shortly after this interpretation was proposed, the writer[5] questioned the existence of the fault and advocated a Paleozoic age for the Glenarm series. Subsequently, Miller[6] and Mackin[7] expressed similar views and still more recently the Martic Overthrust problem has been thoroughly discussed by Cloos and Hietanen[8] without reaching a definite conclusion. Finally, Stose and Stose[9] have suggested that part of the Glenarm series—the Setters and Cockeysville formations—may be Cambrian and the crystalline schists may be in part Cambrian to Ordovician, thus recalling the earliest views of Bliss and Jonas.[10] The whole problem has been reviewed in concise fashion by Swartz[11] who concludes that "there is much evidence favoring the opinion that the Glenarm series . . . is Cambro-Ordovician. . . . "

The writer is still of the opinion that the Glenarm series is Paleozoic

[3] Limestone is used in this paper in its broader sense to include dolomite and marble.

[4] Knopf, Eleanora Bliss, and Jonas, Anna I., Geology of the McCalls Ferry-Quarryville District, Penna.: *U.S.G.S.*, *Bulletin* 799, 71–84 (1929).

[5] McKinstry, H. E., Review, *Jour. Geol.*, **38**, 472–474 (1930).

[6] Miller, B. L., Age of the schists of the South Valley Hills, Penna.: *Bulletin G.S.A.*, **46**, 715–756 (1935).

[7] Mackin, J. Hoover, Problem of the Martic Overthrust and the age of the Glenarm series in southeast Penna.: *Jour. Geol.*, **43**, 356–380 (1935).

[8] Cloos, Ernst, and Hietanen, Anna, Geology of the "Martic Overthrust" and the Glenarm Series in Penna. and Md.: *G.S.A.*, *Special Paper* No. **35** (1941).

[9] Stose, Anna J., and George W., Geology of Carrol and Frederick Counties, Md., Physical features of Carrol and Frederick Counties: *Md. Geol. Survey*, p. 83 (1946).

[10] Bliss, Eleanora F., and Jonas, Anna I., Relation of the Wissahickon mica gneiss to the Shenandoah limestone and Octoraro schist of the Doe Run and Avondale region, Chester County, Pa.: *U.S.G.S.*, *Prof. Paper* **98-B** (1916).

[11] Swartz, Frank M., Trenton and sub-Trenton of outcrop areas in New York, Pennsylvania and Maryland: *Bull. A.A.P.G.*, **32**, 1506–1512 (1948); reprinted as *Penna. Topog. and Geol. Survey, Bull. G-22.*

and that the necessity for a Martic overthrust is not demonstrated. While the distribution of metamorphic minerals is quite compatible with this view, the present paper is not offered as direct evidence either for or against the Martic overthrust hypothesis.

The alternative interpretations are compared in the accompanying stratigraphic columns:

In and North of Chester Valley	*South of Chester Valley*	
	Martic overthrust Interpretation	*Alternative Interpretation*
Ordovician		*Glenarm Series*
Martinsburg shale	- - - - - - - - - - - -	Peters Creek fm. Wissahickon fm.
Conestoga ls. *Cambrian* Limestones and Dolomites	- - - - - - - - - - - -	Cockeysville marble
Antietam quartzite Harpers schist Chickies qte.	- - - - - - - - - - - -	Setters fm.
Pre-Cambrian	*Glenarm Series*	
- - - - - - - - - - - -	Peters Creek fm.	- - - - - - - - - - - -
- - - - - - - - - - - -	Wissahickon fm.	- - - - - - - - - - - -
- - - - - - - - - - - -	Cockeysville marble	- - - - - - - - - - - -
- - - - - - - - - - - -	Setters qte.	- - - - - - - - - - - -
Pickering Gneiss	Baltimore Gneiss	Baltimore Gneiss

Igneous Rocks

The pre-Glenarm rocks (Baltimore and Pickering gneisses) contain igneous intrusions ranging from ultrabasic (peridotite) through basic (gabbro) and calcic (anorthosite) to granite. Much of this igneous material is restricted to the pre-Glenarm complex but certain igneous rocks occur within the Glenarm series. There they are confined almost exclusively to the middle grade and high- rather than the low-grade zones of metamorphism.[12]

Within the Wissahickon formation are lenticular areas of serpentine up to 6 miles in length. Also partly or wholly surrounded by Wissahickon are bodies of basic rock that have been mapped as gabbro and resemble

[12] Two long dikes of Triassic diabase which cross the whole area are not considered in this discussion.

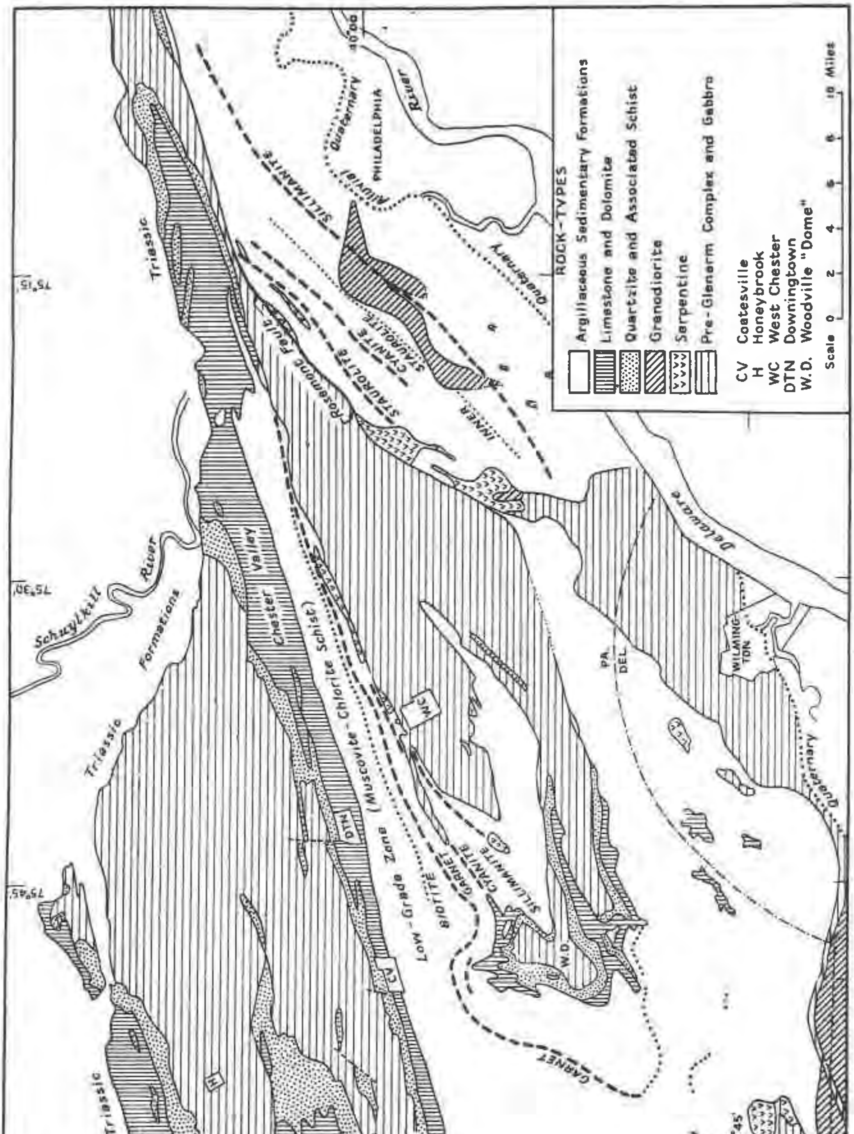

FIG 2 Isograds in the Coatesville-West Chester and Philadelphia Districts.

some of the mafic material in the Baltimore gneiss. It is conceivable that some, though by no means all, of this material is metamorphosed basic lava, as no other equivalent of either the Catoctin greenstone or the basic volcanics of Maryland[13] have been recognized east of the Susquehanna watershed.

Insofar as metamorphism is concerned, the most significant of the igneous rocks is a granitic intrusive mapped by Bascom as granite gneiss and by Postel[14] as granodiorite. The largest body, six miles long, lies between the Rosemont Fault and the Delaware River extending approximately parallel to the fault. Here, Postel recognizes a porphyritic phase which he considers a hydrothermal replacement of the Wissahickon formation. He separates it from two "truly igneous" phases, the Springfield aplitic granodiorite and the Ridley Park granodiorite. Another large area of granodiorite, which Bascom correlates with the Springfield body as well as with the Port Deposit granite, occurs along the Maryland state line in the extreme southern edge of the area covered by Fig. 2.

Pegmatite, widespread throughout the area, has two modes of occurrence: (1) broad dike-like bodies, some of them many yards wide and up to three miles long, (2) thin sheets and lenses conforming to the contorted foliation of the mica gneisses.

Rock-Units Shown in Figures 2 to 4

The maps, figs. 2, 3, and 4 are intended to show distribution of types of rock as a basis for depiction of the metamorphic zoning. Such formation boundaries as are shown are taken mainly from the maps of the U.S. Geological Survey.[15] A few minor modifications in the West Chester

[13] Cloos, Ernst, Geology and structure of the Union Bridge-New Windsor areas, Carrol and Frederick Counties, Md., in Geology of the "Martic Overthrust" and the Glenarm Series in Penna. and Md.: *G.S.A., Special Paper* **35,** 85–93 (1941).

Marshall, John, Structure and age of the volcanic complex of Cecil County, Md.: *Md. Geol. Survey,* **13,** 191–213 (1937).

Jonas, Anna I., and Stose, G. W., Geol. Map of Frederick Co.: *Md. Geol. Survey* (**1938**).

Jonas, Anna I., Geol. Map of Cecil Co.: *Md. Geol. Survey* (**1928**).

[14] Postel, A. Williams, Hydrothermal emplacement of granodiorite near Philadelphia: *Proc. Acad. Nat. Sci., Phila.,* **92,** 123–152 (1940).

Watson, E. H., Emplacement of granite at Springfield, near Philadelphia: (Abstract) *G.S.A. Proc. for 1935,* p. 117 (1936).

[15] Bascom, F., and Stose, G. W., Geology and mineral resources of the Honeybrook and Phoenixville Quadrangles, Penna.: *U.S.G.S., Bulletin* **891** (1938).

Bascom, F., and Stose, G. W., Coatesville-West Chester Folio: *U.S.G.S., Folio No.* **223** (1932).

Bascom, F., *et al.,* Philadelphia Folio: *U.S.G.S., Folio No.* **162** (1909).

Bascom, F., and Miller, B. L., Elkton-Wilmington Folio: *U.S.G.S., Folio No.* **211** (1920).

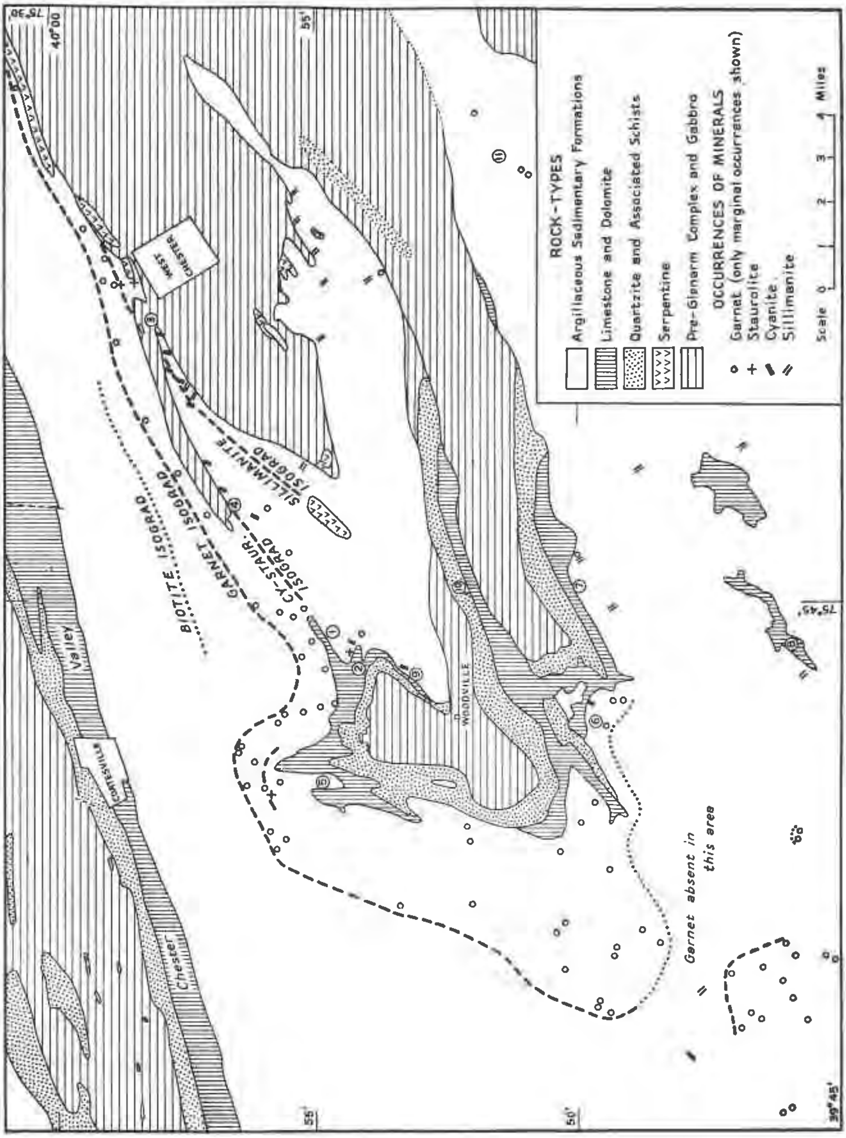

FIG. 3. Isograds and Occurrences of Minerals in the Coatesville-West Chester District (Numbers refer to localities in Table 1.)

quadrangle are based on the writer's detailed field mapping; modifications in the Norristown and Chester Quadrangles are based on mapping by Armstrong,[16] Hietanen,[17] and Postel.[18] But as the present purpose is to show types of rock rather than stratigraphic units, certain formations which the U.S.G.S. maps show separately have been combined under a single pattern. Some explanation of this grouping seems desirable.

PRE-GLENARM COMPLEX includes the Pickering and Baltimore gneisses, which are both pre-Cambrian and presumably contemporaneous. The same pattern is used for gabbro; actually separation of pre-Glenarm from post-Glenarm gabbros and amphibolites would have been highly desirable, but the writer doubts that such a separation can be made consistently in the present state of knowledge.

QUARTZITE AND ASSOCIATED SCHISTS. A single pattern is used for the Cambrian Chickies and Antietam quartzites together with the intervening Harpers schist. The same pattern is used south of the Chester Valley for Setters formation. The quartzites of the Setters are indistinguishable lithologically from the quartzites mapped as Cambrian north of the Chester Valley; both are hard quartzites showing micaceous flakes and tourmaline needles on bedding planes.

LIMESTONES. In the Philadelphia district the limestones of the Chester Valley have been mapped by Bascom as Shenandoah limestone, but in the quadrangles farther west Stose and Jonas[19] have subdivided the Cambro-Ordovician group into seven formations. The carbonate rocks of this belt are in general gray or bluish to white and finely granular. The limestones south of the Chester Valley are marmorized and have been mapped as Cockeysville marble.

ARGILLACEOUS SEDIMENTARY ROCKS. The argillaceous sediment of the Wissahickon formation grades upward into material containing an increasing amount of quartz. Although the transition is gradational, the contrast is sufficient to warrant recognition of the more highly quartzose beds as a separate formation, the Peters Creek schist. Such a distinction is not difficult within the low-grade zone, but there is reason to doubt that Peters Creek can be distinguished from Wissahickon in the middle grade

[16] Armstrong, Elizabeth, Mylonitization of hybrid rocks near Philadelphia: *Bulletin G.S.A.*, **52**, Plate 1 (1941).

[17] Cloos, Ernst, and Hietanen, Anna, Geology of the "Martic Overthrust" and the Glenarm Series in Penna. and Md.: *G.S.A., Special Paper No.* **35**, Plate 20 (1941).

[18] Postel, A. Williams, Hydrothermal emplacement of granodiorite near Philadelphia: *Acad. Nat. Sci. Phila.*, **92** (1940).

[19] Stose, G. W., and Jonas, A. I., Lower Paleozoic section of southeastern Pennsylvania: *Wash. Acad. Sci. Jour.*, **12**, 358–366 (1922).

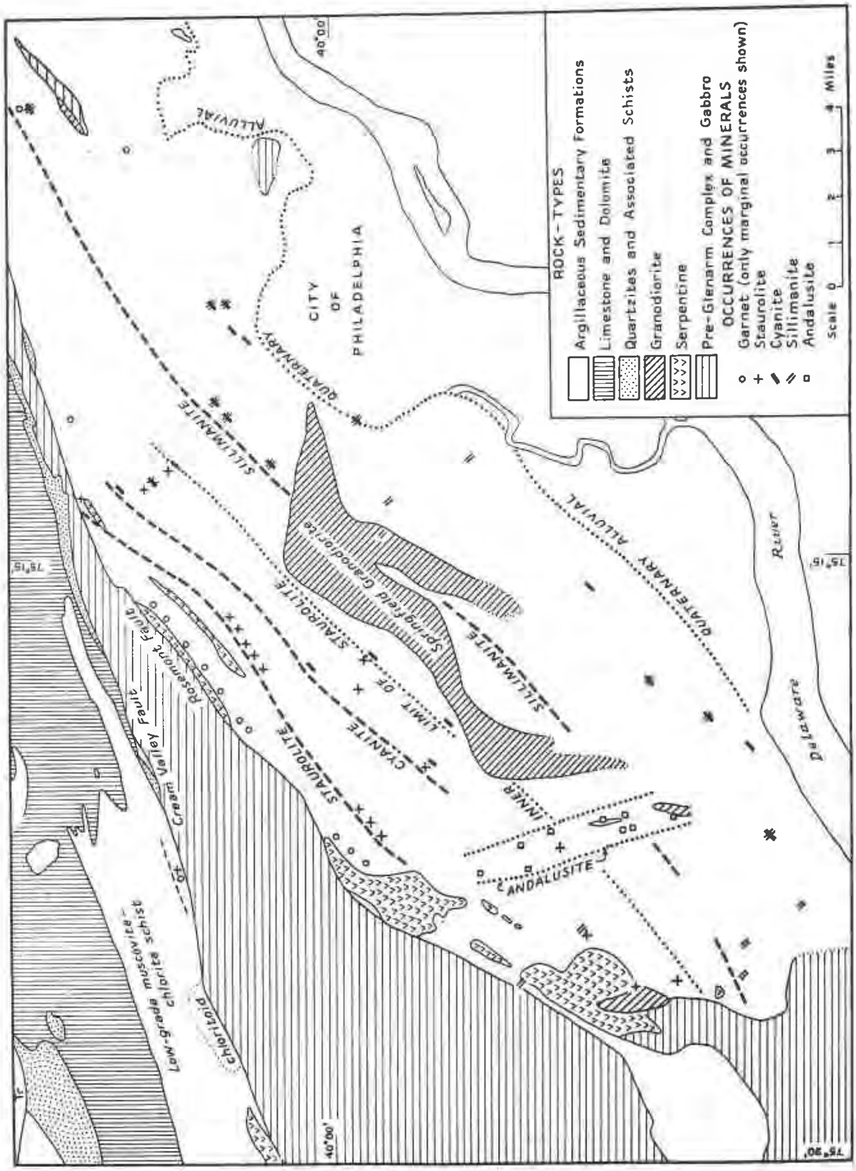

FIG. 4. Isograds and Occurrences of Minerals in the Philadelphia District.

and high-grade zones if it occurs there. The two formations have been shown by a single pattern in Figs. 2, 3 and 4 in order to avoid confusion of lines. The Peters Creek schist occurs in a syncline between the Chester Valley and the pre-Glenarm gneiss of Buck Ridge and the Woodville "Dome" line of structures.

Structure

Contacts of formations have a general northeasterly strike (N40 to 60E) except, of course, on the noses of major folds. Most of the folds are overturned to the north and some are recumbent. South of the Chester Valley, the broader structure is outlined by anticlines cored with Baltimore gneiss and bordered successively by Setters and Cockeysville formations, though either or both of these formations are locally missing so that in places the Wissahickon formation lies directly on the Baltimore gneiss.

The most northerly emergence of Baltimore gneiss south of the Chester Valley is in a fold which Bascom has termed the Buck Ridge Anticline. On its western prolongation stands the borough of West Chester. Still farther west, in line with this fold is the so-called Woodville dome, bootshaped in plan. (W.D. Fig. 2). The suggestion of Bailey and Mackin[20] that this is a recumbent fold has been confirmed by the writer's detailed observations of fold axes and plunge lines. Accordingly, the embayment of schist between the Woodville dome and the end of Buck Ridge is interpreted as a nappe-like recumbent syncline.

The next anticline to the south, termed by Bascom the Avondale anticline merges eastward with the Buck Ridge anticline, the cores of the two uniting to form a broad area of Baltimore gneiss. Still farther east the gneiss is all but cut off along a lineament which Armstrong has named the Rosemont Fault.[21] This fault, striking more northerly than the general trend of formations, curves on approaching the Chester Valley to a more easterly direction and merges with the Huntington Valley fault which, in the eastern part of the area, separates the Baltimore on the north from the Wissahickon on the south.

Distribution of Metamorphic Minerals

Previous Observations

A general southeastward increase in intensity of metamorphism in this

[20] Bailey, E. B., and Mackin, J. Hoover, Recumbent folding in the Pennsylvania Piedmont: *Am. Jour. Sci.*, ser. 5, **33**, 187–189 (1937).

[21] Armstrong, Elizabeth, Mylonization of hybrid rocks near Philadelphia, Pa.: *Bulletin G.S.A.*, **52**, 684 (1941).

region has long been recognized. Thus Bascom[22] noted that "crystallinity increases eastward in all formations. . . . " More recent publications depict variation in degree of metamorphism but, except as noted below, the existing maps are generalized and do not show mineral isograds.

Knopf and Jonas[23] published a small-scale map (about 30 miles to the inch) showing diagrammatically the distribution of metamorphic intensity in the crystalline schists of the Piedmont Province in Pennsylvania and Maryland. "Metamorphic intensity" was based on both texture and mineralogical composition, but the occurrence of index minerals was not shown specifically. Within the area described in the present paper, their map shows strong metamorphism in the southeast corner of the Coatesville-West Chester district and, except for a belt of "weak metamorphism" one to two miles south of the Chester Valley, "moderate metamorphism" in the northwestern half.

Zoning of metamorphic minerals in the area was observed by the writer about 1936 and described in a paper read before the Philadelphia Mineralogical Society in 1937, but pending an opportunity for further field work, no observations were published. Since then, Cloos and Hietanen[24] have published a map of a much larger area (scale not stated but approximately 15.5 miles to the inch) showing "distribution of metamorphic facies." In the same volume (p. 177) Hietanen shows the distribution of chlorite schist, chloritoid schist, garnet schist and staurolite schist in an area three by ten miles just west of the Schuylkill River, and on page 128 the distribution of similar rock types between Mine Ridge and the Susquehanna River (west of the present area.)

Sources of Data

Most of the occurrences of metamorphic minerals within the West Chester and Coatesville quadrangles (Fig. 3) are based on the writer's field observations made at intervals during the past fifteen years. In contrast, the occurrences in the Philadelphia district are chiefly from records in the literature, many of them from Gordon's[25] compilation. Such observations, although made by mineral collectors rather than by

[22] Bascom, F., Description of geology, Piedmont Plateau Area, Pre-Triassic metamorphic rocks: *U.S.G.S., Philadelphia Folio No.* **162** (1909).

[23] Knopf, Eleanora Bliss, and Jonas, Anna I., Geology of the McCalls Ferry-Quarryville District, Penna.: *U.S.G.S., Bulletin* **799**, 122 (1929).

[24] Cloos, Ernst, and Hietanen, Anna, Geology of the "Martic Overthrust" and the Glenarm Series in Pa. and Md.: *Geol. Soc. Am., Special Paper No.* **35** (1941).

[25] Gordon, Samuel G., Mineralogy of Pennsylvania: *Acad. Nat. Sci. Phila., Special Publication No.* **1** (1922). In addition, data for a ten-mile belt west of the Schuylkill River were taken from Hietanen's map. Cloos and Hietanen, *Op. cit.*, p. 137.

geologists primarily interested in metamorphism, yield a wealth of information, some of which is no longer available from the field now that so many quarries and exposures in the city and suburbs have been filled in or built upon. Despite the existence of the records, it was not until the occurrences had been plotted that any systematic distribution became evident. However, a more detailed and accurate portrayal of mineral isograds in this part of the area will doubtless emerge from a study of the Wissahickon formation in the Philadelphia district in preparation by Dr. Judith Weiss[25a] of the U.S. Geological Survey. Meanwhile, the map (Fig. 4) is presented here in order to show broader relationships than are available in the Coatesville-West Chester district alone.

In the Pre-Glenarm Complex

The Baltimore gneiss is a complex of hornblendic and biotitic gneisses with basic and granitic intrusives. It suffered intense metamorphism prior to the deposition of the Glenarm Series and must also have experienced the metamorphic influences that affected the Glenarm, but no attempt is made here to disentangle the two processes nor, for that matter, to discuss the metamorphism of the pre-Glenarm rocks. Where the Baltimore and its basic intrusives adjoin the high-grade zone of the Wissahickon formation and especially along zones of shearing, the gabbroic and hornblendic rocks are converted into coarse biotite gneiss and in such places there is room for difference of opinion as to the correct position of the contact. Metamorphism of gabbro associated with the Baltimore gneiss has been investigated by Watson.[26]

In Argillaceous Rocks

Except for narrow belts of Harpers and Setters schist, the principal argillaceous formations of the area are the Wissahickon and Peters Creek.

LOW-GRADE ZONE. Within the low-grade zone, the Wissahickon formation is a fine-grained phyllitic schist consisting chiefly of muscovite, quartz and albite. Chlorite is present but in most places subordinate. A chloritoid-bearing belt about a mile wide and two miles long within

[25a] Weiss, Judith, Wissahickon schist at Philadelphia, Pa.: *Bulletin G.S.A.*, **60**, 1689–1726 (1949). Appeared after the present paper was in type. The only conspicuous discrepancy between Dr. Weiss' isograds and mine is in the extrapolation of "sillimanite isograd" north of "City of Philadelphia" in my figures 2 and 4. As figure 4 clearly shows, this extrapolation is postulated on incomplete data. Dr. Weiss' map shows both the cyanite and staurolite isograds extending in a more northerly direction north of Philadelphia.—H.E.McK.

[26] Watson, E. H., Alteration of gabbro near Philadelphia: (Abstract) *Am. Mineral.*, **21**, pp. 200, 201 (1936).

this zone has been recognized by Hietanen eight miles west of the Schuylkill River (Fig. 4).

The schist of the low-grade zone has an even slaty cleavage interrupted by local warping and by zones of buckling. Flakes of mica and chlorite are 0.1 mm., or less in diameter usually too fine to be distinguished macroscopically so that cleavage surfaces have a silvery rather than a sparkling luster. A thorough description of the microscopic and petrofabric characteristics of the Wissahickon formation in the Norristown quadrangle has been published by Hietanen.[27] It is noteworthy that she found no evidence of retrogressive metamorphism (diaphtoresis) in the Octoraro schist[28] but states that the "sequence of recrystallization indicates progressive metamorphism contemporaneously with the deformation" (p. 135).

In the present study, however, a series of specimens taken along the West Branch of Brandywine Creek (from two to six miles southeast of Coatesville) showed consistent evidence of biotite altering to chlorite, an effect that might correctly be designated retrogressive metamorphism. Nevertheless, there is no evidence of any profound retrogressive reconstitution of the rock. On the contrary, barring this late chloritization of biotite, the transition from the low-grade to the middle-grade zone is characteristic of progressive metamorphism—deformation of smooth cleavage planes of the phyllite accompanied by recrystallization and coarsening of the mineral constituents of the rock. With this gradual increase in grain size the cleavage surfaces become less silvery and more sparkling and with incipient deformation they become warty or wavy with wave length on the order of two to four inches and amplitude one-half inch. Shortly biotite is recognizable. Within another mile, as measured in the West Brandywine section, the rock becomes a mica gneiss rather than a mica schist and garnet begins to appear.

The most definite reference line for descriptive purposes is the garnet isograd as mapped from observations of megascopically visible garnet. On the map (Fig. 3) each circle represents an occurrence of garnet observed in the field. The mapping of megascopic occurrences has the advantage of yielding a much better sampling than would be possible without a prohibitive number of thin sections. The limited number of thin sections examined would indicate that consistent occurrences of microscopic garnet are not to be expected more than a few thousand feet to the low-grade side of the isograd as mapped, although it is true that rare and

[27] Cloos and Hietanen, *Op. cit.*, pp. 139–185.

[28] The low-grade facies of the Wissahickon formation in the Philadelphia District was mapped by Bascom as "Octoraro Schist."

sporadic microscopic crystals have been noted as much as three miles away from it.

The biotite isograd is less easy to locate than the garnet isograd, partly because of the chloritization of biotite already mentioned. Because of the difficulty of defining it sharply in the field, the biotite isograd has been mapped in only part of the area. In the West Brandywine section there is an interval of 3½ miles between the first sparse appearance of biotite and the last occurrence of chlorite, and chlorite persists to half a mile inside (i.e., on the high-grade side of) the garnet isograd. The first abundant biotite makes its appearance a little more than a mile north of the garnet isograd. For purposes of description the garnet isograd is taken as the approximate boundary between the low and the middle-grade zones, recognizing, of course, that the more conventional boundary, the biotite isograd, is probably one to two miles outside it.

As already noted, the Glenarm series is separated into two tracts by the mass of Baltimore gneiss that lies west of the Rosemont fault. Although zoning of metamorphic minerals is noted in each of the tracts, the trends of isograds on opposite sides of the Baltimore gneiss are not in line with each other. Therefore, it will be convenient to discuss the two districts separately.

ISOGRADS IN THE COATESVILLE-WEST CHESTER DISTRICT. The northern boundary of the middle-grade zone, as marked by the garnet isograd, lies north of the Buck Ridge anticline. From the Schuylkill River it strikes S. 70° W. for twenty miles, roughly paralleling the Chester Valley and the regional strike. Farther west it swings southward around the Woodville "Dome," where it is separated from the Cockeysville marble by a horizontal distance of one to four miles.

Staurolite appears a mile or less south of the garnet isograd. Although staurolite is not common in the West Chester-Coatesville district, the six localities in which it has been noted all lie within a belt ½ to 1½ miles wide, parallel to the garnet isograd.

Cyanite occurrences form a well-defined belt about a mile south of the garnet isograd, extending for ten miles from near West Chester to the margin of the Woodville dome. This belt is marked by abundant pegmatite in the gneiss—more than is found either north or south of it. An occurrence of both staurolite and cyanite from a single locality[29] has been reported but not confirmed by the writer. Elsewhere, cyanite begins

[29] "Near Logan's quarry" in the East Marlborough Township, Chester County. Listed by Gordon from Dana, J. D., System of Mineralogy, 3d edition (1850), p. 615. After the present paper had gone to the printer the writer succeeded in confirming this occurrence in the field.

about $\frac{1}{4}$ mile south of the trend-line of the staurolite belt. Cyanite has not been found on the west flank of the Woodville "dome," probably because exposures in that area are few and poor. Sillimanite is found together with cyanite at one locality, but its more abundant development begins two miles or more south of the cyanite isograd.

An anomalous feature of the metamorphism is that south of the Woodville dome and the Avondale anticline there is a belt one to four miles wide in which garnet is very scarce or absent. This can hardly be due to local lowering of the grade of metamorphism because here the gneiss is coarse grained and in at least two localities contains sillimanite. Pegmatite is abundant in the belt and in a few places garnet occurs in the pegmatite but not in the gneiss itself. The possibility that the gneiss of this belt differs in chemical composition from typical Wissahickon calls for investigation. Alternatively, the possibility that deformation in this zone was accomplished under conditions of lowered differential stress deserves consideration, for under such conditions sillimanite, but not cyanite or almandite, would be stable.

Quartz Veins, Pegmatite and Feldspars. In the low-grade zone quartz is abundant in veins cutting the cleavage at various angles. The veins commonly contain cubes of pyrite and grains of an iron-bearing carbonate. Similar veinlets carry grains of albite, but pegmatitic material, except for a very few dikes, which are cleancut and well defined, does not occur in the low-grade zone. In the Peters Creek schist thin lenses and laminae of quartz, probably representing sedimentary beds, are characteristic. But at about the beginning of the middle-grade zone, similar thin lenses consist of quartz microcline and plagioclase, with or without biotite and muscovite. With increasing degree of metamorphism these lenses of pegmatitic material become thicker, coarser and more numerous. Locally they contain garnet, cyanite or tourmaline. In addition, definite veins of quartz are common. This rough correspondence between amount and texture of pegmatitic material and degree of metamorphism, as well as the similarity in mineralogy between the pegmatitic lenses and the enclosing rock, suggest that development of pegmatite is a concomitant result rather than a primary cause of the metamorphic process.

Hietanen's[30] mapping of the anorthite content of plagioclase shows that the feldspars become more calcic as one proceeds toward the southeast. At about the biotite isograd the plagioclase is An_{16}. Near the cyanite isograd it is An_{19}, and within the sillimanite isograd An_{25} to An_{30}.

Isograds in the Philadelphia District. In the area southeast of the Rosemont fault, isograds can be drawn approximately parallel to the fault and to the axis of the Springfield granodiorite. The low-grade

[30] Cloos and Hietanen, *op. cit.*, plate 19 and p. 130.

zone is missing, the area where it might be expected to appear being occupied by Baltimore gneiss. The staurolite and cyanite zones overlap somewhat, cyanite appearing about a mile before the disappearance of staurolite. The cyanite zone also overlaps the sillimanite zone; the two minerals occur together in several localities. The distance between the cyanite and the sillimanite isograds is about three miles.

ANTI-STRESS MINERALS. From evidence in many districts of simple thermal metamorphism it is known that cordierite and andalusite are the characteristic anti-stress minerals of argillaceous rocks.[31] In the region under discussion, cordierite has not been reported and andalusite occurs in a single restricted belt. It has been observed in eight localities, all within a belt five miles long and a mile wide in or near the valley of Crum Creek, which flows just west of Swarthmore; nowhere else in Pennsylvania is an occurrence of andalusite listed by Gordon. This belt, striking a little west of north, crosses the regional trend of isograds. However, it is parallel to the trend of local foliation and to a dikelike body of hornblende gneiss which lies on the northward prolongation of a narrow body of Springfield granodiorite. Postel[32] has observed cyanite forming borders around andalusite and similarly around bundles of sillimanite and accordingly suggests that "the region was first subjected to high-grade metamorphism and then later was acted on by high differential pressure."

In Carbonate Rocks

The Cambrian and Ordovician limestones and dolomites of the Chester Valley, being in contact (a fault contact according to Knopf, Stose and Stose) with argillaceous rocks of the low-grade zone, nowhere show tremolite or other middle-grade minerals. Cubes of pyrite are common, fluorite has been found sparingly and rutile is sparse but widespread. It would be instructive to know whether the carbonate rocks of the Cockeysville formation where surrounded by low-grade phyllites would show a similar lack of middle-grade minerals, but unfortunately their first appearance south of the valley is well within the garnet isograd in contact with argillaceous rocks that contain minerals ranging from staurolite through cyanite to sillimanite. These limestones are marmorized and have a fine to coarse sugary texture. Tremolite is present in all localities except one, namely Edward's quarry (no. 1 on Fig. 3) which is very close to the staurolite isograd.

[31] Harker, Alfred, Metamorphism. London, Methuen and Co., Ltd., pp. 147–151 (1932).

[32] Postel, A. Williams, Hydrothermal emplacement of granodiorite near Philadelphia: *Proc. Acad. Nat. Sci. Phila.*, **92**, 128, (1940).

Within the zones designated as middle-grade and high-grade on the basis of minerals in the aluminous rocks, the minerals of the limestones do not show any striking zonal arrangement. Tourmaline (usually a brown variety) occurs in both zones. Scapolite has been found in five localities within the high-grade zone and also in the quarries near Doe Run (No. 5 on Fig. 3) which are presumably in the middle-grade zone although the position of the sillimanite isograd in this vicinity has not been well defined. Microcline of the variety chesterlite[33] occurs in two localities.

TABLE 1

	Number on Map	Fluorite	Rutile	Tourmaline	Epidote or Zoisite	Vesuvianite	Tremolite	Scapolite	Diopside	Potash feldspar	Apatite
Low-Grade Zone											
Chester Valley		x	x								
Middle-Grade Zone											
Edwards' Quarry	1	x	x	x							
Logan's Quarry	2		x	x			x				
Cope's Quarry	3				?		x	?			
Poorhouse Quarry	4		x		?		x			x	
Doe Run Quarries	5		x	x		x	x	x			x
Avondale Quarries	6		x	x	x		x				x
High-Grade Zone											
Kennett Quarries	7		x	x			x	x			
Nevin's Quarries	8		x	x			x	x			x
Bailey's (Upland)	9		x		x		x	x	x		
Willowdale	10			x		x	x	x	x	x	
Elam	11		x					x	x	x	x

Of the minerals occurring in the limestones of this region, diopside is the one generally regarded as representing the highest grade of metamorphism. If it can be taken as an index mineral, its occurrence in localities 9 and 10 near the axis of the Buck Ridge structure and its absence[34]

[33] Chesterlite from the Poorhouse quarry was originally described by Dana as a new mineral species and named for Chester County. Later, Descloizeaux used chesterlite from this locality as one of his types in establishing the species microcline.

[34] Chondrodite together with diopside occurs in limestone surrounded by Baltimore gneiss at Brinton's Bridge on the Brandywine. This occurrence has been mapped as Franklin limestone of pre-Glenarm age.

in the localities farther south (Nos. 6, 7 and 8) might suggest a belt of metamorphic intensity that is locally high and diminishes southward as well as northward. No corresponding contrast is evident, however, in the adjoining schists, which are all in the sillimanite zone. No higher grade of metamorphism than that represented by diopside was attained in the limestone, as grossularite is not observed and even where diopside is found, tremolite is still present. Whether or not a still higher intensity is reached farther east cannot be determined on the basis of calcareous rocks since none are exposed in the sillimanite zone in the Philadelphia area. As would be expected in the absence of purely thermal metamorphism, wollastonite is not known in the region.

Table 1 gives the minerals reported in the principal exposures. Numbers on the table refer to numbers on the map, Fig. 3.

Cause and Significance of Metamorphism

Discussion of a number of the questions that the zonal relationship suggests would call for a presentation of detailed structural data which the writer hopes to offer in a later paper. The answers to still other questions must remain conjectural in the absence of more than the very limited number of chemical analyses and quantitative microscopic studies now available. Nevertheless, certain observations seem warranted at the present time.

The marked increase in grade of metamorphism southward and eastward toward the areas of granitic rocks near Philadelphia and along the Maryland state line strongly suggests the influence of subjacent igneous bodies in accordance with ideas long ago proposed by Barrell.[35] The isograds are not strictly parallel to the observed boundaries of the granitic bodies. If they are spatially related to an underlying magma they reflect general proximity to a mass of igneous material rather than to relatively small exposed sills or stocks.

The metamorphism is not limited to rocks of pre-Cambrian or undetermined age, for, although within the area mapped all of the unquestionned Paleozoic rocks are in the low-grade zone, Hietanen has noted that in the McCalls Ferry Quadrangle (west of the present area), Cambrian schists show garnet-staurolite grade of metamorphism. Therefore, if a single period of igneous activity is responsible for the metamorphism its age cannot have been pre-Cambrian.

In any case, the general, though locally interrupted, increase in grade from northwest to southeast suggests that the relatively high grade of

[35] Barrell, Joseph, Relation of subjacent igneous invasion to regional metamorphism: *Am. Jour. Sci.*, 5th Ser., **1**, pp. 1 ff. (1921).

metamorphism in parts of the Glenarm series as compared with the Paleozoic rocks of the Chester Valley, as well as with tracts of Glenarm rocks adjoining it, is due to geographical position with respect to the isograds, and not to difference in age of the rocks. For this reason the observed zonal relations are entirely compatible with Paleozoic age for the Glenarm series including the Wissahickon formation.

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