[AMERICAN JOURNAL OF SCIENCE, VOL. 275, JUNE, 1975, P. 653-682]

POLYMETAMORPHISM OF THE PRECAMBRIAN BALTIMORE GNEISS IN SOUTHEASTERN PENNSYLVANIA

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ABSTRACT. Precambrian gneisses in southeastern Pennsylvania, exposed south of Chester Valley in Delaware and Chester Counties, have compositions that range from olivine gabbro to granite. A few are quartzose rocks containing kyanite and/or garnet. Two distinct periods of metamorphism are recorded. In the first (~1000 m.y. ago), the rocks were completely recrystallized in the granulite facies. During the second episode, probably at the time of intense deformation and metamorphism of the overlying Wissahickon Schist, the Precambrian rocks were recrystallized to amphibolite facies assemblages wherever water was available. In dry rocks the only effect of the later metamorphism was the development of garnet coronas between mafic minerals and plagioclase. Diabase dikes, intruded between the two metamorphic episodes, display garnet coronas similar to those in the granulites. P-T conditions of 775° to 850°C, 8 to 9 kb, are inferred for the granulite facies metamorphism, based on the lack of olivine and presence of garnet + clinopyroxene in olivine normative rocks, mesoperthite + garnet + clinopyroxene in quartzofeldspathic granulites, and sillimanite in quartzites. For the second metamorphism, P-T conditions of 650° to 700°C, 7 to 8 kb, are inferred, based on the occurrence of the assemblage garnet + clinopyroxene + quartz in the coronas and the inversion of sillimanite to kyanite.

INTRODUCTION

The crystalline rocks of the Piedmont Province of the Middle Atlantic states have undergone a complex metamorphic and tectonic history of which the earliest recorded event was the Grenville orogeny (~1000 m.y. ago). In Pennsylvania considerable attention has been, and continues to be, directed toward the younger units that were deposited, at least in part, on the Grenville age basement and that were initially metamorphosed during the Taconic orogeny (~440 m.y. ago) (for example, Cloos and Hietanen, 1941; Weiss, 1949; Wyckoff, 1952; O'Connor, ms; Amenta, 1974). However, the history of the region cannot be understood completely without attempting to determine the history of the older rocks and the role they have played in subsequent metamorphism and deformation. This paper describes the petrology and metamorphic history of the granulite facies gneisses that form the central part of the blocks of Grenville age rocks lying west of Philadelphia (fig. 1).

Florence Bascom mapped the crystalline rocks of the Philadelphia area (1909, 1932) and distinguished two major units in the Precambrian. One, a felsic biotite garnet gneiss, she thought to be of sedimentary origin. She called it Baltimore Gneiss because of its similar stratigraphic relationships and lithologic character to rocks in the Baltimore Gneiss domes near Baltimore. Her second unit was what she considered to be a gabbro intrusive into the gneiss. Armstrong (1941) presented the only previous detailed study of the Precambrian rocks. In her area, east of the block described here, the rocks are extensively crushed and her paper concen-

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trated on the formation of the mylonites. A preliminary petrographic study (Wagner, ms) showed that the rocks in the area chosen for the present paper (figs. 1 and 2) were for the most part in the granulite facies, in contrast to the amphibolite facies assemblages prevalent in Armstrong's area. In addition, almost all the granulites display extremely well-developed corona textures, described by Bascom (1909) but never studied in detail.

REGIONAL SETTING

The Precambrian gneisses in southeastern Pennsylvania form an elongate belt, divided into several blocks by major faults (fig. 1). The westernmost exposures of Precambrian rocks are unconformably over-

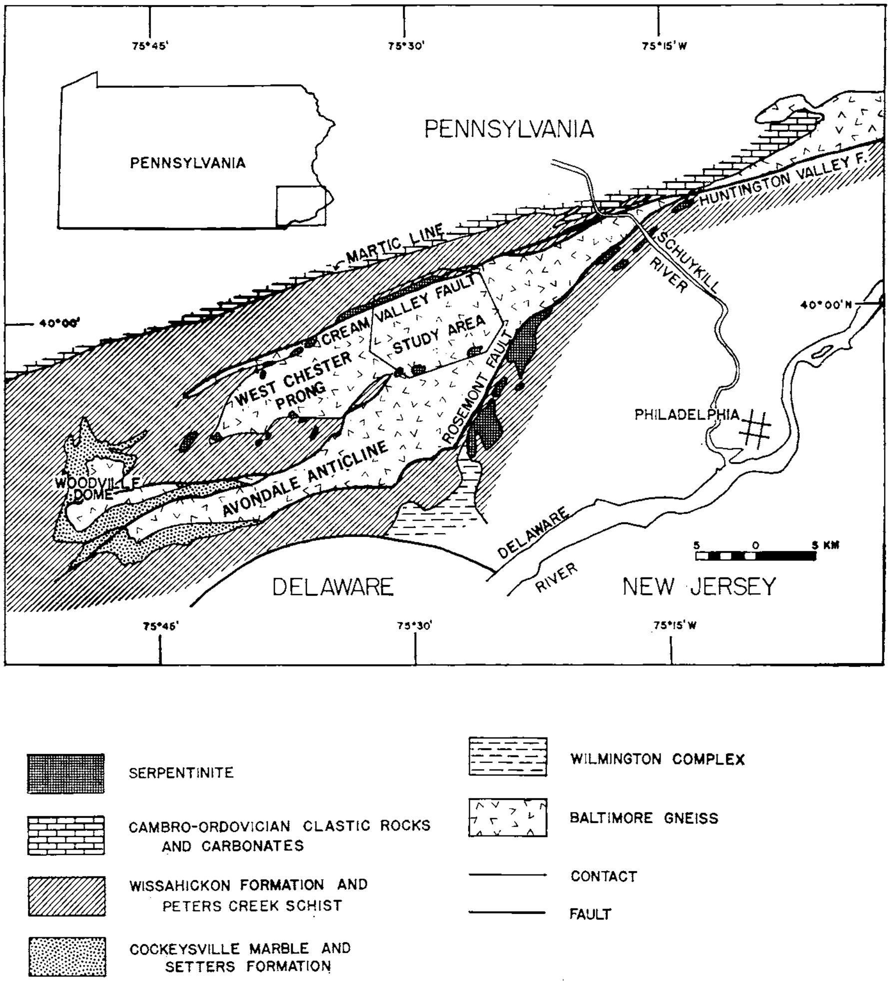

Fig. 1. Simplified geologic map of southeastern Pennsylvania showing area of this study.

lain by lower Glenarm Series rocks: the Setters Formation (quartzite and mica schist) and Cockeysville Marble. The age of the Glenarm Series, which includes the Wissahickon Formation, has been debated for many years and could range from late Precambrian to Ordovician. Higgins (1972) gives an excellent summary of the long controversy and the many interpretations of the relationship of the Wissahickon Formation to other members of the Glenarm Series. East of the Schuylkill River, the Precambrian gneisses are unconformably overlain by Cambrian Chickies Formation (quartzite and phyllite) and Cambro-Ordovician carbonates.

The area chosen for this study lies in the central part of the belt of Precambrian gneisses, in the block called the West Chester prong (fig. 1). In the West Chester prong, quartzite and carbonate are missing, and the gneiss is in direct contact (usually a fault) with the Wissahickon Formation, which in many places contains pods of ultramafic rock near the contact. The structural data in both the Grenville rocks (Wagner, ms) and

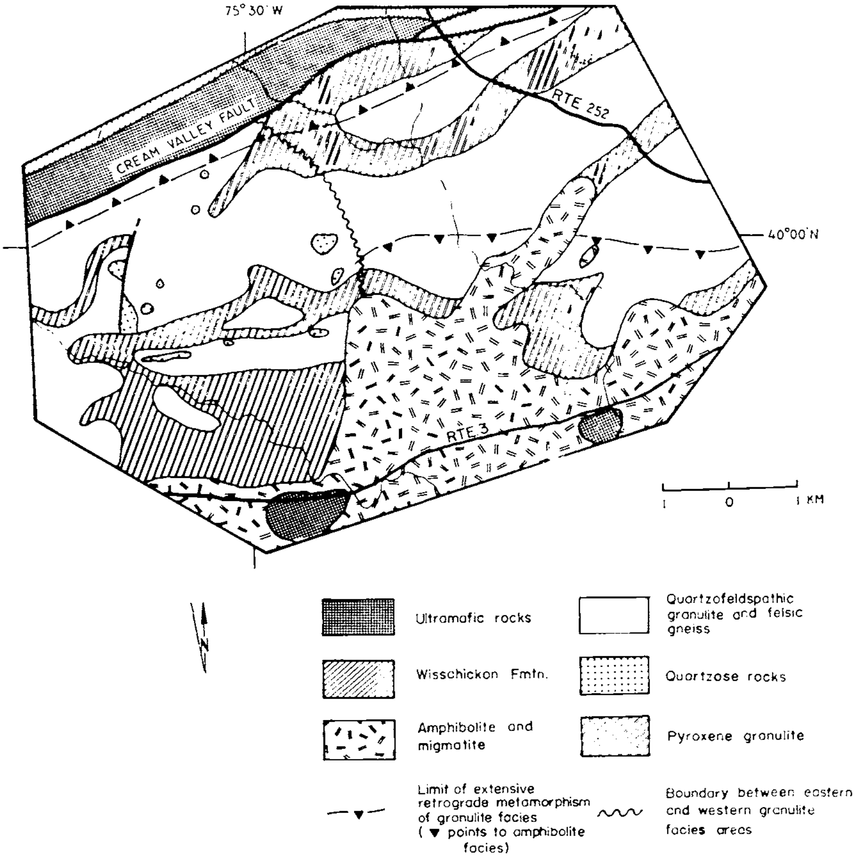

Fig. 2. Geologic and metamorphic map of area covered in this study.

Table 1

Modes of granulite facies rocks

Pyroxene granulites

	Eastern area			Western area						
	11	39	43a	71	325a	326b	67	60**	58	366
Plagioclase	52.2	49.5	63.5	54.8	49.2	50.9	30.6	30.6	49.7	40.3
An%	37	43	42	38	40	30	41	26	33	37
Orthoclase	3.9	2.4	0.9	0.4						1.9
Quartz	1.2	0.5	3.4	0.4	1.4	0.7				10.2
Clinoproxene	21.8	15.0	5.5	16.1	15.1	13.2	22.4	11.6	24.9	12.5
Hypersthene	14.1	13.4	2.2	14.1	15.2	12.3	5.4	11.5		8.6
Garnet 1st generation						7.3	4.3	33.3	18.6	23.0*
Garnet second generation	4.5	7.0	11.5	9.2	12.4	7.4	8.3	3.6	2.8	
Hornblende	0.2	0.6	4.1	0.2			27.8			
Biotite	0.4	7.0	6.6	2.9	1.8	5.0	0.3			1.0
Opaques	1.3	3.8	1.6	1.4	4.8	2.8	0.7	5.9	4.0	2.4
Apatite	0.2	0.5	0.1	0.4	0.1	0.4	0.2	3.5		0.1
Zircon	tr	tr	tr	0.1						
Scapolite		0.2	0.6							
Total points	2104	968	678	1635	1568	1830	2303	902	2251	862

	Quartzofeldspathic granulites							Quartzose rocks			
	Eastern area		E-W	Western area				Western area			
	14	64	270A	134	221	322	375	316	55A	397	220
Mesoperthite					32.4	46.2	22.1				
Plagioclase	48.3	37.1	31.0	25.2							
An%	33	30	28	37							
Orthoclase	14.0	26.7	6.5	5.2							
Quartz	22.3	15.7	27.6	40.4	46.6	45.6	50.0	64.0	85.0	68.5	41.9
Myrmekite	0.2										
Clinopyroxene	0.5	0.1	9.2								
Hypersthene	1.6	7.6		0.8	2.1						
Garnet*	6.5	9.0	15.0	26.1	18.1	7.1	13.6			31.0	37.2
Hornblende	0.8	0.1									
Biotite—phlogopite	2.9	1.0	5.8	1.1			11.8				
Opaques	2.4	2.0	3.4	0.3	0.3	0.7			1.2		1.7
Apatite	0.4	0.7	1.5	0.1							0.6
Zircon	tr	tr								0.5	0.1
Rutile				0.8	0.5			tr	0.5		2.1
Kyanite							2.5	36.0	13.1		16.4
Staurolite									0.2		
Spinel								tr			
Total points	834	1359	1080	1303	1080	1080	1713	2772	1288	1308	1599

* Includes both first and second generation garnets.

** Thin section of sample 60 is not representative: less plagioclase and more mafic minerals in thin section than in rock as whole.

in surrounding schists (Amenta, 1974) permits the interpretation of vertical upward movement of this basement block during the Paleozoic. The structure of the West Chester prong is that of a steep anticline overturned to the north, with a faulted northern limb (Cream Valley fault, figs. 1 and 2). The fault separates the gneiss from serpentinite and Wissahickon Formation. Mylonitized Precambrian rocks occur in an extensive zone up to a third km wide all along this fault. This mylonite and other smaller zones are very similar to those described by Armstrong (1941) and will not be described further here. Most of the Wissahickon north of the gneiss is a greenschist facies muscovite–albite–chlorite phyllite. In places, however, fault slices of amphibolite facies garnet mica schist occur between the Baltimore Gneiss and the low-grade phyllites. The southern edge of the field area coincides with a line of ultramafic bodies which appears to mark the convergence of two separate Baltimore Gneiss blocks, the West Chester prong and the Avondale anticline (fig. 1).

Although the Precambrian rocks may originally have been of sedimentary and igneous origin, as suggested by Bascom (1909), the mineral compositions and textural evidence reported in later sections of this paper show that the rocks are now completely recrystallized. To emphasize the metamorphic character of the rocks, Bascom's terminology has been dropped. Her "gabbros" are here called pyroxene granulites, and her "felsic gneisses" are quartzofeldspathic granulites.

Throughout the West Chester prong granulite facies assemblages predominate. Diabase dikes with well-preserved ophitic texture, sharp contacts, and chilled margins cut the granulite facies rocks. Both granulites and dikes were partially recrystallized during a second metamorphism. In many of the granulites and in the diabase dikes, the only effect of the second metamorphism was the formation of garnet coronas on mafic minerals. Other granulites were completely retrograded to the amphibolite facies. Textures of the latter, to be described later, show that they are derived from the granulite facies rocks, and hence they are called retrograded granulites. In the southern part of the study area other amphibolite facies rocks occur, most of which show no evidence of having been at a higher metamorphic grade. These rocks are mafic amphibolites and intensely folded migmatites (amphibolite and migmatite of fig. 2), at least some of which are probably younger than the granulite facies metamorphism. Since this paper deals with those rocks that clearly show two episodes of metamorphism, the amphibolites and migmatites will not be discussed in detail.

In the sections that follow, the effects of the billion year old granulite facies metamorphism will be described first, followed by a discussion of the mineralogical and chemical evidence pertaining to the P-T conditions that prevailed during that metamorphism. Next the garnet coronas and other effects of the second metamorphism on the granulite facies rocks as well as on later cross-cutting diabase dikes will be described and discussed.

Modes of twenty one granulite facies rocks are given in table 1. Chemical analyses of four rocks were made using a Hitachi Perkin-Elmer spectrophotometer and Techtron atomic absorption spectrophotometer. Twenty additional chemical analyses were calculated from modes using analyses of minerals from the same samples or from very similar samples (Wagner, ms). A large number of chemical analyses of minerals from thirteen different rocks were made with the ARL-EMX-SM electron probe microanalyzer at Princeton University using the correction procedure of Bence and Albee (1968). Analyses of representative samples are given in tables 2 and 3; the remaining analyses are on file at Bryn Mawr College and are available on request from either author.

FIRST METAMORPHISM

There are a number of differences in the metamorphic assemblages formed in the eastern and western parts of the study area during the first metamorphism. In both areas quartzofeldspathic and pyroxene granulites occur. In addition, there are very quartz-rich aluminous rocks in the western area. The assemblages found in the pyroxene granulites and quartzofeldspathic granulites are shown on an ACF diagram (fig. 3A), and the assemblages found in quartzose rocks and calcium-poor quartzofeldspathic granulites of the western area on an AMF diagram (fig. 3B). The chief differences in mineral assemblages in the eastern and western granulite facies areas can be summarized as follows:

Western	Eastern
brown hornblende	green hornblende
mesoperthite	orthoclase + plagioclase
garnet + clinopyroxene in some mafic and felsic rocks.	hypersthene + clinopyroxene in mafic rocks hypersthene + garnet + minor clinopyroxene in felsic rocks
no biotite	biotite possible in all rock types
kyanite-quartz and garnet-quartz rocks.	no quartzose rocks

The above comparison must be qualified by the fact that a pale-colored, very magnesium-rich phlogopite (table 2, sample 375) occurs in the quartzose rocks and a darker colored somewhat more iron-rich phlogopite-biotite (table 2, sample 71) reappears in the mafic rocks in the southwestern part of the western area. Near the boundary between the eastern and western areas the hornblendes have a brownish green or greenish brown color.

Eastern area.—The *pyroxene granulites* are of medium grain size (1.5 mm) and have chemical compositions that range from dioritic to gabbroic. They have an equigranular granoblastic texture, and in the field a faint foliation can be seen. All are two-pyroxene-plagioclase rocks with accessory magnetite and/or ilmenite, zircon, and apatite. The orthopyroxene is hypersthene, the clinopyroxene salite. Plagioclase is well-

TABLE 2
Electron microprobe analyses of pyroxenes, hornblendes, and biotites

	Orthopyroxene		Clinopyroxene					Hornblende				Biotite		
	px gran	qf gran	px gran				qf gran	px gran		retr qf gran	amph	px gran		qf gran
	67	322C	58		67		322C	67	207A	150	133	207A	71	375
			1 gen	2 gen	1 gen	2 gen	2 gen	brown	green brown	green	green			
SiO_2	52.4	50.3	50.4	50.8	51.8	52.2	50.4	42.6	41.6	40.8	42.3	37.2	38.6	40.8
TiO_2	0.09	0.04	0.33	0.23	0.30	0.15	0.17	2.3	2.0	1.82	1.24	5.3	4.9	3.2
Al_2O_3	1.00	0.76	3.57	2.73	3.12	2.49	2.28	11.2	13.2	13.6	12.3	14.0	12.6	14.0
FeO	26.2	29.3	11.5	10.0	9.3	9.1	11.7	12.4	13.1	18.1	18.8	12.9	12.7	3.3
MnO	0.32	0.33	0.10	0.09	0.15	0.18	0.13	0.08	0.12	0.09	0.35	0.04		.02
MgO	21.1	18.3	11.0	12.2	13.1	13.7	12.2	14.0	12.7	9.2	9.2	16.7	15.6	24.0
CaO	0.46	0.45	21.2	22.0	21.2	21.2	20.9	11.5	11.6	11.4	11.7			
Na_2O			1.33	0.65	1.14	1.11	1.22	2.32	1.80	1.41	1.69	0.04	0.10	0.17
K_2O								1.76	2.04	1.54	.80	10.4	9.8	10.3
H_2O*								1.8	1.7	2.0	1.6	3.4	5.7	4.2
Total	100.6	99.5	99.5	98.8	100.2	100.2	99.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

px gran = pyroxene granulite
qf gran = quartzofeldspathic granulite
1 gen = first generation
2 gen = second generation
retr = retrograded
amph = amphibolite facies

* H_2O determined by difference

322C: mesoperthite, quartz, hypersthene, opaque, coronas of garnet, clinopyroxene, quartz
207A: plagioclase, hypersthene, clinopyroxene, biotite, hornblende, garnet coronas
150: garnet (1 gen and 2 gen.), biotite, hornblende, plagioclase, quartz, apatite, opaque
133: hornblende, garnet, plagioclase, quartz, sphene

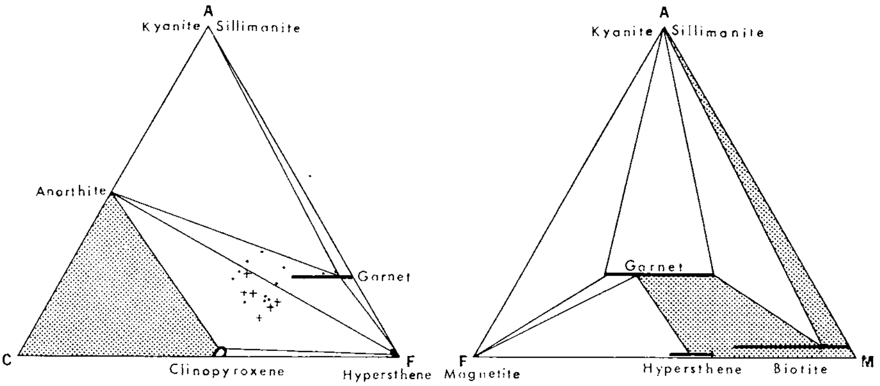

Fig. 3.A. ACF diagram for the granulite facies. Closed circle: indicated assemblage present; plus sign: garnet + clinopyroxene + plagioclase ± hypersthene. No rocks that plot in the shaded area were found.

B. AFM projection from K-feldspar showing the assemblages in quartzose rocks and calcium-poor quartzofeldspathic granulites of the western area. No rocks that plot in the shaded areas were found.

twinned and frequently antiperthitic, ranging in composition from An_{26} to An_{50} with values near An_{38} most common. Microprobe analyses show little potassium in the plagioclase ($Or_{1\text{-}3}$) except for that contained in exsolved antiperthitic blebs. Some of the pyroxene granulites contain hornblende and/or biotite in apparent equilibrium with the pyroxenes. Untwinned K-feldspar occurs as narrow intergranular films or small grains. It occasionally has a 2V close to 0°, but its concentration in these rocks is too low (1-2 percent) to permit separation for X-ray determination of structural state.

The *quartzofeldspathic granulites* are coarse-grained (1.5 to 5 mm) rocks with highly variable composition and mineralogy. A prominent feature of weathered exposures is a strong lineation, due to the concentration of mafic minerals in streaks. The lineation is difficult to discern on a fresh surface because the dark color of feldspar and quartz makes them hard to distinguish from the mafic minerals.

The quartzofeldspathic granulites differ mineralogically from the pyroxene granulites in that they contain fairly abundant quartz and moderate amounts of K-feldspar, first generation[1] garnet, and very little clinoproxene. Biotite is common, and green hornblende is occasionally present. The K-feldspar is usually untwinned but occasionally shows a wavy extinction which is interpreted as incipient microcline twinning.

Western area.—There are three main lithologies in the western granulite facies: pyroxene granulites, quartzofeldspathic granulites, and quartzose rocks.

The *pyroxene granulites* of the western area are massive, lacking even the faint foliation seen in the pyroxene granulites of the eastern

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[1] The term first generation is used to denote minerals formed during the first metamorphism, and second generation for those formed during the second metamorphism.

TABLE 3

Electron microprobe analyses of garnets

	px gran				qf gran						amph
	58		67		150		375	379	322C		133
	1 gen	2 gen	1 gen	2 gen	1 gen	2 gen	1 gen	1 gen	2 gen		
SiO_2	38.5	38.6	39.9	39.2	37.5	37.3	41.2	39.0	37.6		38.8
TiO_2	0.13	0.06	0.06	0.12	0.04	0.03	0.01	0.04	0.04		0.12
Al_2O_3	21.0	21.2	21.4	20.9	22.6	22.8	23.4	21.8	22.0		21.0
FeO	27.6	26.0	27.2	27.7	29.2	28.6	18.8	26.8	29.4		23.6
MnO	0.72	0.68	1.02	0.91	1.07	1.00	0.26	0.47	0.96		3.48
MgO	4.99	4.58	6.8	6.2	4.00	3.54	17.4	6.77	4.52		2.49
CaO	7.73	9.08	6.52	6.62	6.40	8.68	0.82	5.92	6.45		12.4
Total	100.6	100.2	102.9	101.5	100.8	101.9	101.9	100.7	101.0		101.8
alm	58	56	57	58	64	61	37	57	63		50
py	19	18	24	23	16	13	61	26	17		9
gro	21	25	18	18	18	24	2	16	18		33
spess	2	1	2	2	2	2	1	1	2		8

Abbreviations as in table 2.

area. Many are two-pyroxene-plagioclase rocks mineralogically similar to those in the eastern area. In some samples the hypersthene grains have exsolution lamellae of clinopyroxene parallel to (100); more rare are orthopyroxene lamellae in clinopyroxene. Biotite occurs only in the southwestern part of the western area. In some rocks hornblende is present in addition to two pyroxenes; it is brown, in contrast to the green hornblende in the eastern area.

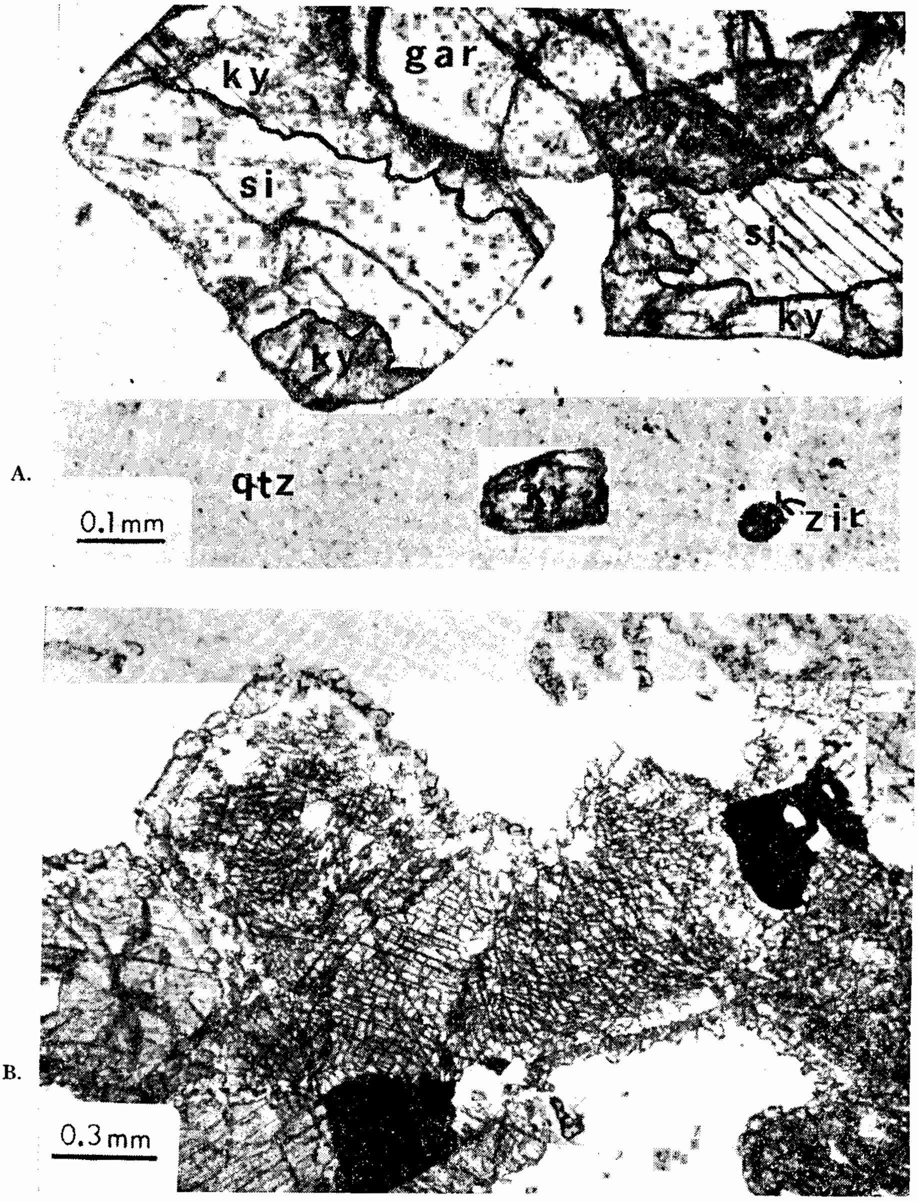
The assemblage of coarse-grained, first generation garnet and clinopyroxene occurs in the western area, both in rocks without quartz (samples 58, 60, 67) and in some that contain abundant quartz (sample 366). Some of the former are unusual looking rocks with 0.5 to 2 cm clots of red garnet intergrown with green clinopyroxene in a plagioclase matrix. In the quartz-bearing samples, the quartz and garnet are frequently in a coarse dactylitic intergrowth. Where garnet and clinopyroxene coexist in hornblende granulites, the garnet-rich portions have a patchy distribution, and there is some indication that the garnet-clinopyroxene assemblage has replaced hornblende, hypersthene, and plagioclase. The plagioclase compositions (An_{25} to An_{57}) have a larger range than in the eastern area; the more sodic varieties occur in samples with abundant garnet.

There are bands and lenses of coarse-grained pyroxenite in the pyroxene granulites at a few localities in the western area. They are made up of more than 90 percent hypersthene and less than 10 percent clinopyroxene. The bands range from 1 cm in width to about 10 to 15 cm, and the hypersthene grains average 3 to 4 mm in diameter. The clinopyroxene grains are smaller, less than 1 mm.

The *quartzofeldspathic granulites* in the western area are very different from those in the eastern area, partly due to differences in metamorphism, partly perhaps to different origins. As in the eastern area, their composition is highly variable. The western rocks, however, contain much more quartz (up to 40-50 percent), tend to be finer grained (0.5-2 mm as compared to 1.5-5 mm in the eastern area), and most lack the very dark color of the eastern rocks. Where K-feldspar is abundant, it occurs in grains of coarse mesoperthite in which the K-feldspar and plagioclase appear to be about equal in abundance, although in some K-feldspar forms only about 35 to 40 percent of the feldspar. The width of the exsolution lamellae varies from about 35 to 200 microns and is widest where the proportions of K-feldspar and plagioclase are approximately equal. Mesoperthite bearing rocks which show some crushing contain small discrete grains of plagioclase and orthoclase, probably recrystallized from crushed mesoperthite. The plagioclase in the mesoperthites is oligoclase; in the rocks that contain only minor K-feldspar, the plagioclase is oligoclase or sodic andesine. The mafic minerals are hypersthene and/or garnet, but a few samples also contain clinopyroxene. Much of the hypersthene is corroded. The accessories include magnetite, ilmenite, rutile, apatite, and zircon.

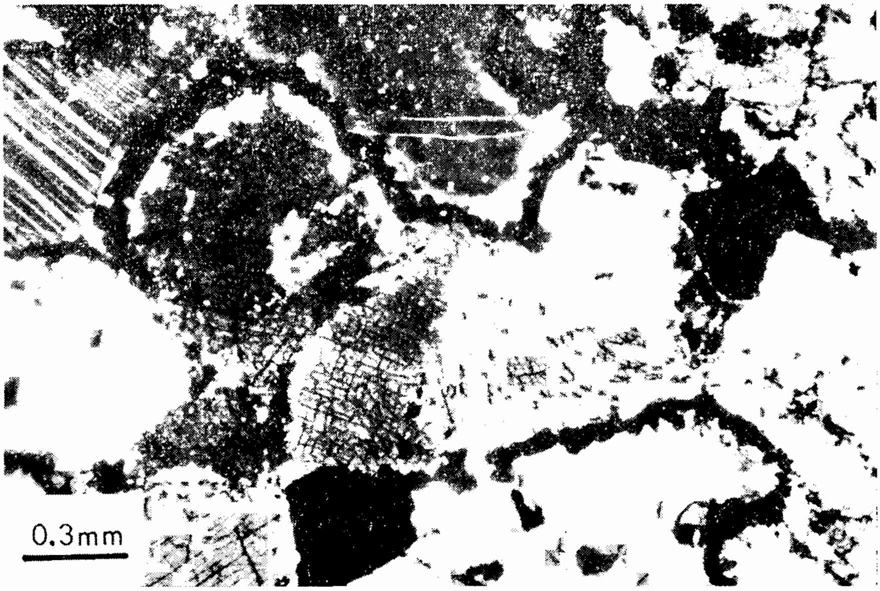
Quartzose rocks occur only in the western area of the granulite facies terrain. Most are kyanite-quartz rocks (up to 40 percent kyanite) with or

PLATE 1

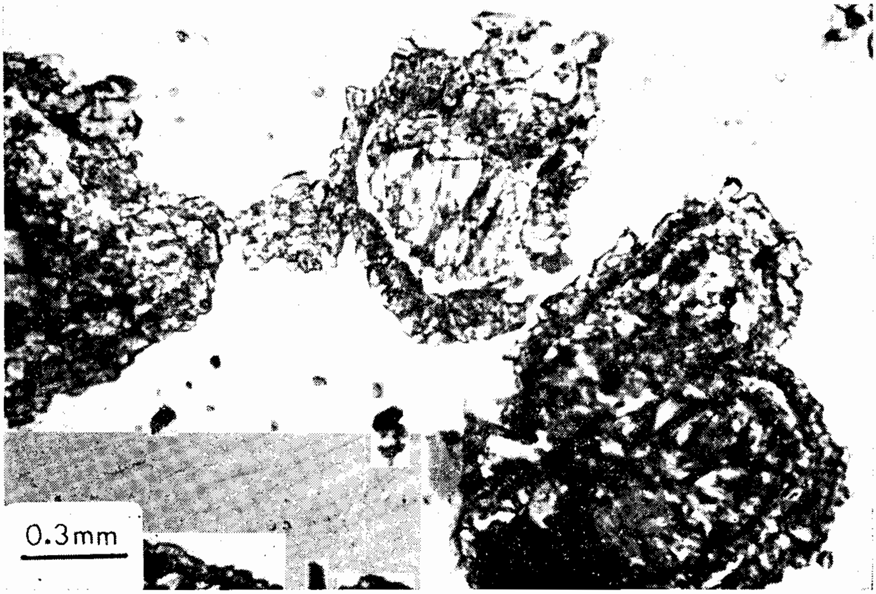


A. Sillimanite pseudomorphed in part by kyanite. Sillimanite in grain on left (approx horizontal cleavage) and in grain on right (diagonal cleavage) have been replaced by small grains of kyanite around margins as indicated. ky—kyanite; si—sillimanite; gar—garnet; qtz—quartz; zir—zircon. Sample 90; plane polarized light.

B. Garnet coronas separate hypersthene from plagioclase. There are small grains of quartz between the hypersthene and garnet in places. Sample 325a; plane polarized light.



C.



D.

C. Same as A, crossed polarizers. Note the zoning adjacent to the garnet corona in the plagioclase grain at top center.

D. Wide garnet coronas. Corona near top center surrounds hypersthene, with fine-grained clinopyroxene and quartz between the hypersthene and garnet. Corona on left surrounds a symplectite of clinopyroxene and quartz, with a remnant of hypersthene at edge of photograph. Two adjacent coronas near lower right surround a complex intergrowth of clinopyroxene, quartz, biotite, and hornblende, with a coarser-grained hornblende and an opaque mineral near lower edge. Sample 43b; plane polarized light.

without garnet, but there are also rocks consisting entirely of garnet (40 percent of rock) and quartz, with accessory zircon. Phlogopite occurs in some of the kyanite quartzites and is usually accompanied by a small amount of plagioclase, orthoclase, or very fine perthite. Rutile is present in most of the kyanite quartzites, graphite in a few, and zircon and hematite are common accessories. As graphite and hematite are not compatible, it is probable that the hematite is a result of surface oxidation of magnetite during weathering.

In most of the quartzose rocks the kyanite occurs as aggregates with square or elongate outlines. Within the aggregates the grains are in apparently random orientation. The shapes of the aggregates suggest they are pseudomorphs after sillimanite, and in two thin sections from different localities sillimanite is preserved in the center of some of the kyanite aggregates (pl. 1-A). In these same samples sillimanite occurs also as small euhedral grains. In some rocks there are solid bands or veins of fine-grained kyanite up to 1 cm wide.

Zincian spinel occurs as an accessory in kyanite quartzite in two localities; at one the spinel is magnesian ($Ga_{48}Sp_{36}He_{16}$) and is colorless (table 1, sample 316), at the other it is more iron-rich ($Ga_{45}Sp_{19}He_{36}$) and is pale green (sample 214, similar to 316 except for the color of the spinel). The colorless spinel appears to be in equilibrium with quartz, but a kyanite-iron oxide reaction rim has formed between quartz and the green spinel. Sample 55A (table 1) has a few grains of zincian staurolite (3.7 percent ZnO). In this sample the kyanite is in single lath-shaped grains rather than as sillimanite pseudomorphs.

Discussion of first metamorphism.—Several lines of evidence show that the assemblages now present in the Baltimore Gneiss are metamorphic rather than igneous. The distribution coefficient K_D(Fe-Mg) for coexisting clino- and orthopyroxene from this area ranges from 0.51 to 0.66 with an average value of 0.61. This value would be slightly lower if ferric iron had been determined. Kretz (1963) has shown that K_D is about 0.73 for igneous rocks and 0.54 for metamorphic rocks. Bhattacharya (1971) makes a distinction between igneous and metamorphic orthopyroxenes on the basis of percentage ($MgO + FeO + Fe_2O_3$) versus Al_2O_3. The orthopyroxenes of this area clearly fall in the metamorphic field on such a plot. Further evidence that the assemblages are metamorphic is given by the absence of olivine from all mafic granulites, even though most are olivine normative, and two samples (60 and 67) also have a small amount of nepheline in the norm. The metamorphic textures and mineral assemblages of this area contrast with rocks containing similar coronas in the Adirondacks, where metagabbros retain ophitic texture and some igneous minerals (Buddington, 1952, 1963; de Waard, 1970; Whitney and McLelland, 1973). (The metagabbros of the Adirondacks are, in many respects, similar to the post-granulite facies diabase dikes of the West Chester prong.)

Low pressure minerals are absent from the assemblages observed in this study. The absence of both olivine and spinel from rocks of undersaturated basaltic composition (samples 58, 60, 67) indicates pressures above the transition from low- to intermediate-pressure granulites (Green and Ringwood, 1967). No cordierite was found anywhere in the area, rather the alternate mineral assemblage garnet + sillimanite (now mostly kyanite) occurs in the quartz-rich rocks.

In contrast to the lack of low-pressure minerals, the high pressure assemblage clinopyroxene-garnet occurs in both mafic and felsic rocks in the western part of the area (samples 58, 60, 67, 270A, 366). Green and Ringwood (1967), in experimental work on the basalt to eclogite transition, have established the P-T conditions at which the reaction

$$\underset{\text{orthopyroxene}}{4(Mg,Fe)SiO_3} + \underset{\text{anorthite}}{CaAl_2Si_2O_8} = \underset{\text{garnet}}{(Mg,Fe)_3Al_2Si_3O_{12}} + \underset{\text{clinopyroxene}}{Ca(Mg,Fe)Si_2O_6} + \underset{\text{quartz}}{Si0_2} \quad (1)$$

takes place for rocks of various basaltic compositions. For alkali basalts reaction (1) proceeds to the right at lower pressures than it does for quartz tholeiites, so that the garnet-clinopyroxene assemblage is stable for moderately undersaturated basaltic compositions at pressures between the two. The appearance of garnet in saturated rocks of basaltic composition marks the transition from intermediate-pressure granulites to high-pressure granulites. This transition occurs at lower pressures in rocks with a low Mg/Fe ratio than it does in more magnesian compositions. Binns (1965b) and de Waard (1970) also noted the dependence of the garnet-clinopyroxene association on the iron content of the rocks.

Since both the silica saturation of the rocks and the Mg/Fe ratio are important in stabilizing the garnet-clinopyroxene assemblage, the rocks of this area that fall below the anorthite–garnet join of an ACF diagram are shown on a diagram with normative quartz, or olivine + nepheline, plotted against $Mg/(Mg + Fe^{2+})$ (fig. 4). On this diagram, assemblages containing two pyroxenes + plagioclase can be separated from those that contain clinopyroxene + first generation garnet + plagioclase ± hypersthene. It should be emphasized that figure 4 applies to the coarse-grained mineral associations that formed during the first metamorphism in the Baltimore Gneiss and not to the later coronas. The compositions of rocks that contain garnet coronas will be discussed later.

The rocks from the western area that contain large clots of intergrown garnet and clinopyroxene (samples 58 and 60) fall far below and to the left of the solid line in figure 4. They are not only very rich in iron, but one is also undersaturated enough to contain nepheline in the norm. The garnet-clinopyroxene assemblage would be stable at moderate pressures in rocks of this composition. Sample 67 is also undersaturated enough to contain nepheline in the norm, but it is much more magnesian than samples 58 and 60. It contains garnet, two pyroxenes, and brown hornblende. The assemblage garnet-clinopyroxene appears to be in a reaction relationship with hypersthene, hornblende, and plagioclase. The pressure required to stabilize garnet-clinopyroxene in this rock was probably considerably higher than that required in samples 58 and 60. Sam-

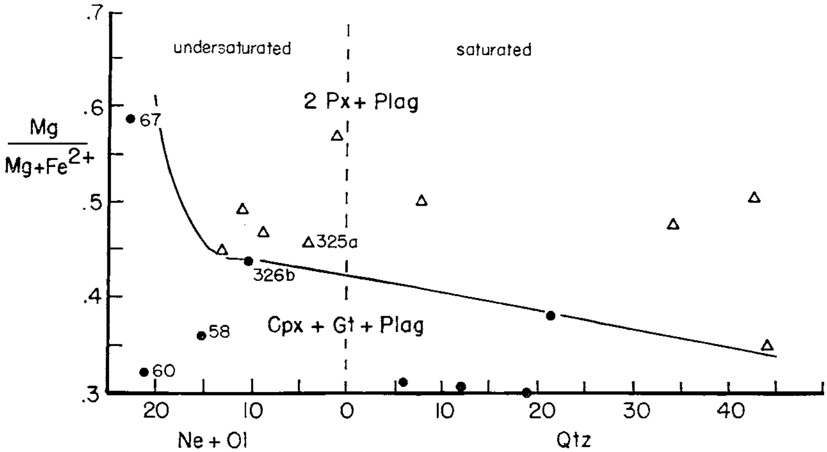


Fig. 4. Diagram with Mg/(Mg + Fe^{2+}) plotted against degree of silica saturation as evidenced by normative nepheline and olivine or normative quartz. Those rocks of this area that contain the assemblage clinopyroxene + garnet can be separated from those in which this assemblage does not occur. Solid circle: cpx + gt + plag ± hy; open triangle: 2 pxs + plag.

ples 325a and 326b are particularly interesting, as they are from immediately adjacent localities, not more than 100 m apart. Sample 326b has abundant primary garnet, while 325a has none (table 1). In other respects they are very similar except that the plagioclase in sample 326b (An 30) is more sodic than that in sample 325a (An 40), a difference to be expected if anorthite and hypersthene have reacted to form clinopyroxene and garnet (reaction (1)). Although these rocks plot very close to each other on an ACF diagram and would be expected to contain 2 pyroxenes + plagioclase and no garnet, there is sufficient difference in their positions on figure 4 to explain the presence of garnet in 326b.

The garnet–clinopyroxene assemblage is found in olivine–nepheline normative rocks with Mg/(Mg + Fe^{2+}) as high as 0.585 (sample 67), in olivine–hypersthene normative rocks with a ratio as high as 0.435 (sample 326b), and in quartz–normative rocks with a ratio as high as 0.38 (sample 270A). A comparison of these values with the data of Green and Ringwood (1967) for various basaltic compositions indicates that P-T conditions in this area must have been intermediate between those estimated by them for the first appearance of garnet in quartz tholeiites with Mg/(Mg + Fe^{2+}) = 0.10 and those with a ratio = 0.61. This would indicate a P-T gradient in this area near the lower limit of the transition from intermediate pressure granulites to high pressure granulites (Green and Ringwood, 1967). The absence of clinopyroxenes + garnet in mafic rocks of the eastern area is probably due to compositional control; all these samples plot above the line in figure 4. Minor clinopyroxene is associated with garnet and quartz in felsic rocks of the eastern area that plot below the line (samples 14 and 64), so that the separation into two fields on figure 4 holds for the entire granulite facies area covered in this study. At higher pressures the composition field of two pyroxenes plus plagioclase would contract, and the field containing garnet plus clinopyroxene would expand.

The compositions of the garnets analyzed by microprobe are listed in table 3 and plotted on figure 5. Proportions of the end members almandine, pyrope, and grossularite were calculated for additional garnets from measurements of cell dimensions and refractive indices (Winchell, 1958), and these are also plotted on figure 5. Most of the garnets represented on figure 5 are first and second generation garnets from the granulite facies rocks, but for comparison three garnets from amphibolite facies rocks are also plotted, two from the area of amphibolite and migmatite (fig. 2) and one from the mylonite zone along the Cream Valley fault (fig. 2). The garnet compositions fall into three groups: groups 1 and 2 include all the granulite facies garnets, as well as the corona garnets in the granulite facies rocks; group 3 contains the amphibolite facies garnets and one second generation garnet from a completely retrograded granulite. All the garnets from the quartz-rich rocks and most of those from the quartzofeldspathic granulites of the western area fall in group 1. Both the most iron-rich (Alm_{70}) and the most magnesium-rich (Py_{61}) garnets are in this group, and both are from quartz-rich rocks containing kyanite. The garnets from the western pyroxene granulites, the eastern quartzofeldspathic granulites, and all the corona garnets fall in group 2. The differences in composition between group 1 garnets and first generation garnets in group 2 probably reflect differences in host rock compositions.

The compositions of the second generation garnets will be discussed in the section on corona formation and the second metamorphism.

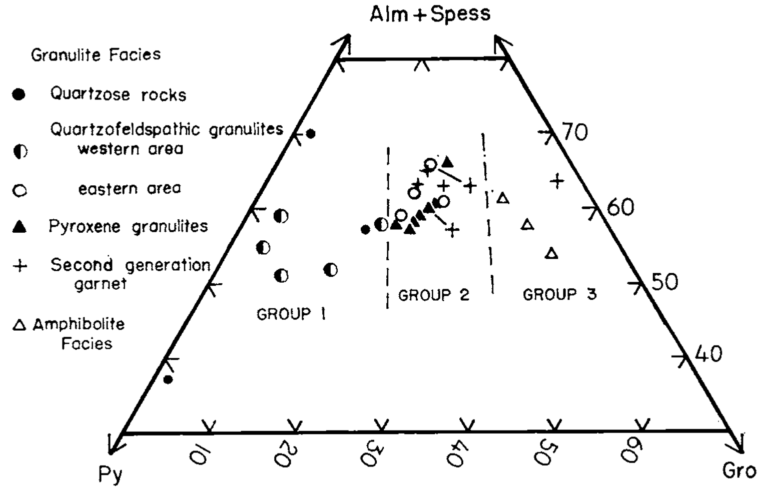


Fig. 5. Garnets of the Baltimore Gneiss. Short lines connect first and second generation garnets from the same rock. See discussion in text on groups 1, 2, and 3.

The brown color of hornblende has been attributed to a high titanium content (Deer, 1938; Binns, 1965a). Analyses of a brown hornblende from the western granulite facies, a brownish green hornblende and green hornblende from the eastern granulite facies, and a green hornblende from the area of amphibolites and migmatites tend to confirm the importance of titanium in producing a brown color (table 2). The titanium content generally increases with increasing temperatures of metamorphism (Leake, 1965; Binns, 1965a; Raase, 1974), although the composition of the rock may have a large effect on the titanium content of the hornblende (Engel and Engel, 1962; Bard, 1970). The alkali content is thought by Binns (1965a) and Bard (1970) to be a more useful indicator of grade. The alkali content of the brown hornblende from the western granulite facies is unusually high, and this together with the high titanium content suggests that the brown hornblendes of the western area crystallized at higher temperatures than the green hornblendes of the eastern area.

The presence of mesoperthite in the western area also suggests that these rocks crystallized at higher temperatures than those in the eastern area where two feldspars are present. Curve 5 of figure 6 is the Ab-Or critical curve from Morse (1970). The curve intersects the P-T gradient for this area deduced from the data of Green and Ringwood (1967) (fig. 6, curve 7) at 800°C. Curve 5 gives a minimum temperature for the boundary between the eastern and western areas, because the position of the critical line is shifted to higher temperatures with increasing An content (Morse, 1968, 1970); its position is not known for high pressures. According to Morse (1968) the top of the solvus for a feldspar of composition $Or_{29.6}Ab_{62.2}An_{8.2}$ at 500 bars P_{H_2O} lies at 920° ± 5°C. If extrapolated to higher pressure with the same slope as the An-free critical line, the line for An_8 would cross the P-T gradient for this area (curve 7) at 14 kb, 1170°C. The An content of plagioclase in some mesoperthites from this area is as high as An_{22} giving a bulk composition for the mesoperthite of about An_{13}. Unless the slopes of critical curves for increasing An contents are steeper and approach the An-free critical line at high pressures, the temperatures deduced from these granulites would be unreasonably high, well above the basalt solidus.

Mysen and Heier (1972) and Wood and Banno (1973) have developed geothermometers based on the compositions of coexisting pyroxenes and garnet. The empirical formula of Wood and Banno based on the compositions of coexisting clinopyroxene and orthopyroxene gives temperatures between 800° and 825°C for the rocks from this area in which these minerals were analyzed. The data of Mysen and Heier (1972), based on the distribution coefficient K_D(Fe-Mg) cpx-gar, give temperatures of about 600° to 700°C. These latter temperatures seem too low, especially in the western area where garnet–clinopyroxene rocks are closely associated with quartzofeldspathic granulites containing mesoperthite.

Brown and Fyfe (1970) conducted experiments on the partial melting of quartzofeldspathic minerals from a granite and quartz diorite mixed with varying proportions of hydrous minerals. The experiments

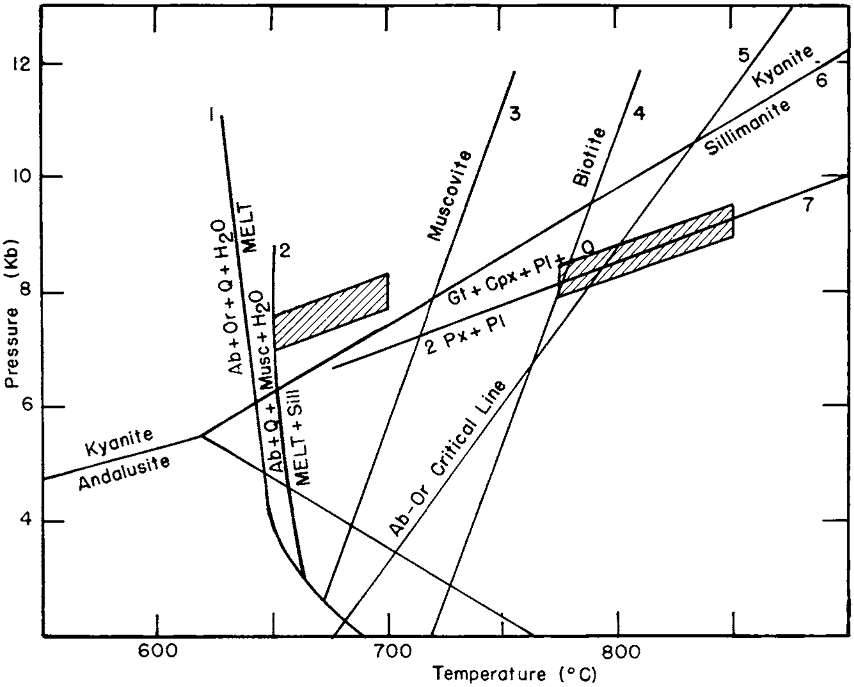


Fig. 6. Diagram showing P-T conditions inferred for the two episodes of metamorphism, the right-hand shaded area for the billion year old granulite facies metamorphism and the left-hand shaded area for the later metamorphism, which produced garnet coronas in many of the granulites and diabase dikes. The curves numbered 3 and 4 are from Brown and Fyfe (1970) and indicate beginning of melting in granitic compositions without excess water due to the breakdown of muscovite (curve 3) and biotite (curve 4). Other curves are from the following sources: (1) Tuttle and Bowen (1958); (2) Storre and Karotke (1971); (5) Morse (1970); (6) Richardson, Bell, and Gilbert (1968) and Richardson, Gilbert, and Bell (1969); (7) position for this area of reaction indicated, from data in Green and Ringwood (1967).

were anhydrous except for the water bound in the hydrous minerals, conditions analogous to those that probably existed in the Baltimore Gneiss. At the temperatures and pressures that prevailed during the metamorphism of the gneiss, the breakdown of muscovite (which may once have been present although there is no trace of it now) and biotite would permit partial melting in both dry granitic and dioritic systems (fig. 6, curves 3 and 4). The presence of a very magnesian phlogopite and lack of biotite in most of the western area is consistent with temperatures between 800° and 900°C at the P-T gradient deduced for this area. Temperatures were probably somewhat lower in the eastern area, where magnesian biotite was stable. This is again consistent with the lower temperatures already deduced for the eastern area on the basis of the hornblende compositions and the presence of two feldspars.

The quartz-rich rocks are unusual. Based on their mineralogy, most are completely devoid of alkalis, and samples without garnet also contain little calcium. It is possible that they are metamorphosed clay deposits. A mixture of kaolinite and quartz could have a composition equivalent to the quartz–kyanite rocks. Serdyuchenko (1968) has ascribed the origin of rocks of similar composition to weathering crusts of the Precambrian, which have subsequently been metamorphosed. However, the fact that all the quartzose rocks occur in a part of the western granulite facies area where biotite is lacking, mesoperthite quartzofeldspathic granulites are abundant, and in which most of the nepheline normative type rocks occur suggests a genetic association among these different rock types. Evidence has been presented for higher temperatures in this area. We postulate that the quartzose rocks represent a refractory residue left after partial melting of an originally quartz-rich sediment. At high pressures the minimum melt in the granitic ternary system (that is, qtz–ab–or) becomes enriched in albite and depleted in SiO_2. Any rock whose initial composition lies to the quartz side of the granitic minimum melting composition in this system would have quartz left after all the feldspar was melted, and the temperature required to melt the remaining quartz increases sharply toward the quartz apex of the triangle. Winkler and von Platen (1961) and Winkler (1967) have conducted experiments with the partial melting of graywackes at $P_{H_2O} = 2000$ bars and temperatures up to 810°C. The graywackes were first converted to mineral assemblages comparable to those in high grade gneisses. The gneisses all contained quartz, plagioclase, K-feldspar, cordierite, biotite, and opaques. Two of the four specimens also contained sillimanite. When the samples were about two-thirds melted, the two rocks that were originally quartz-rich (47 and 52 percent quartz) had unmelted residues consisting of quartz, cordierite, and opaques (plus sillimanite in the one that originally contained it). This residue is similar in composition to some of the quartz–kyanite–garnet–(rutile) rocks. Less Mg and Fe would give rocks similar in composition to the quartz–kyanite–spinel rocks, and more Ca would produce a composition similar to the quartz–garnet rocks.

Temperatures in the western granulite facies area ranged from about 800° to 850°C, as deduced from the compositions of coexisting orthopyroxene and clinopyroxene (Wood and Banno, 1973), the presence of mesoperthite, and absence of biotite, at pressures of 8 to 9 kb, as indicated by the stability of clinopyroxene–garnet–quartz (right hand shaded area on fig. 6). These conditions are consistent with sillimanite being the stable aluminosilicate polymorph during the granulite facies metamorphism. In the eastern granulite facies area, where biotite was stable throughout the area and two feldspars formed rather than mesoperthite, temperatures were a little lower.

SECOND METAMORPHISM

Description.—In many of the granulite facies rocks, the only effect of the second metamorphism was the formation of garnet coronas on mafic minerals. Some of the quartzofeldspathic granulites of the eastern granulite facies were more extensively recrystallized.

In both the eastern and western pyroxene granulites, garnet coronas rimming hypersthene, hornblende, biotite, opaque minerals, and occasionally clinopyroxene and apatite are a striking feature of every thin section (pl. 1-B,C,D). The coronas vary in width from 0.03 to 0.25 mm. Where they surround hypersthene, there is usually a zone containing an intergrowth of small grains of quartz and pale green clinopyroxene between the hypersthene and the garnet. Microprobe analyses show there is some quartz, sodic plagioclase, and K-feldspar intergrown with the garnet, and these inclusions contribute to the cloudy appearance characteristic of the corona garnets. Plagioclase grains adjacent to but outside the garnet coronas show a narrow zone of lower calcium content (pl. 1-C). In the western pyroxene granulites, the garnet coronas occupy a larger volume in rocks without first generation garnet than in those in which first generation garnet is an important constituent. Large, clear, first generation garnets in the western pyroxene granulites are in places surrounded by well-define coronas of cloudy garnet. In some samples additional cloudy garnet similar to the garnet of the coronas is found replacing plagioclase along cleavage planes.

The western quartzofeldspathic granulites have garnet coronas similar to those in the pyroxene granulites, most often found around hypersthene and magnetite. In addition the hypersthene is frequently uralitized and corroded.

The eastern quartzofeldspathic granulites show a complete gradation from those in which the only effect of the second metamorphism was the development of garnet coronas to those that are completely retrograded to amphibolite facies assemblages. In this gradational sequence, the garnet coronas first become thicker (up to 0.5 mm) and lose their cloudy aspect. Instead they contain microscopically visible small felsic inclusions. These thick garnet coronas in places surround symplectites of biotite–quartz, clinopyroxene–quartz, or biotite–clinopyroxene–quartz rather than the original hypersthene (pl. 1-D), and the coronas are often penetrated by laths of new biotite. In some rocks the coronas have developed further into moderate-sized, subhedral to euhedral garnets with only a hint of the original rim configuration. These are clearly a second generation of garnet: the same thin sections that contain these moderate-sized, euhedral garnets also contain very large garnets (never euhedral) typical of the granulite facies quartzofeldspathic rocks (pl. 2-A). The rocks with euhedral second-generation garnets have abundant widely distributed biotite, and most or all of the hypersthene has been destroyed. These intensely retrograded quartzofeldspathic granulites are intimately associated in the field with less altered granulite facies assemblages and cannot be mapped separately.

The main effect of the second metamorphism on the quartzose rocks was the inversion of sillimanite to kyanite, as evidenced by the kyanite pseudomorphs after sillimanite. Kyanite rims on green spinel and perthite rims on kyanite pseudomorphs after sillimanite appear to have grown during the second metamorphism.

PLATE 2

A.

B.

A. Two generations of garnet. Large grain in upper left shows about half of a first generation garnet. Small grains with abundant small inclusions at right center are second generation garnets. Remaining minerals are quartz, biotite, plagioclase, and apatite. Sample 150; plane polarized light.

B. Metadiabase with ophitic texture. Black areas are garnet coronas around edges of plagioclase laths. Some laths are completely replaced by garnet. The igneous pyroxene is mostly replaced by a fine-grained aggregate of pyroxenes and a pale-brown amphibole. Sample 8; crossed polarizers.

Diabase dikes, unaffected by the first metamorphism, cut the granulite facies rocks. The dikes are clearly later than the granulite facies metamorphism: they have chilled borders, are discordant to lineations in the granulites, and retain some igneous minerals, in contrast to the pyroxene granulites of similar composition which were completely recrystallized during the first metamorphism. The ophitic texture of the dikes is occasionally quite coarse, with plagioclase laths several millimeters in length. The plagioclase laths have recrystallized to aggregates of small plagioclase grains of much lower An content (calcic oligoclase or andesine) than the original plagioclase (labradorite–bytownite) which is still preserved in some of the diabase. Remnants of the original igneous augite, brownish in thin section, survive in much of the diabase, surrounded by small grains of pale green clinopyroxene or pale brown or greenish hornblende. Minor biotite is found in some rocks. One sample contains large phenocrysts of olivine surrounded by radiating laths of orthopyroxene. Every sample has abundant small garnets around the margins of the plagioclase laths; some laths are almost completely replaced by garnet (pl. 2-B).

Corona formation and the second metamorphism.—Garnet coronas are present around ferromagnesian minerals in almost every granulite facies rock as well as in all the diabase dikes with recognizable ophitic texture. Where the garnet rims orthopyroxene, intergrowths of clinopyroxene and quartz are common between the garnet corona and the central orthopyroxene. Plagioclase grains adjacent to the coronas have narrow margins which are less calcic than the grain centers. This indicates a reaction similar to that shown by reaction (1) (p. 667). Microprobe analysis indicates there is frequently minor oligoclase and K-feldspar intergrown with the garnet, apparently by-products of the breakdown of anorthite. Attempts to balance formula (1) using the chemical compositions of the various minerals involved lead to the conclusion that the corona associations are always more iron rich than any of the minerals they surround except magnetite. Rarely, the margins of first generation green clinopyroxene grains are paler in color than the centers, and microprobe data indicate they may have contributed iron to the garnet coronas. Compositional zoning in the orthopyroxenes has not been detected. It is possible that ore minerals in the rocks have contributed iron to coronas around other minerals, but putting magnetite on the left side of equation (1) requires that quartz be put on the left side also, which is contrary to the textural evidence. The apparent excess of iron in the coronas is not understood.

Although the garnet coronas are found around a number of different minerals the garnets in any one rock differ only slightly from one another in composition. It is apparent that there was intergranular diffusion of ions, particularly Mg^{2+} and Fe^{2+}, involved in the growth of the coronas to give garnets of nearly the same composition around such minerals as hypersthene, magnetite, and apatite. In those granulite facies rocks that contain two generations of garnets, the second generation garnets are always more calcium-rich than the first generation garnets in the same rock (fig. 5). The corona garnets never contain as much calcium as the garnets in the amphibolite facies rocks, but the moderate-sized second generation garnets from a retrograded granulite plot with the calcium-rich garnets from amphibolite facies rocks on figure 5. A comparison of the garnet compositions in figure 5 with the plot given by Coleman and others (1965) shows that most of the granulite facies garnets of this study plot within the range they show for granulite facies garnets, but the amphibolite facies garnets of this study plot with garnets from eclogites in glaucophane schists.

Martignole and Schrijver (1973) have found that the development of garnets in rocks of the anorthosite-charnockite suite in the Adirondacks and Canada was dependent on $Mg/(Mg + Fe^{2+})$ and normative $Ab/(Ab + An)$, no garnets occurring in rocks with high values for these ratios. In contrast, in the Baltimore Gneiss garnet coronas are found in almost every granulite facies rock. Many of these rocks would fall in the "no garnet" field of Martignole and Schrijver (1973). The only samples without garnet coronas are the quartzose rocks and an occasional quartzofeldspathic granulite without hypersthene from the western area. Except for the kyanite quartzites almost every rock without garnet coronas already contained first generation garnet as the only ferromagnesian mineral at the time of the second metamorphism. The kyanite quartzites have no ferromagnesian minerals except for a trace of zincian spinel.

The garnet–clinopyroxene–quartz association of the coronas in rocks of almost all compositions suggests that the coronas formed well above the low temperature extrapolation of the transition from intermediate pressure to high pressure granulites, (that is, well above curve 7, fig. 6), at higher pressures or lower temperatures than the granulite facies assemblages. The distribution of Fe and Mg between coexisting garnet and clinopyroxene of the coronas as compared to that of coexisting first generation garnet and clinopyroxene indicates somewhat lower temperatures for corona formation than for the granulite facies metamorphism (Banno and Matsui, 1965; Saxena, 1968; Mysen and Heier, 1972). The two analyzed samples (58 and 67) that contain both first and second generation garnet and clinopyroxene have an average $K_{D\ Fe\text{-}Mg}$ (gar–cpx) value of 5.4 for the first generation association and 7.1 for the second generation association. However, the most convincing evidence for lower temperatures during corona formation is the progression in the quartzofeldspathic granulites of the eastern area from narrow rims in the least retrograded rocks to wide rims and finally to two generation of garnets in the most retrograded rocks.

Green and Hibberson (1970) have postulated that garnet coronas in the "axial" Caledonide zone represent cooling histories at high pressure of various intrusives emplaced in the pre-Caledonide metamorphic lower crust rather than high pressure metamorphism during the Caledonian. Similar conclusions have been reached by others (Griffin and Heier, 1973; Martignole and Schrijver, 1970, 1971, 1973; Whitney and McLelland,

1973) for corona-bearing rocks in Norway, the southern Laurentian Uplands in Canada, and in the northern Adirondacks. This cannot be the explanation in the present instance, as the coronas have formed not only in intrusive diabase dikes but in all the granulite facies rocks. The diabase dikes are clearly later than the granulite facies metamorphism; they not only have relic igneous minerals and textures but can be seen cross-cutting and truncating lineations of the granulite facies rocks. Therefore, it seems most probable that the coronas formed in the granulite facies rocks and the dikes during a second regional metamorphism. Although the minerals of the coronas represent high pressure granulite facies assemblages, they formed at the same time that other rocks in the area were being retrograded to amphibolite facies assemblages, as shown by the disappearance of granulite facies assemblages in those rocks in which second generation garnets are best developed. The controlling factor appears to have been the availability of water. Where the rocks were dry the only effect of the second metamorphism was the formation of coronas in both granulites and the diabase dikes. Where water was available the rocks were more completely recrystallized to amphibolite facies assemblages. This is the same explanation that Gjelsvik (1952) put forward for laccolithic bodies of metamorphosed dolerite in Norway which have corona mineral assemblages in the centers, stable at P-T conditions between granulite and eclogite facies, but whose borders have assemblages typical of the amphibolite facies. Buddington (1963) used similar arguments for the high grade assemblages in coronas of gneissic metadiabase dikes in amphibolite facies rocks in the Adirondacks.

At the P-T conditions during corona formation the pressure was high enough to stabilize the garnet–clinopyroxene–quartz assemblage rather than hypersthene–anorthite in anhydrous rocks of nearly all compositions. The temperatures were those in which amphibolite facies assemblages are stable in hydrous rocks. Since no muscovite has formed, even in the most retrograded rocks, temperatures must have been in the upper part of the amphibolite facies. An estimate of pressure involves extrapolation of curves of high pressure-high temperature experiments to much lower P-T conditions and therefore may be in error. An estimate based on the extrapolation of the curve for stability of high pressure granulites (Green and Ringwood, 1967) would be about 7 or 8 kb at temperatures of 650° to 700°C (left hand shaded area of fig. 6). These conditions would be consistent with the inversion of sillimanite to kyanite in the quartzose rocks at the time of corona formation. They are also quite close to the maximum P-T conditions inferred for early Paleozoic metamorphism in the Philadelphia area on the basis of studies of the Wissahickon Formation by Wyckoff (1952) and O'Connor (ms).

TIMES OF METAMORPHISM

Uranium-lead determinations on zircons (Grauert, Crawford, and Wagner, 1973; Grauert, Wagner, and Crawford, 1974) from the granulite facies terrain, which underlies most of the West Chester prong, give values that lie near the upper end of a chord that has upper intersections with the concordia curve between 980 and 1050 m.y. and a lower intersection at approximately 450 m.y. Zircons from the amphibolite facies rocks south of the granulite facies terrain are morphologically distinct from those in the granulites, have lower uranium concentrations, and give lower apparent U-Pb ages. Grauert and others (1973, 1974) consider it unlikely that the rocks from which these zircons came were ever granulites. Zircons from a sample of the granulite facies Wilmington Complex, a few kilometers south of the Baltimore Gneiss but separated from it by a belt of high-grade Wissahickon Schist (fig. 1), give a nearly concordant age of 440 m.y. (Grauert and Wagner, 1974, 1975), believed to be the date of the granulite facies metamorphism of the Wilmington Complex. We believe that the 1000 m.y. age indicated by the granulite facies zircons dates the pervasive granulite facies metamorphism of the Baltimore Gneiss which completely recrystallized the rocks and either reset older zircon ages or produced new zircons. The second metamorphism caused an episodic event of lead loss in the granulite facies zircons, produced coronas in the granulites and diabase dikes, and completely retrograded some of the granulites to amphibolite facies assemblages. This event we correlate with the 440 m.y. granulite facies metamorphism of the Wilmington Complex, which was probably also the time of metamorphism of the Wissahickon Schist to high-grade amphibolite facies assemblages. Lapham and Root (1971), in a summary of age determinations in Pennsylvania, conclude that there was plutonism, metamorphism, and deformation during the Taconic (425-460 m.y.) and Acadian (320-380 m.y.) thermal events which affected Piedmont rocks. Amenta (1974) and O'Connor (ms) also present evidence for at least two periods of metamorphism during the Paleozoic. It is probable that both of these Paleozoic events had some effect on the rocks described in this study, but it is not possible to distinguish two separate periods of metamorphism subsequent to the billion year old granulite facies event.

SEQUENCE OF EVENTS IN THE BALTIMORE GNEISS

1. Rocks of unknown age, some of which were probably olivine basalts or gabbros and others of which were sediments, were completely recrystallized to the granulite facies 1000 m.y. ago. P-T conditions were higher in the western part of the area than in the eastern part but ranged from approximately 775° to 850°C, 8 to 9 kb, throughout.

2. Uplift and erosion of the Precambrian rocks took place.

3A. Sediments of the Glenarm Series were deposited unconformably on the Baltimore Gneiss.

3B. Diabase dikes intruded the Precambrian rocks at some period after the 1000 m.y. metamorphism and before the 440 m.y. metamorphism. Although no pre-Triassic diabase dikes are found in the Glenarm Series, the high-grade part of the Wissahickon Formation contains layers of amphibolite of basaltic composition, so that, although the dikes may be Precambrian, a syn- or post-Glenarm age cannot be ruled out.

4. During the Taconic orogeny (~440 m.y.) the area was subjected to intense deformation and metamorphism. At that time garnet coronas formed in those granulite facies rocks and diabase dikes that remained dry, whereas those rocks to which water had access were recrystallized to assemblages more typical of the amphibolite facies. Some of the amphibolite facies rocks of unknown age south of the granulite facies terrain were probably first metamorphosed at that time. This was also the time when the Wissahickon Formation was metamorphosed to the amphibolite facies and the Wilmington Complex to the granulite facies. Conditions during this second metamorphism of the Baltimore Gneiss were approximately 650° to 700°C, 7 or 8 kb.

REGIONAL IMPLICATIONS

The high pressure assemblages of both Grenville and Taconic age in the Precambrian rocks of the West Chester prong suggest that a deep level of the crust is exposed in southeastern Pennsylvania south of the Cream Valley fault. The Taconic granulite facies metamorphism of the Wilmington Complex (Grauert and Wagner, 1974, 1975) and the upper amphibolite facies metamorphism of the Wissahickon Formation, which includes kyanite–orthoclase–bearing assemblages (Wyckoff, 1952), support this conclusion. The preservation in the Precambrian rocks of high-grade assemblages from two separate periods of metamorphism allows us to examine the P-T regime at deep crustal levels at periods separated by more than half a billion years. Although pressures were nearly as high during the Taconic as they were during Grenville time (7-8 kb compared with 8-9 kb), temperatures were much lower during the Taconic (650°-700°C compared to more than 800°C during the Grenville). Apparently the geothermal gradient was steeper a billion years ago than it was 440 m.y. ago. This could be explained by higher heat flow during the earlier period, by depression of isotherms during the Taconic because of rapid subsidence, or by a combination of both these effects. If the Wissahickon were deposited as late as the Ordovician and metamorphosed to the upper amphibolite facies at 7 or 8 kb during the Taconic, then subsidence must have been very rapid. A model involving closing of the proto-Atlantic in southeastern Pennsylvania during the Ordovician could account for the observed tectonic and metamorphic history. The high-grade assemblages in both the Precambrian rocks and in the Wissahickon suggest that this area was either buried deeper, or suffered less retrograde metamorphism at some later time, than many other areas along the axis of intense Taconic deformation and metamorphism.

ACKNOWLEDGMENTS

Much of the research for this paper was done by the first author as a partial fulfillment of the requirements for the Ph.D. at Bryn Mawr College. Financial support was provided by NSF Grant GA-1160 and the Ida H. Ogilvie Bequest to the Department of Geology, Bryn Mawr College, and during preparation of the manuscript, by the Department of Geology, the University of Pennsylvania. We wish to thank William A. Crawford and Dorothy Wyckoff for help during the research and George Fisher, Bruce O'Connor, and K. Schrijver for comments and suggestions which helped improve the manuscript.

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