

SHRIMP AND CONVENTIONAL U-Pb AGES OF ORDOVICIAN GRANITES AND TONALITES IN THE CENTRAL APPALACHIAN PIEDMONT: IMPLICATIONS FOR PALEOZOIC TECTONIC EVENTS

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ABSTRACT. Discordant Cambrian U-Pb ages of questionable reliability for metamorphosed plutonic rocks in the central Appalachian Piedmont of northern Virginia, Maryland, and the District of Columbia have led to different regional geologic interpretations and controversies. In this study, we use the sensitive high resolution ion microprobe (SHRIMP) for dating 25- μ m diameter areas on individual zircons from Piedmont granitoids in an effort to resolve previous controversial ages.

Cathodoluminescence images of zoning within the zircons are used to select pristine areas of cores and overgrowths for dating and to help interpret the results. For comparison, hand-picked fractions of zircons from most of the samples were also dated by the conventional isotope dilution thermal ionization mass spectrometry (TIMS) U-Pb method.

The combined SHRIMP and TIMS results of this study demonstrate that the Dale City Quartz Monzonite, Norbeck Intrusive Suite, Kensington Tonalite, Goldvein pluton, Lake Jackson pluton, Falls Church Intrusive Suite, Occoquan Granite (main batholith and satellite Bull Run Marina pluton), Georgetown Intrusive Suite, Dalecarlia Intrusive Suite, and related granitoids are parts of an extensive Early to Middle Ordovician magmatic arc. Emplacement of these plutons from about 485 to 450 Ma generally was contemporaneous with major regional deformation and metamorphism, called the Taconic orogeny in rocks of the northern Appalachians. The Ordovician ages supersede most of the discordant Cambrian(?) to Neoproterozoic dates that previously suggested a Potomac or Penobscot orogeny in Piedmont rocks of the Potomac Valley, raising questions about the nature and timing of that event. The Devonian Guilford Granite crosscuts all structures, providing a minimum age for these Paleozoic events.

INTRODUCTION

Because fossils are scarce, isotopic dating of igneous rocks is essential for constraining the ages of geologic events in the central Appalachian Piedmont of the eastern United States. The determination of reliable crystallization ages for metamorphosed intrusive rocks in the Piedmont of Maryland, Virginia, and the District of Columbia has been a longstanding problem because many of the rocks contain material inherited from older source rocks. Previously determined U-Pb dates of zircons from these rocks have been mostly discordant and probably older than true igneous emplacement ages because the zircon populations contained mixtures of igneous and inherited components (Higgins and others, 1977). Controversies in regional geology have focused on different interpretations of the questionable discordant dates (Higgins and others, 1977; Seiders, 1978; Zartman, 1978; Pavlides, 1981, p. A6). Current geologic mapping in the Washington-Baltimore urban region (Horton, 1998) provides an opportunity to acquire more reliable isotopic ages and to re-examine the complex geologic history of this region using new age constraints. Consequently, we sampled granitoid rocks from Piedmont plutons and utilized the sensitive high resolution ion microprobe (SHRIMP)

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for U-Pb dating of spots on individual zircons. Conventional isotope dilution thermal ionization mass spectrometry (TIMS) U-Pb ages of small, carefully hand-picked fractions of zircon were also determined for all but two of the samples so that the results by the two methods could be directly compared. This study demonstrates that Ordovician plutonism was important along the eastern margin of Laurentia, not only where previously documented in New England, but in the central Appalachian Piedmont as well. It also shows that the age of the Taconic orogeny (including deformation and metamorphism broadly coeval with plutonism) in the central Appalachians is similar to that previously reported in the northern Appalachians.

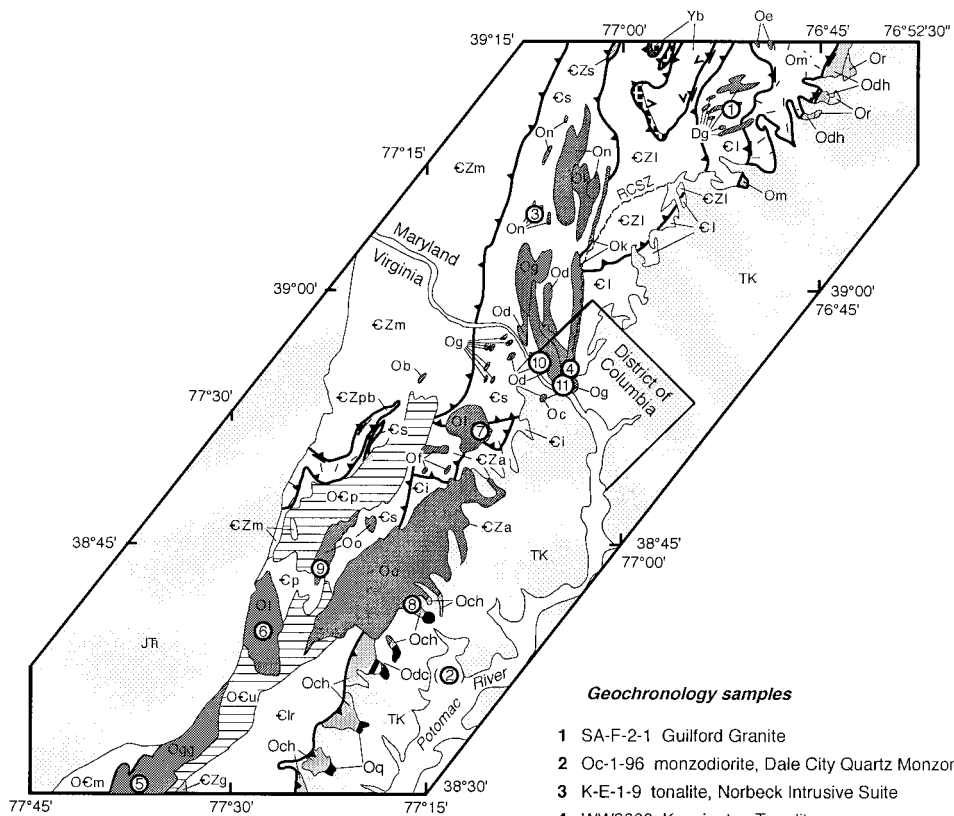
REGIONAL GEOLOGIC SETTING

The central Appalachian Piedmont contains Mesoproterozoic to Paleozoic metamorphosed sedimentary and igneous rocks as well as younger sedimentary and igneous rocks in early Mesozoic extensional basins. In the area of figure 1, exposures of Proterozoic and Paleozoic metamorphic rocks are bounded on the east by overlapping Cretaceous and Tertiary sedimentary deposits of the Atlantic Coastal Plain and on the west by early Mesozoic rocks of the Culpeper basin. This region of the Piedmont contains allochthonous metamorphic rocks, including probable Laurentian basement and continental margin deposits, melange complexes, mafic and ultramafic complexes, volcanic-arc remnants, and granitoid plutons (Drake, 1985b, 1989; Drake and Lyttle, 1981; Drake and others, 1989; Drake and Froelich, 1997; Fleming, Drake, and McCartan, 1994; Gates, Muller, and Valentino, 1991; Higgins and others, 1977; Horton and others, 1989, 1991; Mixon, Southwick, and Reed, 1972, and in press; Mose and Nagel, 1982; Pavlides, 1976, 1989, 1990; Pavlides and others, 1974, 1980; Seiders and Mixon, 1981; Seiders and others, 1975; Southwick, Reed, and Mixon, 1971; Wier, 1977).

The oldest rocks in the region are gneisses of the Mesoproterozoic Baltimore Gneiss (fig. 1), exposed as allochthonous massifs in the cores of antiformal nappes (Muller and Chapin, 1984; Fisher, 1989). These Mesoproterozoic rocks (Aleinikoff and others, 1997) have been interpreted either as part of the Laurentian continental basement or as remnants of a "Baltimore microcontinent" of undetermined origin (Horton, Drake, and Rankin, 1989; Fail, 1997). They are overlain by the Glenarm Group (Drake, 1986a, 1994a; Drake and others, 1989), a continental-margin sequence (fig. 1).

The Potomac composite terrane of Drake (1985a, 1989) contains metamorphosed melange complexes (Drake, 1985b, 1989; Drake and Lyttle, 1981; Drake and Morgan, 1981; Pavlides, 1989) and associated units in a stack of thrust sheets. Sedimentary rock units in the southern part of figure 1 have been considered to be younger than the Chopawamsic Formation (discussed below), because one of them, the Lunga Reservoir melange, contains olistoliths thought to have been derived from the Chopawamsic (Pavlides, 1989). These previous interpretations are currently being addressed and revised.

The largest mafic complex in the United States Appalachians, known as the Baltimore Complex, crops out at the northern end of the study area and includes the Mount Washington Amphibolite (fig. 1) and Hollofield Ultramafite. It consists of metamorphosed mafic rocks and smaller amounts of ultramafic rock (Herz, 1951; Southwick, 1970; Crowley, 1976; Morgan, 1977; Sinha, Hanan, and Wayne, 1997). These rocks are interpreted to constitute the Baltimore thrust sheet (Crowley, 1976; Drake, 1998a, b). It has been proposed that rocks of the Baltimore Complex may have formed in a stratiform intrusive complex (Southwick, 1970), in an ophiolite (Crowley, 1976; Morgan, 1977), in a continental-margin volcanic arc (Sinha and others, 1979; Hanan, ms, 1980; Sinha and Hanan, 1987), or in a back-arc basin (Hanan and Sinha, 1989). Sinha, Hanan, and Wayne (1997) interpreted the Baltimore Complex to have



EXPLANATION

(See figure caption for geologic-unit symbols)

- Cenozoic and Mesozoic overlap sequences
- Tonalitic and granitic rocks (Devonian-Ordovician)
- Quantico Fm. (Ordovician)
- Volcanic-arc sequences (Ordovician)
- Paleozoic overlap sequences
- Mafic and ultramafic complexes (Cambrian?)
- Melanges and related units (Cambrian?)
- Glenarm Group (Cambrian)
- Baltimore Gneiss (Mesoproterozoic)

Geochronology samples

- 1 SA-F-2-1 Guilford Granite
- 2 Oc-1-96 monzodiorite, Dale City Quartz Monzonite
- 3 K-E-1-9 tonalite, Norbeck Intrusive Suite
- 4 WW9000 Kensington Tonalite
- 5 P82-69 granite, Goldvein pluton
- 6 P82-71 tonalite, Lake Jackson pluton
- 7 AN1000 tonalite, Falls Church Intrusive Suite
- 8 Oc-3-98 Occoquan Granite, main batholith
- 9 IH1000, P82-74, Occoquan Granite, Bull Run Marina pluton
- 10 WW5000 monzogranite, Dalecarlia Intrusive Suite
- 11 WW6000 tonalite, Georgetown Intrusive Suite

- Contact
- Thrust fault (teeth on upper plate)
- Overturned thrust fault (base of teeth on upper plate)
- Shear zone

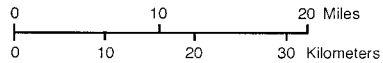


Fig. 1. Geologic setting of plutonic rocks in the northern Virginia, District of Columbia, and Maryland Piedmont. Map symbols: TK = Atlantic Coastal Plain; JTR = Early Mesozoic Culpeper basin. Dg = Guilford Granite. Ob = Bear Island Granodiorite; Oc = Clarendon Granite; Od = Dalecarlia Intrusive Suite; Odc = Dale City Quartz Monzonite; Oe = Ellicott City Granodiorite; Of = Falls Church Intrusive Suite; Og = Georgetown Intrusive Suite; Ogg = Goldvein pluton (metagranite); Ok = Kensington Tonalite; Ol = Lake Jackson pluton (metatonalite); On = Norbeck Intrusive Suite; Oo = Occoquan Granite. Oq = Quantico Formation. Och = Chopawamsic Formation; Odh = Druid Hill Amphibolite; Or = Relay Felsite. OEp = Popes Head Formation, undivided; OEu = phyllite and undivided metasedimentary rocks. OEm = Mine Run Complex; Ep = Purcell Branch Formation; EIr = Lunga Reservoir Formation; Ei = Indian Run Formation; Es = Sykesville Formation; El = Laurel Formation; EZl = Loch Raven Schist; EZm = Mather Gorge Formation, undivided; EZa = Annandale Group, undivided. Om = Mount Washington Amphibolite of Baltimore Complex; EZg = Garrisonville Mafic Complex; EZpb = Piney Branch Complex; EZs = Soldiers Delight Ultramafite. Eg = Glenarm Group. Yb = Baltimore Gneiss. RCSZ = Rock Creek shear zone. Geology from State geologic maps (Cleaves, Edwards, and Glaser, 1968; Virginia Division of Mineral Resources, 1993), regional compilations (Drake and Lyttle, 1981; Drake, 1985b; Drake and others, 1994a), geologic maps of 7.5-minute quadrangles (Fleming, Drake, and McCartan, 1994; Drake and Froelich, 1986, 1997; Drake and Lee, 1989; Drake, 1986b, 1998a, b, c), and unpublished data.

originated as a “sub-arc plutonic complex” at 489 ± 7 Ma based on their synthesis of new and existing (Shaw and Wasserburg, 1984; Hanan and Sinha, 1989) isotopic and geochemical evidence. The Garrisonville Mafic Complex (OZg) is composed of amphibolite, hornblendite, and orthopyroxenite (Pavlidis, 1989). Geochemical studies are needed to test Pavlidis’ (1989) hypotheses that the Garrisonville may be part of a local mafic substrate to a volcanic arc or a remnant of oceanic crust from a back-arc basin.

The Chopawamsic Formation (fig. 1), Druid Hill Amphibolite, and Relay Felsite consist of mafic to felsic metavolcanic rocks, hypabyssal intrusive rocks, and volcanically-derived metasedimentary rocks, and are interpreted to have formed in a volcanic arc (Crowley, 1976; Pavlidis, 1980, 1981, 1989; Pavlidis, Gair, and Cranford, 1982; Horton, Drake, and Rankin, 1989). The Druid Hill Amphibolite and Relay Felsite are interpreted by Drake (1998b, c) to constitute the Soapstone Branch thrust sheet. Although the Chopawamsic and James Run Formations were previously thought to be Early Cambrian in age (Tilton and others, 1970; Higgins and others, 1971; Pavlidis, 1971), new SHRIMP and conventional U-Pb ages (Horton and others, 1998; Coler, Samson, and Hibbard, 1998) for these metavolcanic rocks indicate that they are Ordovician, comparable in age to some of the plutonic rocks investigated here.

The youngest stratified rocks in this area of the Piedmont are the Quantico and Popes Head Formations (fig. 1). The Quantico Formation contains fossils that are Ordovician or younger (Pavlidis and others, 1980). The Popes Head Formation is composed primarily of phyllite and metasiltstone and contains minor interbedded felsic and mafic layers interpreted by Drake and Lyttle (1981) on the basis of igneous mineralogy to be metatuff. The base of the Popes Head is interpreted as an angular unconformity (although a thrust fault is possible) because the bedding is parallel to the contact that cuts across structures in the underlying rocks (Drake and Lyttle, 1981; Drake, 1985a, 1989; Pavlidis, 1989). The significance of newly obtained Ordovician U-Pb zircon ages for the Chopawamsic, James Run, and Quantico Formations is discussed in Horton and others (1998).

Granitoid plutons (discussed below) are the most widespread intrusive rocks. Dikes of early Jurassic unmetamorphosed diabase (not shown in fig. 1) range up to a few meters in thickness and occur sporadically throughout the Piedmont.

Metamorphism in Proterozoic and Paleozoic rocks of the Piedmont ranges from greenschist facies to upper amphibolite facies (sillimanite zone) (Fisher, 1970, 1971; Drake and Morgan, 1981; Drake, 1989). The Popes Head Formation, which is in the biotite zone of the greenschist facies, shows evidence of only one prograde metamorphic event (Drake and Lyttle, 1981).

GRANITOID ROCKS

Metamorphosed granitoid rocks, which are the focus of this isotopic study, range in composition from tonalite to granite. Granitoid units shown on figure 1, most of which were dated in this study, include (from north to south): the Ellicott City Granodiorite (Hopson, 1964; Mario, 1984; Mario and Lidiak, 1984), the Norbeck Intrusive Suite (Drake, 1998a; equivalent to Norbeck Quartz Diorite of Hopson, 1964), the Kensington Tonalite (Cloos and Cooke, 1953; Hopson, 1964; Fleming, Drake, and McCartan, 1994), the Georgetown Intrusive Suite (Drake and Froelich, 1986; Fleming, Drake, and McCartan, 1994), the Dalecarlia Intrusive Suite (Drake and Fleming, 1994), the Bear Island Granodiorite (Cloos and Cooke, 1953; Drake and Lee, 1989), the Clarendon Granite (Drake and Fleming, 1994), the Falls Church Intrusive Suite (Drake and Froelich, 1986, 1997), the Occoquan Granite (Lonsdale, 1927; Seiders and others, 1975; Drake and Froelich, 1986) in the main batholith and satellite bodies such as the Bull Run Marina pluton (Lyttle and others, in press), the Dale City Quartz Monzonite (Seiders and others, 1975; Seiders and Mixon, 1981), the Lake Jackson

pluton (Pavlidis, 1990), and the Goldvein pluton (Pavlidis, 1990). As discussed below, the Guilford Granite (Cloos and Broedel, 1940; Hopson, 1964) postdates all other Paleozoic igneous rocks in this study. The descriptive nomenclature for plutonic rocks in this paper follows the usage of Streckeisen (1973, 1976).

Plutonic rocks dated in this study are described below in order from youngest to oldest (see table 1 for a summary of characteristics for each unit). The Guilford Granite (fig. 1) (Cloos and Broedel, 1940; Drake, 1998a; equivalent to Guilford Quartz Monzonite as used by Hopson, 1964) is a light-gray, medium to fine-grained, homogeneous monzogranite. It differs from the other plutonic rocks in this study because it is neither foliated nor lineated, and because the granite bodies cut across the schistosity and bedding in adjacent metasedimentary rocks of the Laurel Formation as described by Hopson (1964) at the type locality.

The Dale City Quartz Monzonite (fig. 1) consists of quartz monzonite, quartz monzodiorite, and subordinate quartz diorite in a small intrusive body at Dale City, Virginia (Seiders and Mixon, 1981). Exposures of the contact between the Dale City Quartz Monzonite and the Quantico Formation have been documented and interpreted by Seiders and others (1975) as an intrusive contact and by Pavlidis and others (1980) as an unconformity. As part of this study, Pavlidis and others' photographs were reexamined, and the same outcrop and others were visited. The nature of the contact could not be conclusively determined. Previous discordant U-Pb zircon dates, which suggested an age of about 560 Ma for the Dale City Quartz Monzonite (Seiders and others, 1975), are unreliable and are superseded by new data in this paper. Our new U-Pb age is consistent with the interpretation of Pavlidis and others (1980).

The Norbeck Intrusive Suite (fig. 1) as defined by Drake (1998a) is equivalent to the Norbeck Quartz Diorite of Hopson (1964). The Norbeck includes metamorphosed biotite-hornblende tonalite, plus minor pyroxenite, quartz gabbro, and trondhjemite (Drake, 1998a). Field relationships and petrography led Hopson (1964) as well as Drake (1998) to conclude that emplacement of the tonalite was synkinematic.

The Kensington Tonalite (fig. 1) is a metamorphosed muscovite-biotite tonalite (Hopson, 1964; Fleming, Drake, and McCartan, 1994). It intrudes rocks of the Georgetown and Norbeck Intrusive Suites, in addition to metasedimentary rocks of the Sykesville and Laurel Formations (Drake and Fleming, 1994; Fleming, Drake, and McCartan, 1994).

The Goldvein pluton (fig. 1) is a medium- to coarse-grained, weakly to strongly foliated, metamorphosed monzogranite (Pavlidis, 1990). Isolated occurrences (dikes?) of metamorphosed tonalite and diorite within the Goldvein pluton are chemically distinct from metatonalite of the Lake Jackson pluton (L. Pavlidis, oral communication, 1997).

The Lake Jackson pluton (fig. 1), as described by Pavlidis (1990) consists of metamorphosed micaceous, fine- to medium-grained, well foliated tonalite. This tonalite is composed of plagioclase, quartz, biotite (partly replaced by chlorite), muscovite, and minor amounts of perthite, allanite, and epidote and contains inclusions of phyllite.

The Falls Church Intrusive Suite (fig. 1), previously described as the "Falls Church Tonalite" (Drake and Froelich, 1986), was renamed by Drake and Froelich (1997) because the unit contains trondhjemite, granodiorite, and monzogranite in addition to tonalite. The most prevalent rocks are metamorphosed biotite-hornblende tonalite (dated in this study) and biotite tonalite, which are typically medium- to coarse-grained, medium-dark-gray, and well foliated. Chemical and mineralogic similarity between tonalites of the Falls Church Intrusive Suite and those of the Georgetown Intrusive Suite led Drake and Froelich (1997) to speculate that they "may have originated from the same magma stem."

TABLE 1
 Summary descriptions of selected granitic and tonalitic rocks,
 Piedmont of Maryland-D.C.-Virginia

Name	Principal rock type	Composition	Inclusions	Contact relations	Igneous flow structure	Deformational fabrics	References
Guilford Granite	monzogranite, with pegmatite and aplite	calc-alk., peraluminous, S-type	abundant (Laurel Fm.)	crosscuts contact of Laurel Fm. and Mt. Washington Amphibolite	flow foliation parallel to contacts	not foliated or lineated; crosscuts schistosity in Laurel Fm.	Cloos and Broedal (1940), Hopson (1964), Drake (1998a)
Ellicott City Granodiorite	granodiorite	calc-alk., peraluminous, I-type	screens of Mt. Washington Amphibolite	crosscuts mafic Baltimore Complex and Laurel Fm. along thrust contact	common near pluton boundaries	---	Hopson (1964), Mario (1984), Mario and Lidiak (1984)
Dale City Quartz Monzonite	qtz. monzonite, qtz. monzodiorite, diorite	---	non-graphitic mylonitic schist in shear zone (Quantico Fm.?)	elongate parallel to regional foliation; contact with Quantico Fm. interpreted as intrusive or unconformity	---	weakly to strongly foliated	Seiders and others (1975), Pavlides and others (1980), Seiders and Mixon (1981)
Norbeck Intrusive Suite	biotite-hornblende tonalite	metaluminous I-type	abundant (mafic and ultramafic autoliths)	intrudes Sykesville Fm.; contacts parallel internal and external foliation	common	foliated to almost massive	Hopson (1964), Drake (1998a)
Kensington Tonalite	muscovite-biotite tonalite	calc-alk., peraluminous, CO or DI norm. (<2.9% Na ₂ O)	sparse (Sykesville, Laurel Fms. and hbd tonalite)	intrudes Sykesville Fm. and hbd tonalite of Norbeck I. S. and Georgetown I.S.	mostly obliterated by tectonism	strong tectonic foliation, mylonitized in Rock Creek shear zone	Hopson (1964), Fleming and others (1994), Fleming and Drake (1994), Drake (1998a)
Goldvein pluton	monzogranite with minor muscovite and garnet	peraluminous, CO-norm.	roof pendants of phyllite	intruded wall rocks and roof pendants of phyllite lack evidence of contact metamorphism	---	weakly to strongly foliated; muscovite grains commonly bent	Pavlides (1990), Lyttle and others (in press), Mixon and others (in press)
Lake Jackson pluton	muscovite-biotite tonalite	---	screens of phyllite	intrudes phyllite	---	well-developed tectonic foliation, locally lineated	Pavlides (1990), Lyttle and others (in press), Mixon and others (in press)
Falls Church Intrusive Suite	biotite-hornblende tonalite	I-type	abundant (Indian Run, Sykesville Fms., Annandale Group, mafic and ultramafic autoliths)	intrudes Sykesville, Indian Run Popes Head Fms., Annandale Group	common	tectonic foliation and lineation overprints flow fabric; pluton cuts Ravenwood anticline	Drake and Froelich (1986, 1997)
Ocoquan Granite (main batholith)	muscovite-biotite monzogranite, locally garnetiferous	calc-alk., peraluminous, CO-norm., <3% Na ₂ O	abundant (Indian Run, Sykesville Fms., Annandale Group)	intrudes Sykesville, Indian Run Fms., Annandale Group	---	weak to moderately well developed tectonic foliation and quartz rod lineation; eastern margin mylonitized	Lonsdale (1927), Seiders and others (1975), Seiders and Mixon (1981), Mose and Nagel (1982)
Ocoquan Granite (Bull Run Marina pluton)	muscovite-biotite monzogranite	(see above)	abundant (Sykesville and Popes Head Fms.)	intrudes Sykesville, Popes Head, Purcell, and Mather Gorge Fms.	common	weak to moderately well developed tectonic foliation and quartz rod lineation; locally mylonitized	Drake and Lyttle (1981), Lyttle and others (in press)
Dalecaria Intrusive Suite	porphyritic leuco-musc.-biotite monzogranite	calc-alk., peraluminous, CO-norm. S-type	sparse (biot-hbd tonalite, Sykesville Fm.)	crosscuts Georgetown I.S. and Sykesville Fm.	---	weak foliation suggests late kinematic fabric	Drake and Fleming (1994)
Georgetown Intrusive Suite	biotite-hornblende tonalite	metaluminous	abundant (Sykesville, Mather Gorge Fms.; mafic and ultramafic autoliths)	intrudes Sykesville Fm. (hornfelsed)	well-developed flow foliation and lineation	tectonic foliation and lineation overprints flow fabric	Drake and Fleming (1994), Fleming and others (1994) Drake and Froelich (1997)
Clarendon Granite	monzogranite	---	sparse (Sykesville Fm.)	small bodies within Sykesville Fm.	---	---	Drake and Fleming (1994)
Bear Island Granodiorite	leuco-muscovite-biotite granodiorite	---	Mather Gorge Fm.	pegmatites crosscut foliation in Mather Gorge Fm. migmatite	---	undeformed except for some asymmetric lenses	Cloos and Cooke (1953), Muth and others (1979), Drake and Froelich (1997)

The Ocoquan Granite (fig. 1) (Lonsdale, 1927; Seiders and others, 1975; Seiders and Mixon, 1981; Drake and Froelich, 1986) includes metamorphosed biotite-muscovite monzogranite, subordinate, granodiorite, and minor tonalite. The monzogranite and granodiorite are light gray to pinkish gray, medium- to coarse-grained, well foliated, and composed chiefly of quartz, plagioclase, microcline, muscovite, and biotite, which are generally less abundant than muscovite. The Ocoquan Granite forms the Ocoquan batholith as well as satellite plutons (including the Bull Run Marina pluton, Drake and Lyttle, 1981) and may be a composite intrusion (fig. 1).

Sparse inclusions of greenstone led Seiders and Mixon (1981) to suggest that the Occoquan Granite intruded metavolcanic rocks of the Chopawamsic Formation. Direct observation shows that it has intruded the Mather Gorge and Popes Head Formations (Drake and Lyttle, 1981; Drake and others, 1994). Map relations suggest that the Occoquan Granite intrudes the other enclosing formations, and garnet and chlorite porphyroblasts in the Annandale Group appear to be contact metamorphic minerals related to the emplacement of the batholith (Drake and Lyttle, 1981). Contacts of the Occoquan Granite and Chopawamsic Formation examined in this study are sharp and parallel to the metamorphic foliation, as shown in Seiders and others (1975, pl. 1B). Near the southeastern contact of the batholith, rocks of both units are variably mylonitic, as recognized by Heimgartner (ms, 1995). However, Seiders and others' (1975, pl. 1A) photograph, which shows a granite dike or apophysis cutting across layers in the Chopawamsic Formation within 10 m of the main Occoquan Granite contact, suggests that the Occoquan Granite intruded the Chopawamsic Formation.

The Dalecarlia Intrusive Suite (fig. 1), as defined by Drake and Fleming (1994), is mostly biotite monzogranite and leucocratic porphyritic (phenocrysts of K-feldspar) muscovite-biotite monzogranite, as well as minor muscovite trondhjemite and sparse granodiorite and tonalite. All these rocks are weakly foliated, suggesting they are late kinematic (Drake and Fleming, 1994). Rocks of the Dalecarlia Intrusive Suite intrude those of the Georgetown Intrusive Suite and the Sykesville Formation.

The Georgetown Intrusive Suite (fig. 1), named by Fleming, Drake, and McCartan (1994), is mainly metamorphosed biotite-hornblende tonalite, but it includes small plutons of biotite tonalite, pyroxenite, quartz gabbro, and minor quartz diorite (Drake and Froelich, 1986). Metapyroxenite and hornblendite are widespread as small inclusions (autoliths?) within the tonalites and quartz gabbros (Fleming, Drake, and McCartan, 1994). Fleming, Drake, and McCartan, (1994) describe the sequence of intrusions, from oldest to youngest, as pyroxenite, quartz gabbro, biotite-hornblende tonalite, garnetiferous biotite-hornblende tonalite, and biotite tonalite. The biotite-hornblende tonalite is medium- to coarse-grained and massive to well foliated. A relict igneous flow structure is common, and inclusions of mafic-ultramafic rock (autoliths?) and metasedimentary rock (xenoliths) are abundant (Fleming, Drake, and McCartan, 1994).

Two units not dated in this study are the Clarendon Granite and Bear Island Granodiorite. Both occur as small bodies in the central part of the study area. The Clarendon Granite (fig. 1), as named by Drake and Fleming (1994), is a medium-grained, moderately to well foliated, leucocratic biotite-muscovite monzogranite, which is exposed only as saprolite (Drake and Fleming, 1994; Fleming, Drake, and McCartan, 1994). The Bear Island Granodiorite (fig. 1) consists of fine-grained, leucocratic, muscovite-biotite granodiorite, and associated pegmatite composed mainly of quartz, albite, and microcline (Cloos and Cooke, 1953; Drake and Froelich, 1997). It occurs as sheets and crosscutting bodies only within migmatite and phyllonite of the Mather Gorge Formation (Drake and Froelich, 1997). The granodiorite and pegmatite crosscut structures in the host rocks and are essentially undeformed, although some have asymmetric shapes (Lyttle and others, in press).

In summary, biotite-hornblende tonalites of the Georgetown, Norbeck, and Falls Church Intrusive Suites are virtually identical (Drake and Fleming, 1994; Drake and Froelich, 1997; Fleming and Drake, 1998). The Kensington Tonalite is a more leucocratic, muscovite-biotite tonalite, much of which is sheared. It intrudes the Georgetown at multiple localities (Drake and Fleming, 1994; Fleming and Drake, 1998). The Ellicott City Granodiorite is a peraluminous, I-type, biotite granodiorite (Mario and Lidiak, 1984), whereas peraluminous granite of the Dalecarlia Intrusive

Suite has geochemical characteristics of S-type granitoids and probably originated by partial melting of metasedimentary rocks (Drake and Fleming, 1994). Granodiorite and monzogranite of the Falls Church Intrusive Suite may be S-type granitoids because they are peraluminous and commonly contain garnet. Leucocratic monzogranite of the Goldvein pluton is peraluminous and contains rare garnet (Pavlidis, 1990). Trace-element discrimination diagrams for the Dalecarlia Intrusive Suite (Drake and Fleming, 1994) suggest that the rocks are "volcanic arc granitoids" meaning that they originated in a calc-alkaline magmatic arc, either oceanic or continental. Drake and Fleming (1994) favored a continental-margin arc origin for rocks of the Dalecarlia Intrusive Suite. Results of this study indicate that most of the Ordovician igneous rocks contain some Mesoproterozoic zircon, suggesting that the magmatic arc was built on a continental margin.

PREVIOUS AGE DETERMINATIONS

Several of the plutonic rocks dated in this study were subjects of previous U-Pb zircon dating attempts, including: (1) Kensington Tonalite (550 Ma, Davis and others, 1958; 528 Ma, Wetherill and others, 1966; 546 Ma, Sinha, Hund, and Hogan, 1989); (2) Norbeck Intrusive Suite (570 ± 50 Ma, Davis and others, 1960; 554 Ma, Wetherill and others, 1966); (3) Occoquan Granite (558 Ma, Seiders and others, 1975); (4) Dale City Quartz Monzonite (about 560 Ma, Seiders and others, 1975); and (5) Guilford Granite (370 Ma, Tilton and others, 1959). As shown below, only the Devonian age for the Guilford Granite is accurate.

Other previous dating attempts pertinent to this study include: (1) Ellicott City Granodiorite (450 ± 20 Ma discordant U-Pb zircon, Wetherill and others, 1966; 458 Ma, U-Pb upper concordia intercept, Sinha and others, 1989; 375 Ma (A.K. Sinha, personal communication, 1999); (2) Bear Island Granodiorite (469 ± 20 Ma muscovite Rb-Sr, Muth and others, 1979); and (3) Occoquan Granite (494 ± 14 Ma whole-rock Rb-Sr, Mose and Nagel, 1982).

As first pointed out by Higgins and others (1977), many of the zircons in Early Paleozoic plutonic and volcanic rocks in the Central Appalachian Piedmont contain inheritance of radiogenic Pb, probably by magmatic crystallization of zircon around xenocrystic seed crystals. Spot analyses using the SHRIMP enables the analyst to avoid inherited material and to determine the crystallization ages of magmatic portions of individual igneous grains. Our new age data differ significantly from the previously published age determinations, necessitating revision of both the chronology of emplacement and the tectonic models for the origin of rocks of the Maryland-Virginia Piedmont. Because of the nearly ubiquitous occurrence of inherited Proterozoic material in zircons from plutonic rocks of the Maryland-Virginia Piedmont, all previous zircon ages should be viewed with skepticism.

GEOCHRONOLOGY

Procedures.—Zircon was extracted from about 10 to 25 kg of rock by processing through the standard mineral separations procedure, including crushing, pulverizing, and concentration of heavy minerals using a Wilfley table, methylene iodide, and magnetic separator (see table 4 for descriptions of analyzed zircons). For TIMS U-Pb geochronology, zircons were hand-picked under alcohol, abraded moderately (to remove crystal faces, resulting in lozenge-shaped grains) or severely (resulting in spheres) (Aleinikoff and others, 1990, modified from Krogh, 1982), and leached in 7N HNO₃ and 6.5N HCl prior to dissolution. Zircon fractions weighed between 11 to 120 µg; most fractions were in the range of 10 to 40 µg (composed of about 5-10 grains per fraction). All zircons were loaded into PFA microcapsules in a standard Parr bomb (modified from Parrish, 1987), to which was added a mixed ²⁰⁵Pb-²³³U-²³⁶U spike, concentrated HF, and concentrated HNO₃. Dissolution required about 3 days in an

TABLE 2

TIMS U-Pb isotopic data for zircon from granitic and tonalitic rocks, Piedmont of Maryland-D.C.-Virginia

Size fraction ¹	Weight (mg)	Concentrations (ppm)		measured		Pb composition ²		Ratios (percent error) ³				Ages (Ma) ⁴			
		U		Pb		²⁰⁶ Pb	²⁰⁷ Pb	²⁰⁶ Pb	²⁰⁷ Pb	²⁰⁶ Pb	²⁰⁷ Pb	²⁰⁶ Pb	²⁰⁷ Pb	²³⁸ U	²³⁵ U
		²⁰⁶ Pb	²⁰⁷ Pb	²⁰⁶ Pb	²⁰⁷ Pb	²⁰⁶ Pb	²⁰⁷ Pb	²⁰⁶ Pb	²⁰⁷ Pb	²⁰⁶ Pb	²⁰⁷ Pb	²⁰⁶ Pb	²⁰⁷ Pb	²³⁸ U	²³⁵ U
1. SA-F-2-11 Guilford Granite [39°12'40"N, 76°51'14"W] [no TIMS data, SHRIMP data only]															
2. Oc-1-96 monzodiorite, Dale City Quartz Monzonite [38°37'47"N, 77°18'26"W]															
(+150)1	.107	226.3	21.08	9190	48018	17.707	2.4675	.0739(.19)	.5726(.21)	.0562(.10)	460	460	459	459	
(+150)3	.036	360.2	33.30	2933.2	5674.7	17.027	2.4748	.0731(.25)	.5662(.27)	.0562(.10)	455	456	459	459	
(+150)4	.049	343.5	32.81	1135.6	11323.2	14.901	2.3073	.0728(.22)	.5634(.31)	.0561(.21)	453	454	456	456	
(+150)5	.041	444.0	45.08	404.9	423.69	11.042	2.2147	.0731(.55)	.5656(.56)	.0562(.18)	455	455	459	459	
(+100)1	.120	381.8	36.30	675.42	708.69	13.038	2.5036	.0728(.30)	.5633(.32)	.0561(.11)	453	454	457	457	
(+100)4	.090	268.6	25.87	1042.5	1207.5	14.690	2.2251	.0725(.22)	.5600(.26)	.0560(.15)	451	451	452	452	
3. K-E-1-9 tonalite, Norbeck Intrusive Suite [39°03'58"N, 77°06'54"W]															
(-100+150)1	.036	125.8	10.43	552.3	1396.7	14.981	4.7605	.0744(.59)	.5780(.68)	.0563(.33)	463	463	465	465	
(-100+150)2	.030	165.3	13.62	1072.5	2403.4	16.010	4.6470	.0743(.45)	.5780(.50)	.0564(.20)	462	463	468	468	
(-100+150)4	.028	109.8	10.69	206.32	290.59	9.3836	3.1367	.0743(.91)	.5777(.11)	.0564(.52)	462	463	469	469	
(-100+150)5	.030	192.2	20.55	1859.0	4692.9	14.611	7.6248	.1032(.26)	.9304(.30)	.0654(.14)	633	668	786	786	
(-100+150)	.054	217.0	21.12	497.27	789.86	12.773	4.2909	.0842(.46)	.6957(.52)	.0599(.23)	521	536	601	601	
(-100+150)Eq	.082	128.4	10.97	1054.6	2751.5	16.968	5.4895	.0799(.51)	.6436(.57)	.0584(.25)	496	505	545	545	
(-100+150)Eq	.043	147.4	16.557	865.0	1759.3	11.210	5.4345	.1014(.36)	1.135(.43)	.0812(.23)	623	770	1226	1226	
4. WV9000 Kensington Tonalite [38°56'26"N, 77°03'21"W]															
(-100+150)EC1	.020	989.9	70.89	1323.2	1547.2	15.169	11.252	.0712(.27)	.5551(.29)	.0565(.09)	445	448	472	472	
(-100+150)EC2	.020	1190	86.25	1249.7	1409.3	14.965	10.778	.0717(.30)	.5583(.31)	.0565(.08)	446	450	471	471	
(-100+150)EC3	.016	1577	112.1	1131.5	1255.0	14.667	10.264	.0698(.20)	.5448(.35)	.0566(.28)	435	442	475	475	
(-100+150)EC4	.025	1042	78.66	994.1	1080.5	14.346	9.6094	.0734(.20)	.5693(.27)	.0562(.18)	457	458	461	461	
(-100+150)EC5	.032	1032	74.66	1397.9	1539.215160	11.496	11.496	.0721(.21)	.5614(.23)	.0565(.09)	449	452	472	472	
5. P82-69 granite, Goldvein pluton [38°30'50"N, 77°37'29"W]															
(-150+250)1	.026	244.3	24.36	1019.1	2194.4	13.831	5.2596	.09102(.52)	.8250(.56)	.0657(.18)	562	611	798	798	
(-150+250)2	.030	230.3	22.76	1022.0	2041.5	14.025	5.1743	.0900(.50)	.7978(.62)	.0643(.35)	556	596	751	751	
(-150+250)3	.014	290.0	23.52	1008.0	2019.5	15.800	5.3489	.0747(.49)	.5775(.62)	.0561(.35)	464	462	455	455	
(-150+250)4	.005	306.5	26.17	394.00	6514.8	16.751	5.1431	.0789(.70)	.6250(.11)	.0575(.75)	489	493	509	509	

6. P82-71 tonalite, Lake Jackson pluton [38°39'29"N, 77°27'28"W]													
(-150)1	.023	462.7	45.02	305.66	339.14	9.8567	4.2890	.0800(1.0)	6466(1.9)	0586(1.5)	496	506	552
(-150)3	.009	901.9	70.67	2443.0	6519.5	17.007	6.5085	.0749(.28)	.5842(.32)	.0566(.14)	466	467	475
(-150)4	.011	374.2	33.64	1258.8	2762.2	14.338	7.0091	.0856(.43)	.7616(.47)	.0645(.18)	530	575	759
(-150)5	.011	471.1	36.55	842.21	2526.0	16.049	6.4755	.0736(.82)	.5734(.86)	.0565(.25)	458	460	474
7. AN1000 tonalite, Falls Church Intrusive Suite [38°51'37"N, 77°09'56"W]													
(-150+200)EC1	.033	228.4	21.14	1702.7	8781.6	16.106	5.6358	.0866(.61)	.7215(.68)	.0604(.29)	535	552	619
(-150+200)EC2	.028	232.7	33.28	93.100	96.463	4.8087	1.7820	.0756(.53)	.5960(.76)	.0570(.51)	471	475	491
(-150+200)EC3	.050	248.6	20.97	4165.0	12240	17.024	5.8655	.0796(.28)	.6319(.30)	.0576(.10)	494	497	513
(-150+200)EC4	.037	234.8	18.89	2046.7	60684	17.642	5.6023	.0757(.49)	.5889(.54)	.0564(.22)	470	470	470
8. Oc-3-98 Occoquan Granite (main batholith) [38°41'41"N, 77°16'04"W] [no TIMS data; SHRIMP data only]													
9. IH1000 Occoquan Granite of Bull Run Marina pluton [38°44'22"N, 77°22'05"W]													
(+150)1	.062	318.0	30.77	1450.2	1934.0	13.507	6.4503	.0906(.32)	.8321(.34)	.0666(.09)	559	615	825
(+150)2	.022	269.6	21.88	1584.0	3387.4	16.378	6.4339	.0771(.36)	.6036(.38)	.0568(.12)	479	480	482
(+150)3	.027	299.3	25.46	1331.8	3483.7	15.824	7.2292	.0818(.46)	.6661(.48)	.0590(.13)	507	518	568
(+150)4	.039	287.4	26.30	2503.7	11520	15.829	7.4893	.0888(.32)	.7578(.34)	.0619(.10)	548	572	671
9. P82-74 Occoquan Granite of Bull Run Marina pluton [38°42'33"N, 77°23'28"W]													
(-150+200)1	.011	371.2	32.56	335.9	844.29	13.371	4.958	.0781(.92)	.6195(1.1)	.0576(.58)	484	489	513
(-150+200)2	.056	354.0	30.51	5666.0	12563	15.867	6.3671	.0820(.19)	.6993(.20)	.0619(.06)	508	538	670
(-150+200)3	.035	411.3	32.82	3889.0	8676.1	16.449	6.9440	.0768(.20)	.6261(.23)	.0591(.11)	477	494	572
10. WW5000 monzogranite, Dalecarlia Intrusive Suite [38°57'03"N, 77°06'03"W]													
(-150+200)EC1	.020	443.0	35.29	3341.0	12038	16.113	14.040	.0816(.33)	.6849(.36)	.0609(.12)	506	530	634
(-150+200)EC2	.012	486.2	34.84	1015.0	1597.2	15.202	11.269	.0713(.63)	.5572(.84)	.0567(.55)	444	450	478
(-150+200)EC3	.014	375.7	32.57	2408.0	11397	15.820	19.273	.0903(.35)	.7710(.38)	.0619(.13)	557	580	672
11. WW6000 tonalite, Georgetown Intrusive Suite [38°54'20"N, 77°04'47"W]													
(-100+150)EC	.030	284.7	25.05	395.59	433.18	11.111	4.6081	.0748(.32)	.5815(.38)	.0564(.18)	465	465	466
(-100+150)EC2	.012	136.2	10.965	495.0	1183.4	14.556	6.1733	.0749(.63)	.5820(1.2)	.0564(.95)	465	466	468
(-100+150)EC3	.013	157.1	12.632	513.4	993.78	14.199	6.3979	.0748(.54)	.5748(.66)	.0558(.37)	464	461	443
(-100+150)EC4	.015	163.12	13.526	533.6	918.58	13.848	5.2264	.0747(.82)	.5804(.89)	.0563(.31)	464	465	466

[Constants: $^{235}\lambda = 9.8485 \text{ E-10/yr}$; $^{238}\lambda = 1.55125 \text{ E-10/yr}$; $^{238}\text{U}/^{235}\text{U} = 137.88$ (Steiger and Jäger, 1977)]
 1 All zircons hand-picked and abraded (Aleimikoff and others, 1990, modified from Krogh, 1982). Abbreviations: Eq (equant), El (elongate), C (clear).
 2 Blank (8-25 pg, $\pm 50\%$) and fractionation (0.14 \pm .03%) corrected. Assumed blank composition is 204:206:207:208: = 1:18.8:15.65:38.65.
 3 2σ uncertainties.
 4 Common lead corrections from Stacey and Kramers (1975) model.

oven at about 210°C. Extraction of Pb and U from zircon followed procedures of Krogh (1973) and Parrish (1987), with minor modifications. Isotopic ratios of U, loaded on a single Re filament with suspended graphite (aquadaug), and Pb, loaded on a single Re filament with silica gel and 0.5N H₃PO₄, were measured on a VG Micromass 54E mass spectrometer with a single Faraday cup collector and Daly multiplier, using the ANALYST program of Ludwig (1992). Measured Pb isotopic ratios were corrected for the presence of common Pb using appropriate values from Stacey and Kramers (1975). Data were reduced and plotted using the PBDAT and Isoplot/Ex programs of Ludwig (1991, 1999).

Because TIMS U-Pb data from nearly all the analyzed zircon samples are discordant and scattered despite efforts to select pristine, undamaged grains, 8 samples were also analyzed by SHRIMP I or SHRIMP II (table 3) at the Research School of Earth Sciences, Australian National University, Canberra. Standard methods of sample preparation in epoxy mounts were used. The SHRIMP excavates material from the polished surface of a zircon, resulting in a pit about 25 µm in diameter by 1 µm deep. The advantage of *in situ* SHRIMP analysis is that a very small and geochronologically homogeneous area of a zircon can be analyzed, permitting separate determination of different age components in complex grains. Zircon standards AS3 and AS57 (zircon from gabbroic anorthosite from the Duluth Complex, Paces and Miller, 1993) were used to correct Pb/U ratios for instrumental fractionation. All grains were imaged in cathodoluminescence (CL) and photographed in both transmitted and reflected light prior to SHRIMP analysis to identify cores and overgrowths and crack- and inclusion-free areas. Analytical procedures followed the methods described in Compston and others (1984) and Williams and Claesson (1987). All ages in this study are calculated using the weighted average of the ²⁰⁶Pb/²³⁸U ages. All plots of SHRIMP results include: (1) a Tera-Wasserburg plot (²³⁸U/²⁰⁶Pb versus ²⁰⁷Pb/²⁰⁶Pb using data corrected for common Pb; Tera and Wasserburg, 1972) which allows a visual assessment of the data to determine which data points should be used for the age calculation, and, (2) a weighted averages plot of ²⁰⁶Pb/²³⁸U ages (using the ²⁰⁷Pb-common Pb correction method, Compston and others, 1984).

In general, uncertainty of a SHRIMP analysis of Paleozoic age is limited by counting statistics of the unknown and the scatter of isotopic data of the standard. In most cases, the minimum 2-sigma uncertainty of the weighted average of the ²⁰⁶Pb/²³⁸U ages approaches ± 1 percent; greater uncertainty results under non-optimum circumstances such as instrument noise, less than ideal standard material, or complex or damaged zircons. For TIMS analyses, the far greater amount of analyzed material allows much smaller propagated errors (as low as about 0.08 percent for ²⁰⁷Pb/²⁰⁶Pb ages and 0.2 percent for ²⁰⁶Pb/²³⁸U ages). However, when whole grains or even parts of individual grains are analyzed, it may be difficult or impossible to physically separate the different age components. Thus, no matter how precise the analysis of isotopic ratios, the resulting age data may be a mixture of age components and therefore may be geologically meaningless. Concordance of Pb/U and ²⁰⁷Pb/²⁰⁶Pb data generally (but not always, particularly in Mesozoic and younger rocks) allows for a straightforward or unique interpretation. Discordant data can be interpreted in many ways, frequently resulting in specious conclusions. In summary, SHRIMP analyses of zircon can be very accurate (if appropriate precautions are taken to decipher multi-age components) but are relatively imprecise, whereas TIMS analyses can be very precise but not necessarily accurate. A combination of the two methods typically yields the most reliable interpretation.

Results.—In the following descriptions of the geochronology, dated plutonic rocks of the Maryland-D.C.-Virginia Piedmont are discussed in order of increasing age (tables 2, 3, and 4).

TABLE 3

SHRIMP U-Th-Pb data for zircon from granitic and tonalitic rocks, Piedmont of Maryland-D.C.-Virginia

sample ¹	measured ²⁰⁴ Pb ²⁰⁶ Pb	measured ²⁰⁷ Pb ²⁰⁶ Pb	% common ²⁰⁶ Pb	U (ppm)	Th/U	²⁰⁶ Pb ² ²³⁸ U (Ma)	err ³ (Ma)	²³⁸ U ² ²⁰⁶ Pb	err ³ (%)	²⁰⁷ Pb ² ²⁰⁶ Pb	err ³ (%)
1. SA-F-2-1 Guilford Granite											
1.1	---	0.054	---	271	0.94	361	4	17.33	1.1	0.0559	3.4
2.1	---	0.055	---	691	0.69	357	4	17.51	1.2	0.055	1
3.1	0.00009	0.054	0.15	416	1.11	369	4	17.03	1.2	0.0523	2.2
4.1	0.00060	0.054	0.01	528	0.27	353	7	17.79	1.9	0.0535	1.5
5.1	---	0.094	---	81	0.4	1398	35	4.09	2.6	0.0952	1.5
6.1	---	0.054	---	691	0.75	361	4	17.37	1	0.0542	1
7.1	0.00003	0.054	0.05	677	0.46	362	4	17.29	1	0.0539	1.6
8.1	0.00013	0.054	0.24	649	0.46	370	4	16.99	1	0.0521	1.7
9.1	0.00004	0.055	0.08	806	0.28	360	4	17.42	1.1	0.0541	1.5
10.1	0.000016	0.054	0.03	338	0.82	356	4	17.58	1.1	0.054	1.6
11.1	---	0.08	---	194	0.1	1142	45	5.14	4.1	0.0805	2.9
12.1	0.000054	0.054	0.1	495	0.16	371	4	16.91	1.1	0.0533	1.7
13.1	---	0.053	---	153	0.56	365	5	17.14	1.3	0.054	2.6
14.1	---	0.055	---	668	0.78	358	4	17.45	1	0.0553	1
15.1	0.00007	0.055	0.13	531	0.81	369	4	16.97	1	0.0535	1.5
16.1	0.00052	0.055	0.94	155	0.65	361	5	17.49	1.5	0.0475	5.8
17.1	0.000026	0.053	0.05	518	0.11	358	4	17.54	1.3	0.0526	1.7
18.1	0.00016	0.054	0.28	239	0.97	349	7	18	2.1	0.0514	2.7
2. Oc-1-96 Dale City Monzonite [no SHRIMP data; TIMS data only]											
3. K-E-1-9 Norbeck Intrusive Suite tonalite											
1.1	0.00015	0.061	0.27	346	1.16	466	6	13.3	1.2	0.0593	2.5
2.1	0.002	0.076	3.57	60	0.68	433	7	14.53	1.9	0.0473	19.4
3.1	0.0021	0.082	3.71	63	0.53	385	12	16.32	3.5	0.0515	21.1
4.1	0.0019	0.068	3.35	112	0.92	446	8	14.22	2	0.0405	18.6
5.1	0.0022	0.075	3.99	72	0.89	429	10	14.77	2.6	0.0421	21.6
6.1	0.00046	0.062	0.83	268	1.05	421	7	14.84	1.8	0.0549	4.7
7.1	0.00065	0.067	1.17	175	1.2	441	6	14.07	1.4	0.0578	6.1
8.1	0.00047	0.064	0.84	207	0.61	452	7	13.74	1.6	0.0575	4.6
9.1	0.00056	0.063	1.01	297	1.02	452	8	13.79	1.7	0.0544	4.2
10.1	0.00057	0.06	1.02	240	1.03	461	6	13.56	1.4	0.0521	5.8
11.1	0.0016	0.076	2.81	84	0.53	454	8	13.74	2.1	0.0537	20
12.1	0.00095	0.065	1.72	168	0.85	439	8	14.28	1.8	0.0511	7.7
13.1	0.00023	0.06	0.41	376	1.11	458	8	13.57	1.8	0.0563	2.5
14.1	0.00091	0.076	1.65	65	0.72	445	9	13.87	2.3	0.0629	10.7
15.1	0.00098	0.069	1.77	78	0.68	372	6	16.8	1.9	0.0551	14
16.1	0.00075	0.064	1.36	167	0.57	459	6	13.6	1.4	0.0529	6
17.1	0.0016	0.075	2.96	63	0.62	443	8	14.14	2.1	0.0507	16.4
4. WW9000 Kensington Tonalite											
1.1	0.000043	0.057	0.08	630	0.19	458	7	13.59	1.6	0.0559	1.2
2.1	0.000022	0.057	0.04	1066	0.22	460	7	13.51	1.6	0.0565	0.8
3.1	0.00057	0.064	1.02	961	0.36	462	7	13.47	1.6	0.0559	3.6
4.1	---	0.056	---	379	0.3	483	8	12.86	1.7	0.0562	1
5.1	---	0.056	---	642	0.24	450	7	13.82	1.6	0.0563	3.3
6.1	0.000065	0.057	0.12	899	0.24	453	7	13.75	1.6	0.0558	1.2
7.1	0.000034	0.056	0.06	763	0.22	460	7	13.53	1.6	0.0555	0.9
8.1	0.000055	0.056	0.1	991	0.21	460	7	13.52	1.6	0.0557	1.7
9.1	---	0.057	---	292	0.29	459	7	13.53	1.6	0.0566	1.3
10.1	0.00048	0.126	8.54	1151	0.21	376	7	16.57	1.7	0.057	19.2
11.1	0.00019	0.06	0.34	983	0.27	464	7	13.38	1.6	0.0568	1.4
12.1	0.000073	0.057	0.13	611	0.24	475	7	13.07	1.6	0.0562	1.3
13.1	---	0.057	---	741	0.28	446	7	13.93	1.6	0.0571	1.1
14.1	0.00041	0.062	0.73	332	0.22	438	10	14.21	2.2	0.0562	3.8
14.2	0.01	0.203	17.88	2045	0.2	400	13	15.57	2.2	0.0576	44
15.1	0.00088	0.071	1.58	997	0.25	476	8	13.04	1.7	0.0578	3.7
16.1	0.000034	0.059	0.06	575	0.19	515	8	12.02	1.6	0.0582	1.1
17.1	0.000024	0.056	0.04	996	0.18	463	7	13.44	1.6	0.0555	0.8
18.1	---	0.056	---	787	0.28	493	8	12.6	1.6	0.0563	0.7
19.1	0.000021	0.057	0.04	674	0.22	491	8	12.66	1.6	0.0562	0.8
20.1	0.0003	0.061	0.55	863	0.22	439	7	14.17	1.6	0.0568	2.2
5. P82-69 Goldvein pluton											
1.1	0.00032	0.058	0.56	230	1.19	473	17	13.17	3.8	0.0538	12.8
2.1	0.00099	0.061	1.73	150	0.62	447	17	14.11	4.2	0.0463	25.3
3.1	---	0.059	---	180	0.68	454	17	13.59	3.9	0.0619	11.8
4.1	0.00034	0.056	0.59	280	0.88	468	20	13.36	4.5	0.0514	16.3
5.1	0.0016	0.058	2.73	280	0.51	442	16	14.47	4	0.0344	37
6.1	0.00043	0.058	0.76	250	0.71	463	18	13.51	4.1	0.0514	17.4
7.1	0.00019	0.062	0.33	140	0.53	470	18	13.16	4	0.0595	16.9
8.1	0.021	0.389	36.89	340	1.48	470	31	12.56	9	0.0966	77.3
9.1	---	0.054	---	140	0.59	446	17	14	4	0.0542	5
10.1	0.0026	0.064	4.48	170	0.63	447	17	14.45	4.6	0.0256	80.7
11.1	---	0.056	---	570	1.04	464	16	13.41	3.6	0.0557	2.3
12.1	0.000019	0.059	0.03	190	0.64	439	16	14.12	3.9	0.0586	13.1
13.1	0.0004	0.061	0.71	190	0.5	441	18	14.14	4.4	0.0548	18.3
14.1	0.00013	0.059	0.23	330	0.88	465	18	13.57	3.9	0.0572	6.8
15.1	---	0.063	---	130	0.71	465	18	13.25	3.9	0.0628	4.4

TABLE 3
(continued)

sample ¹	measured $\frac{^{204}\text{Pb}}{^{206}\text{Pb}}$	measured $\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	% common ^{206}Pb	U (ppm)	Th/U	$\frac{^{206}\text{Pb}^2}{^{238}\text{U}}$ (Ma)	err ³ (Ma)	$\frac{^{238}\text{U}^2}{^{206}\text{Pb}}$	err ³ (%)	$\frac{^{207}\text{Pb}^2}{^{206}\text{Pb}}$	err ³ (%)
6. P8271 Lake Jackson pluton											
1.1	0.00011	0.058	0.19	747	0.42	467	7	13.3	1.6	0.0561	1.3
2.1	0.000092	0.059	0.17	1649	0.38	463	9	13.4	2	0.0578	0.8
3.1	0.000023	0.057	0.04	1753	0.39	468	7	13.27	1.6	0.0564	0.5
4.1	0.00013	0.06	0.23	885	0.4	464	8	13.38	1.7	0.0581	1.2
5.1	0.000015	0.056	0.03	2182	0.48	461	7	13.49	1.6	0.056	0.6
6.1	0.0013	0.074	2.37	1421	0.42	442	8	14.1	1.7	0.0543	5.5
7.1	0.000048	0.057	0.09	2123	0.47	459	7	13.56	1.6	0.0564	0.7
8.1	0.00021	0.061	0.37	1337	0.36	458	7	13.56	1.7	0.0578	1.4
9.1	0.00015	0.059	0.27	1753	0.32	468	9	13.28	2.1	0.0568	1
10.1	0.0018	0.087	3.31	2525	0.46	441	7	14.05	1.7	0.0601	6.7
7. AN1000 Falls Church Intrusive Suite tonalite											
1.1	---	0.057	---	138	0.62	482	10	12.87	2	0.0571	2.6
2.1	0.00028	0.058	0.51	171	0.72	475	8	13.13	1.7	0.054	3.4
3.1	---	0.057	---	186	0.59	470	8	13.21	1.7	0.0574	1.8
4.1	0.00032	0.058	0.57	99	0.69	454	10	13.74	2.2	0.0534	4.5
5.1	---	0.057	---	165	0.93	485	14	12.8	2.9	0.0569	1.9
6.1	---	0.055	---	198	0.51	473	8	13.12	1.7	0.0566	2.5
7.1	0.00017	0.056	0.3	173	0.86	468	9	13.34	1.9	0.0533	3.2
8.1	---	0.058	---	232	1.2	463	8	13.39	1.7	0.0578	1.6
9.1	---	0.057	---	285	0.79	466	8	13.32	1.7	0.0581	2
10.1	0.000095	0.056	0.17	188	0.53	469	8	13.26	1.7	0.0548	2.3
11.1	---	0.056	---	299	0.85	458	7	13.57	1.7	0.0565	1.6
12.1	---	0.057	---	96	1.04	449	9	13.85	2	0.0569	2.8
13.1	0.00016	0.056	0.29	193	0.66	459	8	13.59	1.8	0.054	3.2
14.1	0.000067	0.058	0.12	384	0.52	460	8	13.52	1.7	0.0568	1.7
15.1	0.000016	0.057	0.03	1311	0.94	433	7	14.36	1.6	0.0564	0.9
16.1	---	0.055	---	280	0.65	467	8	13.33	1.7	0.0553	1.7
17.1	---	0.057	---	119	0.7	463	8	13.43	1.8	0.0569	3
18.1	---	0.055	---	222	0.92	476	8	13.07	1.7	0.0549	1.9
8. Oc-3-98 Occoquan Granite (main batholith)											
1.1	0.00034	0.059	0.32	122	0.58	459	5	13.59	1.1	0.0537	4
2.1	---	0.056	---	79	0.83	465	5	13.48	1.2	0.049	5.5
2.2	0.000033	0.058	0.12	159	0.57	486	5	12.75	1.1	0.0573	1.9
3.1	0.00018	0.057	0.12	194	0.92	469	5	13.29	1.1	0.0547	2
4.1	0.0000052	0.059	0.35	103	0.92	466	5	13.31	1.1	0.0591	2.3
5.1	0.00031	0.058	0.28	136	0.94	455	5	13.7	1.1	0.0539	3.7
6.1	0.000084	0.057	0.08	218	0.61	476	5	13.07	1.1	0.056	2.2
7.1	0.00018	0.058	0.17	256	0.79	478	5	13.02	1.1	0.0553	2.2
8.1	0.000099	0.059	0.3	154	0.69	474	6	13.08	1.3	0.0576	1.9
9.1	0.000016	0.059	0.35	80	0.92	474	5	13.08	1.1	0.0592	2.5
10.1	0.00001	0.059	0.48	170	1.13	424	33	14.63	8	0.059	1.9
11.1	0.0000045	0.058	0.21	110	0.97	470	5	13.2	1.1	0.0581	1.8
12.1	0.00018	0.058	0.19	162	0.74	481	5	12.93	1.1	0.0557	2.6
13.1	0.00017	0.057	0.04	128	0.63	471	5	13.21	1.1	0.0544	3.8
14.1	0.00012	0.057	0.12	181	1.2	471	7	13.2	1.6	0.0557	2.4
15.1	0.0003	0.06	0.44	50	0.57	478	6	13	1.3	0.0558	6.6
16.1	---	0.056	---	142	1.1	478	5	12.98	1.1	0.0575	1.5
17.1	0.00011	0.057	0.03	217	0.79	475	5	13.11	1.1	0.0552	2.7
18.1	0.000077	0.058	0.17	312	0.56	468	5	13.27	1.1	0.0566	1.3
19.1	0.00018	0.064	0.04	181	1.52	726	8	8.42	1.1	0.0612	1.7
19.2	0.00009	0.059	0.37	124	0.58	469	5	13.23	1.1	0.0581	2
20.2	0.00029	0.061	0.51	92	0.71	472	5	13.17	1.2	0.0565	4.2
9. IH1000 Occoquan Granite of Bull Run Marina pluton											
1.1	---	0.059	---	227	0.37	500	13	12.26	2.7	0.0672	5.7
2.1	0.00023	0.074	0.42	410	0.66	1001	25	5.97	2.6	0.0708	2.4
3.1	0.00064	0.06	1.16	498	0.36	475	12	13.19	2.6	0.0502	5.8
3.2	---	0.055	---	388	0.72	463	12	13.45	2.6	0.0556	2.9
4.1	0.0027	0.057	4.85	237	0.39	496	13	13.15	3	---	---
5.1	0.00013	0.06	0.24	502	0.53	488	16	12.70	3.3	0.0583	2.5
6.1	0.0017	0.056	3.11	230	0.38	504	13	12.72	3.1	---	---
7.1	0.00026	0.057	0.48	391	0.45	501	13	12.43	2.6	0.0531	3.6
8.1	0.0026	0.059	4.67	234	0.41	474	13	13.70	3	---	---
9.1	0.00092	0.056	1.65	414	0.47	467	12	13.55	2.6	0.0419	11.9
10.1	---	0.059	---	291	0.36	475	13	12.93	2.8	0.0648	7.8
11.1	0.00051	0.075	0.92	171	0.29	947	25	6.34	2.8	0.0681	6.1
12.1	0.0011	0.058	1.96	375	0.51	495	12	12.77	2.6	0.0418	13.5
13.1	0.00089	0.057	1.61	313	0.34	472	12	13.38	2.6	0.0433	10.9
14.1	0.000058	0.057	0.1	372	0.35	494	24	12.55	4.9	0.0566	4.2
15.1	---	0.059	---	331	0.43	487	12	12.66	2.6	0.0633	5.7

1. Guilford Granite (sample SA-F-2-11). Because the Guilford Granite is peraluminous, we suspected that the zircons would contain a significant component of inherited radiogenic Pb that would be difficult to decipher by TIMS analysis. Thus, only SHRIMP analyses were made on this sample. All the zircons are prismatic, euhedral, and clear, with few cracks or inclusions (fig. 2A). Of the 18 grains analyzed,

TABLE 3
(continued)

sample ¹	measured $\frac{^{204}\text{Pb}}{^{206}\text{Pb}}$	measured $\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	% common ^{206}Pb	U (ppm)	Th/U	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$ (Ma)	err ³ (Ma)	$\frac{^{238}\text{U}}{^{206}\text{Pb}}$	err ³ (%)	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	err ³ (%)
10. WW5000 Dalecarlia Intrusive Suite monzogranite											
1.1	0.0014	0.116	2.5	297	0.29	1587	26	3.59	1.7	0.0966	7.4
1.2	0.00052	0.07	0.93	670	0.12	526	8	11.68	1.6	0.0629	2.9
1.3	0.0003	0.061	0.53	1339	0.08	472	7	13.16	1.6	0.057	2.3
2.1	---	0.075	---	176	0.35	1011	16	5.88	1.6	0.0747	0.9
2.2	0.019	0.344	34.7	2190	0.2	463	37	13.28	5.2		
3.1	0.000033	0.056	0.06	655	0.23	481	8	12.92	1.7	0.0557	0.8
3.2	0.000011	0.056	0.02	1270	0.09	490	8	12.67	1.6	0.0557	0.6
4.1	0.00061	0.08	1.09	16	0.89	990	19	6.03	2	0.0713	5.1
4.2	0.00016	0.059	0.29	1136	0.15	477	7	13.02	1.6	0.0563	1
5.1	---	0.083	---	420	0.43	1153	18	5.08	1.6	0.0831	0.4
5.2	0.000093	0.084	0.17	308	0.29	1241	19	4.71	1.6	0.0825	0.8
6.1	0.00035	0.062	0.63	964	0.12	470	7	13.22	1.6	0.0568	1.8
7.1	0.000016	0.057	0.03	1411	0.07	495	8	12.53	1.6	0.0565	0.6
8.1	0.00042	0.063	0.76	767	0.09	479	8	12.96	1.7	0.0566	2.3
9.1	0.00083	0.069	1.48	1283	0.18	456	7	13.63	1.6	0.0572	3.6
10.1	0.000039	0.058	0.07	1167	0.13	474	10	13.1	2.2	0.0576	0.8
11.1	0.000087	0.059	0.16	553	0.05	474	7	13.1	1.6	0.0576	1.2
12.1	0.00013	0.058	0.23	1071	0.11	481	8	12.93	1.6	0.0558	1.2
13.1	0.000067	0.059	0.12	996	0.13	476	7	13.01	1.6	0.058	0.9
14.1	0.00042	0.063	0.76	1166	0.14	462	7	13.44	1.6	0.0569	2.1
15.1	0.00018	0.059	0.32	665	0.11	454	7	13.69	1.6	0.0566	1.8
16.1	0.00017	0.059	0.31	955	0.08	490	10	12.67	2.2	0.0561	2
17.1	0.000036	0.057	0.06	942	0.09	482	9	12.88	1.8	0.0569	0.8
11. WW6000 Georgetown Intrusive Suite tonalite											
1.1	0.000059	0.058	0.11	291	0.56	463	5	13.41	1.2	0.0568	1.8
2.1	0.000075	0.057	0.13	452	0.75	477	4	13.02	1	0.0563	1.8
3.1	0.00023	0.056	0.42	245	0.51	476	7	13.11	1.4	0.0528	3.2
4.1	0.00025	0.06	0.45	86	0.41	489	7	12.69	1.4	0.0564	7.1
5.1	0.000065	0.057	0.12	360	0.6	477	5	13.04	1	0.0561	1.5
6.1	0.00013	0.058	0.23	168	0.47	471	6	13.19	1.2	0.0566	3.4
7.1	0.00016	0.057	0.28	380	0.62	475	5	13.1	1	0.0546	2.2
8.1	0.00019	0.058	0.35	207	0.45	481	6	12.93	1.3	0.0551	3.5
9.1	0.00028	0.057	0.5	168	0.43	481	7	12.97	1.4	0.0531	3.4
10.1	0.00038	0.059	0.69	167	0.49	479	7	13.02	1.5	0.053	4.2
11.1	0.00026	0.058	0.47	172	0.49	457	5	13.65	1.1	0.0545	2.9
12.1	0.00012	0.058	0.21	188	0.45	478	5	13	1.1	0.0561	3.6
13.1	0.00013	0.057	0.24	264	0.66	399	4	15.67	1.1	0.0549	1.8
14.1	0.000066	0.057	0.12	428	0.69	466	4	13.35	1	0.0558	1.7
15.1	0.000075	0.058	0.13	206	0.45	464	5	13.39	1.2	0.0572	2.2
16.1	0.00022	0.057	0.39	409	0.64	482	5	12.91	1	0.0539	1.9

1 Analytical sessions: 2/93 (P82-69, IH1000), 4/97 (SA-F-2-11), 11/97 (K-E-1-9), 10/98 (OC-3-98), 4/99 (WW6000), 9/99 (P82-71, AN1000, WW5000, WW9000). Session 2/93 on SHRIMP I, sessions 4/97, 11/97, 10/98, and 4/99 on SHRIMP II, session 9/99 on USGS/Stanford SHRIMP-RG.

2 corrected for common Pb.

3 1-sigma error.

two grains with length-to-width (l/w) ratios of about 3 to 4 have Mesoproterozoic $^{207}\text{Pb}/^{206}\text{Pb}$ ages (table 3), whereas all other grains (mostly with l/w > 6) have $^{206}\text{Pb}/^{238}\text{U}$ ages of 350 to 371 Ma. The weighted average of $^{206}\text{Pb}/^{238}\text{U}$ ages from 16 of the latter grains yields an age of 362 ± 3 Ma (fig. 3).

2. Dale City Quartz Monzonite (sample OC-1-96). Zircons from this monzodiorite are clear, euhedral, and most lack one or both pyramidal terminations (fig. 2B). Five of 6 fractions, ranging from concordant to about 1.5 percent discordant, have $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 456 to 459 Ma (TIMS data, table 2). The best-fit line through this data array has an upper intercept age of 459 ± 4 Ma (fig. 3). The sixth fraction plots off the discordia, perhaps due to the presence of slightly younger overgrowths (see discussion section). Because of the excellent linearity of the isotopic data and the minor degree of discordance resulting in a well-constrained age, zircons from this sample were not analyzed by SHRIMP.

3. Norbeck Intrusive Suite (sample K-E-1-9). Zircons are euhedral, clear, and doubly terminated. Some grains are elongate (l/w > 4), whereas others are nearly equant (l/w = 1-3) (fig. 2C). Three fractions of elongate grains yield concordant or slightly discordant TIMS ages, whereas four other fractions, including two composed

TABLE 4

Summary of conventional and SHRIMP U-Pb ages of granitic and tonalitic rocks, Piedmont of Maryland-D.C.-Virginia

sample number	name	zircon morphology ¹	previous age (Ma) ²	ID-TIMS age (Ma)	SHRIMP age (Ma) ³
1. SA-F-2-11	Guilford Granite	el, eu, cl, fi	370a	nd	362 ± 3
2. Oc-1-96	monzodiorite, Dale City Quartz Monzonite	p, eu, cl, fi	~560e	459 ± 4	nd
3. K-E-1-9	tonalite, Norbeck Intrusive Suite	el, eu, cl, fi	570 ± 50f; 554c	460 ± 3	449 ± 7
4. WW9000	Kensington Tonalite	p, eu, cr, mi	550b; 528c; 546d	468 ± 8 (or 461 ± 4)	463 ± 8
5. P82-69	granite, Goldvein pluton	p, eu, cl, fi	487-524h	455 ± 8	456 ± 9
6. P82-71	tonalite, Lake Jackson pluton	el, eu-su, cr, fi	472-487h	476 ± 3	461 ± 7
7. AN1000	tonalite, Falls Church Intrusive Suite	el, eu, cl, mi		470 ± 5	469 ± 6
8. Oc-3-98	Occoquan Granite (main batholith)	el, eu, cl, mi, cr	558e; 494 ± 14g	nd	472 ± 4
9. IH1000, P82-74	Occoquan Granite of Bull Run Marina pluton	el, eu, cl, fi, cr		482 ± 3	483 ± 9
10. WW5000	monzogranite, Dalecarlia Intrusive Suite	p, eu, cl, fi, eq, cr		478 ± 12 discordant	478 ± 6
11. WW6000	tonalite, Georgetown Intrusive Suite	el, eu, cl, fi		466 ± 3	472 ± 4

1 Abbreviations: el (elongate), eu (euhedral), cl (clear), fi (few inclusions), p (prismatic), cr (cracks), mi (many inclusions), eq (equant), su (subhedral). Prismatic (length-to-width ratio 2-4); elongate (length-to-width ratio >6); nd (not determined).

2 References: a Tilton and others (1959), b Davis and others (1958), c Wetherill and others (1966), d Sinha and others (1989), e Seiders and others (1975), f Davis and others (1960), g Mose and Nagel, (1982), h T. Stern, unpublished data-Pb/Pb ages.

3 weighted average of ²⁰⁶Pb/²³⁸U ages.

of equant zircons, have older ²⁰⁷Pb/²⁰⁶Pb ages ranging from 545 to 1226 Ma. A best-fit line calculated through 5 of 6 data points has concordia intercepts ages of 459.7 ± 3.2 and 1029 ± 42 Ma (fig. 3). SHRIMP data from 15 analyses result in an age of 449 ± 7 Ma (fig. 3A, table 3). Two overgrowths have Late Paleozoic ages.

4. Kensington Tonalite (sample WW9000). Zircons are euhedral, prismatic (l/w = 2-5), clear, and contain many inclusions (fig. 2D). TIMS data from four discordant fractions result in a best-fit line with intercept ages of 468 ± 8 and -93 ± 200 Ma (fig. 3, table 2). However, a fifth fraction is nearly concordant with a ²⁰⁷Pb/²⁰⁶Pb age of 461 ± 4 Ma, suggesting that the other fractions contain minor inheritance. SHRIMP analyses of zircon from the Kensington Tonalite (table 3) yield a wide range of ages (380-519 Ma); the weighted average of 19 analyses results in an age of 463 ± 8 Ma (fig. 3). One older age of 519 Ma indicates the presence of Early Paleozoic inheritance,

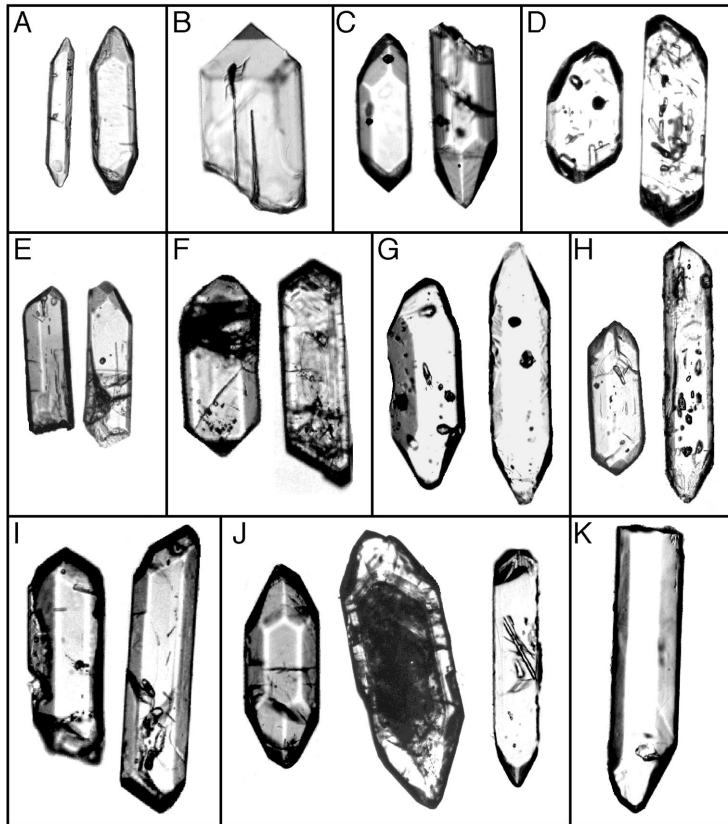


Fig. 2. Photomicrographs of representative zircons from granitoids of the Maryland-D.C.-Virginia Piedmont. All grains are between 100 and 150 μm in length. (A) Guilford Granite, (B) Dale City Quartz Monzonite, (C) Norbeck Intrusive Suite tonalite, (D) Kensington Tonalite, (E) Goldvein pluton granite, (F) Lake Jackson pluton tonalite, (G) Falls Church Intrusive Suite tonalite, (H) Occoquan Granite (main batholith), (I) Occoquan Granite of Bull Run Marina pluton, (J) Dalecarlia Intrusive Suite quartz monzonite, (K) Georgetown Intrusive Suite tonalite.

whereas younger post-crystallization ages (380-404) suggest subsequent Paleozoic thermal events.

5. Goldvein pluton (sample P82-69). Zircons, finer-grained than in all other samples from this study, are prismatic ($l/w = 3-4$), clear to light brown, and contain few inclusions (fig. 2E). Of the four fractions of zircon from this granite that were analyzed by TIMS, one fraction is slightly reversely discordant with a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 455 ± 8 Ma (table 2). The other three fractions have $^{207}\text{Pb}/^{206}\text{Pb}$ ages between 509 and 798 Ma (fig. 3B). SHRIMP data yield an age of 456 ± 9 Ma (fig. 3, table 3).

6. Lake Jackson pluton (sample P82-71). Zircons from this tonalite are euhedral, clear, stubby to prismatic ($l/w = 2-5$), contain few inclusions, and abundant cracks (fig. 2F). TIMS data for four fractions have $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from 474 to 759 Ma (table 2). A best-fit line forced through a lower intercept of 50 ± 50 Ma and data from two slightly discordant fractions has an upper intercept age of 476 ± 3 Ma (fig. 3). Ten SHRIMP analyses yield a younger age of 461 ± 7 Ma (fig. 3).

7. Falls Church Intrusive Suite (sample AN1000). Zircons from this tonalite are euhedral, clear, prismatic ($l/w = 5-8$), and contain many inclusions (fig. 2G). TIMS

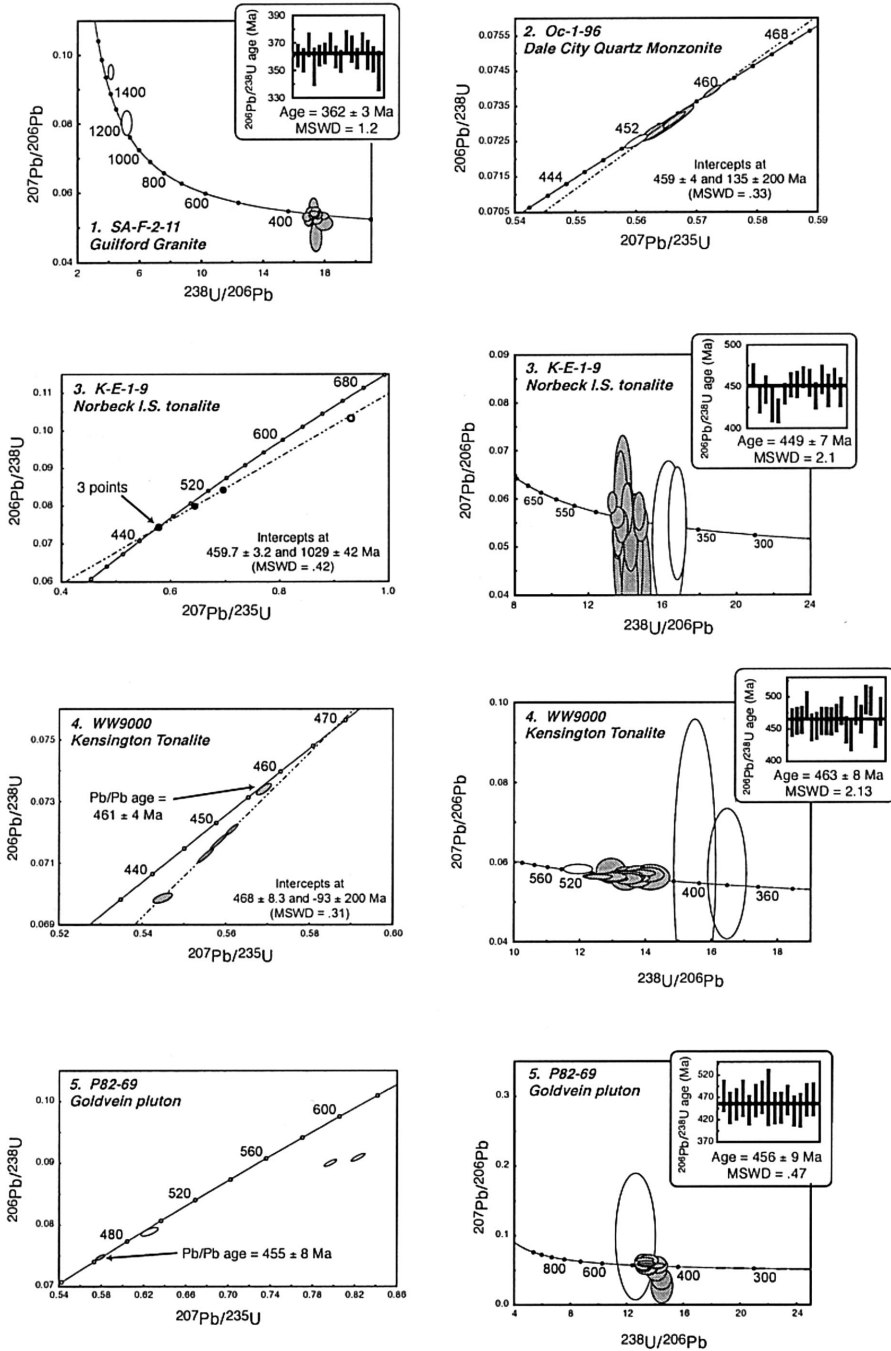


Fig. 3. U-Pb geochronologic data for plutons from the Maryland-D.C.-Virginia Piedmont. In this and other figures, shaded ellipses or symbols represent data that are used in the age calculations. Symbols are plotted when error ellipses are too small to be easily seen. Standard concordia plots are used for TIMS data (always plotted as 2-sigma), whereas Tera-Wasserburg plots are used for SHRIMP data (always plotted as 1-sigma). Weighted averages error bars and uncertainties on all age calculations are 2-sigma.

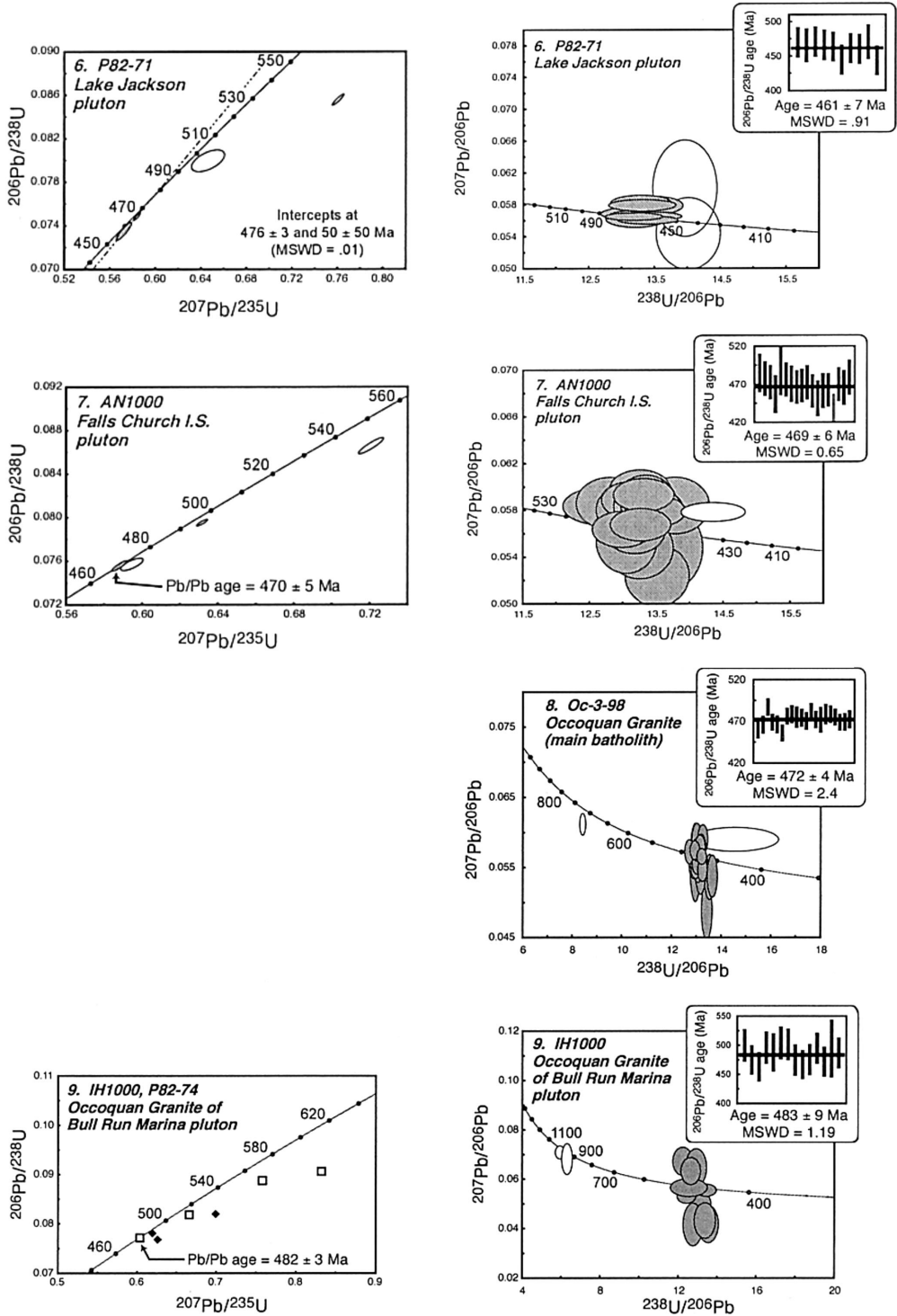


Fig. 3 (continued) Age data for the Lake Jackson pluton and Falls Church Intrusive Suite tonalite. Age data for Occoquan Granite, main batholith (dated by SHRIMP only), and satellitic Bull Run Marina pluton. Filled diamonds from sample P82-74; opensquares from sample IH1000.

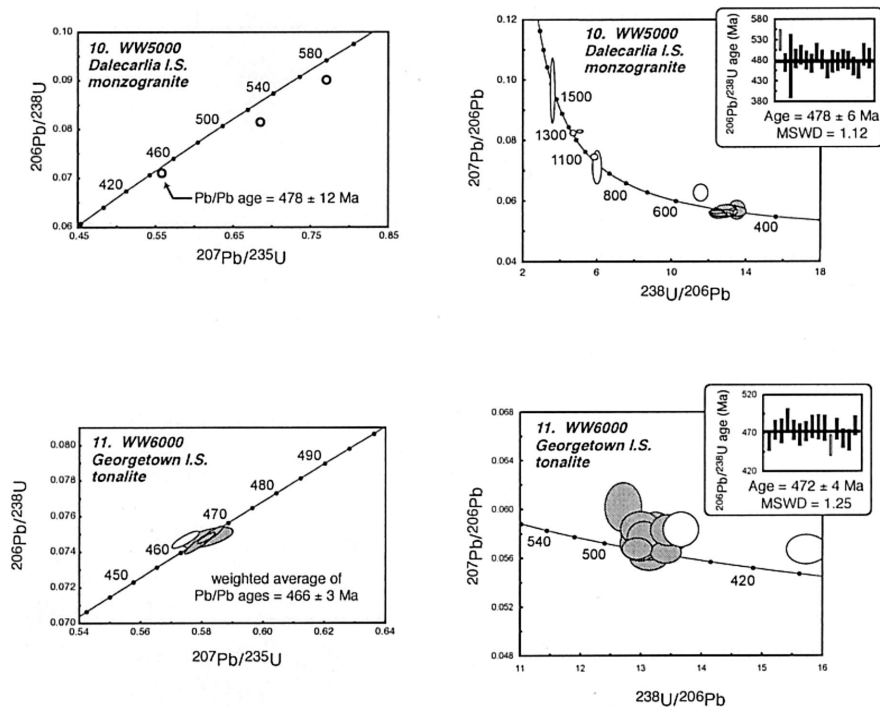


Fig. 3 (continued). Age data for tonalite of the Dalecarlia Intrusive Suite and tonalite of the Georgetown Intrusive Suite. Data for analysis 2.2 from sample WW500 not plotted because ^{204}Pb counts overcorrected the $^{207}\text{Pb}/^{206}\text{Pb}$ age for common Pb (table 2).

data from 5 fractions have $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from 470 to 619 Ma (table 2). One fraction is concordant at about 470 ± 5 Ma (fig. 3). Seventeen SHRIMP analyses yield an age of 469 ± 6 Ma (table 3, fig. 3). One other analysis is slightly younger.

8. Occoquan Granite (sample OC-3-98). Zircons from a sample of Occoquan Granite collected within the main batholith are euhedral, clear, prismatic ($l/w = 4-8$), and contain numerous inclusions (fig. 2H). Because previous TIMS data from the satellitic Bull Run Marina pluton indicated the presence of large components of inheritance (see below), we analyzed this sample by SHRIMP only (table 3, fig. 3). Twenty analyses yield an age of 472 ± 4 Ma interpreted as the time of emplacement of the Occoquan Granite batholith. One grain yielded a $^{206}\text{Pb}/^{238}\text{U}$ age of 726 Ma.

9. Bull Run Marina pluton (samples IH1000 and P82-74). TIMS $^{207}\text{Pb}/^{206}\text{Pb}$ ages of prismatic, clear zircons (fig. 2I) from the Bull Run Marina pluton range from 482 ± 3 (nearly concordant) to about 825 Ma; data with older $^{207}\text{Pb}/^{206}\text{Pb}$ ages are quite discordant and do not form a linear array (table 2, fig. 3). SHRIMP data for zircons from sample IH1000 yield an age of 483 ± 9 Ma (table 3, fig. 3). The similarity within uncertainty of the Occoquan and Bull Run Marina ages supports petrologic and geophysical data suggesting that the Bull Run Marina pluton is a satellitic body related to emplacement of the Occoquan batholith.

10. Dalecarlia Intrusive Suite (sample WW5000). Zircons from this monzogranite occur in a range of morphologies including elongate ($l/w = 4-6$), blocky ($l/w = 2-4$), and nearly equant ($l/w = 2-3$); most grains are euhedral and clear and contain cracks and inclusions. Only the elongate grains were analyzed (fig. 2J). In CL, nearly all grains have large cores (occupying about 50-90% of the grain) that show either completely

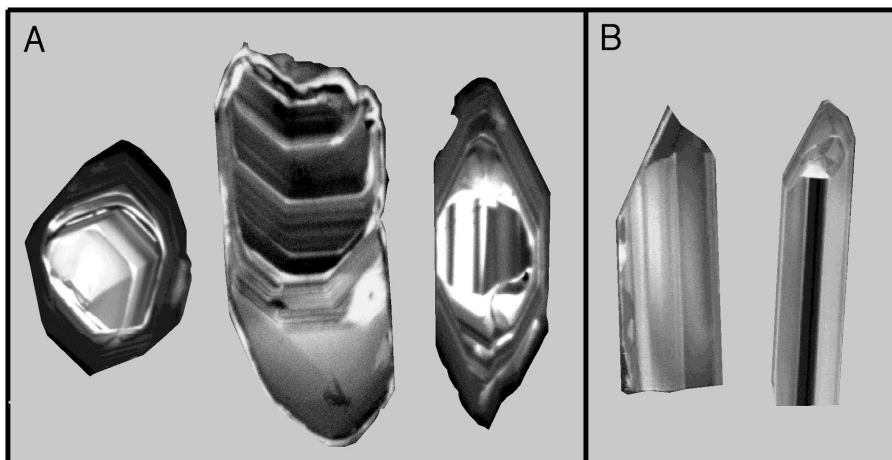


Fig. 4. Cathodoluminescence images of zircon. (A) Sample WW5000 (tonalite of the Dalecarlia Intrusive Suite). Note large, rounded, partially resorbed inherited cores with discontinuous oscillatory zoning and dark, zoned or unzoned igneous overgrowths. (B) Sample WW6000 (tonalite of the Georgetown Intrusive Suite). Note fine oscillatory zoning in igneous cores and dark or light overgrowths at tips.

enclosing or partial oscillatory zoning, or patchwork zoning (fig. 4A). Many cores are partially resorbed and some are rounded, similar in appearance to typical detrital zircons. The cores are overgrown by very dark, finely zoned to unzoned rims, most of which have sharp pyramidal terminations. The overgrowths are interpreted to be the igneous component of the zircons, whereas the more voluminous cores are considered to be inherited, as would be expected in an S-type, peraluminous rock (table 4). $^{207}\text{Pb}/^{206}\text{Pb}$ TIMS ages for three fractions range from 478 to 672 Ma (fig. 3, table 2), indicating a significant inherited component. The youngest $^{207}\text{Pb}/^{206}\text{Pb}$ age is 478 ± 12 Ma. SHRIMP data confirm the presence of inherited radiogenic Pb (five analyses with $^{206}\text{Pb}/^{238}\text{U}$ ages of 1000-1600 Ma, table 3). Seventeen analyses of dark rims yield an age of 478 ± 6 Ma (fig. 3).

11. Georgetown Intrusive Suite (sample WW6000). Zircons from this tonalite are euhedral, elongate, clear, and contain very few inclusions or cracks (fig. 2K). Three of 4 fractions analyzed by TIMS are concordant, yielding an age (weighted average of $^{207}\text{Pb}/^{206}\text{Pb}$ ages) of 466 ± 3 Ma (fig. 3, table 2). Fourteen of 16 SHRIMP analyses yield an age of 472 ± 4 Ma (table 3). Many grains have simple oscillatory zoning overgrown by a very thin rim of dark (that is, U-rich) material (fig. 4B). We could not date this rim component because it is much smaller than the diameter of the primary ion beam. However, if it formed in response to Ordovician events (such as intrusion of the Norbeck or Kensington Intrusive Suites), the resulting mixture would still yield concordant data (that is, plot on the concordia curve). It is possible that this hypothesized thermal event not only caused the formation of overgrowths on igneous zircons, but also caused the growth of wholly new grains, as shown by age data from analysis 11.1. CL zoning in this zircon is similar to the oscillatory zoning pattern of all other zircons from this sample. However, its external morphology is slightly different in that it lacks sharp pyramidal terminations and its $^{206}\text{Pb}/^{238}\text{U}$ age is 461 ± 10 Ma. Thus, this grain may be metamorphic in origin. Grains of this morphologic population could have been included in the TIMS fractions because they are clear and uncracked; the resulting mixed population would yield slightly younger ages.

In summary, foliated intrusive rocks of the Maryland-D.C.-Virginia Piedmont dated in this study were emplaced over a time span of about 35 my., from about 485 to

450 Ma. Tonalitic rocks of the Norbeck, Falls Church, and Georgetown Intrusive Suites are nearly identical in appearance and chemical composition, and although they may have formed from the same magma source as postulated by Drake (1998a), they were not emplaced contemporaneously. The Guilford Granite is unfoliated and clearly post-dates all deformational structures in the Ordovician rocks.

DISCUSSION

Significance for host rocks.—The new zircon ages provide minimum-age limits for metamorphic units intruded by the dated granitoids. These units include the Loch Raven Schist, Laurel Formation, Sykesville Formation, Mather Gorge Formation, Annandale Group, Indian Run Formation, Lunga Reservoir Formation, Purcell Branch Formation and Popes Head Formation. On the basis of cross-cutting relationships, the minimum age of these host units is Ordovician, rather than Cambrian as previously proposed. A study in progress addresses the problem of the age of the Sykesville by dating detrital zircons, the youngest of which will provide a maximum age constraint for the time of deposition.

Timing of regional deformation and metamorphism.—Five sequential phases of folding have been recognized in the northern Virginia Piedmont (Drake, 1987). Rocks of the Annandale Group contain the two earliest phases of folding, the Tripps Run and Ravenwood folds, which are interpreted to pre-date thrust emplacement of the Annandale Group onto the Indian Run Formation because the Indian Run Formation contains olistoliths of rocks interpreted to be previously deformed and metamorphosed Annandale Group (Drake, 1985b). These folding events also predate the deposition of the Popes Head Formation (Drake, 1987, p. 10). The earliest folds that have been described in the Popes Head Formation, the Clifton folds, typically are isoclinal and have a strong axial-surface schistosity; the Clifton folds and associated schistosity also occur in rocks of the Annandale Group where they overprint the Tripps Run and Ravenwood folds (Drake, 1987). At the contact of the Occoquan Granite (Bull Run Marina pluton), seams of granite occur in the schistosity of the Popes Head Formation, and foliation within the granite is approximately parallel to that schistosity (Drake, 1987). Within the Occoquan Granite batholith, quartz-rod lineations also appear to be related to Clifton phase folding (Drake, 1987). Based on these relationships, Drake (1987) concluded that the Clifton folds and the even later Accotink Creek folds formed in a single deformational continuum synchronous with emplacement of the Occoquan Granite.

Drake (1987, 1991) and Drake and Froelich (1997) attributed the Clifton deformation and biotite-zone metamorphism in the Popes Head Formation to the Penobscot orogeny because they are synkinematic with emplacement of the Occoquan Granite, which had previously been dated at 558 Ma (U-Pb method; Seiders and others, 1975) and 494 Ma (Rb-Sr isochron; Mose and Nagel, 1982). Based on the newly determined zircon age of 472 ± 4 Ma for the Occoquan Granite, the Clifton-phase folds, associated schistosity, and regional metamorphism are reinterpreted here and by Drake (1998a) as early manifestations of the Taconic orogeny (as described to the north in New England). The age of this Taconian deformation and metamorphism is further constrained by U-Pb ages of the Dalecarlia Intrusive Suite (478 ± 6 Ma), Georgetown Intrusive Suite (472 ± 4 Ma), and Kensington Tonalite (463 ± 8 Ma), all of which are interpreted to be syn-kinematic because they form lenticular plutons that have concordant contacts and contain foliated xenoliths composed of rocks interpreted to be Mather Gorge and Sykesville Formations (Hopson, 1964; Drake, 1998a).

The age of the pre-Popes Head (pre-Clifton) deformation is not well constrained but must be younger than the deformed rocks. Early deformation associated with pre-Clifton folds must be older than the Sykesville Formation, which contains meso-

scopic and megascopic blocks of rocks interpreted to be Mather Gorge Formation polyfolded migmatite and phyllonite, showing that the Mather Gorge had a complicated pre-Sykesville geologic history (Drake, 1985b, 1987, 1989; Drake and Lee, 1989; Drake and Froelich, 1997; see particularly photographs in Drake, 1985b, 1989). This deformation was ascribed to the Potomac (formerly Penobscot) orogeny by Drake (1994b, 1995).

Farther north in the Maryland Piedmont, field relationships and petrography indicate that the predominant regional schistosity was synkinematic with respect to Ordovician (455 ± 8 Ma) tonalite of the Norbeck Intrusive Suite. The Guilford Granite (362 ± 3 Ma) is undeformed, cuts all tectonic structures, and therefore is postkinematic.

In the Washington, D.C., area, the Rock Creek shear zone separates rocks of the Sykesville and Mather Gorge Formations from those of the Loch Raven thrust sheet and Laurel Formation (Fleming, Drake, and McCartan, 1994; Drake, 1998a). The Rock Creek shear zone experienced early sinistral slip and later dextral slip. The Kensington Tonalite was interpreted to have been emplaced into the Rock Creek shear zone late in the early sinistral-slip movement, which, therefore, would be Ordovician (Taconic) in age (Fleming, Drake, and McCartan, 1994; Fleming and Drake, 1998; Drake, 1998a). The age of the dextral shearing along the Rock Creek shear zone cannot be directly determined, but it took place under greenschist facies (or lesser) conditions, and the microstructures associated with this event are the latest observed in the area (Fleming and Drake, 1998). Similar structures common throughout the Appalachian Piedmont are Alleghanian in age. Therefore, dextral slip along the Rock Creek shear zone was interpreted by Fleming and Drake (1998) to be Alleghanian in age.

Recent Silurian age determinations on foliated plutonic rocks elsewhere in the Maryland-Virginia Piedmont (J.N. Aleinikoff, unpublished data; A.K. Sinha, personal communication, 1999) imply the occurrence of a post-Silurian deformational event. Because the Guilford Granite is unfoliated, the deformation cannot be attributed to the late Paleozoic Alleghanian Orogeny, but rather could have formed in response to the Early Devonian Acadian Orogeny, as is thoroughly documented in rocks of the northern Appalachians.

Significance of Devonian zircon overgrowths.—Thirteen analyses from 4 samples have $^{206}\text{Pb}/^{238}\text{U}$ ages that are significantly younger than the Early to Late Ordovician emplacement ages of the igneous rocks. Weighted averages of $^{206}\text{Pb}/^{238}\text{U}$ data yield composite ages of 439 ± 23 (7 analyses) and 386 ± 27 Ma (4 analyses). Although it may be capricious to group data from different samples, particularly because the younger ages may be due to Pb-loss as opposed to new zircon growth or overgrowth, these ages may have geologic significance because they do not seem to be random, as one might expect if Pb-loss were the cause. The 439 ± 23 Ma age, although imprecise, may reflect a Silurian magmatic event (described in the previous section). The 386 ± 27 Ma overgrowth age, although imprecise, agrees with a huge body of data from New England documenting the timing of the Acadian Orogeny.

CONCLUSIONS

1. New SHRIMP ages on foliated granitoid rocks of the Maryland-Virginia Piedmont (some of which were also dated by the conventional TIMS method in this study and by previous workers) indicate that these rocks are Ordovician in age (about 485–450 Ma). In addition, the Guilford Granite, which cross-cuts all Paleozoic structures, is Late Devonian. Contrary to data in previous publications, no igneous rocks of Cambrian age were found.

2. As documented by SHRIMP analyses, previously published Cambrian ages for some Piedmont granitoids probably are due to mixtures of inherited Proterozoic radiogenic Pb and Ordovician igneous zircon.

3. The age of the Taconic orogeny (including deformation and metamorphism broadly coeval with plutonism) in the central Appalachians is similar to that previously documented in the northern Appalachians.

4. Silurian and Devonian ages of overgrowths suggest additional Paleozoic events previously not known for the rocks of the central Appalachians. Thus, all orogenic events that are well documented in New England (Taconic, Acadian, and Alleghanian) may have also affected rocks of the Maryland-Virginia Piedmont.

5. The Ordovician ages of all foliated igneous rocks in the study area indicate that current tectonic models describing a mid-Cambrian Potomac (or Penobscot) event need to be revised, as discussed by Drake (1994b, 1995, 1998a, b, c) and Horton and others (1998).

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