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EVIDENCE FROM METAMORPHIC ROCKS FOR OVERTHRUSTING. PENNSYLVANIA PIEDMONT, U.S.A.

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Abstract

In southeastern Pennsylvania the pelitic and semi-pelitic Wissahickon schist shows evidence of two superimposed metamorphic events. The first, a high-temperature (>550°C) and low-pressure (<5 kbar) event, produced andalusite- and cordierite-bearing assemblages. A second, more widespread high-temperature (550–650°C) and medium-pressure (6.5–7 kbar) metamorphism, produced kyanite- and staurolite-bearing assemblages that replaced minerals formed in the low-pressure event. The higher-pressure metamorphism probably resulted from tectonic crustal thickening owing to the emplacement of a pile of thrust slices totaling at least 15 km in thickness. Previously metamorphosed units under the thrust slices record the new metamorphic gradient superimposed on older metamorphic assemblages. Rocks that were unmetamorphosed prior to thrusting show evidence of only the later metamorphism.

Keywords: metamorphic overprinting, regional metamorphism, Pennsylvania, Piedmont, tectonic model.

Sommaire

Le schiste, pélitique ou semi-pélitique, de la formation Wissahickon a subi, dans le sud-est de la Pennsylvanie (E-U.), deux événements métamorphiques successifs. Le premier, de haute température (>550°C) et basse pression (<5 kbar), a donné des assemblages à andalousite + cordiérite. Le deuxième épisode, plus répandu, de haute température (550–650°C) et de pression intermédiaire (6.5–7 kbar) a produit des assemblages dans lesquels disthène et staurotide ont remplacé les minéraux de basse pression précédemment formés. L'événement de haute pression résulterait de l'épaississement tectonique de la croûte dû à un empilement d'écailles de chevauchement d'au moins 15 km de puissance. Les unités antérieurement métamorphisées montrent, sous cet empilement, le nouveau gradient métamorphique superposé aux assemblages originels. Les roches non-métamorphisées avant le chevauchement témoignent seulement de l'épisode plus récent.

(Traduit par la Rédaction)

Mots-clés: superposition métamorphique, métamorphisme régional, Pennsylvanie, Piedmont, modèle tectonique.

Introduction

The southeastern corner of Pennsylvania is underlain by metamorphosed sedimentary and igneous rocks that comprise the northern end of the southern Appalachian Piedmont. These rock units can be subdivided into four groups, based both on their present geographic distribution (Fig. 1) and their geological history (Crawford & Hoersch 1982). From north to south these are: 1) the Honey Brook Upland granulite- and amphibolite-facies gneisses, metamorphosed during the Grenville orogeny (Crawford & Crawford 1982). 2) Cambrian and Ordovician metasediments of the Whitemarsh, Chester and Lancaster valleys. These unconformably overlie the Honey Brook Upland and were metamorphosed after the middle Ordovician but before 360 Ma, as inferred from K/Ar ages of micas (Lapham & Bassett 1964). 3) The Glenarm terrane, which includes the Glenarm Series of pelitic and semi-pelitic schists, is underlain by marble and quartzite. The rocks lie south of the known lower Paleozoic succession and are probably metamorphosed, at least in part, during the same event as the Paleozoic rocks. This terrane also includes Grenville-age gneisses (Wagner 1972) that underlie the Glenarm succession. The Grenville metamorphism ended at about 980 Ma (Grauert *et al.* 1973). The regional metamorphism of the Glenarm Series also affected the Grenville basement (Wagner & Crawford 1975). 4) The Wilmington Complex, a group of metagreywacke and mafic metavolcanic rocks, is exposed in the southeasternmost corner of Pennsylvania and adjacent northern Delaware. A nearly concordant zircon age suggests that the granulite-facies metamorphism of these gneisses occurred at 440 Ma (Grauert & Wagner 1975).

The Wissahickon Group of the Glenarm Series consists predominantly of pelitic and quartzofeldspathic metasediments well suited for recording metamorphic conditions. Of the four groups listed above, rocks of the Glenarm

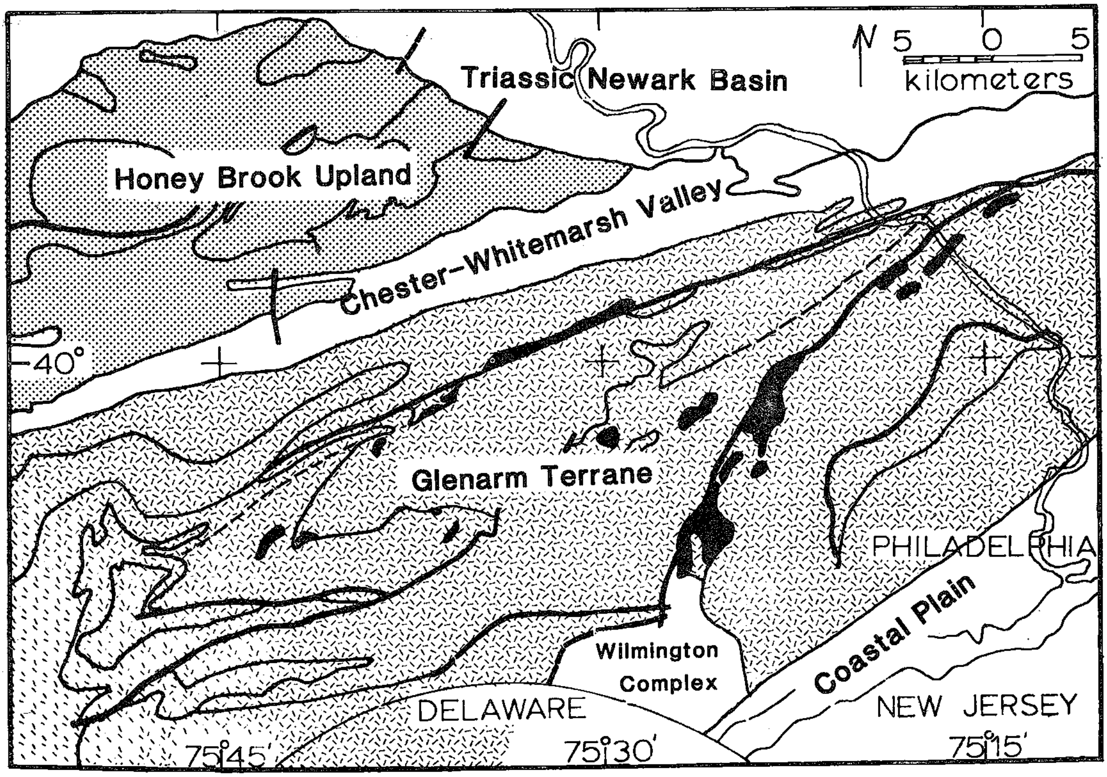

FIG. 1. Location map showing the subdivisions of the Pennsylvania Piedmont.

terrane also show the greatest variation in metamorphic grade. In the northern part of the belt of Glenarm Series rocks (Fig. 2), Wissahickon Group phyllites (Octoraro phyllite) and the Peters Creek Schist show chlorite- and biotite-zone assemblages of the greenschist facies. South of the outcrop area of Peters Creek Schist, the Wissahickon Group schists are in the amphibolite facies, with kyanite–staurolite–biotite–garnet and, further south, sillimanite-bearing assemblages (McKinstry 1949). South of the intervening belt of Grenville-age basement gneisses (Fig. 2), the metamorphic grade in the schists increases from staurolite-bearing lower-amphibolite-facies schists to granulite-facies assemblages above the second sillimanite isograd (Wyckoff 1952).

Detailed work in selected areas has shown, however, that the apparent regular increase in metamorphic grade from north to south across the Glenarm Series is the result of superimposition of at least two successive episodes of metamorphism. This is particularly evident in areas close to the contact of the Wissahickon Group schists with the Wilmington Complex granulite-facies gneisses. In this paper, we describe mineral assemblages that record an early high-temperature ($\simeq$600°C) and low-pressure ($\simeq$4 kbar) metamorphic event that has been overprinted by a later high-temperature ($\simeq$500–650°C) but high-pressure ($\simeq$7 kbar) event. The rocks that contain the diagnostic mineral assemblages occur in the Chester 15′ quadrangle, between the cities of Marcus Hook, Chester and Media and along Chester, Ridley and Crum Creeks (Figs. 2, 3).

Low-Pressure Assemblages

The Wissahickon schists along the northern and eastern margin of the Wilmington Complex are sillimanite–orthoclase–biotite–garnet migmatites. Cordierite has been identified at localities 1 to 4 (Fig. 3). At locality 1, cordierite occurs in the melanosome of a migmatite, intergrown with sillimanite and biotite. Garnet

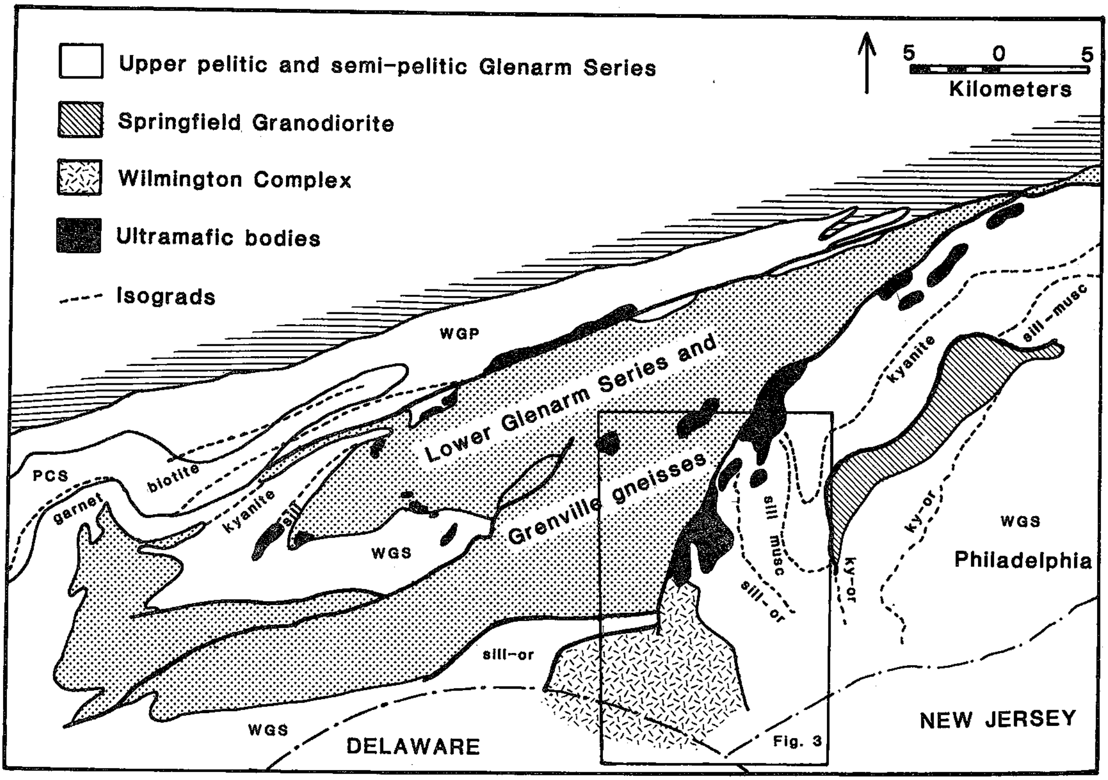

FIG. 2. Units within the Glenarm Terrane. Isograds in the Wissahickon Group schists are labeled on the high-grade side. PCS Peters Creek Schist, WGP Wissahickon Group Phyllite, WGS Wissahickon Group Schist.

also occurs in the melanosome but is now separated from cordierite by biotite–sillimanite aggregates. Orthoclase and plagioclase are concentrated in the leucosome. As all the minerals have been considerably affected by a subsequent high-pressure metamorphic event, as described below, the details of the original textures are obliterated. The effects of the later metamorphism make it impossible to determine whether cordierite and orthoclase or cordierite and garnet were in direct contact. However, the intimate mixture of aluminous melanosome and granitic leucosome on hand-specimen and thin-section scales suggests that all the leucosome and melanosome minerals were initially in chemical equilibrium. A second type of cordierite-bearing assemblage consists of granitic and trondhjemitic rocks with scattered clots of aluminous minerals, *e.g.*, sillimanite, cordierite, garnet and biotite. Antiperthitic albite and quartz compose the matrix of the trondhjemite at locality 2; orthoclase is also present in the granite at locality 3. In these samples, cordierite is the most abundant aluminous mineral, forming 10–20% of the rock. Other aluminous phases (garnet, primary sillimanite, primary biotite and minor spinel) are present in smaller amounts. The third type of cordierite-bearing assemblages was found in a sample recovered from a drill core penetrating the contact zone of the Wissahickon Group schists and the Wilmington Complex gneisses (locality 4). It is a charnockite composed of hypersthene, orthoclase, plagioclase and quartz, in addition to cordierite. In this rock, cordierite and hypersthene are invariably separated by a thin rind of plagioclase.

Northeast of the sillimanite–orthoclase–cordierite-bearing schists, along Crum Creek (Fig. 3), the Wissahickon schist consists of medium- to coarse-grained metapelites and metasiltstones with interlayered amphibolites, which may be up to tens of metres thick. Euhedral square prisms of "andalusite" up to 20 cm long, collected from outcrops along Crum Creek, are

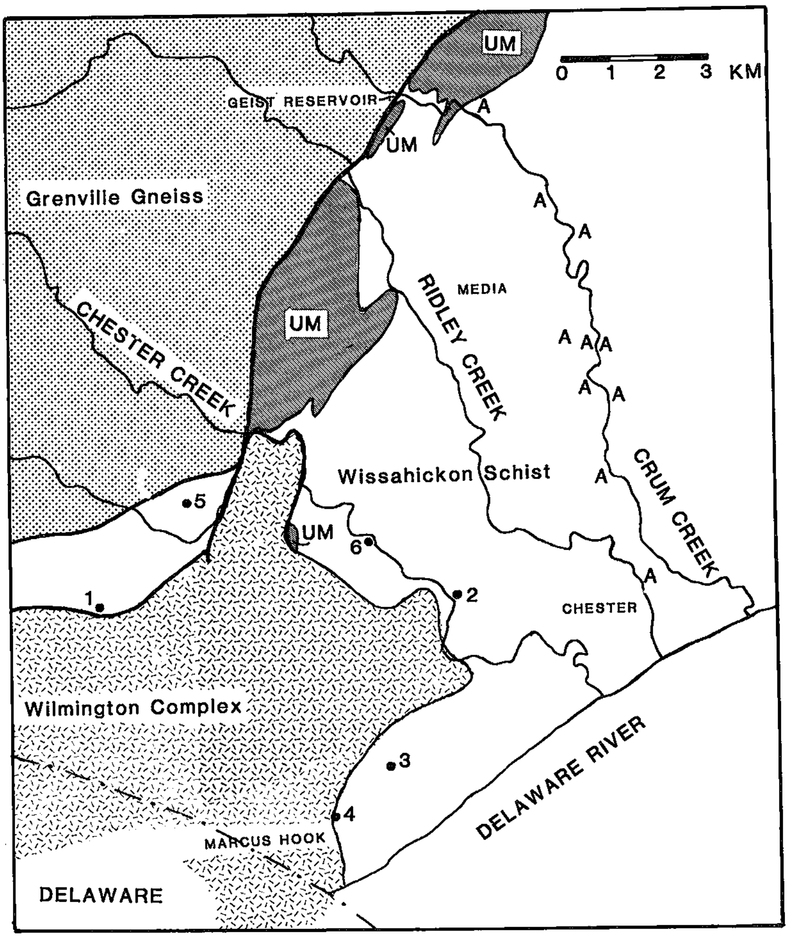

FIG. 3. Study area, part of the Chester 15′ quadrangle. Samples from localities 1 to 4 are cordierite-bearing. Localities 5 and 6 show kyanite–staurolite assemblages. Andalusite and andalusite pseudomorphs have been observed along Crum Creek at the localities marked A.

widely represented in collections of minerals from southeastern Pennsylvania. Examination of a number of these specimens shows that they are composed of randomly oriented, felted, millimetre-sized blades of kyanite. Several specimens, however, preserve the original andalusite. The one sample we have examined that contains unaltered andalusite (courtesy of A. Hyle) comes from just south of the Geist Reservoir (Fig. 3). It shows andalusite rimmed by a rind of fibrolite. Information on the exact localities at which the unaltered andalusite was collected is not available, and there are no data to suggest why some of the andalusite prisms were replaced by kyanite, whereas others were not. Along the southern half of Crum Creek, the pelitic schists locally display elongate prismatic knots 1–2 cm long on weathered surfaces. These knots are composed of random kyanite aggregates intergrown with small amounts of staurolite. The roughly square-prismatic shape of the knots and their composition suggest that the aggregates are also pseudomorphs of andalusite. All localities at which "andalusite" has been reported are marked in Figure 3.

The kyanite pseudomorphs of andalusite are set in a schist composed of quartz, plagioclase, muscovite, biotite, kyanite and staurolite, all in apparent textural equilibrium. In some of these muscovite–kyanite–staurolite schists, individual coarse grains of muscovite, or clusters of muscovite flakes, enclose needles of an aluminosilicate mineral. As the kyanite occurs in coarse blades that cut across the mica fabric and appears to be in equilibrium with muscovite, we assume that the needles are sillimanite, also relics of the early, low-pressure metamorphism, now almost entirely obliterated.

High-Pressure Assemblage

The extent of replacement of the early, low-pressure mineral assemblages by high-pressure assemblages increases from west to east across the area. In addition, adjacent outcrops may show different degrees of replacement, apparently as a function both of the amount of deformation and of availability of water. At locality 1, the migmatite-containing relict cordierite-bearing assemblages occurs as a pod or lens several metres wide surrounded by schists that show no textural or mineralogical evidence for the early metamorphic event. The details of the relationship between the two rock types cannot be ascertained owing to the sparse outcrop. At this locality, specimens that preserve the relict cordierite–sillimanite–biotite assemblages show a highly contorted fabric. Cordierite in the sillimanite–biotite layers is rimmed by secondary fine-grained sillimanite and biotite selvages; cordierite adjacent to the leucosomes is more extensively replaced by sillimanite and biotite aggregates. Garnet and sillimanite are intergrown with magnetite, occasionally in a vermicular or graphic habit. Myrmekite is abundantly developed along plagioclase–orthoclase grain boundaries. The enclosing schists are foliated, but not strongly folded, on the scale of the outcrop and contain a more hydrous assemblage characterized by abundant muscovite and lacking sillimanite and orthoclase.

At locality 2, alteration of cordierite is nearly complete. In contrast to the other localities, the sample from this locality lacks primary potassic minerals, except for a small amount of antiperthitic K-feldspar in scattered albite grains. Cordierite is replaced by a fibrous intergrowth of green biotite, sillimanite and blue to yellow pleochroic aluminous gedrite. The formation of gedrite, apparently, is a result of the low potassium content of the rock, as it was not observed in any of the other samples.

In the samples from locality 3, cordierite coexists with patches of coarse sillimanite, magnetite and hercynite. Garnet is also associated with magnetite and hercynite. The textures suggest that the sillimanite, magnetite and hercynite are derived from the cordierite and garnet in which they occur.

At locality 4, the outcrop suggests that a cordierite-bearing charnockite has intruded the granulite-facies gneisses of the Wilmington Complex. The rocks are undeformed, and both

TABLE 1A. SELECTED MINERAL COMPOSITIONS, LOW-P LOCALITIES

	(1) co	co	gt	bi	(2) co	gd	bi	(3) co	gt	bi	(4) co	hy	bi	(5A) gt core	gt rim	bi
SiO_2	50.1	49.0	38.7	36.7	50.0	40.0	38.0	49.6	37.6	35.9	49.8	51.1	37.7	37.4	36.6	35.6
TiO_2	.01		.02	4.01		.01	.00		.04	3.06		.09	4.05			4.34
Al_2O_3	32.9	33.2	21.1	17.1	33.9	21.8	18.9	33.5	21.7	17.8	33.7	4.77	16.5	21.2	21.2	17.4
FeO*	3.49	8.01	29.4	10.3	4.04	17.2	9.45	4.20	32.2	15.4	2.92	18.7	10.1	33.6	33.6	17.6
MnO	.11	.04	2.02	.07	.32	2.10	.12	.19	3.12	.03		.23		1.15	1.46	
MgO	11.2	8.88	8.18	16.6	11.1	14.6	18.7	11.1	4.70	13.1	11.3	23.9	17.3	5.41	3.93	10.5
CaO	.02	.01	.90	.11	.02	.08	.07		1.84			.11	.08	1.33	3.01	.02
Na_2O				.32		2.36	.45			.18			.18			.14
K_2O				9.84		.02	9.29			9.46			9.79			9.62
TOTAL	98.0	99.1	100.9	95.8	99.8	98.2	95.3	98.6	101.3	94.7	97.8	98.9	95.7	100.1	99.8	95.3
# of oxygen atoms	18	18	12	11	18	23	11	18	12	11	18	6	11	12	12	11
Si	5.06	4.99	3.00	2.69	4.99	5.80	2.75	5.00	2.96	2.70	5.02	1.83	2.74	2.97	2.95	2.70
Ti				.22			0.0			.18			.22			.25
Al	3.91	3.99	1.94	1.48	3.99	3.70	1.61	3.98	2.02	1.58	4.00	.20	1.41	1.99	2.01	1.55
Fe	.30	.68	1.90	.63	.34	2.07	.57	.35	2.12	.97	.25	.58	.61	2.23	2.26	1.12
Mn	.01	.00	.13	.00	.01	.00	.13	.02	.21	.00		.01		.08	.10	
Mg	1.69	1.38	.94	1.81	1.68	3.15	2.02	1.67	.55	1.46	1.71	1.32	1.87	.64	.47	1.19
Ca	.00	.00	.08	.01	.00	.02	.00		.16			.00	.01	.11	.26	.00
Na				.04		.67	.06			.03			.03			.02
K				.92		.00	.86			.91			.91			.93

*All Fe = FeO.

co = cordierite, gt = garnet, bi = biotite, gd = gedrite, hy = hypersthene

TABLE 1B. SELECTED MINERAL COMPOSITIONS, HIGH-P LOCALITIES

	(5B)				(6)		
	gt core	gt rim	bi	st	bi	st	ch
SiO_2	37.8	35.8	36.4	28.2	37.3	28.2	26.2
TiO_2			1.38	.47	1.74	.53	.10
Al_2O_3	21.0	22.3	18.9	53.0	18.7	53.4	22.6
FeO*	31.7	33.6	17.4	13.6	16.6	13.9	19.5
MnO	2.15	2.00		.13	.12		.08
MgO	5.81	3.26	11.9	1.76	12.7	2.04	19.0
CaO	1.34	3.00	.02				
Na_2O			.22		.43		
K_2O			9.10		9.43		
TOTAL	99.8	100.0	95.3	97.2	97.0	98.4	87.5
# of oxygen atoms	12	12	11	23	11	23	14
Si	3.00	2.88	2.74	3.92	2.74	3.89	2.67
Ti			.08	.05	.10	.06	.01
Al	1.97	2.12	1.67	8.68	1.62	8.68	2.71
Fe	2.10	2.26	1.09	1.58	1.02	1.60	1.66
Mn	.14	.14		.02	.01	.04	.01
Mg	.69	.39	1.33	.36	1.39	.42	2.88
Ca	.11	.26	.00				
Na			.03		.06		
K			.87		.88		

* Fe expressed as FeO; abbreviations: gt garnet, bi biotite, st staurolite, ch chlorite.

charnockite and gneiss show only minor alteration of anhydrous minerals to more hydrous phases. The cordierite shows incipient replacement by sillimanite and biotite; minor biotite rims the hypersthene, and myrmekite replaces orthoclase in places.

Other schists in the area around the Wilmington Complex also show evidence of two metamorphic events. Migmatitic sillimanite–orthoclase schists commonly show recrystallization of fine needles of sillimanite to coarser prisms superimposed on the earlier highly contorted fabric. Garnet apparently has grown over the early fabric as well, replacing biotite and sillimanite and incorporating sillimanite needles as inclusions. Toward the eastern margin of the area of migmatitic schists, sillimanite–orthoclase assemblages are replaced by muscovite, staurolite overprints the sillimanite fabric and, in one sample, kyanite clearly replaces sillimanite.

Although the replacement of the anhydrous sillimanite-bearing assemblages by more hydrous kyanite-bearing ones increases eastward, the degree of replacement varies considerably. As with the cordierite-bearing samples, this appears to be a function of the degree of deformation during the high-pressure metamorphic event. Two samples from locality 5 (Fig. 3) provide the most well-constrained evidence for the replacement of sillimanite–orthoclase–biotite–garnet assemblages by kyanite–staurolite–muscovite ones. The two samples were collected from outcrops about 50 m apart. Specimen 5A is a typical migmatitic rock with a contorted foliation defined by sillimanite–biotite layers, whereas 5B has a strongly developed planar foliation. Kyanite and staurolite porphyroblasts grow over this foliation, which wraps around the garnet. The only evidence preserved in 5B that it may have been derived from an assemblage similar to that in 5A are ubiquitous needles of sillimanite enclosed in the garnet and similar compositions of the garnet cores (Table 1). Locality 5 lies in an area in which other schist samples having relics of the low-pressure metamorphic episode occur within schists that preserve no record of that event.

Mineral Compositions and Metamorphic Conditions

Compositions of selected minerals from cordierite-bearing samples from localities 1 to 4, the cordierite-free sillimanite–orthoclase rock from locality 5 (sample 5A), and two kyanite–muscovite–staurolite-bearing samples (5B and 6) are given in Table 1 and Figure 4. Calculations of the garnet–biotite geothermometer and garnet–plagioclase geobarometer (Table 2) for

TABLE 2. T AND P FROM GARNET-BIOTITE-PLAGIOCLASE

	Mg/Fe garnet	Mg/Fe biotite	T(1) °C	T(2) °C	X^{ga}_{Ca}	X^{pl}_{Ca}	P kbar
5A rims	0.2117	1.183	565	583	0.079	0.36	5.5
5B	0.2075	1.215	553	570	0.096	0.33	6.1
	0.2261	1.195	579	607	0.096	0.35	6.6

T(1) from Thompson (1976), T(2) from Ferry & Spear (1978). Pressure is calculated using Ferry & Spear temperature; calculation follows Ghent *et al.* (1979).

the minerals crystallized during the high-pressure metamorphic event (sample 5B) agree well with pressure and temperature estimates of the conditions of high-pressure metamorphism based on observations of the mineral assemblages (Fig. 5). The presence of kyanite and staurolite fix the temperature between 550 and 650°C. Northeast of the area discussed here, kyanite and orthoclase coexist in a migmatite terrane at the margin of the Springfield granodiorite (Fig. 2). The more hydrous parts of the leucosome of this migmatite contain muscovite and quartz, but staurolite has not been observed, suggesting that these migmatites lie above the temperature of staurolite breakdown

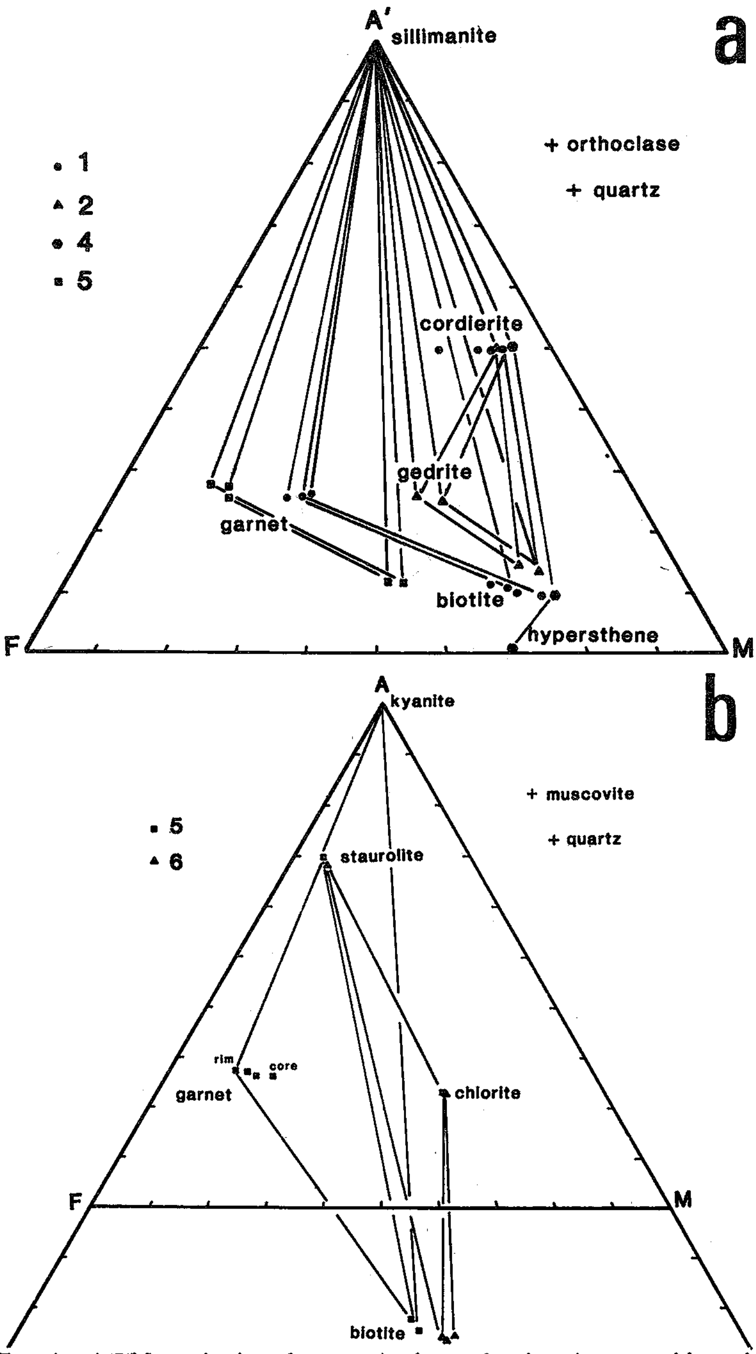

FIG. 4a. A'FM projection from orthoclase of mineral compositions in rocks containing the low-pressure mineral assemblages. Coexisting minerals are connected with tie lines. The high Na content of the gedrite removes it from the plane of the projection. Specimens are numbered 1,2,4 and 5. A': $(Al_2O_3 - K_2O)/(Al_2O_3 - K_2O + FeO + MgO)$; M: $MgO/(MgO + FeO)$. 4b. AFM projection from muscovite of mineral compositions in rocks containing the high-pressure mineral assemblages. Coexisting minerals are connected with tie lines. Specimens are numbered 5 and 6. A: $(Al_2O_3 - 3K_2O)/(Al_2O_3 - 3K_2O + MgO + FeO)$; M: $MgO/(MgO + FeO)$.

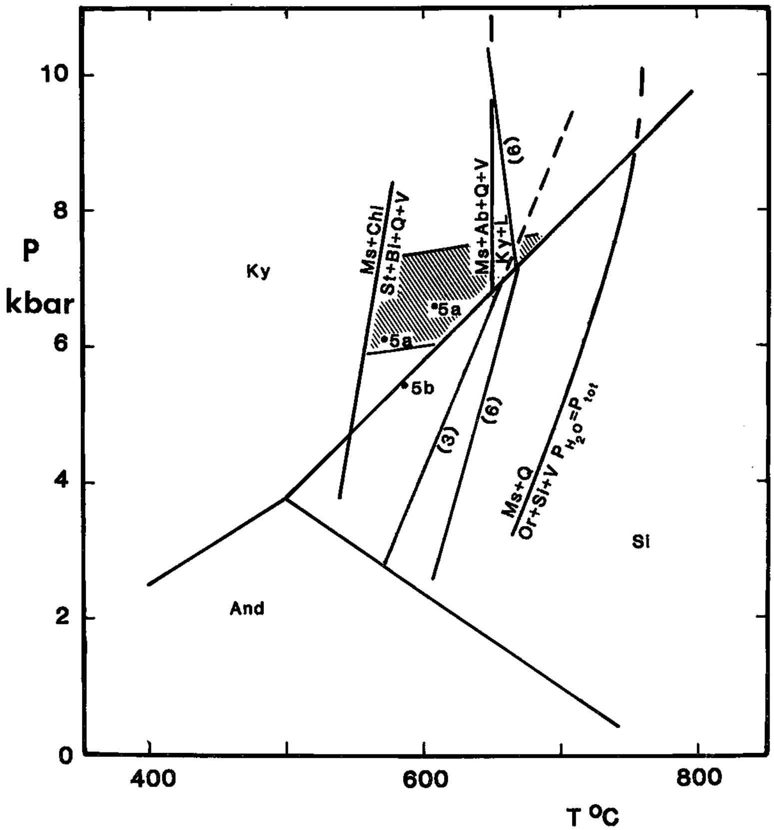

FIG. 5. The metamorphic conditions inferred for the episode of high-pressure metamorphism lie within the ruled area; points 5a and 5b are the P,T conditions calculated for samples from locality 5. Curve (3): Ms + Q = Or + Si + V [$P(H_2O)$ = $0.5P_{tot}$]. Curve (6): St + Q = Gt + Al_2SiO_5 + V. Al_2SiO_5 curves from Holdaway (1971), Ms + Q = Or + Si + V and Ms + Ab + Q + V = Ky + L curves from Kerrick (1972), Ms + Chl = St + Bi + Q + V from Thompson (1976), and St + Q = Gt + Al_2SiO_5 + V from Yardley (1981).

in the kyanite field. This requires pressures above 6.5 kbar.

The overprinting and recrystallization, which affected the minerals formed during the low-pressure event, make those metamorphic conditions harder to estimate. The presence of sillimanite and orthoclase and the absence of muscovite in the cordierite-bearing samples suggest that temperatures at these localities must have reached at least 600°C if the partial pressure of water was half the total pressure (Fig. 6). Higher water-pressures would require higher temperatures. Thompson (1976) suggested that the assemblage garnet–cordierite–orthoclase occurs below 5 kbar at temperatures below 750°C in most common pelitic assemblages. The cordierite-breakdown curves of Holdaway & Lee (1977) show that the most Mg-rich cordierite preserved in these samples (X_{Mg} 0.17) reacts with orthoclase to form the observed biotite–sillimanite product-assemblage at pressures below 6 kbar (Fig. 6). More iron-rich cordierite reacts at lower pressures. In these rocks, both cordierite and garnet show an increase in Mg/Fe with increasing amounts of alteration (Table 1, Fig. 4). It is, therefore, reasonable to assume that the original cordierite was more iron-rich than that preserved in relict grains and thus, the replacement of cordierite started at pressures below 6 kbar. The andalusite-bearing assemblages must have crystallized at pressures below the triple point of the Al_2SiO_5 system (3.8 kbar:

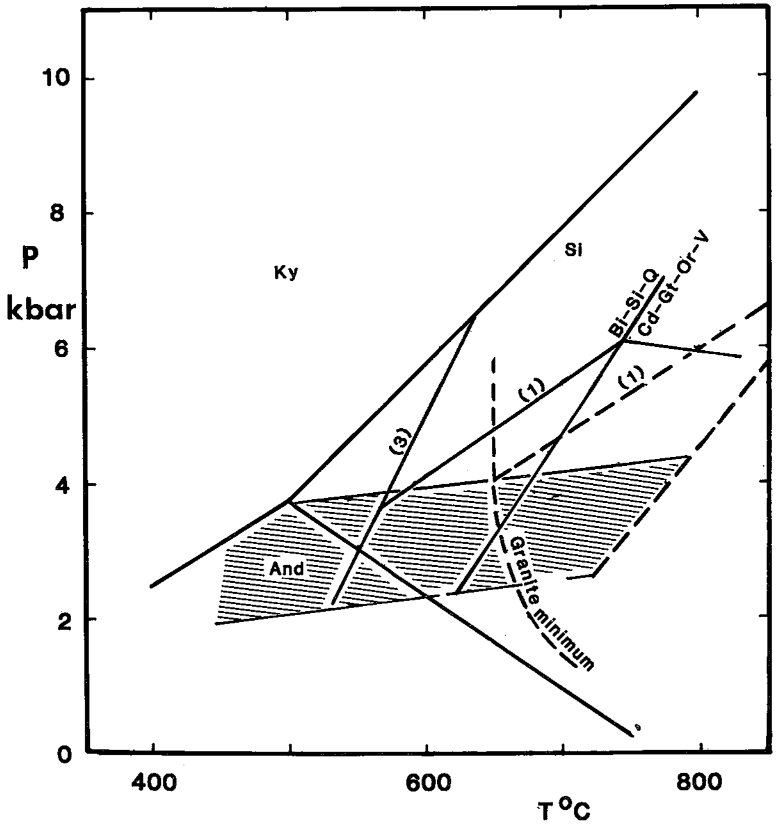

FIG. 6. The metamorphic conditions inferred for the episode of low-pressure metamorphism lie within the lined area. Curve (1): Cd + Or + V = Bi + Si + Q drawn for X_{Mg} = 0.17 in cordierite, the most magnesian composition observed. This reaction is displaced to lower pressure for more iron-rich cordierite. Curve (1) and Cd + Gt + Or + V = Bi + Si + Q from Holdaway & Lee (1977). Other curves as on Figure 5. The dashed curves represent reactions for $P(H_2O) = P_{tot}$ and the solid curves, for $P(H_2O) = 0.4P_{tot}$.

Holdaway 1971).

It is unlikely that the present chemical compositions of the minerals preserved from the low-pressure metamorphic event represent the original compositions of these phases. This is due to the extensive replacement of the early phases by those formed during the higher-pressure metamorphic event. In addition, at these temperatures, solid-state diffusion is rapid, even in refractory minerals such as garnet (Anderson & Olimpio 1977). In fact, the garnets are zoned, although other minerals are not. As shown in Table 1, garnet rims are enriched in calcium, an observation that supports the suggestion that the pressure increased during the later stages of garnet growth, but that the cores are relics of the lower-pressure episode. Pressure and temperature calculations (Table 2) using rim compositions of garnet, biotite and plagioclase in sample 5A, which is least affected by later recrystallization, show pressures slightly lower than those in the extensively recrystallized sample 5B. We do not report pressure and temperature calculations using the relict low-pressure minerals in the extensively recrystallized samples because of the obvious lack of equilibrium.

The observed assemblages of minerals suggest that the following reactions took place during the second metamorphic interval:

cordierite + orthoclase + H_2O = biotite + sillimanite + quartz .... (1)
cordierite + albite + H_2O = Na-gedrite + sillimanite + quartz .... (2)
orthoclase + sillimanite + H_2O = muscovite + quartz .... (3)
sillimanite = kyanite .... (4)
biotite + sillimanite + quartz = muscovite + garnet .... (5)
garnet + sillimanite + H_2O = staurolite + quartz .... (6)
biotite + sillimanite = chlorite + staurolite + muscovite + quartz .... (7)

Evidence for reaction (1) comes from the obvious replacement of cordierite by sillimanite-biotite aggregates and the absence of any cordierite–orthoclase grain contacts. At locality 2, reaction (2) also occurred. The gedrite that formed has a composition that lies in the envelope of compositions described by Schumacher (1980) for two specimens of high-aluminum sodic gedrite found coexisting with cordierite. The biotite in these cordierite replacement-aggregates is pale green, in contrast to the orange-brown biotite in the rock matrix. The color difference is due mainly to the absence of Ti from the biotite replacing the cordierite (Table 1). Kyanite, staurolite, garnet and muscovite all enclose sillimanite needles, demonstrating that they are derived from a sillimanite-bearing precursor. Staurolite generally shows a vermicular intergrowth with quartz. A small amount of chlorite is present in many staurolite-bearing samples. Myrmekite, developed along the contacts between plagioclase and orthoclase, shows that these phases also participated in the reactions. Orthoclase probably provided potassium for secondary biotite. The position and slopes of these reaction curves on P–T diagrams (1, 3 and 6 shown on Figs. 5, 6) support the conclusion that the early-metamorphic assemblage was overprinted by a later higher-pressure and, for the cordierite-bearing assemblages, slightly lower-temperature event.

The formation of magnetite suggests that oxidation also occurred during the second episode of metamorphism. This oxidation probably accompanied the introduction of water that hydrated the low-pressure mineral assemblage. Magnetite is not seen in localities, such as 5A, where rehydration has not occurred. As described above, it was this influx of water, accompanying a penetrative deformation, that resulted in the recrystallization of many of the schists, obliterating the low-pressure early-metamorphic assemblage during the later high-pressure metamorphism.

Regional Relations

The original distribution of low-pressure metamorphism is uncertain; the evidence for this event decreases eastward, away from the margin of the Wilmington Complex. The contact between the Wilmington Complex gneisses and the Wissahickon schist is poorly exposed, but it appears to be a fault. This is suggested by complex folding and the development of shear zones along the northern and northwestern margins of the Complex, as well as by the occurrence of a jumble of rock types, including serpentinite, along the contact (W. Parrott, pers. comm.). Srogi (1982) suggests the Wilmington Complex is thrust over the Wissahickon along its western margin in Delaware; our observations support this interpretation. The Wissahickon schist is also separated from the Grenville gneisses to the north (Fig. 3) by a fault and several large masses of ultramafic rock (Roberts 1969).

The Wilmington Complex gneisses are in the granulite facies. No assemblages suitable for geobarometry have been found in these rocks; the only estimate of metamorphic pressure comes from the observation that the rocks do not contain garnet, in contrast to Grenville gneisses of similar composition exposed a few kilometres to the north (Wagner & Crawford 1975). Also, in contrast to the Grenville gneisses and to the Wissahickon schist, the Wilmington Complex gneisses show little evidence of polymetamorphism, other than rims of blue-green hornblende around grains of pyroxene and brown hornblende and local zones of retrograde alteration of pyroxene to hornblende–quartz aggregates.

To the east and northeast of the area outlined in Figure 3, the Wissahickon Group schists do not contain unambiguous evidence of an early low-pressure assemblage. Staurolite and staurolite–kyanite schists apparently grade southward into fibrolite–muscovite gneisses with minor migmatite (Weiss 1949, Wyckoff 1952). However, at least two samples collected from the high-temperature side of the sillimanite + muscovite isograd north of Philadelphia (Fig. 2) contain both kyanite and fibrolite. The kyanite cuts the mica foliation, whereas the fibrolite occurs in contorted clusters primarily in fold noses. Fibrolite is also locally replaced by muscovite, whereas kyanite never is. These data suggest that the sillimanite assemblages may be older than the kyanite assemblages, at least as far east as Philadelphia.

Tectonic Implications

High-pressure metamorphic conditions similar to those described in this paper are common in regional metamorphic belts. It is, however, uncommon to find evidence preserved for high-pressure metamorphism superimposed on a low-pressure–high-temperature metamorphic terrane. Progressive metamorphism generally involves successive dehydration steps, effectively recrystallizing the rock at each stage. In southeastern Pennsylvania, however, high temperatures created anhydrous assemblages prior to the loading and burial that generated the high-pressure assemblages. From a comparison of Figures 5 and 6, it is clear that the principal change required to achieve the later metamorphic effects in the schists is a pressure increase of $\sim$4 kbar. This corresponds to a loading by approximately 15 km of rock; more loading would be required if the low-pressure metamorphic terrane had been partially unroofed, either by erosion or tectonically, prior to the higher-pressure metamorphism.

The metamorphic relations described in this paper occur in an area with a complex structural history. Major faults separate the schists from the underlying Grenville-age gneisses and from the Wilmington Complex to the southwest. Each of these units has a unique metamorphic history. There is some evidence that the Wissahickon Group itself consists of several units that have been tectonically juxtaposed. It is, therefore, impossible at this time to completely explain the details of the origin of the low-pressure–high-temperature metamorphic assemblage. The high geothermal gradient required for the low-pressure metamorphism resembles the gradient calculated for regions of igneous activity and high heat flow above subduction zones (*e.g.*, Oxburgh & Turcotte 1971).

A charnockite intruding the Wilmington Complex has been dated at 502 ± 20 Ma (Foland & Muessig 1978), establishing a Cambrian or older age for these rocks. The Wilmington Complex of metavolcanic and metavolcaniclastic rocks has been correlated with the James Run Formation of Maryland (Southwick 1969). Higgins (1972) suggested that the James Run Formation is also Cambrian. The belt of early Cambrian igneous activity continues into Virginia (Central Virginia volcanic-plutonic belt: Pavlides 1981). Crawford & Crawford (1980), Crowley (1976) and Pavlides (1981) suggested that these metavolcanic units are portions of an island-arc complex developed east or southeast of the continental margin. The low-pressure–high-temperature metamorphic rocks could then have formed at moderate depth within the island-arc igneous complex, or they may have been generated in a zone of high geothermal gradients and possible magmatic activity on the continent side of the arc, in a setting resembling the modern Sea of Japan (Horai & Uyeda 1969).

After low-pressure–high-temperature metamorphism, the metamorphic record shows that the tectonic history must involve significant crustal thickening, most readily explained by postulating thrust emplacement of one or more thick slabs of rock over the sediments of the Wissahickon Group. We suggest that the Wilmington Complex, accompanied by slices of ultramafic rock, forms one of these slabs. The low-pressure and high-temperature schists may also have been displaced toward the continent at this time, under the Wilmington Complex slab. Crowley (1976) suggested that the James Run Formation of Maryland is similarly thrust over the Baltimore Mafic Complex which, in turn, was thrust over the Wissahickon Group and other units of the Glenarm Series. Additional thrust slices may have been emplaced over the one containing the Wilmington Complex, eventually burying the Wissahickon Group to depths of 25 to 30 km. During this tectonic thickening, the heat flow from below cannot have been high, as the temperatures in the now-deeply-buried schists under the Wilmington Complex did not rise above the values recorded in the earlier, low-pressure metamorphism. This implies either that the low-pressure–high-temperature sequence formed elsewhere and the rocks were tectonically emplaced in their present position, as suggested above, or enough time elapsed between the two events to permit a decrease in the geothermal gradient in these rocks.

This model of tectonic thickening of the crust is similar to that proposed for the development of the southern Appalachians by Hatcher (1978) and supported by COCORP results (Cook *et al.* 1979, 1981). Whereas the COCORP and available structural data suggest that much of the thrusting in the southern Appalachians is late Paleozoic in age, we propose that the events we describe occurred early, probably during the Ordovician Taconic orogeny. We base this conclusion on the 440 Ma age for the Wilmington Complex metamorphism (Grauert & Wagner 1975), on $^{40}Ar/^{39}Ar$ ages of hornblende as old as 410 ± 4 Ma (Sutter *et al.* 1980), and on 330 ± 15 Ma K/Ar ages of muscovite from the Wissahickon along the Susquehanna (Lapham

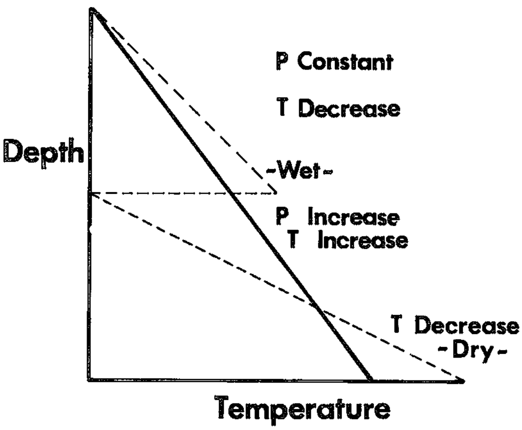

FIG. 7. Schematic representation of the effects of loading a segment of lithosphere characterized by a high-temperature gradient with an overthrust slab. The original distribution of temperatures is illustrated with the dashed line and the adjusted thermal gradient after equilibration, by the solid line. The post-thrusting imposed metamorphic conditions are summarized at the right and discussed in the text.

& Bassett 1964); the latter data record ages of cooling during uplift.

METAMORPHIC MODEL

Figure 7, adapted from Oxburgh & Turcotte (1974) who used an overthrust model to explain the metamorphism of the eastern Alps, schematically illustrates the distribution of metamorphic assemblages that might be expected in this tectonic situation. The model illustrated in Figure 7 assumes a lower block that originally contained, at its top, unmetamorphosed rocks at surface conditions. These graded down into a low-pressure–high-temperature metamorphic complex. It also assumes a block of overthrust material, emplaced as one thick slab. After thrusting, the previously unmetamorphosed rocks at the top of the lower block undergo prograde regional metamorphism and record a final metamorphic gradient that depends on the thickness of the overthrust slab, on the heat generated in the tectonically thickened pile of rocks, on heat flow from the mantle, and on the length of time available before the rocks are exhumed by erosion (England & Richardson 1977, England 1978). We assume that the initial geothermal gradient in the overthrust slab is not re-established owing to the effects of cooling during uplift and erosion, which must start shortly after the thrusting event. The overlying slab may record metamorphic temperatures at its base higher than those produced in the top of the underlying block, but these would correspond to relict mineral assemblages crystallized before the overlying slab was detached and thrust. After thrusting, volatiles given off during the metamorphism of the top of the underlying block can be expected to escape upward into the base of the overriding material, causing retrograde metamorphism of the relict assemblages. The extent of retrograde metamorphism depends on the nature of the overlying rocks, the final distribution of temperature, and the paths taken by the escaping volatiles.

The high-temperature part of the lower block, which was already metamorphosed, will be subject to an increase in pressure, accompanied by a temperature decrease. If the rocks were dehydrated by the earlier metamorphism, it is unlikely that there will be significant recrystallization; the pressure increase may thus not be recorded in the mineral assemblage.

This simple model may be extended to illustrate the effects that could occur in a more complex tectonic setting. Figure 8 shows how we presently interpret the observed relations in

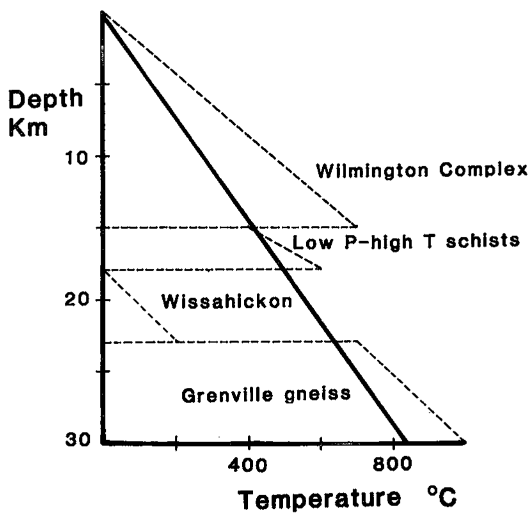

FIG. 8. Interpretation of the development of the post-thrusting metamorphic gradients recorded in the several tectonic units identified in the Pennsylvania Piedmont. The prethrusting metamorphic gradients are shown by the dotted line, the gradient established after equilibration by the solid line. The details of the prograde or retrograde nature of the post-thrusting metamorphism depend on the prethrusting metamorphic gradient recorded by each unit, as discussed in the text.

southeastern Pennsylvania. The highest overthrust slab preserved has the Wilmington Complex at its base. The low-pressure–high-temperature metamorphic rocks are preserved in a separate thrust slice under this slab. This, in turn, is emplaced on lower-temperature, possibly unmetamorphosed sediments that rest on the Precambrian Grenville-age gneisses. Each group of rocks contains mineral assemblages that record a prethrusting metamorphic gradient; this gradient is schematically illustrated by the dashed line in Figure 8. In the Precambrian gneisses, the gradient was imposed during the Grenville orogeny; the record of that gradient was preserved when the rocks were uplifted and eroded before the Cambrian. The low-pressure–high-temperature schists and the Wilmington Complex also preserve a record of the metamorphic pressures and temperatures at which they originally crystallized (Fig. 8). The gradient in the sediments overlying the Grenville basement was that characteristic of the region at the time of thrusting.

After thrusting, mineral assemblages reflecting the new conditions were superimposed on the initial set. The post-thrusting gradient is shown as the solid line in Figure 8. The Precambrian gneisses now contain upper amphibolite assemblages superimposed on Grenville granulites-facies assemblages (Wagner & Crawford 1975); thus, the post-thrusting gradient is shown at a lower temperature in this block than the original Precambrian gradient. The previously unmetamorphosed sediments were metamorphosed to the new gradient; these are the Wissahickon and other Glenarm Series metamorphic rocks that do not preserve relics of the early low-pressure–high-temperature assemblage. The minerals in the low-pressure high-temperature schists reacted to high-pressure assemblages without significant peak-temperature differences, as described above and illustrated in the simple model of Figure 7. A substantial amount of water released during the recrystallization of the previously unmetamorphosed Wissahickon sediments helped promote the reactions in the overlying blocks, and in the top of the underlying Grenville basement. The Wilmington Complex also was affected by local retrograde metamorphism as a consequence of a post-thrusting gradient with temperatures lower than those for the earlier metamorphism.

Summary

The distribution of assemblages of metamorphic minerals in the pelitic schists in southeastern Pennsylvania can be explained by metamorphism accompanying the emplacement of thrust slices onto the continental slope and the edge of the continental shelf of eastern North America. A complex metamorphic history is recorded by those rocks that were metamorphosed prior to the thrusting and that lie at depth within the tectonically thickened crust. These rocks were identified in this area, as they show evidence of overprinting of low-pressure, high-temperature mineral assemblages containing andalusite and cordierite by a regional high-pressure metamorphism characterized by kyanite and staurolite. The relict assemblages were preserved in those schists that remained dry during the high-pressure metamorphism; zones open to water influx and affected by deformation during the high-pressure metamorphism were thoroughly recrystallized. This model for the development of the metamorphic history of the rocks in the area may serve to further unravel the complex early Paleozoic tectonic history of southeastern Pennsylvania.

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