Introduction

Metamorphic and plutonic rocks of Proterozoic and Paleozoic age constitute the crystalline bedrock shown on figure 1 which is part of a collage of tectonostratigraphic terranes in the northern Virginia Piedmont (fig. 2) Sediments of Cretaceous and Cenozoic age of the Coastal Plain province overlay the Piedmont crystalline rocks on the east and erosional remnants of these sediments occur on upland areas to the west of the Coastal Plain-Piedmont contact (fig. 1). The Coastal Plain sediments will not be described herein; their stratigraphy and lithology have been described elsewhere (Mixon and others, 1989). The geology of the area described in this report (fig. 1) differs from that presented in some of the earlier reports (Lonsdale, 1927; Subitzky, 1968, and Neuschel, 1970). The stratigraphic and tectonic framework of figures 1 and 2, in part, have been given by Pavlides (1976, 1980, 1981, 1989 and 1990), Pavlides and others (1974, 1980, and 1982), Sutter and others (1985) and Flohr and Pavlides (1986). The present discussion will be based on the terrane concept of figure 2.

Regional setting

Part of the Piedmont of northern Virginia has been subdivided into six tectonostratigraphic terranes (fig. 2). The tectonic model adopted for this region proposes that the terranes east of the Mountain Run fault zone (fig. 2) along with most of their intrusive rocks, formed offshore of ancestral North America during the early Paleozoic and are allochthonous (Pavlides, 1989). The continental margin terrane (fig. 2) is also allochthonous (Pavlides, 1989) and its metasedimentary rocks are in part coeval (Cambrian[1] and Ordovician) with the melange terrane (Pavlides, 1989, 1994). Rocks making up the various thrust blocks of the melange terrane (part of the Potomac terrane of Horton and others (1989)) were originally deposited as sediments containing olistoliths of various types, including blocks of Chopawamsic Formation, in a postulated back-arc basin. Two types of melanges, the block-in-phyllite type and the diamictic type eventually formed under different sedimentologic-tectonic conditions (Pavlides, 1989). To the east (present day coordinates) of the melange or back-arc terrane is the Cambrian island-arc terrane (Chopawamsic terrane of Williams and Hatcher (1983)) composed of two metavolcanic types (fig. 2). The Chopawamsic belt (figs. 1 and 2) is interpreted as the continentward facing volcanic belt whereas the Ta River Metamorphic Suite was the mafic oceanward facing volcanic belt (Pavlides, 1981, 1989 and Pavlides and others, 1982a). Various sandy and sandy-pelitic sediments including the Quantico Formation (figs. 1 and 2) accumulated in successor basins during Late Ordovician time after the deformed melange and island arc terranes collapsed (Pavlides, 1989). All allochthonous terranes east of the Mountain Run fault zone were accreted onto ancestral North America (Laurentia) by the close of the Ordovician. The deformed and polymetamorphosed Po River Metamorphic Suite (fig. 1) or Po River terrane (fig. 2) and the Salem Church allochthon were accreted during the Carboniferous. In addition to Taconic thrusting, pre-Jurassic strike-slip movement and Cenozoic normal faulting also have occurred along the Mountain Run fault zone (Pavlides, 1994).

Tectonostratigraphic terrane

The area under discussion (fig. 1) encompasses a critical part of four terranes of figure 2. The terranes will be discussed, in general, from east to west which is also the general sequence of oldest to youngest terranes.

Po River (Matta nappe) terrane

This terrane, composed of the Late Proterozoic and (or) Paleozoic Po River Metamorphic Suite (PzZp, fig. 1) constitutes the Matta allochthon or nappe (fig. 2). The Po River is primarily a biotite gneiss having lesser amounts of amphibole gneiss and schist and with sill-like pegmatoids and foliated granitoids (Pavlides, 1980). It is considered to be coeval and coextensive with the Maidens Gneiss of the James River area to the southwest. The Po River Metamorphic Suite is at amphibolite metamorphic grade and locally is migmatitic (Pavlides, 1980).

Salem Church allochthon

This allochthon lies mostly on Quantico Formation (Oq) and part of the Ta River Metamorphic Suite (Ꞓt) (fig. 1). It consists of the Late Proterozoic and (or) Cambrian Holly Corner Gneiss (ꞒZh) and associated discontinuous quartzitic lenses (Oqq). The thin discontinuous lenticular quartzite (Oqq) along parts of the south limb of the Salem Church allochthon may be a distal part of the basal quartzite of the Quantico Formation of Late Ordovician age deposited upon the Holly Corner Gneiss prior to the westward displacement of the Holly Corner. The Holly Corner Gneiss is intruded by the Falls Run Granite Gneiss (Sfr, fig. 1) of Silurian age (Pavlides and others, 1982b). The Holly Corner Gneiss is primarily a well-foliated hornblende- and biotite-rich gneiss with sparse, thin, calc-silicate layers of quartz, andesine, epidote, and diopside. Locally potassic porphyroblasts occur in thin zones within the Holly Corner at the contact with the Falls Run. These porphyroblasts are attributed to contact metamorphism accompanied by potassic metasomatism during emplacement of the protolith of the Falls Run Granite Gneiss (Pavlides, 1980) of the Berea pluton (fig. 2).

The Holly Corner Gneiss is interpreted as part of an island-arc assemblage which, from west to east, consisted of the Cambrian Chopawamsic Formation, Ta River Metamorphic Suite and the Holly Corner as a possible distal oceanward facies (Pavlides, 1980, p. 7 and Pavlides, 1981). Alternatively, the Holly Corner may be an older formation, possibly of Proterozoic age, which happens to be overlain by the basal quartzite unit of the Quantico Formation. Because of these temporal uncertainties the Holly Corner is now assigned a Late Proterozoic and (or) Cambrian age.

The rocks enclosed within the Salem Church allochthon, as herein designated (figs. 1 and 2) are considered allochthonous rather than autochthonous for several reasons. One major consideration is the very restricted geographic distribution of these rocks, namely, the Holly Corner Gneiss and Falls Run Granite Gneiss to the area designated as the Salem Church allochthon along the Rappahannock anticlinorium. This contrasts with the widespread distribution of other lithologies subjacent to these rocks along or parallel with this anticlinorium, such as the Quantico Formation and Ta River Metamorphic Suite (fig. 2). Furthermore, if the Salem Church allochthon rocks actually were autochthonous, then the Silurian Falls Run must have intruded through the older Quantico Formation (Late Ordovician) and the Chopawamsic Formation (Early Cambrian?) and should be found as plutons, dikes or plugs in these older rocks. The restriction of the Falls Run intrusion within the Holly Corner Gneiss and its absence in the subjacent strata supports an allochthonous nature to the Falls Run Granite Gneiss and the Holly Corner Gneiss host rocks. An additional support for the allochthonous nature of the Falls Run Granite Gneiss is the absence of contact metamorphism within the Quantico Formation where the Quantico and Falls Run are in direct contact at the southeast end of the Storck Quadrangle (fig. 1). The basal quartzite (Oqq) of the Quantico Formation immediately north and south of the Rappahannock River in the Salem Church Quadrangle, and assigned to the terrane of the Salem Church allochthon (fig. 1) is locally closely plicated with small intrastratal folds, generally less than one foot in amplitude. This can be seen in the quartzite exposed on the east side of Motts Run below the outlets of Motts Run Reservoir and south of route 618 (fig. 1). The intrastratal folds in the basal Quantico Formation quartzites contained in the Salem Church allochthon are considered to reflect deformation undergone by these quartzites when the allochthon was tectonically emplaced. In contrast, the basal quartzites (Oqq) of the Quantico Formation elsewhere are free of small intrastratal folds.

Island Arc

The Chopawamsic Formation (Ꞓc) is considered to be of Early Cambrian(?) (550 Ma) age (Pavlides, 1981, p. A-6). The Chopawamsic and contains a tholeiitic island arc suite and associated calc-alkaline metavolcanic rocks as well as metasedimentary rocks. Its felsic metavolcanic rocks are keratophyres, characteristically containing quartz and albitic plagioclase as well as chlorite and sparse saussuritic epidote as granular alteration on plagioclase that was originally more calcic than albite. Metavolcanic rocks of intermediate composition are dark-green and commonly have a nematoblastic groundmass texture formed by aligned prismatic actinolitic amphibole intergrown with fine-grained quartz and feldspar. Blue-green actinolitic amphibole locally forms fine-grained porphyroblasts that, in some rocks, are arranged in small bundles (fascicles). Epidote, chlorite, and accessory magnetite are common minor constituents of these amphibolitic rocks. Locally, carbonate- and(or) quartz-filled vesicles or amygdules are present. Greenstones composed of quartz, chlorite, generally albitic plagioclase, and blue-green amphibole, locally with relict basaltic textures, are interpreted as metabasalt. The Chopawamsic Formation is considered to have been a continentward facing segment of the island-arc terrane. It is within the greenschist facies of regional metamorphism and is intruded by oceanic trondhjemite (OꞒtj) and tonalitic plagiogranite (OꞒpg) as described by Pavlides (1981, p. A18-A21) contained, respectively, in the Horse Pen Run and Richland Run plutons (see figs. 1 and 2).

The tholeiitic amphibolites of the Ta River Metamorphic Suite (Ꞓt) are interpreted to have been an oceanward facing segment of the island arc, if not part of the oceanic floor. The negative Ce anomalies of their REE patterns (Pavlides, 1981, fig. 4B) is a pattern recognized in some oceanic basalts. In contrast to the Chopawamsic, the Ta River Metamorphic Suite is within the amphibolite facies of metamorphism. Although the Ta River lacks large trondhjemitic intrusions, many of the tabular granitoid bodies within it are plagiogranitic tonalites in that they plot along the quartz-plagioclase line (Coleman and Peterman, 1975) of the tonalite field (Pavlides, 1981, fig. 6) of the Streckeisen (1976) classification diagram.

Garrisonville Mafic Complex

The Garrisonville Mafic Complex was first described by Pavlides (1990). It is here formally named after Garrisonville, located in the northcentral part of the Stafford Quadrangle (fig. 1). The Garrisonville Mafic Complex is best exposed along Aquia Creek in the Stafford and Storck Quadrangle (fig. 1) which is designated as its type area.

The Garrisonville (ꞒZgm) is interpreted as a possible fragment of oceanic floor of the back-arc basin terrane and thus part of the substrate upon which metavolcanic rocks of the Chopawamsic Formation formed in Early Cambrian time (Pavlides, 1989). However, the contact between the Garrisonville and Chopawamsic is not exposed and it is not now known with certainty if this contact is an unconformity or a fault or even locally an intrusive contact.

This complex consists chiefly of massive to foliated amphibolite and hornblendites. The western part of the complex, contains metapyroxenite (clinopyroxene and enstatite-bearing) and other altered rocks whose protoliths may have been websterite and norite. Talc-amphibole schist is present locally along the western margin of the complex.

Amphibolite normally consists of common hornblende that may or may not have blue-green "uralitic" hornblende. In places, large hornblende grains are poikilitic. Actinolitic and cummingtonitic amphibole is present locally. Plagioclase ranging in composition from oligoclase to calcic andesine (flat-stage measurements) is generally slightly to heavily altered to clinozoisite or epidote. Quartz and chlorite are present in variable amounts in some of the amphibolites; magnetite and ilmenite are common accessory minerals.

Hornblendite consists essentially of coarse-grained common hornblende in a groundmass of finer grained common hornblende and sparse amounts of quartz or plagioclase or both.

The Garrisonville is intruded by plagiogranite of the Richland Run pluton as well as by plagiogranitic dikes. Such dikes are abundant along and near the southern margin of the complex where they form complex networks of intrusion breccia (Pavlides, 1976, fig. 6).

Age

The age of the Garrisonville Mafic Complex is not closely known. It is assigned a Late Proterozoic and (or) Early Cambrian age on the basis that it is pre-Chopawamsic and is possibly a fragment of oceanic floor that formed in the back arc terrane in Proterozoic time (Pavlides, 1989).

Melange

Two types of melange deposits have been recognized in the northern Virginia Piedmont. These are the block-in-phyllite and the diamictic types of Cambrian and (or) Ordovician age as described elsewhere (Pavlides, 1989 and fig. 2). Only the diamictic variety, represented in the Lunga Reservoir Formation (OꞒl), is present within the area of figure 1. There are few exotic blocks in the portion of Lunga Reservoir in figure 1, but they do include a few ultramafic fragments of the Garrisonville Mafic Complex (ꞒZgm) and greenstone of the Chopawamsic Formation (Ꞓc). Blocks of Chopawamsic Formation are more abundant in the Lunga Reservoir to the northeast, especially near the Chopawamsic thrust. Such blocks were shed from the lithified and deformed Chopawamsic into unconsolidated sediments, now the graywacke matrix of the Lunga Reservoir Formation, which is commonly nonstratified, micaceous and quartzofeldspathic. Similarly, Chopawamsic Formation blocks were shed from the overthrust Chopawamsic into various melanges to the west and northwest of figure 1 (fig. 2 and Pavlides, 1989).

The melange deposits of the northern Virginia Piedmont are interpreted as having formed in a back-arc basin that lay between a volcanic arc (the Central Virginia Volcanic-Plutonic Belt) on its east (present day coordinates) and the continental margin of ancestral North America on its west. The mafic and ultramafic blocks in some of the melange deposits are interpreted as derived from the ocean floor of the back-arc basin by various tectonic and sedimentologic processes (Pavlides, 1989).

Successor basins

Successor basins developed in the northern Virginia Piedmont after the island arc terrane had been deformed and initially metamorphosed, and when westward thrusting along the Chopawamsic fault (described below) had ceased during the Late Cambrian. The most extensive successor basin within the map area contains the Quantico Formation (Oq) of Late Ordovician age. The Quantico lies with unconformity upon the Chopawamsic northeast of the Accokeek fault (figs. 1 and 2). This unconformity is exposed north of figures 1 and 2 in Dale City, Virginia (Pavlides and others, 1980). From the Accokeek fault southwestward the Quantico Formation, where it is extensively developed within the Quantico synclinorium, is in fault contact with the Chopawamsic. A small inlier of Quantico schist and its basal quartzite occurs in a refolded fold within the Ta River Metamorphic Suite (Ꞓt) (fig. 1).

Parts of two successor basins also lie in the northwest corner of figure 1. The rocks within these basins (Ou and Op) are provisionally assigned an Ordovician age because they lie athwart the Chopawamsic fault and unconformably overlie rocks of some of the melange zones and intrusions (fig. 2). They may have been deposited penecontemporaneous with the Quantico Formation.

Plutonism

The various terranes contain intrusions that are to some extent characteristic of certain tectonic settings. The ensuing discussion on plutonism is therefore organized by terranes, except for the Carboniferous Falmouth Intrusive Suite (Cfi), which occurs in almost all terranes.

Intrusions in the Po River (Matta nappe) terrane

Numerous foliated gneissic granitoid rocks, including pegmatoids, are found as tabular bodies, as well as nontabular masses, in the Po River Metamorphic Suite (PzZp). The largest intrusion in this terrane is the Potomac Creek pluton (PzZd) which lies mostly in the southwest corner of the Stafford Quadrangle (fig. 1). It is gray, fine- to medium-grained, well-foliated, quartz-plagioclase-biotite granodioritic gneiss containing abundant well-formed, highly lineated accessory epidote and locally sparse garnet and minor amounts of muscovite. Tabular, smaller granitoid and pegmatoid bodies form concordant, sill-like layers within the gneiss (not differentiated in fig. 1). They range from less than 2.5 cm wide to as much as about 7.6 m wide. The nontabular irregularly shaped granitoid bodies generally form masses that may be parts of plugs of various sizes. Locally, thinner granitoid layers about 0.5-1.0 cm wide are conformable with the foliation in the gneiss (Pavlides, 1980, fig. 4). The lack of restite selvages of biotite or hornblende in these layers suggests that if the granitoid layers are leucosomes they are arterites.

In general the granitoid rocks of the Po River are two-mica gneissic monzogranite, and granodiorite (Pavlides, 1980). Within the area of figure 1 monzogranite contains quartz (22-30 percent), plagioclase (31-39 percent), potassic feldspar (20-47 percent), biotite (0.5-11 percent) and muscovite (1-14 percent). Biotite is both green as well as brown and commonly is intergrown with muscovite; locally biotite is altered to chlorite. Ubiquitous myrmekite occurs at the margins of plagioclase in contact with potassic feldspar both at rims and as bulbous protrusions in the plagioclase. Some feldspars are poikilitic and some occur as phenocrysts enclosed by a finer grained quartz-feldspar matrix locally characterized by recrystallized, granoblastic-textured quartz or quartz that locally suggests a recrystallized mortar texture. Quartz in some of these rocks occurs in elongate, discontinuous ribbons. Garnet is a rare accessory in subhedral, partial grains that locally are poikilitic.

The metagranodiorites of the Po River Metamorphic Suite generally contain quartz (23-30 percent), poikilitic and nonpoikilitic plagioclase (22-30 percent) and potassic feldspar (7-42 percent). Biotite (2-9 percent) ranges in color from brown to red, to reddish brown to green and locally is altered to chlorite. Epidote is generally present with the chlorite. Muscovite (0-9 percent) is locally intergrown with biotite and both minerals are dimensionally aligned and impart the strong foliation of the rock. As in the monzonites described above, myrmekite is ever present and garnet is a rare constituent. Evidence for late strain is similarly present in many granodiorites.

Within the Po River Metamorphic Suite, granitoid dikes and sills of the Falmouth Intrusive Suite (Cfi) have the same general compositional range as do the Po River granitoids. The Po River granitoids, however, contain somewhat less quartz than the Falmouth granitoids. Where suitable exposures are present the Po River granitoids are crosscut by the Falmouth granitoids. Also, Falmouth granitoids are less foliated to nonfoliated in contrast to the more well-foliated Po River granitoids.

Age

The age of the granitoids rocks of the Po River Metamorphic Suite is uncertain; they are considered Late Proterozoic and (or) early Paleozoic based on their position within the formation of this age.

Salem Church allochthon

Falls Run Granite Gneiss

The Falls Run Granite Gneiss (Sfi), a medium- to coarse-grained granite gneiss, has a well-developed anastamosing but discontinuous foliation (Pavlides, 1980, fig. 8). Modally the granitoids that constitute the Falls Run range in composition from monzonite to quartz monzonite and monzogranite (Pavlides, 1980, fig. 9). The folia consist of dimensionally aligned green hornblende (2-8 percent), and greenish-brown biotite (2-6 percent) and also contain 0.5 percent titanite (sphene) and epidote (1.5 percent). Biotite and hornblende locally occur as intergrowths. These folia wrap around elongate feldspar grains that also are dimensionally aligned with the rock foliation. Microcline (22-49 percent) is mostly coarse-grained, grid-iron twinned and poikilitic. It is generally more abundant than andesine plagioclase (24-48 percent) which occurs mostly as a fine-grained groundmass constituent. Quartz ranges in abundance from 9 to 32 percent. Myrmekite is common and occurs in plagioclase that is in contact with potassic feldspar and in places forms cauliflower-like growths into potassic feldspar. Some plagioclase has clear albitic rims where in contact with potassic feldspar.

The monzonite of the Falls Run intrudes the Holly Corner Gneiss in a tabular sill-like manner. Together the Falls Run and Holly Corner are interpreted to be allochthonous remnants (described below) of the inverted limb of a recumbent fold which subsequently was deformed into a type-2 interference fold. The Falls Run granitoids have an initial $^{87}Sr/^{86}Sr$ of 0.7070 which suggests crustal involvement in its magma generation (Pavlides and others, 1982b). The Falls Run Granite Gness and Holly Corner Gneiss of the Salem Church allochthon are intruded by granitic and pegmatitic dikes and small plutons of the Carboniferous Falmouth Intrusive Suite which will be described later.

Age

The Falls Run Granite Gneiss has been isotopically dated by U/Pb (zircons) and Rb/Sr (whole rock) studies that indicate an age of about 410 Ma (Pavlides and others, 1982b).

Island arc terrane

Intrusions in the Chopawamsic Formation

The Chopawamsic Formation (Ꞓc), the presumed continentward facies of a Cambrian island arc, is intruded by felsic and mafic plutons and dikes (Pavlides, 1981). The Horse Pen Run pluton (figs. 1 and 2) and associated felsic dikes are composed of fine-grained metatrondhjemite (OꞒtj) that is typically granophyric and composed of albitic plagioclase (27-57 percent) intergrown with quartz (25-40 percent). Blue green amphibole (1-36 percent) is a major accessory whereas garnet (0.1-2 percent) is a rarer accessory. Epidote (0.6-7 percent) is a granular alteration mineral. Characteristically, potassic feldspar is absent. Geochemically the trondhjemite of the Horse Pen Run pluton has oceanic rather than continental characteristics (Pavlides, 1981, fig. 7) and is petrologically consistent with the island arc setting proposed for the volcanic rocks it intrudes.

The Richland Run pluton (figs. 1 and 2) is composed of metaplagiogranitic rocks (OꞒpg) that intrude both the Chopawamsic Formation and the Garrisonville Mafic Complex. Modally the metaplagiogranitic rocks consist of quartz (41-48 percent) and plagioclase (34-46 percent) as the major constituents. As in the case of the metatrondhjemite discussed above, potassic feldspar is absent. Accessory minerals include amphibole (0-5 percent), biotite (0-5 percent), and muscovite (0.1-8 percent). Minerals formed through alteration of biotite and plagioclase include respectively, chlorite (0-7 percent) and epidote (0.1-19 percent). Quartz within the plagiogranite has an aggregate texture and on weathered rock surfaces stands out as distinct grains that impart a "hobnail" texture to the rock. As discussed elsewhere (Pavlides, 1981) plagiogranites of this region contrast with the rare-earth element pattern of the trondhjemites of the Horse Pen Run pluton in that they more closely resemble continental rather than oceanic patterns. For example, they have positive rather than negative europium anomalies. However, for various other reasons, including the fact that they plot within the oceanic field of trondhjemite (Pavlides, 1981, fig. 7), they are not considered of continental affinities, but perhaps of a transitional type to oceanic plagiogranite.

A small metagabbroic pluton (Ꞓg) intrudes the Chopawamsic along the boundary between the Storck and Stafford Quadrangles (fig. 1) and contains inclusions of Chopawamsic volcanic fragments (Pavlides, 1976, fig. 5). The Chopawamsic also is intruded by mafic dikes which locally have foliated chilled margins and irregular contacts with the host metagabbro (Pavlides, 1976, figs. 9 and 10), possibly reflecting a plastic state for the crystalline gabbro at the time it was intruded by the basaltic rocks. These dikes are too small to be shown on figure 1.

Age

The trondhjemite and plagiogranite bodies intrusive into the Chopawamsic Formation, however, do not intrude the Quantico Formation. They therefore postdate the Chopawamsic (or Early Cambrian?) and predate the Quantico (Late Ordovician). They are probably of Cambrian age but an Early Ordovician age cannot be ruled out and they are therefore assigned a Cambrian and (or) Ordovician age. Furthermore, an isotopic U/Pb age from a sample of plagiogranite is discordant but its $^{207}Pb/^{206}Pb$ age of 459 Ma (Pavlides, 1976, table 1) may be representative of the minimum age for this sample and is not in conflict with the generally accepted 550 Ma for the Chopawamsic Formation.

The thin mafic dikes cutting the gabbroic pluton (see above) also cut plagiogranite within the Richland pluton. They are therefore the youngest intrusive rocks of the island arc terrane. They may also be of Cambrian and (or) Ordovician age.

Intrusions in the Ta River Metamorphic Suite

The Ta River Metamorphic Suite (Ꞓt) is interpreted as the more highly metamorphosed, oceanward facies of the Cambrian island arc terrane (Pavlides, 1981 and 1989). Only a small part of this terrane is exposed in figure 1 (compare with fig. 2). Aside from plutonic rocks of the Carboniferous Falmouth Intrusive Suite, small masses of older granitoid and mafic rocks also have been emplaced in the Ta River. The granitoid rocks occur as foliated tabular masses conformable to the compositional layering of the host amphibolitic gneisses and include monzogranite, granodiorite, and tonalite. Modal analyses of these granitoids (Pavlides, 1980, table 5) are from the Ta River terrane south of figure 1 (see fig. 2). Modally monzogranites are composed of quartz (28-38 percent), plagioclase (28-36 percent), potassic feldspar (25-36 percent), brown to green biotite (1-6 percent) and muscovite (0.3-4 percent). Myrmekite is nearly always present and may constitute up to 2 percent of the rock. Granular epidote, also a minor constituent, may form 2 percent of the rock. Granodiorite, less abundant than monzogranite, has a generally similar mineralogy to monzogranite but with different proportions of these minerals (Pavlides, 1980, fig. 2). Its modal composition is quartz (3-23 percent), plagioclase (44-45 percent), potassic feldspar (12-23 percent), biotite (6-10 percent), muscovite (1 percent), myrmekite (0.3-3 percent) and epidote up to 2 percent.

The granitoid rocks formally classified as tonalite (Pavlides, 1980) are, for the most part plagiogranite, in that modally they plot along the quartz-plagioclase line of the quartz-plagioclase-alkali feldspar diagram (Pavlides, 1980, fig. 7). Such plagiogranitic rocks consist of quartz (13-41 percent) and plagioclase (54-73 percent). Potassic feldspar is always absent. Minor minerals however include biotite (1-8 percent) and, in places, muscovite (0.2 to 2 percent) and hornblende (1-13 percent). A few of these plagiogranites contain sparse garnet. The presence of plagiogranite within the Ta River Metamorphic Suite is consistent with the island arc setting interpreted for this formation and is analogous to the plagiogranite of the Richland Run pluton that intrudes the Chopawamsic Formation as discussed above. Another analogous intrusion is the amphibole gabbro (Pavlides, 1990) in the Ta River terrane (fig. 2) south of figure 1.

Age

The ages of the intrusions within the Ta River Metamorphic Suite have not been determined isotopically. By analogy with granitoids intrusive into the Chopawamsic, the granitoids of the Ta River are assigned a Cambrian and (or) Ordovician age and the amphibole gabbro a Cambrian(?) age.

Falmouth Intrusive Suite

The Falmouth Intrusive Suite (Cfi) has been described elsewhere (Pavlides, 1980 and Pavlides and others, 1982b) and only a brief summary is given in this report. The granitoids and pegmatoids of this suite are the youngest felsic rocks recognized in the region. They intrude the Matta nappe, the Salem Church allochthon, all rocks within the Rappahannock anticlinorium and at one place, the easternmost part of Chopawamsic Formation.

The granitoid rocks are predominantly monzogranite and granodiorite; tonalite is sparse (Pavlides, 1980, figs. 9, 11, 12, and 13 and tables 8-11).

Monzogranites of the Falmouth Intrusive Suite modally consist primarily of: quartz (21-36 percent), plagioclase (18-42 percent), potassic feldspar (16-43 percent), biotite (2-8 percent), muscovite (1-7 percent) and myrmekite (0.5-5 percent). The monzogranites vary from massive to foliated. The foliation of some of the rocks is imparted by the dimensionally aligned micas and to some extent by dimensionally aligned quartz and feldspar. Myrmekite occurs as bulbous protrusions within plagioclase grains where such grains are in contact with potassic feldspar. Both orthoclase and microcline are present but microcline is generally the common potassic feldspar. At potassic feldspar-plagioclase contacts some plagioclase has a clear albite selvage. Epidote is a minor constituent and locally is intergrown with biotite to form elongate clots. Rare garnet is locally present as poikilitic subhedral grains.

Mineralogically and texturally the granodiorites of the Falmouth Intrusive Suite are similar to the monzogranites except for a greater abundance of plagioclase in the granodiorites. Modally, granodiorite consists of quartz (21-40 percent), plagioclase (32-55 percent), potassic feldspar (2-31 percent), biotite (2-13 percent), muscovite (0-8 percent) and myrmekite (0-5 percent).

Tonalite is less abundant than monzogranite and granodiorite in the suite. Like all the granitoids of the Falmouth Intrusive Suite it has foliated to massive allotriomorphic granular textures. Modally the tonalite is composed of quartz (30-47 percent), plagioclase (32-53 percent), potassic feldspar (0-6 percent), brown biotite (2-13 percent), muscovite (0-21 percent), myrmekite (0-1 percent) and locally, green hornblende (2-6 percent). Tonalite free of potassic feldspar is of plagiogranitic composition. The tonalites of the suite are distinguished from the monzogranites and granodiorites not only by their plagioclase-potassic feldspar ratios but by the absence or minor content of myrmekite and also by the local presence of green hornblende. Chemically at least 2 and possibly 3 groups (A-C) of granitoids have been recognized on the basis of their Rb and Sr content as well as their Rb/Sr isochron and initial $^{87}Sr/^{86}Sr$ ratios (Pavlides and others, 1982b, figs. 3 and 4). The initial $^{87}Sr/^{86}Sr$ of group A is 0.704 which suggests a lower crust or mantle origin whereas that of group B is .7088, which is close to the .7070 for the Fall Run Granite Gneiss and suggests crustal involvement in the magma generation.

Age

Concordant zircon ages and two whole-rock Rb/Sr isochrons indicate that rocks of group A and B range in age from 325 to 300 Ma (Carboniferous) (Pavlides and others, 1982b).

Metamorphism

Regional metamorphism

The Long Branch and Accokeek faults (figs. 1 and 2) juxtapose amphibolite facies rocks that lie, respectively, on the southeast and southwest side of the faults, against rocks to the northeast and northwest that are, for the most part, within the greenschist facies of metamorphism.

Greenschist facies rocks

The Quantico Formation (Oq) northeast of the Accokeek fault consists of slate and phyllite that contain white mica, chlorite, garnet (sparse) and locally, rare chloritoid. The Chopawamsic Formation (Ꞓc) along its entire length is also at greenschist facies grade as its mineralogy, described earlier, indicates.

Other low grade greenschist facies rocks occur within the Storck Quadrangle in the northwest part of figure 1 and provisionally are assigned an Ordovician age. These phyllites and slates (Ou, Op, and Opm, fig. 1) contain white mica, quartz and chlorite. Higher grade greenschist facies rocks are present in the Lunga Reservoir Formation (OꞒl of fig. 1). Typically the groundmass of this formation is micaceous and quartzofeldspathic. Fine-grained muscovite is abundant in the groundmass and also occurs as coarse poikilitic porphyroblasts. Green biotite forms smaller porphyroblasts that are commonly inclusion-free. Garnet is locally a common minor constituent, and euhedral to subhedral magnetite is ubiquitous. Chlorite is common and locally has replaced biotite. Epidote is generally a minor accessory. Staurolite and fibrolite occur within the Lunga Reservoir Formation north of figure 1 as minor constituents at a few places. These two minerals may have formed there, however, by contact metamorphism from an unexposed pluton (Pavlides, 1989).

The Garrisonville Mafic Complex (ꞒZgm) contains mostly amphibolites and hornblendites; in its western part it also contains lesser amounts of hornblendic enstatite-bearing metapyroxenite as well as metawebsterite and metanorite (Pavlides, 1976). Some of these amphibole-and-pyroxene bearing rocks within the Garrisonville may not have been affected by greenschist facies metamorphism and retain some of their original mineralogy.

The granophyric metatrondhjemite of the Horse Pen pluton (figs. 1 and 2) contains albitic plagioclase some of which is graphically intergrown with quartz. Blue green amphibole is common and locally may form as much as 36 percent of the rock. The plagiogranitic metatonalite (OꞒpg) of the Richland Run pluton is characterized by minor biotite and muscovite but greater amounts of chlorite and particularly epidote. Amphibole is sparse to absent in the northeast part of the pluton but is more abundant in its southwestern part. The mineral assemblages of the metatrondhjemite and metaplagiogranite therefore are consistent with a metamorphic grade within the greenschist facies of metamorphism. The small mafic pluton at the join between the Stafford and Storck quadrangles (fig. 1) contains coarse grained amphibole, and altered plagioclase in a groundmass of fine-grained plagioclase. The pluton may be an amphibole gabbro that was not affected by greenschist facies metamorphism.

Age of greenschist metamorphism

Deformed and metamorphosed blocks of the Chopawamsic Formation (Ꞓc) of Early Cambrian age occurs locally within the Lunga Reservoir Formation (fig. 1), which is coeval with the lithologically similar Sykesville Formation (Pavlides, 1989). To the north of figure 1, the Sykesville is intruded by the Occoquan pluton (Drake and Lyttle, 1981) and the Occoquan is now assigned an Early Ordovician age (Mose and Nagel, 1982 and Pavlides, 1989). Therefore the Chopawamsic must have been deformed and metamorphosed in Middle to Upper Cambrian time possibly during the Penobscot disturbance. The Upper Ordovician Quantico Formation northeast of the Accokeek fault, that is unconformably above the Chopawamsic Formation, and the greenschist grade metasediments of the successor basins in the northwest part of figure 1 were metamorphosed in the Late Ordovician during the Taconian orogeny or later.

Amphibolite facies rocks

Regionally metamorphosed amphibolite grade rocks are enclosed by the Long Branch and Accokeek faults and restricted to the east side of figures 1 and 2. This area includes the Quantico Formation of the Quantico synclinorium, the Rappahannock anticlinorium along which is the Salem Church allochthon, the Ta River Metamorphic Suite with an infold of the Quantico Formation, and the Po River Metamorphic Suite of the Matta nappe (figs. 2 and 3).

Po River Metamorphic Suite

The Po River Metamorphic Suite (PzZp) within the Matta nappe (figs. 1 and 2) is composed mostly of strongly foliated biotite gneiss, lesser amounts of hornblende gneiss and two-mica schist. Modal analyses of the gneisses have been published elsewhere (Pavlides, 1980, table 1). In general biotite gneiss contains 43 to 56 percent plagioclase and 0 to 8 percent microcline. Quartz content ranges from 8 to 29 percent. Feldspar is principally a groundmass constituent as well as forming augen (Pavlides, 1980, fig. 2). Dimensionally aligned brown biotite, the characterizing accessory mineral of these rocks, ranges in abundance from 18 to 31 percent. Garnet is generally sparse, as is muscovite. Locally however, muscovite constitutes 20 percent of the rock and it wraps around equidimensional, subhedral garnet. In a few rocks, sparse euhedral epidote has allanite cores. Locally plagioclase is myrmekitic where in contact with microcline.

The hornblende gneisses of the Po River Metamorphic Suite contain from 35 to 55 percent green hornblende that is dimensionally aligned along foliation planes. Plagioclase is both a groundmass as well as augen-forming constituent (Pavlides, 1980, fig. 3) and ranges in abundance from 38 to 43 percent. Quartz content is from 5 to 28 percent. Greenish brown biotite ranges from 1 to 10 percent in abundance. Carboniferous Ar/Ar dates (Louis Pavlides, Sutter, J.F., and Kunk, M.J., unpub. data) obtained from hornblende of gneisses from the Po River Metamorphic Suite (Late Proterozoic to early Paleozoic age) within the Matta nappe along strike southwest of figure 1 (see fig. 2) support the metamorphic origin of these amphibolites.

Small plugs and thin sills of granitoids and pegmatoids within the Po River terrane are generally two mica monzogranite, granodiorite and tonalite. Some of these rocks may be migmatites, probably arteritic leucosomes (Pavlides, 1980, fig. 4).

Rocks of the Salem Church allochthon

The Salem Church allochthon (figs. 1 and 2) contains two amphibolite-grade metamorphic units in a downward facing refolded synform (described elsewhere). These units are the Holly Corner Gneiss (ꞒZh), and the sill-like Berea pluton that is composed of the Falls Run Granite Gneiss (Sfr) and which has intruded the Holly Corner. The Holly Corner Gneiss has been described (Pavlides, 1980) as a well-foliated hornblende and biotite-rich gneiss in which rare compositional layering is defined by thin calc-silicate layers. Andesitic plagioclase (12 to 38 percent) occurs as both twinned and untwinned grains and is locally poikilitic; in places it is myrmekitic where in contact with potassic feldspar. Green hornblende (12-30 percent) is dimensionally aligned along the rock foliation and occurs as inclusion-free as well as poikilitic grains. Dimensionally aligned reddish brown biotite (0-23 percent), along with hornblende, defines the rock folia. Minor constituents include microcline (0-5 percent) and epidote (0-6 percent); the epidote commonly occurs within the hornblende-biotite folia. $^{40}Ar/^{39}Ar$ Carboniferous dates have also been obtained from the hornblende of the Holly Corner Gneiss (Sutter and others, 1985).

The Falls Run Granite Gneiss and Holly Corner Gneiss have been folded together and have undergone similar recrystallization and foliation-development events. Thus the amphiboles and biotites of these gneisses clearly formed through recrystallization under stress to develop their common foliation that defines their synformal structure. The Carboniferous age (Sutter and others, 1985) of hornblende from both of these gneisses contrasts with their respective Silurian and Late Proterozoic(?) to early Paleozoic protolithic ages and further attests to their metamorphic origin.

Ta River Metamorphic Suite

With the area of figure 1, the Ta River Metamorphic Suite (Ꞓt), the presumed oceanward facies of the island arc terrane, is chiefly hornblende gneiss with lesser amounts of biotite gneiss and schist. Granitoid bodies within the Ta River are generally conformable with the enclosing well developed rock foliation. To the southwest of figure 1 (see fig. 2) the Ta River contains more biotite gneiss and schist and lesser amounts of amphibole gneiss. Amphibole gneiss within figure 1 contains green, generally poikiloblastic hornblende (26-69 percent), calcic plagioclase (17-47 percent), quartz (13-27 percent) and opaque minerals (0.5-3 percent). Generally biotite is absent in hornblende gneisses whereas in biotite gneiss, at least at one place, biotite and hornblende may be equally abundant (47 percent). Up to 5 percent epidote is present in some rocks. Although the Ta River is considered coeval to the Early Cambrian(?) Chopawamsic Formation its metamorphism is of Carboniferous age as indicated by $^{40}Ar/^{39}Ar$ plateau ages of hornblende (Louis Pavlides, J.F. Sutter and M.J. Kunk, unpub. data) from gneisses to the southwest of figure 1 (fig. 2).

Quantico Formation

The Quantico Formation (Oq), formed in the easternmost successor basins terrane, is characterized south of the Accokeek fault by schist generally composed of biotite-muscovite-garnet-staurolite ± chloritoid assemblage. Modal analyses of some of the schist and quartzite lenses of the Quantico are given in Pavlides (1980, table 7). Dimensionally aligned muscovite and biotite define the foliation of the schists and were probably formed during the initial metamorphism that affected these rocks. Locally coarse-grained muscovite and biotite and some staurolite overgrow and lie athwart the rock foliation. These are interpreted as the products of a later or second metamorphic event that affected these rocks. Chloritoid, where present, invariably has its long dimension athwart or at a high angle to the rock foliation. Schists of the Quantico Formation enclosed between the Salem Church allochthon and the refolded Ta River Metamorphic Suite (figs. 1 and 2) typically contain staurolite, some of which encloses garnet (Pavlides, 1976, fig. 4). Fibrolite, generally enclosed in megacrystic muscovite and in quartz grains, is present in the eastern part of the Quantico in this area. Quartz-kyanite veins and veinlets, also are present in the western part of this region (fig. 1). The Quantico immediately south of Accokeek fault locally contains quartz lumps (fig. 1) that are mantled by kyanite and staurolite. The garnet and staurolite in schists of this region, particularly along the reservoir of Abel Lake in the southern part of the Storck Quadrangle (fig. 1) have undergone considerable retrogression. Partial to complete alteration of staurolite to micaceous shimmer aggregates and of garnet margins to chlorite is common.

Age of amphibolite facies metamorphism

As mentioned above Ar/Ar hornblende dates for metamorphism from several formations have yielded Carboniferous dates. Carboniferous dates have also been obtained for muscovite from schists of the Quantico Formation (Louis Pavlides, J.F. Sutter, and M.J. Kunk, unpub. data). Therefore, at some time after metamorphism during the Carboniferous, the amphibolite grade rocks of the Rappahannock anticlinorium (fig. 2) which were metamorphosed elsewhere (described below) were juxtaposed against greenschist facies rocks.

Contact Metamorphism

Contact metamorphism is of a limited nature in the area of study and is not shown on figure 1. Locally, potassic feldspar porphyroblasts are present in thin zones within the Holly Corner Gneiss at the contact within the Falls Run Granite Gneiss. One such place is along Rocky Pen Run south of its intersection with state route 654 where the first tributary enters Rocky Pen Run from the east (fig. 1). Similar potassic megacrysts occur within the Holly Corner Gneiss in the area between the Falls Run Granite Gneiss and the Rappahannock pluton (figs. 1 and 2). Here the contact metamorphism is presumably related to the emplacement of the Falls Run rather than the Carboniferous Falmouth Intrusive Suite pluton by analogy with the situation along Rocky Pen Run (see above) and because contact metamorphism has not been recognized marginal to Carboniferous plutons elsewhere.

Structural features

Folds, foliation and lineation

The names of folds and faults described below are contained mostly on figure 2 whereas the structural data for these features is contained in figure 1.

The rocks of the island-arc terrane have two distinct structural styles. The Chopawamsic Formation has a different style of deformation from that of the Ta River Metamorphic Suite (discussed below). North of the Accokeek fault, the Chopawamsic Formation locally has stratigraphic or bedding folds below the unconformably overlying Quantico Formation (fig. 1). Where the North Branch thrust separates these two formations the structure within the Chopawamsic is more obscure. Bedding and compositional layering are commonly parallel with phyllitic foliation as a result of close folding and probably transposition of bedding and compositional layering.

The folds and foliation found within the Rappahannock anticlinorium (fig. 2) are readily recognized as of several generations and geometries (fig. 1). The anticlinorium is a large regional structural feature essentially enclosed by the Long Branch, Accokeek, and Spotsylvania faults. It extends from the northeast corner of figure 1 southward to below the James River (Pavlides, 1989, fig. 1A and 1B).

Most folds along the Rappahannock anticlinorium are foliation folds formed through the folding of an earlier schistosity. Very locally, as along the eastern part of the Pipe Dam Run synform, an axial planar foliation is present. However the latest foliation is not axial planar, generally trending athwart the axial surfaces of foliation folds (fig. 1). In foliation folds, bedding and compositional layering or both may trend essentially parallel to the foliation (fig. 1) and locally represent transposed bedding and compositional layering in closely folded to nearly isoclinally folded rocks. Intrafolial folds are rare, although some small-scale folds are present in the Holly Corner Gneiss (Pavlides, 1980, fig. 6) of the Salem Church allochthon.

In the Quantico Formation east of the Long Branch fault and south of the Accokeek fault, however, transposed folds have not been recognized. Probably the layer-parallel schistosity in this part of the Quantico, like some of the phyllitic foliation to the west, may have formed through mimetic crystallization of sedimentary, bedding-aligned phyllosilicates. In this part of the Quantico, which underwent greater deformation and metamorphism than its counterpart to the north, such mimetically formed layer-parallel foliation produced a well-developed schistosity.

In the part of the Rappahannock anticlinorium south of figure 1 (fig. 2), foliation folds generally are upright, northeast plunging or doubly plunging (Pavlides in Mixon and others, in press). In the northern part of the Rappahannock anticlinorium (fig. 1) foliation folds have been refolded by a late set of folds (discussed below). The Quantico Formation along the core of the Rappahannock anticlinorium is contained in a compound synform overturned to the southwest in the region of the Salem Church allochthon and north of the Ta River Metamorphic Suite (see cross section D-D'). The recumbent synform is succeeded to the northwest by the slightly overturned (a few tens of degrees to the northwest) La Roque synform (LRs, fig. 2), a faulted segment of the Quantico synclinorium. Farther to the southwest (fig. 2), the Quantico is contained mostly within the Quantico synclinorium which in this area is a generally upright foliation fold.

The Ta River Metamorphic Suite along the core of the Rappahannock anticlinorium also contains refolded folds whose axial surfaces, as in the case of the Quantico Formation to the north, are warped around late folds such as the Mine Road antiform (MRa, fig. 2). This antiform also refolds the Massaponax synform (Ms, figs. 1 and 2) that is cored by a thin inlier of Quantico Formation originally deposited on the Ta River Metamorphic Suite.

Sparse mineral lineation within both the Quantico and Ta River is rotated around the Mine Road antiform (fig. 2) and the plunge direction of this lineation indicates a clockwise rotation of axial surfaces of folds from an original northeast trend to a southeast trend.

The Salem Church allochthon is interpreted as the lower overturned limb of a recumbent nappe. This interpretation stems from the present structural position of the basal quartzite lenses (Oqq) of the Quantico Formation. The lenses occur structurally beneath the Holly Corner Gneiss in the Salem Church allochthon (fig. 1) whereas they probably were deposited originally on top of the Holly Corner as discussed elsewhere. The allochthon is a refolded, essentially doubly plunging and downward facing synform outlined by the Pipe Dam Run synform (PDRs, fig. 2). This synform, which is also a foliation fold, has been folded by the Rocky Pen antiform (RPa, fig. 2). Like the structurally conformable synforms and antiforms within the subjacent Quantico Formation and Ta River Metamorphic Suite, the Pipe Dam synform is also considered to have been originally a northeast trending fold.

The Po River Metamorphic Suite is contained within the northwest verging, recumbent Matta nappe (Pavlides in Mixon and others, in press). This nappe was thrust westward onto the island-arc terrane along the Spotsylvania fault. Westward verging small-scale recumbent sinistral folds at several places within the Matta nappe south of figure 1 suggest that the Po River Metamorphic Suite represents the upper limb of the nappe. The Matta nappe therefore is also a large-scale recumbent foliation fold.

The youngest folds in the region such as the Mine Run and Rocky Pen antiforms (figs. 1 and 2) typically fold the earlier foliation folds or foliation within the Rappahannock anticlinorium and the Matta nappe. The stratigraphic synclines containing the successor basin rocks (Ou and Op) within the back-arc basin and island arc terranes in the northwest corner of figure 1 are also interpreted as part of this late fold system. Generally the young folds have rectilinear to slightly curvilinear northeast trending axial surfaces. A gentle (about 15°-20°) northeast plunging mineral lineation (fig. 1) commonly is associated with a late foliation in this area and may reflect the degree of plunge of the Rappahannock anticlinorium. A similar mineral-lineation trend and plunge occurs within the Potomac Creek pluton within the Matta nappe immediately to the northeast of the Salem Church allochthon. This suggests the same kinematic process of penetrative extensional deformation has affected both the Rappahannock anticlinorium and the Matta nappe in this area.

Faults

The Long Branch thrust bounds the Quantico Formation on its northwest side and merges into the Accokeek fault at it's northeast end (figs. 1 and 2). Fluxion textured mylonite developed within basal quartzite of the Quantico Formation (Pavlides, 1976, fig. 3) has been recognized at several places along strike of the Long Branch fault. The linear trace of this fault along the northwest side of the Quantico synclinorium (fig. 2) may have formed as a consequence of late strike-slip movement. The Spotsylvania thrust, although not exposed, is well documented by geophysical data. The rocks on either side of the fault have markedly different lithologies as well as strongly contrasting aeromagnetic and aeroradiometric signatures (Neuschel, 1970; Pavlides, 1980; Bobyarchick and others, 1981; and Wier and Pavlides, 1985). However, rather than a single fault, the Spotsylvania may represent a zone of movement (Pavlides, 1980). The Spotsylvania thrust extends for a considerable distance southwest of the map area (fig. 2 and Pavlides, 1989). After it developed as a thrust, the Spotsylvania is interpreted to have had the rocks on its southeast side undergo dextral or southwestward strike-slip movement. Such strike-slip movement may have resulted in its linear trend up to about the latitude of the Salem Church allochthon (fig. 2). Additional thrusting along the Spotsylvania may have occurred west and northwest of this latitude. The high-angle, reverse, Hazel Run fault (Wier and Pavlides, 1985) may have formed in the Cenozoic along a northeast-trending fracture, offset from but related to the Spotsylvania fault south of where the Spotsylvania changes from a northeast trend to an irregular north trend (figs. 1 and 2).

The Dumfries, Fall Hill, and Hazel Run faults (fig. 2) along the east side of the Piedmont and the Brookes fault zone (not shown) within the Coastal Plain east of the Hazel Run fault are part of the Stafford fault system as defined by Mixon and Newell (1977, p. 437-440). The faults of the Stafford system are reverse faults that dip steeply northwest with the west side being the upthrown side. As much as 120 feet (39 m) of reverse displacement has occurred, for example, along parts of the Hazel Run fault (Wier and Pavlides, 1985, fig. 2). Reverse fault movement along the Stafford fault system occurred mainly in the Cretaceous and the middle(?) Tertiary but some late movement along these faults in latest Tertiary or in the Quaternary is possible (Mixon and Newell, 1977).

Tectonic synthesis

The Early Cambrian[1](?) (about 550 Ma) Chopawamsic Formation of the island-arc terrane had undergone deformation and greenschist facies metamorphism by about Middle Cambrian time at the beginning of the Penobscot orogeny (Pavlides, 1989). The early phases of the Penobscot may also have initiated westward (present-day coordinates) thrusting followed, in part, by northward thrusting of the island-arc terrane and the associated shedding of foliated blocks from the Chopawamsic Formation into eastern parts of the back-arc basin (melange terrane of figure 2) where sediments of the Mine Run Complex (Pavlides, 1989), that constitute the melange terrane, were accumulating. With the initial westward-directed transport during Penobscot deformation it is possible that thrusts could have developed within the back-arc basin and helped supply some of the mafic and ultramafic blocks now found in melange zone III of the Mine Run Complex of Pavlides (1989). In any event, thrusting during Middle Cambrian to Early Ordovician time is considered to be the initial phase of the telescoping of the back-arc basin during the Penobscot orogeny. This orogeny therefore is considered to be a long-lived episodic event and a precursor to the Taconic orogeny. Deformation and metamorphism within the back-arc basin terrane (Pavlides, 1989 and Pavlides and others, 1994) was essentially completed with a few exceptions when at about 450 Ma the Lahore pluton (west central part of figure 2) was intruded into the melange terrane of the Mine Run Complex (Pavlides and others, 1994).

The tectonic process or processes by which the deformation of the Quantico Formation and the structurally conformable superjacent Salem Church allochthon took place are complex. The geographic position of the Quantico when it was folded poses problems as to the nature and timing of the deformation process as well as the grade of metamorphism. Staurolite- and higher-grade rocks of the Quantico Formation, bounded by the North Branch and Accokeek faults (fig. 2), had been previously considered structurally and stratigraphically continuous with the low-grade Quantico north of that latitude (Pavlides, 1989, 1990). It is now accepted that the Long Branch and Accokeek faults separate the high- and low-grade metamorphic parts of the Quantico. The general on-strike occurrence of these Quantico segments is considered fortuitous. This interpretation stems from considerations of the tectonic history necessary to explain the area that contains the Salem Church allochthon, the immediately enclosing Quantico Formation, the Ta River Metamorphic Suite below the Quantico Formation, as well as the structure and metamorphic grade of the rocks of the Quantico synclinorium with relation to the Chopawamsic Formation on its west side. The scenario adopted herein is that the early Paleozoic folding of the Chopawamsic prior to the deposition of the Quantico Formation did not affect the coeval Ta River Metamorphic Suite nor the Holly Corner Gneiss, both of which lay successively eastward of the Chopawamsic terrane. The Holly Corner Gneiss is assigned a Late Proterozoic or Cambrian age because of its presumed, in part, stratigraphic correlation with the Ta River and Chopawamsic rocks. The stratigraphic relationship envisioned is that the Quantico Formation was deposited unconformably above the collapsed terrane of the deformed Chopawamsic Formation but disconformably on the protoliths of the Ta River Metamorphic Suite as well as the Holly Corner Gneiss to the east. However, only the basal quartzite of the Quantico was deposited disconformably on the Holly Corner. By 440 Ma the Ellisville pluton (fig. 2) had been emplaced and the trench and associated westward dipping subduction zone over which the island arc terrane had formed in the Early Cambrian (Pavlides, 1981) had ceased to exist (Pavlides and others, 1994). After about 440 Ma the Po River Metamorphic Suite terrane was being accreted against Holly Corner Gneiss terrane as the Matta nappe. Furthermore, all of the rocks from the Po River terrane and westward had been accreted over continental crust by 440 m.y. ago as the $^{87}Sr/^{86}Sr$ of 0.7062 of the granodiorite of the Ellisville pluton in the southwest corner of figure 2 suggests crustal involvement in its origin (Pavlides and others, 1994), as does the $^{87}Sr/^{86}Sr$ of 0.7070 of the Falls Run granite that was emplaced into the Holly Corner Gneiss as a sill at about 410 Ma. By this time the recumbent, westward verging Matta nappe was being thrust against the eastern edge of the Holly Corner Gneiss terrane.

Following intrusion of the Falls Run granitic rocks at 410 Ma and prior to the emplacement of the Falmouth Intrusive Suite granitoids at 320-300 Ma (Pavlides and others, 1982b) the Po River Metamorphic Suite and particularly rocks of the Rappahannock anticlinorium underwent major additional deformation as well as metamorphism. In the time interval 410-300 Ma the generally undeformed Quantico Formation and the subjacent Ta River Metamorphic Suite and Holly Corner Gneiss with the sill-like Falls Run Granite Gneiss, were folded into structurally conformable, essentially upright isoclinal folds with axial-plane foliation parallel to bedding and compositional layering along the limbs of the folds. Such folds within the Quantico Formation are preserved within the La Roque synform and the Quantico synclinorium. Probably, at this time, along the west side of the Rappahannock anticlinorium, the unconformity between the Chopawamsic and the Quantico Formations (Pavlides and others, 1980) became a decollement surface along which the Long Branch thrust developed. The upright isoclinal folding is inferred to be related to westward thrusting by the Matta nappe along the developing Spotsylvania thrust. With continuing deformation all the upright isoclinal folds to the east of the La Roque synform and Quantico synclinorium eventually became westward verging recumbent isoclinal folds. In the terrane now containing the Salem Church allochthon the recumbent folds with the structurally conformable limbs of the Quantico Formation and Ta River Metamorphic Suite were depressed into a structural basin. The Holly Corner Gneiss along with intrusive Falls Run had developed into an overturned isoclinal nappe, the Salem Church allochthon. The allochthon was emplaced onto part of the structural basin. This resulted in the Salem Church locally having the geometry of a doubly plunging northeast trending synform, now the Pipe Dam Run synform. Following these events a combination of thrusting and dextral strike-slip along the Spotsylvania fault folded the Pipe Dam Run synform, and northeast trending folds within Quantico Formation, the Ta River Metamorphic Suite, including the Massaponax synform, around late folds such as the Mine Road and Rocky Pen antiforms. Thrusting and dextral strike-slip movement along the Spotsylvania fault locally tilted down the eastern part of the Rappahannock anticlinorium and carried a thicker cover of the Matta nappe over it (see below). The late gently plunging mineral lineation may have formed in part due to late pervasive extensional deformation. Such lineation also became well-developed in the granitoids of the Potomac Creek pluton of the Matta nappe.

The rocks of the Rappahannock anticlinorium and Matta nappe have undergone polymetamorphism. At least two metamorphic events can be recognized by the porphyroblasts within the Quantico Formation as described above. The first metamorphism probably occurred when the isoclinal folds developed and the later metamorphic overgrowths possibly when deeper burial occurred as parts of the Matta nappe were overthrust onto the subjacent rocks.

An $^{40}Ar/^{39}Ar$ traverse was made along the Rappahannock River across the Salem Church allochthon by Sutter and others (1985) using amphiboles from the Holly Corner Gneiss. From west to east plateau ages were obtained which ranged from 321 Ma to 307 Ma. These data indicate an Alleghanian metamorphic event. They suggest that the closure temperature of amphibole (about 500°C) was attained at about the time of intrusion of the Falmouth Intrusive Suite granitoids (320-300 Ma) and that the western part of the Holly Corner had passed through the 500° isotherm about 14 m.y. earlier than the eastern end of the Holly Corner Gneiss. This may possibly reflect the deeper burial of the eastern part of the Rappahannock anticlinorium suggested above. Also, a thermobarometric study using garnet and coexisting biotite (Flohr and Pavlides, 1986) was made within the Quantico Formation essentially parallel to the $^{40}Ar/^{39}Ar$ traverse. From staurolite-grade schists in the west to fibrolitic schists on the east the temperature and pressure ranges respectively from 487°C and 4.3 kb on the west to 615°C and 4.8 kb on the east. This is also consistent with an eastward increase in temperature and pressure related to deeper burial of the eastern part of the Rappahannock anticlinorium.

Geophysical features

The area of figure 1 has been covered in part or in whole by various aeromagnetic and aeroradioactivity surveys (Neuschel, S.K., 1970; Pavlides and others, 1974) and by a ground gravity survey (Pavlides and others, 1974). Correlations between bedrock geology and these geophysical data have been given by the above cited investigators. Therefore only a brief review of these correlations will be given here.

Aeromagnetic anomalies

The area west and southwest of figure 1 (as outlined on figure 2), between latitude 38° and 38°30' and longitude 77°37'30" and 78° and the correlative relationship of the aeromagnetic data in this region to the bedrock geology has been described, in part, elsewhere (Pavlides and others, 1994, Pl. 1A and p. 4-5) and will not be discussed further in this report.

The aeromagnetic maps superposed on the geologic map of figure 1 and on figure 2 contain magnetic anomalies caused by differences in the content of disseminated magnetic minerals in the bedrock lithologies. Thus the Garrisonville Mafic Complex and the Lunga Reservoir Formation that contain roughly similar amounts of disseminated magnetite together form a single magnetic unit (fig. 1). The metavolcanic rocks of the Chopawamsic Formation are delineated rather closely by a pronounced, more or less linear trending group of magnetic highs. In contrast, the plagiogranite of the Richland Run pluton is defined by a series of aligned magnetic lows along the trend of the pluton (fig. 1). The only exception to this correlation is the northeast projection of plagiogranite that, in part, bifurcates the Garrisonville Mafic Complex in the Storck and Stafford Quadrangles (fig. 1). Here the positive aeromagnetic anomaly associated with the Garrisonville has a gradient that continues uninterrupted to the south until it impinges against the magnetic low of the main body of the Richland Run pluton. This relationships suggest that the plagiogranite mass bifurcating the Garrisonville Mafic Complex is very thin in that area and its magnetic signature is swamped by that of the thicker, mafic and more magnetite-bearing rocks of the Garrisonville.

The granitoid rocks of the Chancellor pluton in the southwest part of the Salem Church Quadrangle and the Falls Run Granite Gneiss in the Berea pluton (fig. 1), as well as the trondhjemite of the Horse Pen Run pluton are locally characterized by magnetic lows. In contrast the amphibolite-rich terranes of the Ta River Metamorphic Suite, with a higher magnetite content than its enclosing rocks, also is generally typified by magnetic highs. These highs, along the Rappahannock anticlinorium, in part, outline the geometry of the Ta River refolded rocks. In contrast there is a linear northeast trending positive magnetic anomaly that overlies, in part, the northeast trending Ta River amphibolic rocks on the east side of the Salem Church Quadrangle. The amphibolitic Holly Corner Gneiss contrasts with the other amphibolitic units in the area in having a low magnetite content and hence is characterized by magnetic lows.

The Quantico Formation has a lower magnetic susceptibility, in general, than its enclosing, more magnetite-rich rocks and is characterized by a featureless to negative magnetic signature.

The Spotsylvania fault is also in part delineated by aeromagnetic data. In general, it occurs at the foot of the southeast trending gradient of the magnetic highs that characterize the Piedmont rocks to the west (figs. 1 and 2). The magnetic high on the east side of the Spotsylvania fault, in the northeast part of the Stafford Quadrangle, is attributed to a local, unexposed magnetite-rich unit in the Po River terrane east of the Spotsylvania fault in this area.

Aeroradioactivity data

At least two published reports (Neuschel, 1970 and Pavlides and others, 1974) have described the correlation between aeroradiometric data and bedrock and soil within the area of figure 1. These investigations report the total gamma ray flux and present the data as contour intervals; the contours represent gamma radiation in counts per second. The ground component of radioactivity is derived from gamma rays of natural radionuclides from the soil and bedrock exposures and results from the decay of ^{40}K and members of the uranium and thorium radioactive-decay series.

The regionally extensive aeroradiometric survey of Neuschel (1970, fig. 3) covers only the Salem Church quadrangle of figure 1. Although the geologic map of Neuschel (1970, fig. 4) differs considerably from that of figure 1 similar major lithologic units are shown on Neuchels' map as well as figure 1. The aeroradioactivity map of Neuschel (1970, fig. 3) when overlain on figure 1 displays a pronounced positive aeroradiometric anomaly with a maximum contour closure of 1200 counts per second that is centered over the Berea pluton. This pluton contains the Falls Run Granite Gneiss, a highly potassic rock (22-49 percent potassic feldspar). In addition, Neuschel, Bunker and Bush (1971) analyzed 22 auger samples across this high aeroradiometric anomaly by gamma-ray spectrometry. They found that rocks now designated as the Falls Run Granite Gneiss on figure 1 contain two and three times the amounts of thorium and uranium generally found in granitoids of similar composition. Superposing of the aeroradiometric map of Neuschel (1970, fig. 3) on figure 1 also shows positive aeroradiometric anomalies of a lesser magnitude centered over the muscovitic (potassic mica) Quantico Formation. In contrast, the Ta River Metamorphic Suite, which is low in potassium generally has negative or very low positive radiometric anomalies centered over it.

An aeroradiometric map of the Stafford and Storck Quadrangles of figure 1 (Pavlides and others, 1974, fig. 4) also characteristically shows positive aeroradiometric anomalies associated with highly potassic rocks. Thus the rocks now assigned to the muscovitic Lunga Reservoir Formation are clearly defined by a positive anomaly that defines their separation from the Garrisonville Mafic Complex. As stated earlier these two formations were indistinguishable from one another on the basis of aeromagnetic anomalies. The plagioclase-rich granitoid rocks of plagiogranite and trondhjemite contained respectively in the Richland Run and Horsepen Run plutons are also characterized by negative to low magnetic anomalies because of their potassium-poor composition.

Gravity data

Gravity data and its relationship to bedrock geology for the area between latitudes 38° and 38°30' and longitude 77°37'30" and 78° on figure 2 has been described elsewhere (Pavlides, 1994, fig. 1B and p. 4-5). It is beyond the scope of this report to further discuss these data and only the partial gravity data available within figure 1 will be discussed herein.

Gravity anomalies are directly related to density contrasts between rock masses. A Bouguer gravity map of the area covered by figure 1 has been published by Pavlides and others (1974, fig. 5). A positive, generally east-trending gravity anomaly is centered over the Garrisonville Mafic Complex, which has high-density rocks in contrast to its enclosing formations. This gravity high has a southward gradient extending about to the contact with the Falls Run Granite Gneiss of the Berea pluton. The rocks along strike to the northeast and southwest of the Berea pluton generally have negative to low northeast trending gravity anomalies. The gradient of the positive anomaly centered over the mafic rocks of the Garrisonville is probably related to the southeast sloping surface of the Garrisonville rocks in this direction (Pavlides and others, 1974).

Economic geology

The only economic resources derived from the Piedmont rocks of figure 1 at this writing (1994), are from the quarry located within the Garrisonville Mafic Complex. Here the mafic rocks are quarried for use as rip rap, road metal and asphalt granules.

In the past, gold and pyrite were propected for, principally in the southwest part of figure 1 immediately north and south of the Rappahannock River. Luttrell (1966) and Sweet and Trimble (1983) have published location maps and brief descriptions of the deposits within the confines of figure 1. The gold mostly occurs in quartz veins as free gold and in auriferous pyrite. Such veins apparently have been emplaced in almost all the formations that underlie this area. These include the Chopawamsic and Quantico Formations of Early Cambrian(?) and Late Ordovician age respectively as well as the metatrondhjemite of Cambrian and (or) Ordovician age of the Horse Pen pluton. Gold-bearing quartz veins are also reported from the Rappahannock pluton (located at the southwest end of the Salem Church allochthon) composed of granitoids assigned to the Falmouth Intrusive Suite of Carboniferous age on the basis of petrography. There is no corroborative isotopic data available from granitoids of this pluton in the vicinity of the quartz veins to unequivocally establish their age as Carboniferous. With this caveat in mind it is assumed therefore that the age of some gold mineralization is of Carboniferous age postdating the Rappahannock pluton. A small amount of lead and zinc are also associated with the gold deposits.

An old abandoned pyrite mine or prospect occurs within the Chopawamsic Formation in the northeast part of the Stafford Quadrangle and zinc mineralization is reported within the same formation in the central part of the Stafford Quadrangle.

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[1] The U.S. Geological Survey has accepted the Proterozoic-Cambrian boundary as being at about 570 Ma in the standard geologic time scale. Recently, however, uranium-lead zircon chronology of volcanic rocks interlayered within a sequence of paleontologically well established Cambrian rocks in Siberia, suggest that the Proterozoic-Cambrian boundary is better placed at about 544 Ma (Bowring and others, 1993). Thus, tectonic events related to rocks older than 544 Ma described in this report may have different temporal settings than those described herein.

PIEDMONT GEOLOGY OF THE STAFFORD, STORCK, SALEM CHURCH, AND FREDERICKSBURG QUADRANGLES, STAFFORD, FAUQUIER AND SPOTSYLVANIA COUNTIES, VIRGINIA

BY
LOUIS PAVLIDES

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