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GEODYNAMIC EVOLUTION OF THE CENTRAL APPALACHIAN OROGEN: GEOCHRONOLOGY AND COMPOSITIONAL DIVERSITY OF MAGMATISM FROM ORDOVICIAN THROUGH DEVONIAN

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ABSTRACT. The spatial and temporal distributions of igneous rocks provide significant limits on the geodynamic and thermal record associated with the growth of continents through different tectonic processes. In the central Appalachian orogen, both published and new ion microprobe U/Pb zircon ages coupled with geochemical data from igneous rocks provide a window into the thermal and temporal evolution of the mid-Ordovician Taconic orogeny, as well as younger subduction, delamination and accretionary events. New Ion microprobe U/Pb ages of zircons screened for inheritance and lead loss, yield five discrete groupings of igneous activity: (1) pre-collision arc stage: 470 to 489 Ma (2) syntectonic: 459 to 472 Ma (3) arc magmatism after change in subduction polarity: 441 to 459 Ma (4) delamination induced extension related plutons: 423 to 438 Ma and (5) Neo-Acadian plutons related to collision of Avalon-Carolina superterrane with Laurentian elements: 362 to 381 Ma. Geochemical signature of mafic and felsic rocks of all age groups are dominated by arc-type attributes for primitive mantle normalized signatures for depletion in Nb, P, and Ti, and enrichment in Pb. Differences in alkalinity and a well-developed positive gadolinium anomaly for Group III rocks is interpreted to be the result of remelting of high to intermediate potassic basalts and their plutonic equivalents during the development of a late Ordovician calc-alkaline arc draped over an earlier (Group I) low-K tholeiitic arc assemblage. We utilize these magmatic events, including their geochemical signatures to suggest a tectonic model which includes: (1) arc-continent collision followed by change in subduction polarity, and (2) development of a second arc followed by slab delamination resulting in extension, as well as post-closure shortening related to docking of peri-Gondwanan tracts. The proposed model enables a more robust coupling of the opening and closing of the Iapetus ocean basin with the preserved igneous record, but we recognize that lack of detailed mapping over the area of study, accompanied by modern geochemical/geochronologic data to place igneous rocks in a regional deformation and metamorphic framework, precludes a complete endorsement of our preferred model.

Key words: Arc magmatism, geochronology, orogeny, Appalachians

INTRODUCTION

Understanding the tectono-magmatic evolution of mountain belts, especially those resulting from arc-continent collisional processes, terrane accretion, and subsequent thermal and tectonic consequences, requires an assessment of contrasting processes that are capable of generating magmas over intervals of time. Models invoking the temporal and spatial relationships between crustal thickening, metamorphism, and faulting to anatexis have been highlighted through modeling thermal profiles in collisional environments (for example, England and Thompson, 1986; Jamieson and Beaumont, 1988; Jamieson and others, 1998), or drawing upon the

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relationship of metamorphism to melt production (Zen, 1988; Sinha and others, 1989; Patino Douce and others, 1990; Brown, 1994; Patino Douce, 1999; Thompson, 1999; Nabelek and Liu, 2004). It is abundantly clear from these and numerous other studies that the relationship between the thermal response of a heterogeneous crust thickened by collision leading to metamorphism, and, in some instances to both crustal anatexis and mantle melting, must be interrelated through many different processes. These may include convergence rate, erosion rate, thermal properties of the rocks involved in collision, crustal thickness of colliding elements, and tectonic histories that immediately precede or follow (for example, post-collision extension) continental collision (Harris and others, 1986; Alsop and Hutton, 1993; Dewey and others, 1993; Thompson and Connelly, 1995; Nabelek and Liu, 2004). In contrast, episodic production of magmas can also be related to rapidly changing plate tectonic conditions, that is, closing of ocean basins, where the first arc-continent collision is followed sequentially by the emplacement of syntectonic plutons, then a change in subduction polarity (for example Suppe, 1984; Teng and others, 2000; Clift and others, 2003) and subsequent delamination (Sacks and Secor, 1990; Nelson, 1992; Davies and Blanckenburg, 1995; Whalen and others, 2006). Although the temporal and spatial distribution of igneous rocks can be modeled through either set of processes, geochemical and isotopic data are required to favor one over the other (Davies and Blanckenburg, 1995; Draut and others, 2009). To this complex thermal/tectonic environment, we suggest that another significant geologic criterion may be responsible for the compositional diversity of the igneous rocks and may lie in the availability of "fertile" lithologies within the orogen, including volcanic rocks of the overriding plate and the buried proximal and distal continental margin stratigraphic section, both for melt production, and as traps for melts derived from subjacent sources.

We present new SIMS (secondary ion mass spectrometry) results of U/Pb zircon ages, as well as geochemical data from igneous rocks of the central Appalachian orogen (fig. 1) to further refine: (1) the range of crystallization ages recorded by igneous rocks (screened for inheritance and lead loss), and (2) the spatial, temporal, and chemical relationships of these plutons to the geometry and stratigraphy (that is, fertile lithologies capable of yielding melts, as well as providing fluids for melting, or acting as lithologic traps for magmas) of the pre-orogenic rifted margin of Laurentia prior to arc-continent collision. This collision is recognized in the central Appalachian region as the Middle Ordovician Taconic orogeny (Rodgers, 1971) and is diachronous along the Appalachian orogen as a whole (Rodgers, 1970; Shanmugam and Lash, 1982; Wise and Ganis, 2009). It has been suggested that along the length of the orogen, the Taconic orogeny may have lasted more than 70 Ma with different tectonic styles and associated magmatism (Wise and Ganis, 2009). In order to unravel possible changes in tectonic settings for the magmatic record associated with the Taconic orogeny and younger events we have focused on radiometric ages of zircons and geochemical signature of igneous rocks from the central Appalachian region. Published and new ages reported in this article, as well as geochemical attributes of igneous rocks, are used to divide the magmatic record into five groups: Group I is bimodal arc (Early Ordovician) magmatism developed on an extended continental lithosphere; Group II includes Early to Middle Ordovician syntectonic plutons related to arc-continent collision; Group III includes arc-related (Late Ordovician) calc-alkaline volcanic rocks and deep-seated plutonic equivalents, and includes a terrane-stitching pluton; Group IV plutons (Silurian) are spatially bimodal and are likely related to delamination; and Group V plutons (Middle-Late Devonian) are felsic, and of limited areal extent. Collectively, the igneous activity (Groups II through IV) is interpreted to represent a complete thermal-magmatic cycle with associated discrete tectonic stages, that is, primary arc-continent collision, polarity change in subduction, and extension

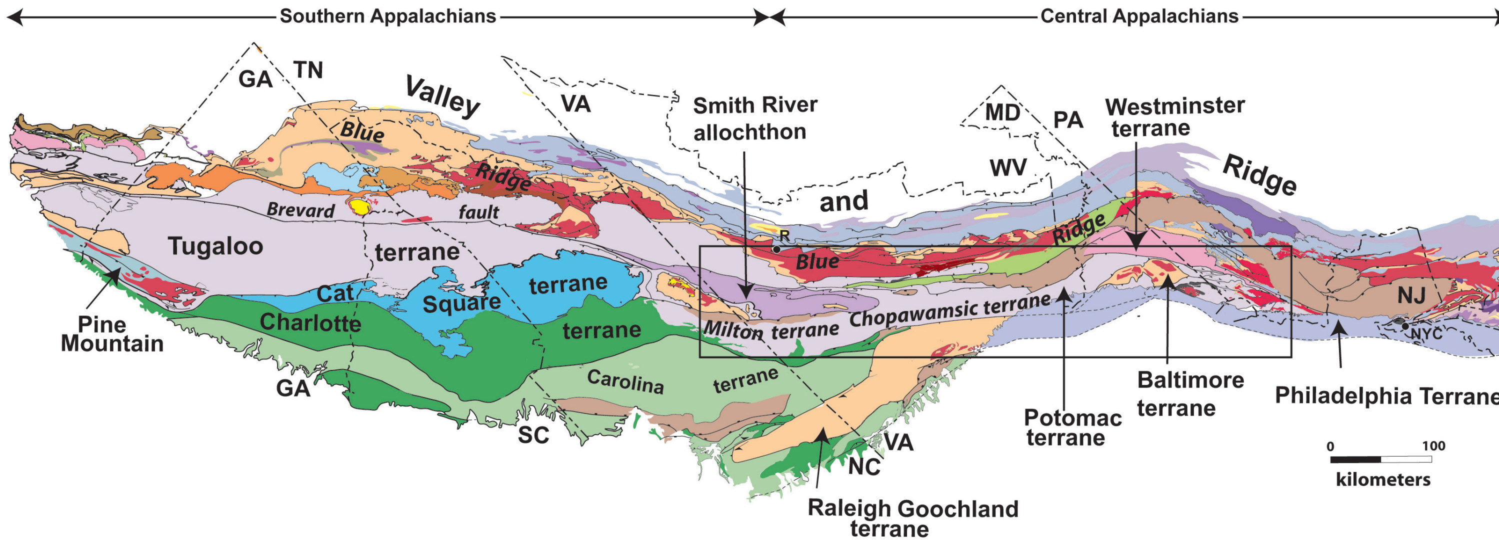

Fig. 1. Regional terrane and lithotectonic map of the central and southern Appalachians (modified from Hatcher and others, 2007). The area bounded by the rectangle in the central Appalachians contains igneous rocks associated with both arc-stage magmatism and those formed as the result of collisional tectonics associated with the Taconic orogeny and subsequent thermal events. Details of terrane assembly and tectonic reconstructions are given in Hatcher and others (2007). NYC = New York City.

through delamination which occurred within a relatively short interval of 30 m.y. (for example, Sinha, 2004; Dewey, 2005; Wise and Ganis, 2009).

REGIONAL GEOLOGY OF THE CENTRAL APPALACHIAN OROGEN

The Appalachian mountain belt is a classic example of a composite orogen with a well-preserved record of multiple collisional and accretionary events (Williams, 1995; Glover and others, 1997; Thomas, 2006; Hibbard and others, 2007; Hatcher, 2010) including the development of continental margins associated with the breakup of supercontinent Rodinia (Thomas, 2006). The rock record also documents the growth and closure of Iapetus, Rheic and Theic oceans (Murphy and others, 2010; Hatcher, 2010). The division of the central and southern Appalachians into lithotectonic provinces, as well as tectonostratigraphic terranes (for example, Williams and Hatcher, 1982; Horton and others, 1989; Hatcher and others, 2004, 2007; Hibbard and others, 2006; Hatcher, 2010), reflects differences in age, lithology, metamorphic grade, structural style, and accretionary history (fig. 1). The terrane accretion history of the central Appalachian region has been summarized by Faill (1997), Hibbard and others (2007), Hatcher and others (2007), and Hatcher (2010), and we briefly summarize the geologic history of the central Appalachian region to provide a framework for the tectonic significance of Ordovician to Devonian magmatism.

The post-Grenville history of the eastern margin of Laurentia was initiated by the Neoproterozoic (750 Ma or earlier, Graybil and others, 2012) development of a failed rift system recorded by A-type granites and volcanic rocks (Rankin, 1993; Tollo and Aleinikoff, 1996; Fokin, ms, 2003), and graben-fill sediments that were derived from the Grenville highlands (Thomas, 1977, 1993; Wehr and Glover, 1985).

During the latest Neoproterozoic (Badger and Sinha, 1988; Aleinikoff and others, 1995), extension along nearly the same axis as the earlier failed rifting event led to the final breakup of supercontinent Rodinia, and was accompanied by deposition of new rift-to-drift facies sediments (Wehr and Glover, 1985; Rankin and others, 1989; Simpson and Eriksson, 1989; Patterson, 1989; Thomas, 1991). The rifted margin and the synrift sedimentary packages were covered by passive-margin sediments associated with the trailing margin and platform of the rifted continent. Thick passive-margin Early Cambrian through Early Ordovician carbonates reflect a stable continental margin (Read, 1989). The depositional history of the carbonates was interrupted through formation of a continent-wide unconformity followed by renewed carbonate and clastic sedimentation (Benedict and Walker, 1978; Shanmugam and Walker, 1980; Read, 1989).

Numerous papers (for example, Rodgers, 1971; Crowley, 1976; Fisher and others, 1979; Higgins and others, 1988; Hatcher, 1989, 2010; Drake and others, 1989; Pavlides, 1989; Sinha and others, 1989; Wagner and others, 1991; Rankin, 1994; Hibbard and Samson, 1995; Dalziel, 1997; Glover and others, 1997; Coler and others, 2000; Hibbard, 2000; Thomas and others, 2002; Hatcher and Merschat, 2006; Miller and others, 2006; Hibbard and others, 2007; Wise and Ganis, 2009; Horton and others, 2010; and others) have carefully documented the complexity of plate tectonic models required for understanding the construction of the Middle Ordovician Taconic orogen and younger events in the central Appalachians. In contrast to the northern Appalachians (for example, Robinson and others, 1998), Devonian (Acadian orogeny) tectonic overprinting in the central Appalachian orogen has been considered to be minimal (Glover and others, 1983; Glover and others, 1989; Butler, 1991), although recent $^{40}Ar/^{39}Ar$ ages in Maryland suggest both Silurian and Devonian age cleavage development was associated with discrete transpressive events (Wintsch and others, 2010). Farther south, however, metamorphic/tectonic overprinting of Middle Ordovician igneous and metamorphic rocks has been suggested to be the result of a Neoacadian (Late Devonian to Mississippian) compressional event (Bream, ms, 2003) caused by the docking of the Carolina superterrane (Merschat and others, 2005; Hatcher and Merschat, 2006; Merschat and Hatcher, 2007; Hatcher, 2010; Merchat and others, 2010). We emphasize that, if the Neoacadian event did occur in the central Appalachian orogen, the magmatic record is cryptic, thus making the region unique for relating the continental-margin geometry to magmatic-tectonic processes in the Taconian collision zone and subsequent plate-tectonic response to change in subduction polarity and extension through delamination. Although younger Alleghanian collisional processes, including strike-slip displacements (Gates, ms, 1986) outboard from the margin, do mask some of the original geometry of the Taconian collision zone, reconstruction of the orogen is possible through correlation of stratigraphic and tectonothermal events along the orogen (Hatcher, 1987, 2010; Thomas, 1991, 2006; Hatcher and others, 2007; Hibbard and others, 2007).

Outboard of the Laurentian continental margin during the Early Ordovician, arcs were developed in both intra-oceanic and continental environments (for example, Hanan and Sinha, 1989; Sinha and Guy, 1989; Swinden and others, 1997; MacNiocaill and others, 1997; Faill, 1997; van Staal and others, 1998, 2007; van Staal and Hatcher, 2010; Murphy and others, 2010) and were associated with subduction mélanges (for example, Higgins and others, 1988). These volcanic arc plates have been modeled as Carolina superterrane (Glover and others, 1989), rifted basement microcontinents of Laurentian affinity (Thomas, 1977; Karabinos and others, 1998; Waldron and van Staal, 2001; Cawood and others, 2001; Miller and others, 2006), and microcontinents of unknown affinity (Horton and others, 1989). In the northern Appalachians, Karabinos and others (1998) suggested two successive arcs existed, but only collision of the older Shelburne Falls arc (485-470 Ma) with Laurentia generated the Taconic orogeny, whereas the younger Bronson Hill arc (454-442 Ma; Tucker and Robinson, 1990) developed on the eastern margin of Laurentia after accretion of the Shelburne Falls arc. Farther north in Newfoundland, three accretionary events have been recognized within the Taconic orogeny (van Staal and others, 2007). In contrast to multiple accretionary events associated with the Taconic orogeny recognized in the northern Appalachians, transport of the Ordovician-age Hillabee arc in the southern Appalachians over the Laurentian Devonian shelf deposits is considered to be a single event during the latest Devonian (Tull and others, 2007). Clearly, such contrasting geologic histories emphasize the significant tectonic differences along the Appalachian orogen.

In the central Appalachians, the subduction of Laurentian margin rocks in the region of study under an outboard terrane formed an arc complex, the collision and obduction of which with the rifted margin of Laurentia led to the Taconic orogeny (Wagner and Srogi, 1987; Hatcher, 1987, 2010; Drake and others, 1989; Glover and others, 1997; Faill, 1997, 1998; Wise and Ganis, 2009). The collisional process resulted in accretion of continental-margin sediments, oceanic crust (Smith, 2006), and arc-stage plutons and volcanic rocks (Hopson, 1964; Higgins, 1972, 1990; Hanan and Sinha, 1989; Drake and others, 1989; Coler and others, 2000; Plank and others, 2000, 2001) along complex orogen-scale thrust and strike-slip systems (Hatcher, 2010). We emphasize that this region, unlike most others in the Appalachian orogen provides a record of a single arc-continent collision and subsequent tectonic events related to the closing of the Iapetus ocean basin prior to docking of peri-Gondwanan tracts. Our new U/Pb ages of zircons coupled with published ages in the region from both pre-collision arc-related rocks and younger igneous rocks, are used to subdivide the igneous chronology to emphasize generation of melts through multiple cycles of magmatism associated with differing tectonic settings. We then develop a model to explain the distribution, age, and composition of some of these igneous rocks in the context of the configuration of the pre-orogenic rifted margin and sediment depocenters (Thomas, 2006), which acted as sources of fluids and lithologic traps for magmas.

ANALYTICAL METHODS

New U/Pb zircon ages were measured using the UCLA CAMECA ims 1270 ion microprobe following the method of Quidelleur and others (1997; and http://sims.ess.ucla.edu/Tutorial/UPbtutorial.php). Zircon grains were mounted in epoxy, polished, and sputter coated with ~100 Å of Au prior to analysis. Scanning electron microscope backscattered images, in conjunction with optical images, were used to select beam target areas. Ion yields of Pb^+ were enhanced by a factor of two by utilizing oxygen flooding of the sample chamber. This leads to increased precision of the measured U/Pb ratios and calculated ages. Because of the signal limits on *in situ* $^{207}Pb/^{206}Pb$ and $^{207}Pb/^{235}U$ ages of Phanerozic zircons, we follow the method of Ludwig (2003) and take the weighted mean $^{206}Pb/^{238}U$ age and its uncertainty as representative of the crystallization age of the granitoid (Quidelleur and others, 1997; Miller and others, 2000). As weighted mean ages can be biased through a small degree of inheritance or lead loss at the point of ion probe analysis, we have used statistical routines provided in ISOPLOT, for example, linearized probability plot to trim the dataset prior to utilization of weighted averages (table 1) (Ludwig, 2003). Linear probability values for data selected for obtaining the weighted $^{206}Pb/^{238}U$ ages are given in table 1 (below each sample analyzed). Computed values range from 1.11 to 1.0 and suggest that the data are normally distributed with no recognizable outliers. These values are comparable to other SIMS-based ages for igneous rocks in the region (Horton and others, 2010) where similarly computed values range from 0.96 to 1.06. For zircons displaying a large range in both U/Pb and Pb/Pb ages commonly associated with inheritance, we take the $^{207}Pb/^{206}Pb$ age as representing a lower bound on the age of the inherited component. The data for crystallization and inherited ages recorded from plutons and volcanic rocks are given in table 1. All reported errors are at 1 sigma confidence level (table 1).

New geochemical data reported in this article were obtained at Actlabs, Ancaster, Ontario, Canada using ICP-MS techniques. References to other data used in this article are given in table 3. Location of samples analyzed for U-Pb ages of zircons are given in Appendix I.

THE MAGMATIC RECORD IN THE CENTRAL APPALACHIAN OROGEN

In the central Appalachians, the magmatic record associated with pre-collision arc (Early Ordovician Central Appalachian Arc Complex: EOCAAC) and igneous rocks generated during subsequent tectonic/thermal events associated with the Taconic orogeny and younger events are best preserved in the central Piedmont region of Virginia, Maryland, Delaware, and Pennsylvania (fig. 2). Two western geologic belts that contain the igneous record are the mélange complexes (Drake and Morgan, 1981; Evans, ms, 1984; Drake, 1987; Muller and others, 1989; Pavlides, 1989; Glover and others, 1997) and the Smith River allochthon (Conley, 1985; Carter and others, 2006), which are separated from Laurentian basement and cover by the Bowens Creek–Mine Run and Pleasant Grove fault systems (fig. 2) (fig. 1A in Pavlides, 1981). East of these two belts, metavolcanic rocks and associated plutonic rocks have been broadly characterized as part of a single arc (Coler and others, 2000), although a geologic distinction has been proposed for volcanic rocks associated with the Milton belt (Butler, 1980; Horton and others, 1989, 2010) from the remainder of the arc terrane comprised of Chopawamsic, Ta River and James Run Formations (fig. 2). Deformation of the Milton belt and northern equivalents had been considered as mid-Ordovician, and related to the Taconic orogeny (Henika, 1977; Glover and others, 1997), but more recent data suggest that the deformation and metamorphism of the Milton belt are related to

TABLE 1

Analytical data for zircon U/Pb ages obtained using secondary ion microprobe (SIMS) technique

Plutonic/volcanic rocks analyzed	$^{207}Pb^*/^{235}U$	s.e.	$^{206}Pb^*/^{238}U$	s.e.	correl. coeff.	$^{206}Pb^*/^{238}U$ age in Ma	s.e.	$^{207}Pb^*/^{235}U$ age in Ma	s.e.	$^{207}Pb^*/^{206}Pb^*$ age in Ma	s.e.	$^{206}Pb^*$ %
GROUP I: ARC STAGE												
Port Deposit												
1.08 +- 0.10	0.5975	0.0348	0.0758	0.0020	0.4916	470.7	11.9	475.7	22.1	499.7	112	98.6
	0.6091	0.0331	0.0769	0.0017	0.4854	477.8	10.4	483.0	20.9	507.7	105	99.1
	0.5776	0.0269	0.0742	0.0020	0.2201	461.6	12.3	462.9	17.3	469.7	108	99.3
	0.6105	0.0287	0.0763	0.0025	0.5972	473.7	15.0	483.9	18.1	532.2	83	100.0
	0.5807	0.0244	0.0773	0.0019	0.5403	479.9	11.2	464.9	15.7	391.8	79	99.8
	0.5976	0.0234	0.0750	0.0018	0.5741	466.3	10.9	475.7	14.9	521.2	70	99.9
	0.6092	0.0322	0.0772	0.0014	0.4611	479.2	8.5	483.0	20.3	501.3	104	98.8
	0.5778	0.0439	0.0759	0.0010	0.4889	471.5	6.2	463.0	28.3	421.1	157	98.1
	0.6113	0.0090	0.0783	0.0007	0.7978	485.7	4.5	484.4	5.6	478.1	20	99.7
	0.5962	0.0277	0.0766	0.0008	0.1471	476.0	4.7	474.8	17.6	469.3	102	98.8
	0.5841	0.0602	0.0746	0.0021	0.6023	464.0	12.6	467.1	38.6	482.0	197	98.9
Ages (weighted average)						476.8	4.6	479.5	8.1	480.0	33	
James Run Formation												
1.07 +-0 .36	0.6172	0.0172	0.0783	0.0006	0.4693	485.9	3.6	487.9	10.8	493.8	62	98.1
	0.6180	0.0307	0.0780	0.0032	0.4782	483.9	19.3	488.4	19.3	507.5	134	97.6
	0.6235	0.0291	0.0785	0.0019	0.5025	487.2	11.4	491.4	18.2	505.3	71	99.0
	0.6179	0.0165	0.0783	0.0008	0.5200	486.1	5.1	488.2	10.3	494.8	58	99.1
	0.5979	0.0350	0.0768	0.0002	0.4829	476.8	1.3	475.8	22.3	468.7	124	99.5
	0.6255	0.0354	0.0793	0.0032	0.7400	491.9	19.2	493.3	22.1	500.0	84	99.2
	0.6270	0.0367	0.0795	0.0034	0.7593	493.0	20.3	494.2	22.9	500.0	84	99.2
Ages (weighted average)						478.5	3.6	488.0	11.0	497.0	57	
inherited												
	4.0830	0.1664	0.2849	0.0103	0.9219	1616.0	51.6	1651.0	33.2	1696.0	29	99.9
	4.0900	0.1310	0.2899	0.0079	0.9309	1641.0	39.4	1652.0	26.1	1667.0	22	100.0
	4.2250	0.1081	0.3027	0.0060	0.8692	1705.0	29.9	1679.0	21.0	1647.0	24	99.7
	4.2560	0.0825	0.2961	0.0059	0.9360	1672.0	29.3	1685.0	15.9	1701.0	13	99.9
	0.6826	0.0616	0.0808	0.0027	0.4694	501.1	16.2	528.3	37.2	647.7	172	98.5
	0.6586	0.0771	0.0752	0.0045	0.5169	467.4	27.1	513.7	47.2	725.5	213	99.1
metamorphic												
	0.5384	0.0170	0.0699	0.0010	0.5683	435.6	6.0	437.4	11.2	446.5	39	100.0

TABLE 1
(continued)

Plutonic/volcanic rocks analyzed	$\frac{^{207}Pb^*}{^{235}U}$	s.e.	$\frac{^{206}Pb^*}{^{238}U}$	s.e.	correl. coeff.	$\frac{^{206}Pb^*}{^{238}U}$ age in Ma	s.e.	$\frac{^{207}Pb^*}{^{235}U}$ age in Ma	s.e.	$\frac{^{207}Pb^*}{^{206}Pb^*}$ age in Ma	s.e.	$^{206}Pb^*$ %
GROUP II: SYNTECTONIC												
Norbeck												
1.02 +- 0.36	0.5304	0.0567	0.0735	0.0021	0.2904	457.0	12.4	432	37.6	301.3	233	99.1
	0.5972	0.0355	0.0749	0.0020	0.6521	465.7	11.8	475.5	22.6	523.1	103	100.0
	0.5726	0.0116	0.0735	0.0010	0.6452	457.0	6.1	459.7	7.5	473.2	34	100.0
	0.5593	0.0185	0.0745	0.0014	0.6489	463.5	8.5	451.1	12.1	388.3	57	99.8
	0.5806	0.0798	0.0770	0.0049	0.6376	478.4	29.1	464.8	51.3	398.3	244	97.5
	0.5796	0.0368	0.0747	0.0016	0.4434	464.3	9.5	464.2	23.7	464	127	99.2
	0.5815	0.0795	0.0772	0.0048	0.6325	479.1	28.5	465.4	51.0	398.3	244	97.5
	0.5812	0.0368	0.0749	0.0016	0.4418	465.5	9.4	465.3	23.7	464	127	99.2
	0.6232	0.0388	0.0742	0.0019	0.3072	461.5	11.2	491.8	24.3	461	51	99.8
Ages (weighted average)						465.4	6.2	461	11	499	74	
GROUP III: SECOND ARC												
Ellisville												
1.03+-0.34	0.5736	0.0163	0.0741	0.0018	0.6436	460.9	11.1	460.3	10.5	456.8	45	99.8
	0.5417	0.0113	0.0713	0.0009	0.5954	444.1	5.5	439.6	7.4	416	37	99.8
	0.5371	0.0105	0.0703	0.0013	0.6051	438.1	7.8	436.5	6.9	428.1	14	99.8
	0.54	0.0105	0.07	0.0009	0.6221	436.3	5.6	438.3	6.9	448.6	18	99.8
	0.5412	0.0076	0.0711	0.0013	0.6115	442.9	7.7	439.2	5	420.3	15	99.8
	0.5419	0.0209	0.0706	0.0012	0.6143	439.8	7.4	439.6	13.7	438.3	47	99.8
	0.553	0.0124	0.0717	0.0018	0.5841	446.1	10.5	446.9	8	451.5	33	99.6
	0.5593	0.0144	0.0727	0.0012	0.7336	452.2	7.3	451.1	9.4	445.5	39	99.7
	0.5491	0.0083	0.0705	0.0004	0.5156	439.2	2.2	444.4	5.4	471.4	22	99.8
Ages (weighted average)						440.9	3.3	442.4	4.7	437	15	
lead loss												
	0.496	0.0095	0.0654	0.0009	0.5929	408.6	5.4	409	6.4	410.9	15	99.8
	0.5197	0.0122	0.068	0.0017	0.5627	424.1	10.2	424.9	8.2	429.4	32	99.7
	0.5185	0.0145	0.0679	0.0018	0.671	423.2	10.6	424.2	9.7	429.3	49	99.8

Table 1
(continued)

Plutonic/volcanic rocks analyzed	$^{207}Pb^*/^{235}U$	s.e.	$^{206}Pb^*/^{238}U$	s.e.	correl. coeff.	$^{206}Pb^*/^{238}U$ age in Ma	s.e.	$^{207}Pb^*/^{235}U$ age in Ma	s.e.	$^{207}Pb^*/^{206}Pb^*$ age in Ma	s.e.	$^{206}Pb^*$ %
GROUP III: SECOND ARC												
Lahore												
1.08+-0.24	0.5445	0.0122	0.0709	0.0014	0.5878	441.5	8.3	441.3	8	440	16	99.7
	0.5495	0.0294	0.0704	0.0043	0.5533	438.3	26.1	447.9	19.3	479.5	42	99.4
	0.5438	0.0279	0.0707	0.0015	0.5414	440.2	8.8	440.4	18.4	433.7	106	99.3
	0.5498	0.0173	0.0713	0.0015	0.5899	444.2	8.9	444.6	11.2	444.9	34	99.7
	0.5561	0.0147	0.072	0.0007	0.5785	448	4.2	448.9	9.5	451.9	39	99.7
	0.5547	0.0129	0.072	0.0011	0.5442	448.1	6.8	448.1	8.4	448.2	44	99.2
	0.5471	0.0279	0.0713	0.0027	0.4445	443.8	16.1	443	18.4	437.3	197	99.7
	0.543	0.0131	0.0713	0.0012	0.5046	444.2	7.1	440.3	8.7	420.1	37	99.8
Ages (weighted average)						445.6	5.2	444.3	7.4	443	23	
Melrose												
1.05+-.0.59	0.5545	0.0106	0.0721	0.0005	0.51	448.7	3	447.8	6.9	442.1	34	99.4
	0.5465	0.0309	0.0702	0.0006	0.445	437.3	3.9	441.7	20.3	447.5	114	97.5
	0.5404	0.0069	0.0703	0.0019	0.5547	438.1	11.6	438.7	4.5	442.5	73	99.9
	0.5709	0.0137	0.0732	0.0018	0.4607	455.3	10.7	458.5	8.8	474.7	44	98.6
	0.5446	0.0132	0.0706	0.0012	0.5053	439.9	7.4	441.2	8.7	447.7	24	99.4
	0.54	0.0337	0.0699	0.0008	0.4828	435.5	5.1	437.9	21.9	442.2	114	97.5
Ages (weighted average)						442.8	7.1	443.5	6.2	450	34	
inherited												
	0.617	0.0248	0.0701	0.0015	0.8708	436.9	9.1	488	15.6	735.7	51	100
	0.673	0.0374	0.0742	0.0012	0.4719	461.1	7.1	521.2	22.4	783.3	84	97.8
	0.6847	0.036	0.0753	0.0026	0.4732	467.6	15.3	528.2	21.3	791.7	95	96.3
	2.1138	0.0609	0.1955	0.0046	0.6692	1150.9	24.8	1152.3	19.5	1155.6	25	98.9
	1.9355	0.0476	0.1835	0.0068	0.7763	1086	36.8	1093.3	16.5	1109.8	39	99.6
Leatherwood												
1.09 +- 0.16	0.5821	0.0375	0.0737	0.0028	0.4400	458.1	16.8	465.2	23.9	493.2	139	98.1
	0.5637	0.0374	0.0732	0.0018	0.4659	455.6	11.0	451.8	25.0	460.2	106	97.5
	0.5699	0.0250	0.0733	0.0018	0.4510	456.3	10.5	457.3	16.1	457.5	51	97.4
	0.5689	0.0202	0.0731	0.0028	0.4745	454.8	16.8	457.2	13.1	469.0	79	96.9
	0.5767	0.0579	0.0728	0.0043	0.4824	452.9	26.1	460.8	37.4	490.7	101	96.6
	0.5768	0.0357	0.0729	0.0020	0.5760	453.5	12.2	461.8	22.8	498.5	82	99.5
	0.5616	0.0286	0.0730	0.0012	0.4863	454.0	7.1	452.3	18.4	440.7	93	99.6

TABLE 1
(continued)

Plutonic/volcanic rocks analyzed	$\frac{^{207}Pb^*}{^{235}U}$	s.e.	$\frac{^{206}Pb^*}{^{238}U}$	s.e.	correl. coeff.	$\frac{^{206}Pb^*}{^{238}U}$ age in Ma	s.e.	$\frac{^{207}Pb^*}{^{235}U}$ age in Ma	s.e.	$\frac{^{207}Pb^*}{^{206}Pb^*}$ age in Ma	s.e.	$^{206}Pb^*$ %
GROUP III: SECOND ARC												
Leatherwood												
1.09 +- 0.16	0.5662	0.0396	0.0735	0.0029	0.5310	457.4	17.7	455.6	25.7	446.1	132	99.9
Ages (weighted average)						455.0	8.3	457.0	14.0	467.0	59	
inherited												
	0.6408	0.0807	0.0720	0.0033	0.4988	448.2	19.8	502.8	50.0	759.4	233	97.3
	0.5975	0.1264	0.0725	0.0021	0.4886	451.4	12.5	475.7	80.4	594.4	432	94.9
	0.6140	0.1172	0.0723	0.0044	0.5493	450.1	26.7	486.1	73.7	659.3	354	97.3
	0.5874	0.0317	0.0706	0.0032	0.4807	439.6	19.5	467.9	20.4	607.7	71	97.0
	0.5796	0.0729	0.0735	0.0015	0.3858	457.1	8.9	464.2	46.9	499.8	263	97.7
	0.5964	0.0732	0.0760	0.0101	0.4310	471.6	60.7	473.5	47.0	493.2	28	95.5
Shelton 1												
1.03 +-0 .28	0.5556	0.0107	0.0718	0.0010	0.6901	447.3	6.2	448.7	7.0	456	30.9	99.96
	0.5590	0.0076	0.0718	0.0010	0.7666	446.7	6.1	450.9	5.0	472	21.0	99.81
	0.5786	0.0088	0.0753	0.0008	0.8502	467.8	5.1	463.6	5.6	443	18.1	99.93
	0.5297	0.0196	0.0722	0.0041	0.4283	449.1	24.7	431.5	13.0	340	45.2	98.88
	0.5860	0.0086	0.0765	0.0047	0.4482	475.3	27.9	468.3	5.5	435	102.9	99.48
	0.5814	0.0065	0.0744	0.0008	0.5812	462.5	4.7	465.4	4.2	480	11.1	100.00
	0.5731	0.0094	0.0733	0.0014	0.4394	456.0	8.5	460.0	6.1	480	63.7	99.23
	0.5638	0.0079	0.0724	0.0009	0.5646	450.6	5.4	454.0	5.1	471	20.4	99.79
	0.5291	0.0396	0.0709	0.0018	0.4256	441.3	11.0	431.2	26.3	378	153.0	99.25
	0.5328	0.0702	0.0718	0.0038	0.4750	446.7	23.1	433.6	46.5	365	262.3	99.25
Ages (weighted average)						455.7	6.3	458.6	6.2	465.0	19	
Shelton 2												
1.05+-0.17	0.5798	0.0451	0.0732	0.0023	0.4457	455.5	13.7	464.3	29.0	508.0	153	99.5
	0.5914	0.0227	0.0753	0.0020	0.5833	467.9	11.7	471.8	14.5	490.9	69	100.0
	0.5904	0.0223	0.0735	0.0019	0.5819	457.0	11.3	471.1	14.2	540.2	68	100.0
	0.5792	0.0220	0.0747	0.0019	0.5829	464.4	11.5	464.0	14.1	461.7	69	100.0
	0.5733	0.0215	0.0731	0.0018	0.5767	455.0	11.0	460.2	13.9	486.3	68	100.0
	0.5754	0.0602	0.0754	0.0025	0.4280	468.4	14.7	461.5	38.8	427.3	213	98.9
	0.5850	0.0467	0.0714	0.0022	0.4457	444.4	13.2	467.7	29.9	583.7	156	99.4
	0.5587	0.0451	0.0732	0.0023	0.4441	455.1	14.0	450.7	29.4	427.8	162	99.5

Table 1
(continued)

Plutonic/volcanic rocks analyzed	$\frac{^{207}Pb^*}{^{235}U}$	s.e.	$\frac{^{206}Pb^*}{^{238}U}$	s.e.	correl. coeff.	$\frac{^{206}Pb^*}{^{238}U}$ age in Ma	s.e.	$\frac{^{207}Pb^*}{^{235}U}$ age in Ma	s.e.	$\frac{^{207}Pb^*}{^{206}Pb^*}$ age in Ma	s.e.	^{206} Pb * %
GROUP III: SECOND ARC												
Shelton 2												
	0.5885	0.0208	0.0758	0.0013	0.4870	471.1	7.6	469.9	13.3	464.2	68	99.6
	0.5513	0.0224	0.0716	0.0015	0.5098	445.6	8.8	445.9	14.7	447.1	78	99.7
	0.5729	0.0218	0.0738	0.0016	0.5691	459.2	9.8	459.9	14.1	463.5	69	99.8
	0.5668	0.0181	0.0717	0.0015	0.6130	446.6	9.1	455.9	11.7	503.3	55	99.9
Ages (weighted average)						457.7	6.1	462.1	9.1	486.0	45	
Columbia												
1.08 +-0 .24	0.5944	0.0577	0.0781	0.0037	0.4955	484.6	22.4	473.7	36.8	421.3	47	99.8
	0.5720	0.0177	0.0743	0.0019	0.5580	462.1	11.5	459.0	11.3	440.3	82	99.8
	0.5808	0.0183	0.0747	0.0010	0.6278	464.6	10.3	464.8	12.0	466.7	41	98.3
	0.5670	0.0236	0.0731	0.0017	0.5691	455.1	10.0	455.7	15.3	455.6	65	99.5
	0.5722	0.0082	0.0739	0.0012	0.5863	459.6	7.3	459.4	5.3	458.7	12	99.7
	0.5882	0.0191	0.0750	0.0031	0.4814	466.0	18.7	469.7	12.2	488.5	21	99.7
	0.5642	0.0557	0.0728	0.0018	0.3864	453.3	10.6	454.3	36.2	459.3	27	94.2
	0.5637	0.0122	0.0729	0.0030	0.4615	454.0	8.9	454.0	7.9	453.0	73	94.4
Ages (weighted average)						459.1	7.3	460.0	7.0	463.0	18	
inherited												
	0.6668	0.0258	0.0759	0.0022	0.4902	471.4	13.0	518.6	15.6	732.0	67	93.4
	0.6109	0.0193	0.0762	0.0019	0.7021	473.1	11.4	483.8	12.2	533.9	27	99.9
Gretna												
1.04 +-0 .48	0.5440	0.0237	0.0707	0.0018	0.4842	440.4	11.1	440.6	15.7	437.2	49	98.9
	0.5468	0.0098	0.0708	0.0008	0.6126	440.7	5.0	442.8	6.4	453.2	23	99.8
	0.5519	0.0143	0.0716	0.0010	0.8326	445.6	6.2	446.2	9.4	449.2	36	99.7
	0.5466	0.0223	0.0709	0.0022	0.5144	441.7	13.5	442.3	14.8	444.0	44	99.2
	0.5528	0.0221	0.0707	0.0003	0.6028	440.5	1.8	446.8	14.4	478.7	79	100.0
	0.5519	0.0143	0.0716	0.0010	0.8326	445.6	6.2	446.2	9.4	449.2	36	99.7
	0.5474	0.0195	0.0712	0.0009	0.5281	443.2	5.2	443.2	12.7	441.4	80	99.8
Ages (weighted average)						441.3	2.9	444.1	7.6	450.0	29	

TABLE 1
(continued)

Plutonic/volcanic rocks analyzed	$^{207}Pb^*/^{235}U$	s.e.	$^{206}Pb^*/^{238}U$	s.e.	correl. coeff.	$^{206}Pb^*/^{238}U$ age in Ma	s.e.	$^{207}Pb^*/^{235}U$ age in Ma	s.e.	$^{207}Pb^*/^{206}Pb^*$ age in Ma	s.e.	$^{206}Pb^*$ %
GROUP III: SECOND ARC												
Gretna												
inherited												
	2.3060	0.1052	0.2079	0.0043	0.5674	1218.0	23.1	1214.0	32.3	1208.0	75	99.3
	3.1000	0.1617	0.2454	0.0109	0.8428	1415.0	56.2	1433.0	40.1	1459.0	53	99.5
	1.4903	0.0264	0.1462	0.0038	0.6555	879.8	21.2	926.4	2.4	1039.3	25	99.8
Carysbrook												
1.08 +-0 .16	0.5901	0.0212	0.0739	0.0015	0.7791	459.7	9.0	470.9	13.5	525.9	52	99.7
	0.5229	0.0264	0.0661	0.0019	0.7145	412.9	11.7	427.1	17.6	504.6	79	99.6
	0.5503	0.0035	0.0727	0.0005	0.4863	452.3	3.3	445.2	2.3	408.6	13	99.8
	0.5714	0.0317	0.0684	0.0009	0.4597	426.3	5.4	458.9	20.5	625.8	110	97.8
	0.5838	0.0296	0.0746	0.0031	0.5386	463.9	18.9	466.8	19.0	481.4	19	99.9
	0.5372	0.0320	0.0698	0.0014	0.4520	435.2	8.6	436.3	21.1	438.4	102	99.6
	0.5572	0.0221	0.0719	0.0021	0.5904	447.8	12.4	449.6	14.5	456.9	102	99.9
	0.5553	0.0211	0.0716	0.0019	0.5483	445.5	11.7	448.4	13.8	463.4	72	99.9
	0.5301	0.0313	0.0676	0.0023	0.8575	421.5	13.7	431.9	20.8	487.5	77	99.9
Ages (weighted average)						444.0	11.0	445.9	4.1	439.0	34	
GROUP IV: EXTENSION												
Mafic Plutons												
Rich Acres												
1.09 +- 0.11	0.5275	0.0250	0.0693	0.0008	0.4759	431.8	4.9	430.0	16.5	416.5	118	98.9
	0.5388	0.0264	0.0705	0.0013	0.4847	439.2	8.0	437.5	17.5	425.5	94	99.1
	0.5388	0.0323	0.0695	0.0024	0.5658	433.2	14.4	437.3	21.5	455.8	99	99.9
	0.5371	0.0071	0.0702	0.0023	0.4791	437.5	14.1	436.5	4.7	433.2	48	99.0
	0.5284	0.0236	0.0693	0.0017	0.6576	431.7	10.1	430.8	15.7	425.7	76	99.2
	0.5295	0.0259	0.0699	0.0017	0.4811	435.3	10.2	431.5	17.2	411.2	96	99.2
	0.5266	0.0271	0.0690	0.0012	0.5359	430.1	7.5	429.6	18.0	426.9	99	99.3
	0.5290	0.0134	0.0681	0.0011	0.5422	424.9	6.7	431.1	8.9	463.7	30	99.8
	0.5365	0.0146	0.0687	0.0012	0.5197	428.1	7.3	436.1	9.6	478.8	52	100.0
Ages (weighted average)						431.3	5.2	434.8	6.6	451.0	38	

Table 1
(continued)

Plutonic/volcanic rocks analyzed	$\frac{^{207}Pb^*}{^{235}U}$	s.e.	$\frac{^{206}Pb^*}{^{238}U}$	s.e.	correl. coeff.	$\frac{^{206}Pb^*}{^{238}U}$ age in Ma	s.e.	$\frac{^{207}Pb^*}{^{235}U}$ age in Ma	s.e.	$\frac{^{207}Pb^*}{^{206}Pb^*}$ age in Ma	s.e.	$^{206}Pb^*$ %
GROUP IV: EXTENSION												
Green Springs and Poore Creek												
1.04 +- 0.30	0.5377	0.0151	0.0705	0.0025	0.4743	439.1	14.9	436.6	10.0	423.7	81	98.5
	0.5320	0.0486	0.0687	0.0015	0.4739	428.5	8.9	430.5	32.4	457.8	153	98.4
	0.5514	0.0355	0.0693	0.0031	0.6359	432.1	18.5	445.9	23.3	517.6	110	99.6
	0.5645	0.0237	0.0693	0.0013	0.5364	432.0	8.0	454.5	15.4	569.9	77	99.9
	0.5257	0.0113	0.0692	0.0026	0.4448	431.4	15.8	429.0	7.6	416.6	36	96.5
	0.5312	0.0131	0.0698	0.0004	0.4543	434.8	2.6	432.6	8.7	419.8	41	98.3
	0.5516	0.0049	0.0724	0.0006	0.5174	450.5	3.7	446.0	3.2	423.0	12	99.3
	0.5350	0.0182	0.0702	0.0005	0.4594	437.4	3.0	435.0	12.0	421.1	60	97.1
	0.5219	0.0115	0.0680	0.0003	0.4766	423.9	1.8	426.4	7.7	439.7	59	99.3
Ages (weighted average)						432.0	7.0	440.3	6.5	426.0	20	
inherited												
	0.6232	0.0542	0.0705	0.0025	0.4963	439.1	15.1	490.0	33.5	720.5	124	93.3
	0.5768	0.0087	0.0745	0.0011	0.4764	463.1	6.5	462.4	5.6	458.7	25	98.6
	2.0770	0.2377	0.1923	0.0080	0.5329	1133.7	43.4	1141.0	78.4	1155.3	196	92.0
	3.1800	0.1011	0.2504	0.0055	0.7500	1440.0	28.5	1452.0	24.6	1470.0	40	98.9
	0.6071	0.0108	0.0773	0.0011	0.5819	480.2	6.5	481.7	6.9	488.8	15	98.5
	1.1560	0.0293	0.1235	0.0019	0.6521	750.6	10.8	780.3	13.8	866.2	40	99.5
	0.6202	0.0633	0.0717	0.0013	0.3802	446.1	7.8	490.0	39.7	700.7	206	98.8
	0.6086	0.0441	0.0730	0.0018	0.1885	453.9	10.7	482.7	27.8	621.5	155	99.2
Diana Mills												
1.11 +0- .29	0.5459	0.0137	0.0709	0.0010	0.6009	441.6	5.9	442.3	9.0	445.9	45	99.8
	0.5341	0.0128	0.0697	0.0010	0.7361	434.4	5.9	434.5	8.5	435.4	37	99.9
	0.5363	0.0195	0.0711	0.0014	0.6253	442.8	8.4	436.0	12.9	399.9	64	99.4
	0.5411	0.0119	0.0700	0.0013	0.8323	436.4	7.9	439.2	7.9	453.9	27	99.9
	0.5422	0.0259	0.0715	0.0017	0.7728	445.2	10.1	439.9	17.1	412.2	74	99.6
	0.5324	0.0103	0.0691	0.0011	0.8926	430.6	6.9	433.4	6.8	448.4	19	100.0
Ages (weighted average)						437.6	5.7	436.9	7.2	445.0	26	
inherited												
	1.6513	0.0677	0.1650	0.0064	0.7193	984.3	35.5	989.5	25.9	1002.2	6	99.5
	0.6637	0.0147	0.0794	0.0015	0.6792	492.2	8.7	516.8	9.0	627.3	36	99.7
	0.6171	0.0327	0.0774	0.0028	0.6451	480.7	16.9	487.9	20.5	521.7	36	99.8

TABLE 1
(continued)

Plutonic/volcanic rocks analyzed	$^{207}Pb^*/^{235}U$	s.e.	$^{206}Pb^*/^{238}U$	s.e.	correl. coeff.	$^{206}Pb^*/^{238}U$ age in Ma	s.e.	$^{207}Pb^*/^{235}U$ age in Ma	s.e.	$^{207}Pb^*/^{206}Pb^*$ age in Ma	s.e.	$^{206}Pb^*$ %
GROUP IV: EXTENSION												
Buckingham												
1.07 +-0 .16	0.5217	0.0138	0.0686	0.0006	0.6172	427.7	3.9	426.3	9.2	418.7	49	99.3
	0.5252	0.0154	0.0693	0.0008	0.6265	432.1	5.1	428.6	10.3	409.6	53	99.3
	0.5375	0.0154	0.0695	0.0012	0.5327	433.4	7.1	436.5	10.2	450.6	44	99.4
	0.5249	0.0129	0.0688	0.0013	0.4840	429.0	8.0	428.0	8.6	426.0	11	99.9
	0.5199	0.0155	0.0701	0.0010	0.6140	436.8	6.0	425.1	10.4	362.2	54	99.6
	0.5358	0.0180	0.0696	0.0015	0.8840	433.6	9.0	435.6	11.9	446.2	40	99.8
	0.5226	0.0618	0.0683	0.0018	0.5025	426.1	10.6	426.9	41.2	431.3	240	98.2
	0.5054	0.0197	0.0688	0.0010	0.4332	428.8	6.3	415.4	13.3	341.2	79	99.6
	0.5426	0.0365	0.0707	0.0014	0.3412	440.1	8.1	440.2	24.0	440.7	141	98.8
	0.5709	0.0328	0.0701	0.0028	0.4527	436.7	16.7	458.6	21.2	570.1	115	99.8
Ages (weighted average)						431.4	4.1	429.6	7.4	425.0	19	
inherited												
	0.6134	0.0271	0.0734	0.0030	0.7696	456.5	18.0	485.7	17.0	625.8	63	100.0
	0.6374	0.0383	0.0757	0.0045	0.9386	470.5	26.9	500.7	23.7	640.9	45	100.0
Felsic Plutons												
Gunpowder												
1.08 +-0 .45	0.5268	0.0067	0.0685	0.0011	0.4976	427.0	6.4	429.7	4.4	444.5	20	100.0
	0.5167	0.0083	0.0672	0.0009	0.4927	419.3	5.6	422.9	5.6	442.7	24	100.0
	0.5219	0.0189	0.0679	0.0010	0.4901	423.3	6.1	426.1	12.7	438.0	63	100.0
	0.5293	0.0129	0.0688	0.0010	0.4861	429.1	6.2	431.3	8.6	442.4	27	99.2
	0.5291	0.0129	0.0687	0.0011	0.4917	428.1	6.5	431.1	8.6	447.1	29	98.9
	0.5277	0.0171	0.0691	0.0011	0.4660	430.5	6.9	430.1	11.3	424.7	70	98.8
Ages (weighted average)						426.0	5.0	428.1	5.6	443.0	23	
inherited												
	1.0589	0.0602	0.1157	0.0037	0.6079	705.6	21.5	731.4	30.2	806.1	63	99.1
	0.5995	0.0207	0.0718	0.0012	0.5075	447.0	6.9	476.6	13.2	617.7	69	98.6
	0.5752	0.0130	0.0712	0.0011	0.5674	443.2	6.9	461.2	8.4	551.0	23	99.4
lead loss												
	0.4972	0.0174	0.0651	0.0007	0.4213	406.4	4.2	409.4	11.7	420.0	58	99.7
	0.5141	0.0280	0.0667	0.0026	0.4872	416.1	15.7	420.7	18.5	443.6	55	98.8
	0.4899	0.0091	0.0648	0.0012	0.4583	404.9	7.6	404.8	6.2	402.8	67	99.7

Table 1
(continued)

Plutonic/volcanic rocks analyzed	$^{207}Pb^*/^{235}U$	s.e.	$^{206}Pb^*/^{238}U$	s.e.	correl. coeff.	$^{206}Pb^*/^{238}U$ age in Ma	s.e.	$^{207}Pb^*/^{235}U$ age in Ma	s.e.	$^{207}Pb^*/^{206}Pb^*$ age in Ma	s.e.	$^{206}Pb^*$ %
GROUP IV: EXTENSION												
Arden												
1.04 +- 0.37	0.5245	0.0111	0.0686	0.0008	0.4832	427.9	4.6	428.1	7.3	429.3	35	99.7
	0.5119	0.0200	0.0676	0.0016	0.4230	421.4	9.6	419.7	13.4	410.3	81	99.5
	0.5208	0.0086	0.0684	0.0010	0.5051	426.2	6.1	425.6	5.7	422.3	20	99.8
	0.5404	0.0082	0.0711	0.0005	0.5972	442.5	3.1	438.6	5.4	416.9	27	99.9
	0.5205	0.0047	0.0671	0.0004	0.5073	418.6	2.6	425.5	3.1	463.1	14	100.0
	0.5087	0.0047	0.0665	0.0004	0.5200	415.0	2.4	417.6	3.1	431.8	8	99.9
	0.5328	0.0143	0.0687	0.0018	0.5475	428.3	10.8	433.5	9.4	461.8	36	99.4
	0.5180	0.0036	0.0676	0.0003	0.5102	421.7	2.0	423.8	2.4	435.0	20	100.0
Ages (weighted average)						423.0	7.7	424.4	4.7	436.0	11	
inherited												
	0.5506	0.0211	0.0670	0.0021	0.4844	418.1	12.4	445.0	13.6	584.4	79	99.6
GROUP V: POST TECTONIC												
Ellicott City 8112												
1.05+-0.25	0.4315	0.0081	0.0567	0.0005	0.4090	355.4	3.3	364.2	5.7	419.2	27	99.8
	0.4640	0.0095	0.0617	0.0004	0.5549	385.9	2.7	387.1	6.6	394.1	39	99.7
	0.4390	0.0029	0.0582	0.0005	0.4686	364.7	3.0	369.6	2.0	400.7	20	99.1
	0.4715	0.0106	0.0629	0.0014	0.7054	393.2	8.6	392.1	7.3	386.0	6	99.9
	0.4519	0.0177	0.0608	0.0011	0.6099	380.3	6.6	378.6	12.4	368.2	71	99.7
	0.4125	0.0038	0.0553	0.0005	0.3663	346.7	3.2	350.7	2.8	376.8	15	99.6
	0.4132	0.0080	0.0560	0.0005	0.5034	351.1	3.2	351.2	5.7	351.7	38	99.8
	0.4290	0.0044	0.0574	0.0006	0.5538	359.9	3.9	362.4	3.1	378.6	13	99.7
	0.4229	0.0046	0.0567	0.0005	0.6115	355.4	3.0	358.1	3.3	375.7	16	99.8
	0.4323	0.0100	0.0581	0.0013	0.8638	364.2	7.8	364.8	7.1	368.5	27	99.9
Ages (weighted average)						363.0	10.0	363.6	7.4	384.2	9	
inherited												
	2.1364	0.0333	0.1960	0.0023	0.7743	1153.6	12.3	1160.6	10.7	1173.6	19	99.6
	0.5607	0.0047	0.0724	0.0006	0.5640	450.8	3.6	452.0	3.1	458.1	2	99.6
	0.8483	0.0166	0.0924	0.0019	0.5866	569.4	11.0	623.6	9.1	825.9	6	99.2
	0.8317	0.0130	0.0924	0.0009	0.6274	569.9	5.3	614.4	7.1	781.6	24	99.6

Table 1

(continued)

Plutonic/volcanic rocks analyzed	$^{207}Pb^*/^{235}U$	s.e.	$^{206}Pb^*/^{238}U$	s.e.	correl. coeff.	$^{206}Pb^*/^{238}U$ age in Ma	s.e.	$^{207}Pb^*/^{235}U$ age in Ma	s.e.	$^{207}Pb^*/^{206}Pb^*$ age in Ma	s.e.	$^{206}Pb^*$ %
GROUP V: POST TECTONIC												
Ellicott City 8112												
inherited												
	1.4747	0.0169	0.1482	0.0012	0.7556	891.1	6.8	920.1	7.0	990.2	12	99.7
	1.4510	0.0078	0.1473	0.0008	0.7847	885.5	4.3	910.3	3.2	970.9	8	99.8
	1.9850	0.0376	0.1875	0.0032	0.8885	1108.0	17.1	1110.0	12.8	1116.0	17	99.9
	0.6365	0.0332	0.0779	0.0015	0.3936	483.3	9.0	500.1	20.6	578.1	104	98.9
lead loss												
	0.4074	0.0222	0.0549	0.0017	0.2178	344.5	10.5	347.0	16.0	363.9	128	99.5
	0.4266	0.0190	0.0550	0.0012	0.4595	345.1	7.0	360.8	13.5	462.5	87	99.8
	0.4066	0.0090	0.0553	0.0009	0.7852	346.9	5.5	346.4	6.5	343.7	31	99.9
Ellicott city 8225												
1.02+-0.98	0.4354	0.0290	0.0583	0.0033	0.5286	365.1	20.1	366.3	20.6	374.0	38	99.3
	0.4354	0.0363	0.0585	0.0024	0.4618	366.4	14.6	367.0	15.0	370.5	27	99.8
	0.4573	0.0132	0.0611	0.0011	0.4903	382.2	6.8	382.4	9.2	383.0	37	99.8
	0.4379	0.0049	0.0587	0.0003	0.4731	367.7	2.0	368.7	3.5	374.3	24	99.0
	0.4415	0.0138	0.0591	0.0009	0.4885	370.3	5.6	371.1	9.8	375.4	54	99.5
Ages (weighted average)						369.0	3.6	370.3	5.8	375.0	28	
inherited												
	0.4627	0.0466	0.0575	0.0021	0.4631	360.4	12.9	385.9	32.3	537.5	140	99.6
	0.6619	0.0430	0.0789	0.0007	0.4611	489.3	4.4	515.6	26.3	631.7	160	99.1
	0.4784	0.0250	0.0581	0.0018	0.4547	363.8	10.8	396.4	17.2	584.7	75	97.8
	0.5210	0.0168	0.0614	0.0014	0.4713	383.9	8.3	425.5	11.2	656.1	28	97.4
lead loss												
	0.4066	0.0090	0.0553	0.0009	0.7852	346.9	5.5	346.4	6.5	343.7	31	99.9
	0.4266	0.0190	0.0550	0.0012	0.4595	345.1	7.0	360.8	13.5	462.5	87	99.8
	0.4147	0.0173	0.0537	0.0011	0.4580	337.5	6.7	352.2	12.4	448.4	82	99.6
Woodstock												
1.05+-0.44	0.4365	0.0073	0.0586	0.0007	0.4614	366.9	4.2	367.7	5.2	372.9	12	99.9
	0.4379	0.0070	0.0590	0.0007	0.6064	369.5	4.3	368.8	4.9	364.2	13	99.9
	0.4771	0.0177	0.0631	0.0008	0.4148	394.7	5.0	396.1	12.1	403.9	76	99.5

TABLE 1
(continued)

Plutonic/volcanic rocks analyzed	$^{207}Pb^*/^{235}U$	s.e.	$^{206}Pb^*/^{238}U$	s.e.	correl. coeff.	$^{206}Pb^*/^{238}U$ age in Ma	s.e.	$^{207}Pb^*/^{235}U$ age in Ma	s.e.	$^{207}Pb^*/^{206}Pb^*$ age in Ma	s.e.	$^{206}Pb^*$ %
GROUP V: POST TECTONIC												
Woodstock												
	0.4665	0.0100	0.0625	0.0009	0.6297	390.9	5.7	388.8	7.0	376.3	15	99.8
	0.4601	0.0188	0.0615	0.0017	0.5419	384.6	10.2	384.0	13.1	378.6	37	99.5
	0.4747	0.0216	0.0631	0.0016	0.5036	394.4	9.6	394.4	14.9	394.8	88	99.9
Ages (weighted average)						381.0	11.0	378.4	9.4	373.0	14	
inherited												
	0.7460	0.0240	0.0848	0.0015	0.6763	525.0	8.6	565.9	14.0	734.2	51	99.5
lead loss												
	0.3814	0.0102	0.0522	0.0011	0.6758	328.0	6.4	328.0	7.5	328.5	45	99.9
	0.4155	0.0087	0.0554	0.0007	0.5801	347.4	4.5	352.8	6.2	388.8	38	100.0
	0.4088	0.0089	0.0539	0.0004	0.4844	338.5	2.6	348.0	6.4	412.4	43	99.5
	0.4135	0.0351	0.0554	0.0012	0.2978	347.7	7.0	351.4	25.2	375.8	183	98.3
	0.4164	0.0143	0.0558	0.0010	0.6136	350.1	6.3	353.5	10.2	375.5	61	99.8
	0.4218	0.0028	0.0568	0.0002	0.5862	356.1	1.4	357.3	2.0	364.9	6	100.0

All errors are reported as standard error (s.e.) at one sigma.

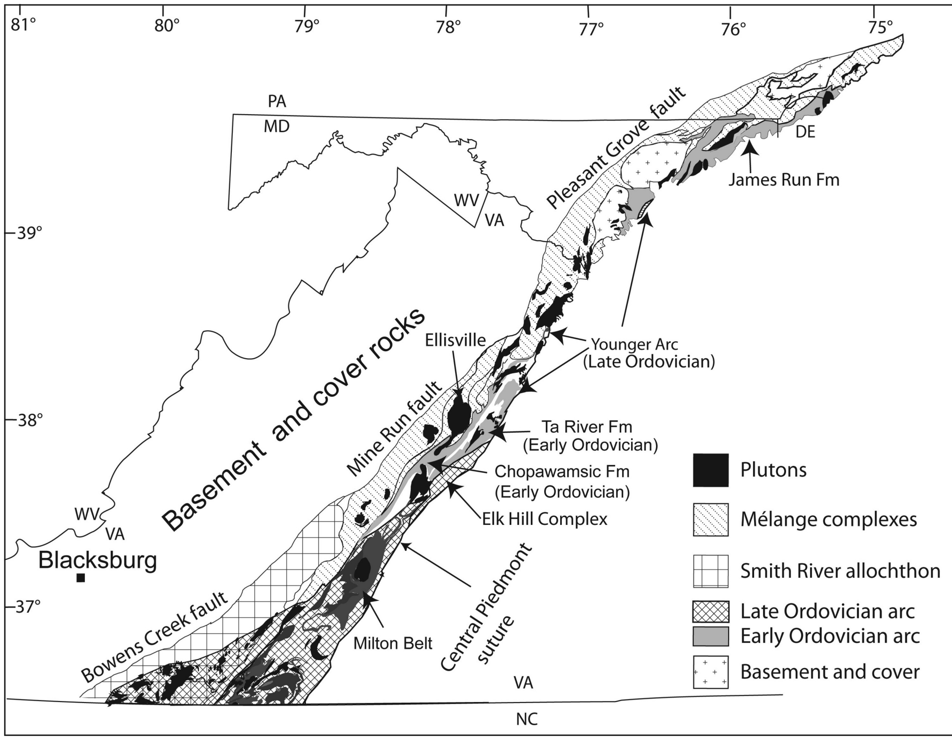

Fig. 2. Generalized geologic map of lithotectonic belts that represent: (1) Central Appalachian Arc Complexes (Early Ordovician Central Appalachian Arc Complex: EOCAAC and Late Ordovician Central Appalachian Arc Complex: LOCAAC), mélange complexes and the Smith River allochthon. (Geologic base map adapted from Pavlides, 1989; Glover and others, 1989; this article).

Neoacadian to Alleghanian orogenesis involving subhorizontal shearing (Hibbard and others, 1998; Hatcher, 2010). In contrast, volcanic rocks of the Chopawamsic and James Run Formations, including the Wilmington and Baltimore mafic complexes, were deformed prior to deposition of the Sykesville mélange in Maryland (Fisher and others, 1979; Higgins, 1990), which is intruded by Middle Ordovician syntectonic plutons (Fleming and others, 1994; Fleming and Drake, 1998 this article). The eastern boundary of the composite volcanic province (fig. 1) (Tugaloo terrane of Hatcher and others, 2007), is marked by Neoacadian to early Alleghanian fault systems related to the Central Piedmont suture zone (Hatcher and others, 2007; Hibbard and others, 2007) and in the central Appalachians is coincident with the Spotsylvania gravity anomaly (Pavlides, 1981; Glover and others, 1989). Recent mapping in the central part of the volcanic terrane suggests that rocks of the Elk Hill Complex (fig. 2) may differ in age and affinity from the adjacent Chopawamsic Formation (Spears and others, 2004). Syn-collision magmatism in the region is best recognized in the northern part of the study area where syntectonic plutons (Group II) are especially well described (Hopson, 1964; Fleming and Drake, 1998). Volcanic rocks associated with the second arc of Late Ordovician age (Late Ordovician Central Appalachian Arc Complex: LOCAAC) identified in this article, as well as by Horton and others (2010) are in a small area along the eastern margin of EOCAAC and farther south as part of the Milton belt (Butler, 1980; Coler and others, 2000) and plutonic equivalents (Group III igneous rocks) in the Smith River allochthon. Two major geologic belts (western mélange and

EOCAAC) are crosscut by the 441 Ma Ellisville pluton (Pavlides, 1981; this article), which is considered to be part of LOCAAC, suggesting that no large-scale tectonic displacement has occurred between these two belts after emplacement of the pluton and its volcanic equivalents. Group IV bimodal igneous rocks are scattered in a linear belt along the entire length of the study area (~700 km); mafic plutons are abundant in the southern part of the study area. Farther north, in the region underlain by a depocenter associated with late Neoproterozoic rifting (Read, 1989), geochemical data support interaction of mafic magmas with volcanic/sedimentary rocks to yield felsic plutons of Group IV. Group V Devonian-age plutons of limited areal extent in the central Appalachians are considered to have been generated by changes in tectonic stresses associated with post-closure shortening during the docking of peri-Gondwanan tracts and transpressional tectonics associated with the transfer of the Cat Square terrane (fig. 1) along the eastern accreted margin (Hatcher, 2010; Merchat and others, 2010). Although the geologic history of this region, including episodes of faulting has been addressed by numerous researchers (Pavlides, 1981; Glover and others, 1983, 1989; Valentino and Gates, 1999; Hibbard and others, 2007), the tectonic significance of the spatial and temporal distribution of igneous rocks in this region is the subject of this article.

For this study we have divided the central Appalachian plutons and volcanic rocks into groups on the basis of ages and petrochemical affinities.

GROUP I (EARLY ORDOVICIAN CENTRAL APPALACHIAN ARC COMPLEX; EOCAAC)

In order to clearly distinguish pre-collision arc magmatism from that associated with collision and subsequent tectono-thermal events, we briefly review the geochronologic data from Late Cambrian to Early Ordovician age volcanic and plutonic rocks (EOCAAC, fig. 2) that have been interpreted to be part of a continental-margin arc (Southwick and others, 1971; Pavlides, 1989; Hanan and Sinha, 1989; Higgins, 1990; Pavlides and others, 1994; Sinha and others, 1997; Faill, 1997; Plank and others, 2001). Although given local names such as Chopawamsic and Ta River Formations (Southwick and others, 1971; Pavlides, 1981, 1989), James Run Formation (Hopson, 1964; Crowley, 1976; Higgins, 1990), Cecil County volcanics (Higgins, 1990), and Rockford Park, Windy Hill, and Faulkland Gneisses of Delaware and Pennsylvania (Plank and others, 2000, 2001), these rocks were first identified by Higgins (1972) as the Atlantic Seaboard volcanic province. Although Higgins (1972) included the volcanic rocks of the Milton belt of Butler (1980) as equivalent of the James Run/Chopawamsic/Ta River Formations, our new data suggest the volcanic rocks of the Milton belt belong to a younger arc (LOCAAC, fig. 2) formed over the older arc terrane and separated in time by a collisional event marking the Taconic orogeny. Notable plutonic bodies associated with these volcanic formations, and commonly in thrust contact, are the Baltimore mafic complex (Hopson, 1964; Southwick, 1969; Hanan and Sinha, 1989; Sinha and others, 1997), Piney Branch complex (Drake and Morgan, 1981), Port Deposit granodiorite (Lesser, ms, 1982), Rolling Mill gneiss (Higgins, 1990), Brandywine felsic gneiss, Barley Mill tonalite, and Christianhead granodiorite (Plank and others, 2000). Recently published and new U/Pb zircon ages (Group I) bracket EOCAAC to lie within a narrow time range of 470 to 489 Ma (fig. 3; tables 1 and 2) with a weighted average $^{206}Pb/^{238}U$ age of 478 ± 5 Ma.

The temporal association of volcanic and plutonic rocks is demonstrated to be especially well correlated with the James Run Formation (Churchville Gneiss member of Horton and others, 2010) and Port Deposit granodiorite, which yield weighted average $^{206}Pb/^{238}U$ ages 479 and 477 Ma, respectively (fig. 3; table 1), and support the observation of Higgins (1990) that the Port Deposit pluton is a subjacent mass within the volcanic pile. U/Pb data for Churchville Gneiss reported by Horton and others (2010) are markedly younger (458 ± 4 Ma), and perhaps the sample analyzed is from

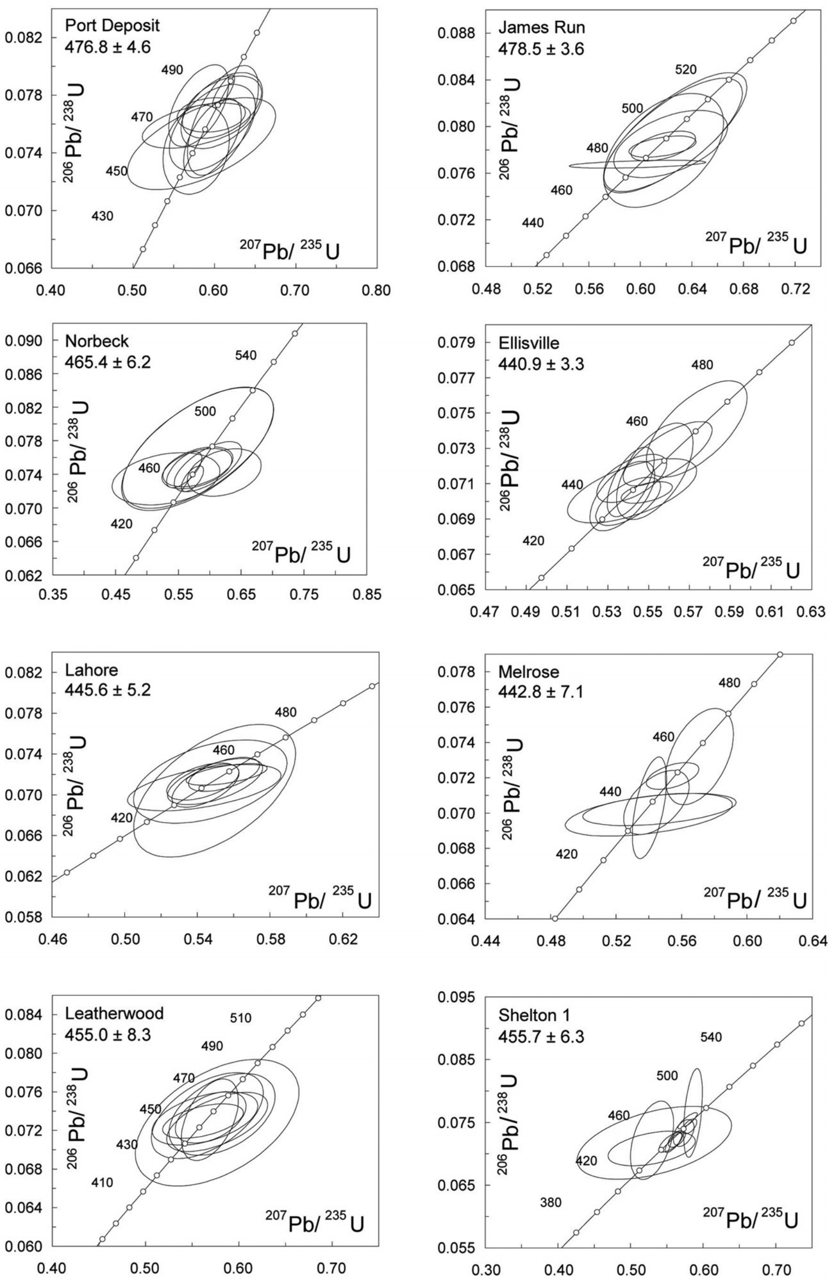

Fig. 3. Zircon U/Pb concordia diagrams (plotted using ISOPLOT, Ludwig, 2003) for igneous rocks analyzed in this study. All errors are reported as weighted average of ^{206}Pb/^{238}U ages following the method of Ludwig (2003).

younger concordant intrusive sheets common in the area and recognized as such by Horton and others (2010). Although zircons from the Port Deposit granodiorite show no isotopic evidence of inheritance or metamorphic overgrowth, those from the coeval

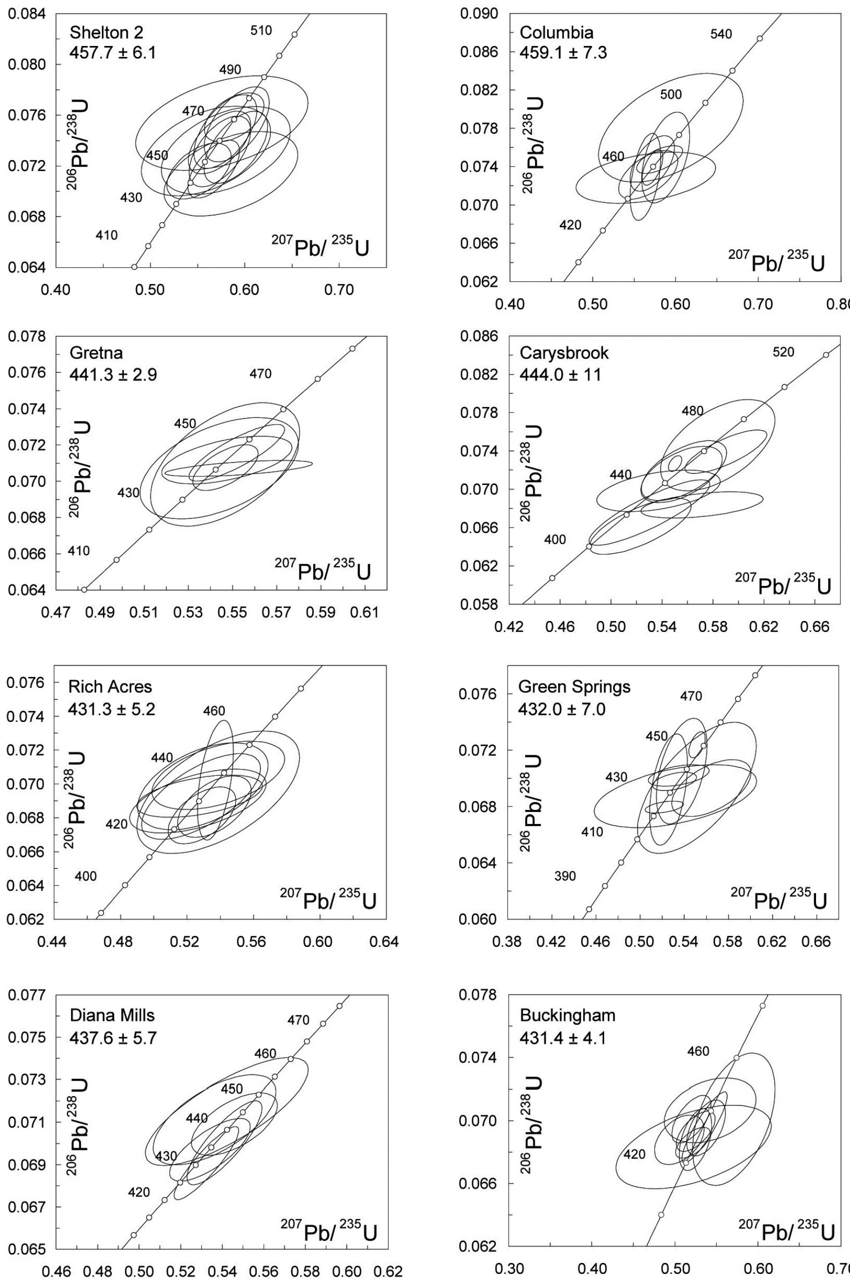

Fig. 3 (continued)

James Run Formation are complex, and record three discrete ages: an inherited age from a protolith of approximately 1650 Ma, a crystallization age of 478 Ma, and an overgrowth at 435 Ma. The data reported by Horton and others (2010) show no evidence of inheritance but record a 430 Ma rim similar to our observation. Although it is possible the rim ages are related to lead loss, the age is similar to other Silurian

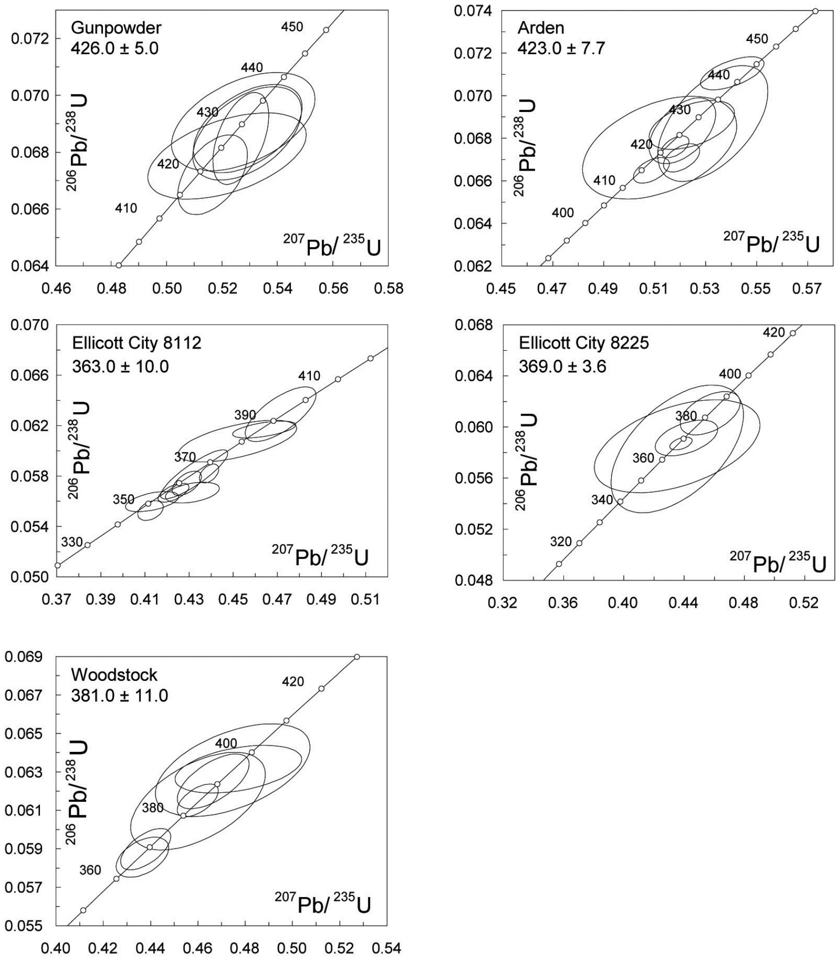

Fig. 3 (continued)

igneous ages, for example, Ardentown pluton in Delaware (table 1), suggesting that overgrowths could have formed during this episode of magmatism and associated thermal perturbation. Although Mesoproterozoic ages have been documented from the northern part of EOCAAC, for example, the Wilmington Complex (Aleinikoff and others, 2006), the range of ages from 1.0 Ga to as old as 2.6 Ga, reported by Coler and others (2000), suggests a complex spectrum of zircon ages in the continental arc environment.

Group II: Syntectonic Magmatism Associated with Arc-Continent Collision (Mid-Ordovician Taconic Orogeny)

Group II zircons from syntectonic plutons [northern Virginia and Maryland (fig. 4)] range in age from 459 to 472 Ma (table 2) (Aleinikoff and others, 2002; Horton and others, 2010; this article) with a weighted average ^{206}Pb/^{238}U age of 464 ± 3 Ma. Published U/Pb ages for syntectonic plutons (Kensington, Georgetown, Falls Church, Lake Jackson, Occoquan, and Norbeck) in Maryland and northern Virginia contain evidence of inheritance (ages between 519 and 798 Ma), although the Dalecarlia pluton yielded an inherited age of 1600 Ma (Aleinikoff and others, 2002). Table 2 also highlights measurable differences in age for some plutons that were analyzed using both SIMS and TIMS methods, and we recognize the need to accept an age that is most consistent with geologic constraints. For example, Norbeck pluton has three reported ages that range from 449 to 465 Ma (Aleinikoff and others, 2002; this article). We suggest that the 449 Ma age obtained by SIMS method is anomalous (lead loss?) because all other similar plutons are consistently older and form a well characterized syntectonic suite.

Group II plutons are compositionally diverse (see table 2 for rock types) and contain field and petrographic evidence of syntectonic emplacement, for example, granitic seams parallel to schistosity of the host rocks, and fabric in plutons coplanar with wallrock structures (for example, Drake, 1987). In many places, isolated parts of the plutons contain magmatic fabrics or weak deformation fabrics, for example, Dalecarlia (Drake and Fleming, 1994), Georgetown (Hopson, 1964; Drake and Froelich, 1997), and Kensington (Fleming and Drake, 1998). We use the average age of 464 ± 3 Ma for the best estimate for regional tectonism and magmatism during the collision phase of the Taconic orogeny in the central Appalachians. These ages are especially well correlated with events recognized in the sedimentary record of Pennsylvania where local transitional basins developed at 461 Ma reflect initial thrusting along the shelf edge (Wise and Ganis, 2009). Metamorphic ages associated with this tectonic event are not well constrained in the region of study, as monazite U/Pb ages record either Early Ordovician (~480 Ma) or Late Ordovician–Silurian (452-435 Ma) growth events (Bosbyshell, ms, 2001).

GROUP III (LATE ORDOVICIAN CENTRAL APPALACHIAN ARC COMPLEX; LOCAAC)

Group III zircon ages were obtained from eight plutons (fig. 4) in central and southern Virginia (Leatherwood, Shelton, Columbia, Carysbrook, Ellisville, Lahore, Melrose, and Gretna that range in age from 441 to 459 Ma with an average age of 451 ± 4 Ma (calculated as weighted mean of all Group III ages and associated errors). Zircons analyzed from Leatherwood, Shelton, and Columbia plutons are commonly euhedral and zoned, and some have both radial and concentric fractures, suggesting complex chemical domains associated with radiation damage (Lee, 1993). Our data for these plutons provide only a weak and noisy signal for inheritance (533-759 Ma) that appears to be related to lower enrichment of radiogenic lead associated with higher ^{204}Pb domains, for example, lower content of radiogenic Pb (table 1). However, Prospect pluton analyzed by TIMS contains no inheritance (Coler and others, 2000), while Gretna and Melrose plutons provide evidence of inheritance whose ages range from 735 to 1459 Ma (table 1).

On basis of the intrusive relationship of the Ellisville pluton (Pavlides and others, 1994) across two mapped lithotectonic units, that is, Chopawamsic Formation and the Mine Run Complex, we consider this pluton as a "stitching pluton," that is, providing a minimum age for the tectonic juxtaposition of lithologic units assembled during the Taconic accretionary event (Sinha, 2004). The Ellisville and Lahore plutons were emplaced into deformed greenschist grade host rocks at temperatures of approximately 750 °C and 4.6 to 6 kb (Pavlides and others, 1994). On the basis of similar ages for metavolcanic rocks, for example Relay felsite and Lapilli metatuff of the Quantico Formation in eastern Virginia (Horton and others, 2010), as well as ages of volcanic rocks in the Milton belt (Coler and others, 2000), our data suggest that these plutons may represent deep-seated equivalents of a Late Ordovician volcanic arc that developed across the tectonically juxtaposed EOCAAC, mélanges, and the Smith River allochthon which were assembled during the Taconic orogeny (fig. 4).

TABLE 2

Summary of secondary ion microprobe (SIMS) and selected thermal ionization mass spectrometry (TIMS) ages for igneous rocks in the central Appalachian orogen

	Age in Ma (1 σ error)	Method	Reference
Volcanic Rocks of early Ordovician arc (EOCAAC) 478 ± 5			
Rockford Park Gneiss (layered mafic and felsic orthogneiss)	476 ± 4	SIMS	Aleinikoff and others, 2006
Faulkland Gneiss (massive amphibolite)	482 ± 4	SIMS	Aleinikoff and others, 2006
Windy Hills Gneiss (interlayered felsic gneiss, amphibolite)	481 ± 4	SIMS	Aleinikoff and others, 2006
James Run Formation (interlayered mafic and felsic orthogneiss)	479 ± 4	SIMS	this paper
Chopawamsic Formation (interlayered mafic and felsic orthogneiss)	471 ± 1	TIMS	Coler and others, 2000
Ta River Formation	470 ± 1	TIMS	Coler and others, 2000
Plutonic Rocks of EOCAAC			
Baltimore Mafic Complex (ultramafic and gabbros)	489 ± 7	TIMS	Sinha and others, 1997
Port Deposit Gneiss (granodiorite)	477 ± 5	SIMS	this paper
Brandywine Gneiss (felsic orthogneiss)	476 ± 6	SIMS	Aleinikoff and others, 2006
Barley Mill Gneiss (tonalite)	470 ± 9	SIMS	Aleinikoff and others, 2006
Christianshead Gneiss(granodiorite)	488 ± 8	SIMS	Aleinikoff and others, 2006
Syntectonic Plutons 464 +- 3			
Franklinville(tonalite)	462 ± 5	SIMS	Horton and others, 2010
Perry Hall (tonalite)	461 ± 5	SIMS	Horton and others, 2010
Norbeck (tonalite)	449 ± 7(460 ± 3 TIMS)	SIMS	Aleinikoff and others, 2002
Norbeck (tonalite)	468 ± 7		this paper
Kensington (tonalite)	463 ± 8	SIMS	Aleinikoff and others, 2002
Georgetown (tonalite)	472 ± 4 (466 ± 3 TIMS)	SIMS	Aleinikoff and others, 2002
Falls Church (tonalite)	469 ± 6	SIMS	Aleinikoff and others, 2002
Lake Jackson (tonalite)	461 ± 7	SIMS	Aleinikoff and others, 2002
Occaquon (granite)	472 ± 4	SIMS	Aleinikoff and others, 2002
Dale City (quartz mozonite)	459 ± 4	TIMS	Aleinikoff and others, 2002
Dalecarlia (granite)	478 ± 6 (465 ± 4 TIMS)	SIMS	Aleinikoff and others, 2002

Table 2
(continued)

	Age in Ma (1 σ error)	Method	Reference
Volcanic and Plutonic rocks of late Ordovician arc (LOCAAC) 451 ± 4			
Carysbrook (granodiorite)	444 ± 11	SIMS	this paper
Ellisville (granodiorite)	441 ± 3	SIMS	this paper
Lahore (monzonite)	446 ± 5	SIMS	this paper
Melrose (granodiorite)	443 ± 7	SIMS	this paper
Gretna (granodiorite)	441 ± 3	SIMS	this paper
Felsic Gneiss	453 ± 4	SIMS	Horton and others, 2010
Quantico Formation (felsic lapilli tuff)	448 ± 4	SIMS	Horton and others, 2010
Metarhyolite, Milton Belt, Va	458 ± 4	TIMS	Coler and others, 2000
Old Mill granite gneiss, Milton Belt, Va	450 ± 1.8	TIMS	Coler and others, 2000
Goldvein (granite)	456 ± 9	SIMS	Aleinikoff and others, 2002
Columbia (granodiorite)	459 ± 7	SIMS	this paper
Leatherwood (granite)	455 ± 8	SIMS	this paper
Shelton (granite)	456 ± 6; 458 ± 6	SIMS	this paper
Prospect (granite)	458 ± 1	TIMS	Coler and others, 2000
Extension Related (delamination) 431 ± 4			
Mafic plutons			
Bringhurst (gabbro)	~430 (inferred)		Plank and others, 2000
Poore Creek/Green Springs (gabbro-diorite)	432 ± 7	SIMS	this paper
Diana Mills (gabbro)	438 ± 6	SIMS	this paper
Buckingham (gabbro)	431 ± 4	SIMS	this paper
Rich Acres (gabbro)	431 ± 5	SIMS	this paper
Felsic Plutons			
Ardentown (Granite)	434 ± 4	SIMS	Aleinikoff and others, 2006
Ardentown (Granite)	423 ± 7	SIMS	this paper
Gunpowder (granite)	426 ± 5	SIMS	this paper
Springfield (granodiorite)	427 ± 3	SIMS	Bosbyshell and others, 2005
Prince William Forest	434 ± 8	SIMS	Horton and others, 2010
Bynum Run	434 ± 4	SIMS	Horton and others, 2010
Post tectonic plutons 365 ± 9			
Woodstock (granite)	381 ± 11	SIMS	this paper
Ellicott City (granodiorite)	363 ± 10; 369 ± 4	SIMS	this paper
Guilford (granite)	362 ± 3	SIMS	Aleinikoff and others, 2002

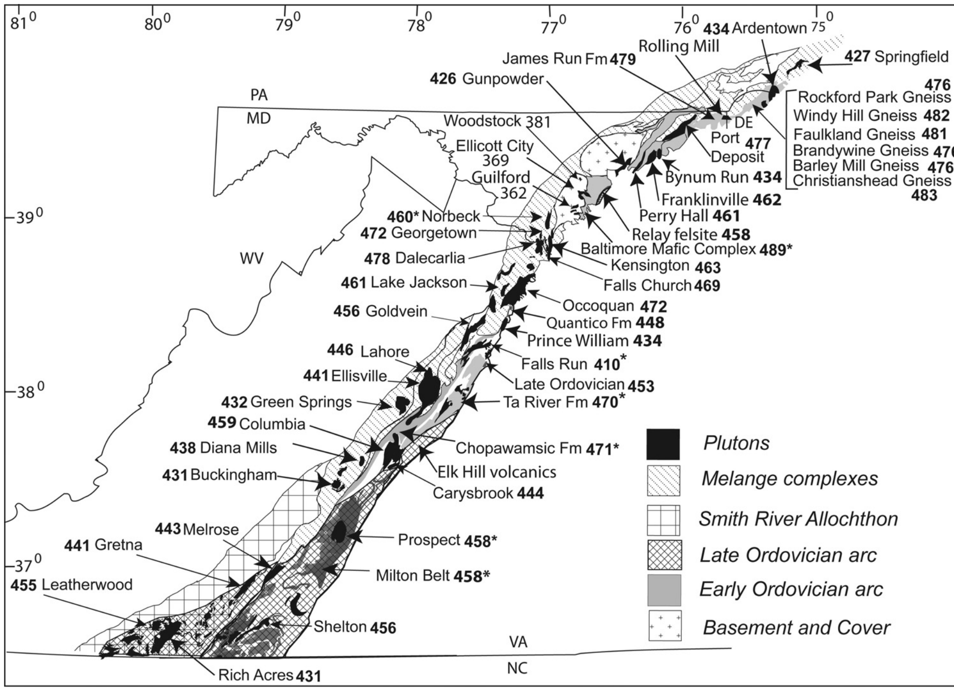

Fig. 4. The distribution and zircon U-Pb ages of igneous rocks in the central Appalachian orogen associated with arc stage magmatism, and those formed as the result of arc-continent collision, extension and accretion of peri-Gondwana terrane. Close examination of data reveals multiple tectonic stages within the collision zone. Ages with an * were obtained by thermal ionization mass spectrometry (TIMS); all other ages were obtained by secondary ion mass spectrometry (SIMS).

Group IV (Silurian magmatism associated with extension)

Group IV plutons extend from Pennsylvania through Virginia and include both mafic and felsic complexes that lie within an age range of 423 to 438 Ma (table 1, fig. 3) with a weighted average age of 431 ± 4 Ma (calculated as weighted mean of all Group IV ages and associated errors). The mafic plutons, for example, Rich Acres, Buckingham, Diana Mills, and Green Springs (Conley and Henika, 1973; Henika and others, 1996; Wilson, ms, 2001; Trujillo and Sinha, 2004), are spatially restricted to south-central Virginia (fig. 4), and yield a range of ages from 431 to 437 Ma. Inherited zircon ages for three of the bodies (Green Springs, Diana Mills, and Buckingham) range from 458 to 1470 Ma and are very similar to those in Group II and III plutons. These plutons are dominantly gabbroic to dioritic in composition (Wilson, ms, 2001 and references therein), and commonly crosscut earlier fabrics. Although it has been suggested that the Rich Acres pluton is coeval with or older than the Leatherwood pluton (Henika and others, 2001), our data show it to be significantly younger than the Leatherwood pluton. We suggest that granitic sills crosscutting the Rich Acres body are not related to the Leatherwood pluton, but possibly are anatectic melts formed during emplacement of the mafic Rich Acres pluton. Average monazite ages of 433 Ma (Tracy and others, 2001) from the contact aureole of the Rich Acres are consistent with the zircon U/Pb Silurian age for the pluton. Two other plutons analyzed for this study (Gunpowder, Ardentown), as well as the Springfield pluton (Bosbyshell and others, 2005) and Bynum Run and Prince William Forest plutons (Horton and others, 2010) are similar in age (figs. 3 and 4; tables 1 and 2) to the mafic complexes, but are dominantly felsic in composition. Gunpowder pluton (426 Ma) is a muscovite granite with a weak gneissic fabric that crosscuts strongly foliated wallrock, suggesting emplacement after deformation (Hopson, 1964; Sinha and others, 1980). Other felsic bodies of similar age, for example, Ardentown plutonic suite (423 Ma) in Delaware and Pennsylvania (Plank and others, 2000), range in composition from norite to granodiorite (Srogi and Lutz, 1997), and crosscut a high-grade fabric that formed at 441 Ma (Grauert and Wagner, 1975). The Ardentown pluton yielded a single $^{207}Pb/^{206}Pb$ inherited age of 584 Ma. Zircons from the Gunpowder pluton, considered to have been derived from the Grenville-age Baltimore Gneiss (see Hammarstrom and others, 1995), also contain very limited inheritance: the oldest $^{207}Pb/^{206}Pb$ age is 806 Ma. The Springfield epidote-hornblende granodiorite (Crawford and Mark, 1982; Becker, ms, 1996) in Pennsylvania has a reported U/Pb zircon age of 427 Ma (Bosbyshell and others, 2005) and is considered to be part of this group. The depth of emplacement has been estimated to be about 9 Kb (Becker, ms, 1996).

Group V (Devonian magmatism associated with accretion of peri-Gondwanan tracts)

Group V plutons include three bodies in Maryland. Two samples of Ellicott City epidote + hornblende granodiorite yield ages of 369 ± 4 and 363 ± 10 Ma, whereas the Woodstock quartz monzonite is older at 381 ± 11 Ma. Utilizing a published age of 362 ± 3 Ma for Guilford granite (Aleinikoff and others, 2002), these Group V plutons yield an average weighted mean age of 365.2 ± 4.6 Ma. Our zircon analyses reveal complex zoning patterns associated with growth history, as shown by very extensive evidence of inheritance ($^{207}Pb/^{206}Pb$ ages range from 458 to 1250 Ma), which is generally not a simple core/mantle relationship. Contact relationships and lack of fabric in the interiors of the plutons suggest that these plutons were emplaced after all locally recognized deformational events (Hopson, 1964; Hammarstrom and others, 1995) and can be labeled as post-Taconic.

A suite of 424 to 360 Ma plutons similar in age to Group V plutons, is located farther south in the Cat Square terrane (fig. 1) (Merschat and Hatcher, 2007; Hatcher and others, 2007). Unlike Group V plutons, these bodies are highly deformed, and appear to be anatecticaly derived from the enclosing rocks (Mapes, ms, 2002). Additional data are required to link Group V plutons and those of the Cat Square terrane as a co-tectonic suite.

Summary of New and Published SIMS Ages

New and published SIMS ages for igneous rocks in the region are summarized in table 2 and shown in figure 4. The SIMS results are broadly similar to, but generally younger than previously determined TIMS ages (Sinha and others, 1989). Differences in interpreted ages between the two methods are generally ascribed to the variable influences of U-Pb discordance and inheritance affecting TIMS analyses (for example, Aleinikoff and others, 2002).

In order to confirm the grouping of the igneous activity in the region we show probability plots (figs. 5A and 5B) using methods described by Ludwig (2003) using the weighted mean $^{206}Pb/^{238}U$ age with error for all the available igneous rocks (Groups I through V). Significant statistical overlap is obvious, but the peak ages for the five groups are easily recognizable. We attribute this level of overlap to a single sample based age for a pluton or volcanic rock, as well as thermal overlap between tectonic episodes. If the weighted mean for each group (not individual pluton/volcanic rock ages shown in fig. 5A) is utilized, a stronger and clearer separation of the five groups (fig. 5B) supports our contention that these groupings are geologically significant and provides insight into the magmatic record associated with the develop-

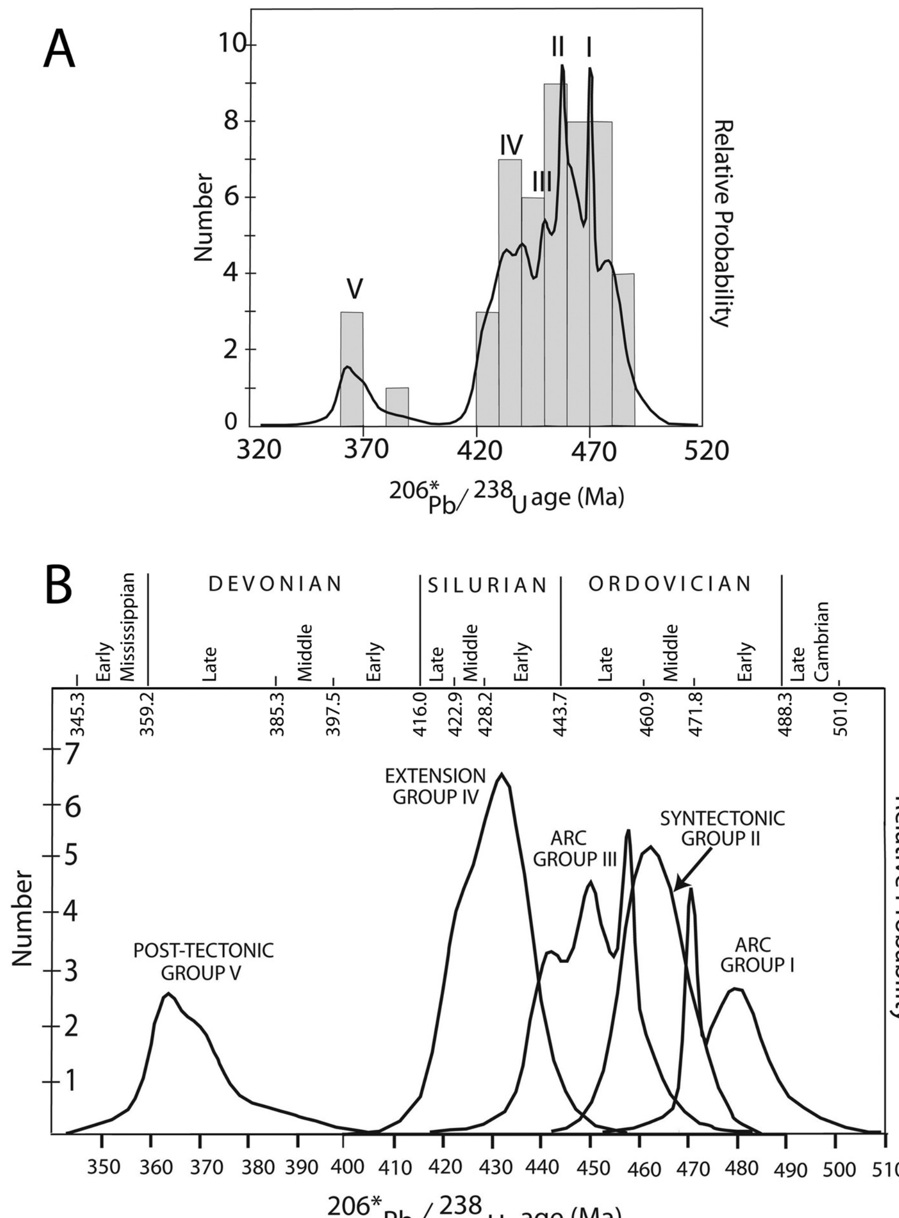

Fig. 5 (A). Cumulative relative probability plot (Ludwig, 2003) of new and published U/Pb zircon ages in the study area. The histogram highlights the short duration of multiple igneous events, and where Groups I through V igneous rocks reflect changing tectonic environments. (B) Relative probability plots for the five separate groups identified in this article. The non-symmetrical curve for any given group is the result of differences in assigned errors associated with reported U/Pb ages. Divisions of Geologic Time adapted from the U.S. Geological Survey (2010).

ment of an Early Ordovician arc followed by arc-continent collision and emplacement of mid-Ordovician syntectonic plutons. By Late Ordovician time renewed igneous activity is modeled as the growth of a second arc, followed by Silurian magmatism associated with delamination-induced extension. Minor Devonian magmatism (in the region of study) is related to post-closure shortening with transpressional docking of peri-Gondwanan Carolina superterrane. This model is further evaluated through geochemical signature of the igneous rocks as a function of time and tectonic setting.

GEOCHEMICAL SIGNATURE OF IGNEOUS ROCKS

General Discussion

Major and trace element data for igneous rocks provide fundamental insight into the thermal state and composition of source rocks in either the crust or mantle, and act as discriminants for tectonic settings during melting events. We strongly emphasize that many plutonic and volcanic rocks in the study area have been variably metamorphosed and that geochemical data from these igneous rocks are sparse and have been gathered over several decades with varying levels of analytical precision. We recognize the need to be cautious in the use of major elements in metamorphosed igneous rocks but through careful selection of samples and application of filters such as those utilized by Plank and others (2001) the available data provide geochemical constraints on tectonic settings and source regions of the magmas. We interpret the geochemical data within these constraints and, in the following section (1) we emphasize the broad compositional diversity of the five groups of igneous rocks through the use of averages for data from published sources to highlight both age and spatially based differences (table 3); and (2) we describe geochemical characteristics of selected plutons (with adequate modern chemical data) within an age group to emphasize differences in magma generation processes within the proposed thermo-tectonic stages. All rare earth and primitive mantle normalization values are from Sun and McDonough (1989).

Major Elements

In general, the plutons reveal a range in modal (Sinha and others, 1980, 1989) and normative compositions (fig. 6) reflecting either differences in source compositions or derivation from similar sources but with varying degrees of partial melting, mixing, or fractionation. The felsic Port Deposit and Rolling Mill plutons, representing Group I, exhibit trondhjemitic affinities and plot within low-K and borderline medium-K suites (fig. 7), as defined by Le Maitre (1989). Volcanic rocks of Group I are dominantly low-K and broadly characterize the arc as a low-K magmatic suite with tholeiitic affinities (Plank and others, 2001). Group II plutons are dominated by metaluminous tonalities although the temporally related Occoquan and Dalecarlia plutons are strongly peraluminous (Seiders and others, 1975; Drake and Fleming, 1994). These plutons commonly represent medium-K suites with the exception of Dalecarlia, which belongs to a high-K suite. All Group III plutons are granodiorites, except for Lahore and Melrose plutons, which are classified as monzonites. The plutons range in affinity from high-K to shoshonitic (Melrose and Lahore) and essentially mimic the medium- to high-K affinity (calc-alkaline series) of the Milton belt volcanic rocks (fig. 7) of similar age reported by Coler and others (2000). Group IV felsic plutons range in normative composition from tonalite to granodiorite with affinities that span from low-K to shoshonitic. Group IV mafic plutons are transitional high-K to borderline shoshonitic with the exception of the Bringhurst pluton, which appears to have been derived from a depleted mantle source. Group V plutons are granodiorite or granite with a high-K affinity. In general younger plutons are more felsic, although the spatially bimodal nature of Group IV plutons provides a window into the nature of the rifted margin discussed later.

Trace Elements

Trace element abundances generally provide insight into processes and tectonic settings responsible for the observed variations in igneous rocks (for example Pearce, 1996; Draut and others, 2009). Such data when, coupled with isotope measurements provide constraints on the sources of the magmas, and provide a useful constraint on thermal changes associated with changing tectonic settings. As very limited isotopic data exist in the region of study, we use a well-studied example from each group to highlight the differences between the proposed groups of igneous rocks.

Group I.—Plutons and volcanic rocks in this group have been extensively modeled as an association of rocks developed within a continental-arc setting (Southwick, 1969; Hanan, ms, 1980; Pavlides, 1981; Barringer, ms, 1983; Hanan and Sinha, 1989; Higgins, 1990; Pavlides and others, 1994; Aleinikoff and others, 2006; Smith and Barnes, 2008) and more specifically within a suprasubduction zone (Plank and others, 2001). These volcanic and plutonic rocks are compositionally bimodal, show both boninitic and tholeiitic trends (Hanan and Sinha, 1989; Plank and others, 2001; Rooney and others, 2006), and are dominantly low-K tholeiites (fig. 7). The largest mafic plutonic complex within this group is the Baltimore mafic complex, which is a layered sub-arc complex (Hanan and Sinha, 1989) where basal dunite and chromitite grade upward through lherzolite and websterite to hypersthene gabbro and quartz gabbro (Hopson, 1964; Crowley, 1976; Hanan, ms, 1980). Although the complex has been variably metamorphosed, major element data are coherent and reveal that the rocks are low-K tholeiites (Hanan and Sinha, 1989), but also show boninitic affinities (Smith and Barnes, 1994; Rooney and others, 2006). Trace element data confirm both types of associations, very similar to the Wilmington Complex in Delaware (Wilmington Complex) as described by Plank and others (2001). Nd and Sr isotopes provide evidence of significant crustal contamination. ε_{Nd} and ε_{Sr} at 490 Ma range from +0.4 to −6.4 and +8 to +127, respectively, suggesting interaction of the magmas with a continental lithosphere (Shaw and Wasserburg, 1984; Hanan and Sinha, 1989; Sinha and others, 1997; Rooney and others, 2006). In contrast to the Baltimore mafic complex, the chemically evolved Port Deposit pluton is a medium-grained, foliated, high silica tonalite gneiss (Lesser, ms, 1982; Higgins, 1990). It is light rare earth enriched with prominent negative Eu, Ti, and Nb anomalies. ε_{Nd} ranges from −2.9 to −4 (Hammarstrom and others, 1995), whereas ε_{Sr} ranges from +60 to +80 (Lesser, ms, 1982). The data are consistent with the emplacement of the pluton in a continental-arc environment similar to the suggested tectonic setting for the Baltimore mafic complex.

In primitive mantle normalized multi-element diagram, gabbros from the Baltimore mafic complex tholeiitic suite are very similar to volcanic rocks from the Chopawamsic, Ta River, and James Run Formations (fig. 8A) where depletion is recognized in both high field strength elements (Nb, Ti) and large ion lithophile elements (Ba) across a broad range in major element compositions. These patterns are very similar to those observed in modern arcs (for example, Rollinson, 1993). Arc affinity is further supported by chondrite normalized rare earth element patterns (fig. 8B) where similarities with modern arc rocks have been presented by Pavlides (1981), Higgins (1990), and Plank and others (2001). Relatively low normalized La/Lu ratios are relatively low (average of 1.4) coupled with flat HREE patterns suggest magma formation in a garnet-free low pressure environment. Wilmington Complex (Group I of Plank and others, 2001) and Baltimore Gabbro (Rooney and others, 2006) boninites contain very low REE abundances, slight positive Eu anomalies and low TiO_2 values (<0.5 wt %) commonly found in forearc regions (Stern and others, 1991). Group I rocks exhibit a positive correlation between SiO_2 abundance and Th/La and La/Sm ratios suggesting that fractionation could not derive the felsic members from the more mafic compositions. Within basaltic (<55 wt % SiO_2) and felsic (>65 wt % SiO_2)

TABLE 3

Whole rock major and trace element data for plutons in the study area (data have been averaged from published analyses)

BodyName	Arden mafic	Arden felsic	Bear Island	Bringhurst	Buckingham mafic	Buckingham felsic
Age in Ma	434	434	465	430	431	431
Plot ID	1M	1F	2	3	4M	4F
Reference ID	1	1	2	3	4	4
Major element						
SIO_2	55.99	66.27	73.75	48.87	51.61	62.90
TIO_2	1.31	0.70	0.11	2.00	0.70	0.38
AL_2O_3	18.69	16.03	15.20	15.74	9.34	15.99
FeO*	7.00	3.98	1.10	11.44	8.68	4.04
CaO	7.34	4.23	1.24	10.34	13.44	4.98
MgO	3.35	1.70	0.26	7.55	12.22	3.09
MnO	0.12	0.08	0.07	0.24	0.19	0.09
K_2O	0.92	2.42	2.45	0.24	0.39	2.99
Na_2O	4.22	3.77	4.49	2.47	0.75	3.60
P_2O_5	0.39	0.21	0.12	0.34	0.10	0.14
LOI			0.18		1.71	1.30
H_2O^+			0.63			
H_2O^-			0.20			
Total	99.34	99.39	98.94	99.23	99.13	99.49
Trace element						
Sc	18.3	11.7	8.0	33.0	75.0	14.0
V	143.3	91.0	26.0	373.0	237.0	104.0
Cr	25.3	17.8	19.0	140.0	1240.0	100.0
Co			20.5		52.0	57.0
Ni	19.0	11.9	7.0	58.0	97.0	32.0
Cu	70.7	29.9	8.5	19.0	20.0	0.0
Zn			40.3	105.0	34.0	0.0
Ga			16.0		13.0	18.5
Rb	1.6	51.6	127.7	9.5	5.0	81.5
Sr	398.0	267.1	99.8	308.0	237.0	878.0
Y			14.7	34.0	32.0	13.5
Zr	330.3	255.4	55.5	127.0	62.0	141.0
Nb			20.3	6.0	6.0	7.0
Cs			5.9		0.0	1.0
Ba	619.3	897.3	248.0	118.0	60.0	1390.0
La			12.9	11.7	16.1	23.4
Ce			23.9	32.0	45.7	45.7
Nd			11.6	21.0	25.9	18.8
Sm			2.6	5.4	5.5	3.6
Eu			0.8	1.9	1.3	0.9
Gd			2.4		5.3	3.0
Tb			0.5	1.0	0.9	0.5
Dy			2.9		5.1	2.3
Ho			0.6		1.0	0.5
Er			2.0		2.9	1.2
Tm			0.3		0.5	0.2
Yb			2.0	3.6	3.1	1.3
Lu			0.3	0.5	0.5	0.2
Hf			2.5	3.3	2.2	3.9
Pb			6.0		6.0	29.0
Th			3.3	0.3	0.9	8.0
U			1.1	0.1	1.8	5.3

TABLE 3
(continued)

BodyName	Carysbrook	Columbia	Dalecarlia	Dale City	Diana Mills	Ellicott City
Age in Ma	444	459	465	459	438	363
Plot ID	5	6	7	8	9	10
Reference ID	5	6	7	8	9	10
Major element						
SIO_2	67.51	72.85	72.81	58.80	48.57	65.28
TIO_2	0.45	0.18	0.26	0.59	0.63	0.52
AL_2O_3	15.44	13.81	14.22	14.40	17.06	16.26
FeO*	3.15	2.55	2.01	6.66	7.54	3.32
CaO	2.87	3.44	1.32	5.90	9.94	3.41
MgO	1.77	0.63	0.74	6.23	8.40	1.76
MnO	0.06	0.05	0.04	0.16	0.13	0.06
K_2O	2.99	2.01	3.57	3.13	1.23	3.61
Na_2O	3.82	3.33	3.03	2.27	2.92	3.41
P_2O_5	0.17	0.05	0.14	0.15	0.30	0.23
LOI	1.67	0.56	0.67		2.59	
H_2O^+		0.54	0.81	1.27		0.75
H_2O^-		0.11	0.17	0.12		
Total	99.89	99.43	98.22	98.29	99.29	97.88
Trace element						
Sc	9.0	9.0	5.5		28.5	7.6
V	75.5	33.0			207.0	65.0
Cr	26.5		13.1		354.5	24.4
Co	43.0	52.0	4.9		40.0	10.2
Ni			8.1		141.5	19.6
Cu	12.0		11.5			17.5
Zn			21.5			60.6
Ga	17.5	11.0			19.5	
Rb	104.0	57.0	107.4		28.0	108.2
Sr	419.0	77.2	127.4		1069.3	818.0
Y	14.0	9.0	64.0		25.5	10.0
Zr	136.0	83.0	175.3		116.0	218.8
Nb	11.5	4.0	31.0		5.0	7.8
Cs	4.3	1.8	3.1		0.1	1.6
Ba	1225.0	394.9	295.1		726.6	1755.0
La	34.9	14.3	22.8		34.7	79.3
Ce	69.5	27.7	51.1		71.4	137.8
Nd	23.8	8.9	21.0		34.5	47.2
Sm	3.8	1.5	4.9		6.6	7.2
Eu	0.9	0.3	0.7		1.6	1.4
Gd	3.1	1.4			5.7	
Tb	0.5	0.2	0.8		0.8	0.5
Dy	2.3	1.3			4.4	
Ho	0.5	0.3			0.9	
Er	1.2	0.9			2.2	
Tm	0.2	0.2			0.3	
Yb	1.2	1.1	3.0		2.1	1.1
Lu	0.2	0.2	1.0		0.3	0.1
Hf	3.4	2.3	5.4		3.4	5.3
Pb	20.0	11.0			9.5	24.3
Th	8.2	2.5	7.5		4.7	22.5
U	2.8	1.2	1.7		1.1	2.7

Table 3

(continued)

BodyName	Ellisville	Falls Church	Georgetown mafic	Georgetown felsic	Georgetown A	Green Springs
Age in Ma	441	469	472	472	472	432
Plot ID	11	12	13M	13F	13A	14
Reference ID	11	12	13	13	this paper	14
Major element						
SIO_2	68.76	63.60	55.65	65.28	66.68	60.68
TIO_2	0.36	0.67	0.53	0.50	0.95	0.47
AL_2O_3	15.47	14.15	15.58	14.23	12.19	15.66
FeO*	2.77	6.32	8.00	5.66	6.09	4.71
CaO	3.41	5.35	7.65	4.86	1.93	5.66
MgO	1.09	3.35	6.94	3.16	1.01	3.67
MnO	0.03	0.10	0.16	0.11	0.07	0.09
K_2O	3.14	1.75	1.00	1.72	3.85	2.94
Na_2O	3.38	2.05	1.88	2.39	3.05	3.48
P_2O_5	0.14	0.15	0.11	0.11	0.46	0.33
LOI	1.01	1.32	1.77	1.19	1.87	1.19
H_2O^+	0.73	1.10	1.64	1.06		
H_2O^-	0.31	0.22	0.13	0.17		
Total	99.57	98.80	99.25	99.19	98.15	98.88
Trace element						
Sc	6.1				16	15.6
V	46.0				27	107.6
Cr	16.4		318.7	92.0	58	95.4
Co	9.5				37	39.3
Ni			105.3	25.0	5	42.8
Cu	34.0		50.7	14.0	5	45.3
Zn	44.9		80.7	66.0	141	55.5
Ga	20.0				26	16.7
Rb	107.9		42.0	93.0	119	71.9
Sr	442.2		148.7	156.0	200	1611.4
Y	6.0		16.0	25.0	36	17.4
Zr	157.8		94.7	136.0	917	200.3
Nb	9.0		17.0	17.0	15	8.3
Cs	1.9					0.6
Ba	791.6		228.7	349.0	1730	1952.9
La	32.9		10.3	30.0	59	47.2
Ce	62.8				122	92.7
Nd	21.2				70	41.5
Sm	3.0				14	7.8
Eu	0.8				4.81	2.1
Gd	3.1				9.9	6.0
Tb	0.3				1.6	0.7
Dy	1.1				8.2	3.4
Ho	0.2				1.5	0.6
Er	0.5				4.1	1.5
Tm	0.1				0.55	0.2
Yb	0.7				3.4	1.4
Lu	0.1				0.48	0.2
Hf	3.8				21	5.2
Pb	21.0				30	21.1
Th	12.0				1.9	14.5
U	3.0				0.4	5.1

Table 3

(continued)

BodyName	Guilford	Gunpowder	Kensington	Kensington	Kensington	Kensington
Age in Ma	362	426	460	460	460	460
Plot ID	15	16	17	17	17	17
Reference ID	15	16	KS-3 this paper	KS-4this paper	KS-9 this paper	17
Major element						
SIO_2	73.85	71.65	68.38	70.93	56.51	64.85
TIO_2	0.11	0.25	0.30	0.26	0.64	0.40
AL_2O_3	15.36	14.39	14.38	13.89	14.29	14.92
FeO*	1.17	1.81	3.48	2.96	8.06	4.72
CaO	1.27	1.23	2.64	2.26	6.47	4.63
MgO	0.26	0.40	2.62	2.28	8.65	3.35
MnO	0.04	0.03	0.08	0.08	0.15	0.11
K_2O	5.01	5.35	2.94	3.44	1.21	2.29
Na_2O	3.90	3.07	2.65	2.88	2.00	2.55
P_2O_5	0.06	0.13	0.07	0.11	0.12	0.15
LOI	0.77	1.26	1.62	1.19	1.88	1.54
H_2O^+	0.46					1.32
H_2O^-	0.10					0.21
Total	101.12	99.56	99.16	100.28	99.98	99.50
Trace element						
Sc	3.0	3.2	15.0	15.0	33.0	21.0
V	14.0	14.3	65.0	56.0	181.0	100.7
Cr			56.0	43.0	487.0	195.3
Co	48.5	66.2	47.0	65.0	50.0	54.0
Ni			80.0	25.0	252.0	119.0
Cu		18.7		12.0	56.0	34.0
Zn	50.0	65.9	50.0	40.0	84.0	58.0
Ga	23.0	20.1	16.0	16.0	15.0	15.7
Rb	198.4	155.9	115.0	129.0	50.0	98.0
Sr	204.5	166.1	129.0	121.0	164.0	138.0
Y	15.0	11.9	22.0	21.0	14.0	19.0
Zr	118.5	149.4	106.0	96.0	75.0	92.3
Nb	19.0	13.8	9.0	11.0	7.0	9.0
Cs	5.2	1.4	5.0	7.2	3.7	5.3
Ba	799.0	1051.8	386.0	581.0	227.0	398.0
La	33.5	61.8	18.0	25.0	12.0	18.3
Ce	55.7	117.9	41.0	51.0	24.0	38.7
Nd	21.0	47.2	17.0	23.0	13.0	17.7
Sm	3.9	7.7	4.2	4.9	3.1	4.1
Eu	0.9	1.2	0.9	1.0	0.7	0.9
Gd	3.1	5.5	3.9	3.8	2.5	3.4
Tb	0.5	0.7	0.7	0.6	0.5	0.6
Dy	2.4	2.5	4.2	3.5	2.7	3.5
Ho	0.4	0.4	0.8	0.6	0.5	0.6
Er	1.2	1.0	2.2	1.8	1.5	1.8
Tm	0.2	0.1	0.4	0.3	0.2	0.3
Yb	1.1	0.6	2.2	1.6	1.5	1.8
Lu	0.2	0.1	0.3	0.2	0.2	0.3
Hf	3.4	4.1	3.0	2.3	2.0	2.4
Pb	19.0	28.0	62.0	52.0	27.0	47.0
Th	15.3	23.1	6.6	11.0	3.5	7.0
U	6.2	2.2	3.4	3.0	0.9	2.4

Table 3
(continued)

BodyName	Lahore	Leatherwood	Melrose	Norbeck	Occaquon	Poore Creek
Age in Ma	446	455	443	460	472	432
Plot ID	18	19	20	21	22	23
Reference ID	18	19	20	21	22	23
Major element						
SIO_2	54.54	71.32	60.88	57.58	72.80	67.89
TIO_2	0.75	0.38	0.86	0.62	0.39	0.34
AL_2O_3	15.34	13.97	18.14	14.60	13.74	16.64
FeO*	6.75	2.25	4.02	8.29	2.57	2.40
CaO	7.01	1.65	2.94	6.20	2.19	3.09
MgO	4.98	0.45	1.34	7.38	0.81	1.32
MnO	0.13	0.02	0.09	0.16	0.07	0.04
K_2O	4.77	4.77	4.61	1.22	2.87	2.65
Na_2O	2.74	3.38	4.62	1.90	2.86	3.87
P_2O_5	0.62	0.09	0.26	0.13	0.09	0.14
LOI		1.38	1.58	2.00		1.26
H_2O^+	4.51	0.38		1.90	0.84	
H_2O^-	0.27	1.17		0.06	0.18	
Total	97.62	99.67	99.34	99.06	98.34	99.63
Trace element						
Sc	23.5	3.0	10.0	31.0		5.0
V		35.0	57.0	181.0		38.0
Cr	129.4			459.0		43.0
Co	25.3	46.5	17.0	45.0		32.0
Ni				107.0		29.0
Cu				36.0		11.0
Zn	87.5			95.0		
Ga		17.0	22.0	16.0		22.0
Rb	235.2	83.3	87.0	48.0		129.0
Sr	1338.4	199.3	524.2	122.0		1040.0
Y	19.4	13.0	33.0	14.0		8.0
Zr	205.8	228.6	511.0	82.0		173.0
Nb	11.9	9.5	34.0	4.0		8.0
Cs	1.8	0.1	0.5	2.5		1.4
Ba	1913.9	1515.0	2310.0	187.0		1340.0
La	66.3	62.3	80.4	17.0		22.6
Ce	126.0	113.5	158.0	33.0		25.1
Nd	64.3	37.8	60.0	15.0		16.5
Sm	11.3	5.4	9.7	3.2		2.8
Eu	2.8	2.1	2.6	0.9		0.7
Gd	9.6	4.3	8.2	2.7		2.4
Tb	1.1	0.5	1.2	0.5		0.3
Dy		2.5	6.0	2.8		1.4
Ho		0.5	1.2	0.5		0.3
Er		1.1	2.9	1.6		0.6
Tm	0.3	0.2	0.4	0.3		0.1
Yb	2.0	1.0	2.6	1.6		0.6
Lu	0.3	0.2	0.4	0.2		0.1
Hf	6.0	8.4	11.1	2.3		4.5
Pb		19.0	16.0	19.0		47.0
Th	17.1	5.8	5.7	7.4		7.9
U	3.6	0.7	1.3	0.8		2.4

TABLE 3
(continued)

BodyName	Port Deposit	Rich Acres	Rolling Mill	Springfield	Woodstock	BG boninite	BG tholeiite
Age in Ma	477	431		423	381	489	489
Plot ID	24	25	26	27	28	29	30
Reference ID	24	25	26	27	28	29	30
Major element							
SIO_2	73.70	51.29	77.65	69.40	70.62	47.61	51.64
TIO_2	0.25	1.19		0.56	0.61	0.60	0.57
AL_2O_3	13.41	17.53	12.05	14.73	14.94	14.71	13.76
FeO*	2.26	7.56	2.70	3.32	2.14	9.82	8.79
CaO	2.25	8.33	1.85	2.41	2.29	12.57	9.62
MgO	0.58	6.06	0.19	0.99	1.45	11.38	9.96
MnO	0.07	0.14	0.08	0.06	0.16	0.19	0.29
K_2O	1.61	1.76	0.55	4.25	4.15	0.02	0.32
Na_2O	4.39	3.45	4.00	3.25	3.27	0.68	1.49
P_2O_5	0.07	0.33	0.49	0.17	0.14	0.05	0.09
LOI	0.84	1.45	0.52	0.63	0.98	1.15	2.10
H_2O^+	0.70	0.38	0.47		0.62		
H_2O^-	0.06	1.13	0.10		0.03		
Total	98.73	99.08	100.06	99.66	99.85	98.60	98.62
Trace element							
Sc	11.7	23.0		11.3	4.3	50.5	45.5
V	15.7	145.7		52.6	32.0	345.3	222.5
Cr	73.0	252.0		16.9	11.0	296.6	610.1
Co	57.7	54.0		25.9	50.8	95.7	50.4
Ni	75.0	71.7		4.1		87.5	130.6
Cu	11.0	40.0		27.2		44.0	66.9
Zn	49.7			59.7	36.3	106.6	170.7
Ga	13.3	18.0		17.8	19.3	14.8	14.5
Rb	55.0	31.8		138.9	74.7	2.1	9.6
Sr	95.7	469.7		151.7	607.3	145.6	126.1
Y	22.0	22.3		27.0	7.0	7.9	13.8
Zr	93.6	309.1		239.4	127.2	17.4	80.6
Nb	10.0	19.0		11.7	5.7	3.6	3.9
Cs	5.2	0.5		3.8	1.4	0.2	0.4
Ba	301.4	627.4		778.7	1281.3	26.9	66.0
La	20.3	39.0		56.1	43.2	2.1	8.6
Ce	32.6	77.6		110.6	84.4	5.1	19.4
Nd	17.7	33.2		49.1	29.3	3.9	11.4
Sm	3.8	6.0		9.3	4.0	1.2	2.7
Eu	0.8	1.8		1.7	1.1	0.6	0.8
Gd	3.5	5.3		8.0	2.7	1.4	2.7
Tb	0.6	0.8		1.3	0.2	0.3	0.4
Dy	4.0	4.0		7.2	1.1	1.6	2.7
Ho	0.8	0.8		1.4	0.2	0.3	0.6
Er	2.5	1.9		4.0	0.7	0.9	1.5
Tm	0.4	0.3		0.6	0.1	0.1	0.2
Yb	2.5	1.8		3.5	0.6	0.8	1.4
Lu	0.4	0.3		0.6	0.1	0.1	0.2
Hf	3.7	4.6		8.1	3.2	0.6	2.0
Pb	23.7	7.0		21.0	33.7	1.4	4.1
Th	6.1	2.2		14.2	18.1	0.1	1.6
U	1.6	0.8		3.4	4.4	0.0	0.4

Table 3

(continued)

References for individual plutons are: (1) Arden: Srogi and Lutz (1997); (2) Bear Island: Hopson (1964); Drake and Lee (1989); Drake and Froelich (1997); (3) Bringhurst: Plank and others (2001); (4) Buckingham: Wilson (2001); (5) Carysbrook: Wilson (2001); (6) Columbia: Wilson (2001); (7) Dalecarlia: Drake and Fleming (1994); Drake (1998); (8) Dale City: Seiders and others (1975); (9) Diana Mills: Wilson (2001); (10) Ellicott City: Hopson (1964); Hammarstrom and others (1995); (11) Ellisville: Pavlides and others (1994); (12) Falls Church: Drake and Froelich (1986); (13) Georgetown: Hopson (1964); Fleming and others (1994); Drake and Froelich (1997); this article; (14) Green Springs: Wilson (2001); (15) Guilford: Hopson (1964); Sinha (1988); (16) Gunpowder: Sinha (1988); (17) Kensington: Hopson (1964); Fleming and others (1994); this article; (18) Lahore: Pavlides and others (1994); (19) Leatherwood: Ragland and others (1997); Wilson (2001); (20) Melrose: Wilson (2001); (21) Norbeck: Hopson (1964); Drake (1998); (22) Occoquan: Seiders and others (1975); Drake and Froelich (1986); (23) Poore Creek: Wilson (2001); (24) Port Deposit: Lesser (1982); Higgins (1990); Hammarstrom and others (1995); (25) Rich Acres: Ragland and others (1997); Wilson (2001); (26) Rolling Mill: Higgins (1990); (27) Springfield: Becker (1996); (28) Woodstock: Hopson (1964); Sinha (1988); (29 and 30) Baltimore Gabbro: Hanan (1980); Hanan and Sinha (1989); Rooney and others (2006).

compositions, however, there is little variation in the same ratios, suggesting that fractionation could be significant within a given compositional range (see for example, Reagan and others, 2003). Europium anomalies for the felsic volcanic rocks of the Chopawamsic Formation, as well as the Port Deposit pluton, are reflective of plagioclase fractionation.

Estimated thickness of the Wilmington arc crust is approximately 33 km (Plank and others, 2001). If the entire complex represented by Group I rocks is similar in origin, a thinned continental lithosphere is indicated as a substrate for arc magmatism.

Group II.—These plutons are dominantly tonalites and granodiorites that were emplaced during regional deformation and associated faulting interpreted to be the result of the collision of the Early Ordovician arc with the Laurentian margin (Rankin, 1976; Drake and others, 1989; Thomas, 2006; Hibbard and others, 2007; Hatcher, 2010). For example, the Kensington Intrusive Suite has been described by Hopson (1964), Fleming and others (1994), Drake and Froelich (1997), and Drake (1998) as a foliated biotite tonalite and granodiorite with abundant muscovite and microcline in deformed shear zones. The pluton is considered to have been intruded into a developing zone of high strain in the Sykesville Formation (Rockfish shear zone of Fleming and Drake, 1998) suggesting a synkinematic mode of emplacement. Geochemical data by the same authors, coupled with new geochemical data (this article, table 3) suggest that the pluton ranges in composition from metaluminous to peraluminous, and that with increasing silica content and ductile deformation-enhanced metamorphism has resulted in A/CNK ratios which range from from 0.75 to 1.2. Comparison of FeO (total) versus Al_2O_3 contents (high observed total FeO with less than 16 wt % Al_2O_3) with experimental melting data (Beard and Lofgren, 1991; Beard, 1997) suggests that this pluton was probably formed at low pressures by dehydration melting of low-K amphibolite with no residual garnet (fig. 9). Relatively low chondrite-normalized La/Lu ratios between 5.8 and 12 (fig. 8C) over a broad range of SiO_2 content suggests minimal garnet control and fractionation of plagioclase to cause the observed range in La/Lu ratios. If the pluton is the result of partial melting of an amphibolitic source, the low Sr abundances (<164 ppm) suggest plagioclase as both a restite and fractionating phase as indicated by the average negative Eu anomaly value of 0.7 (fig. 8D). Additional evidence for a relatively low-pressure environment during tonalite emplacement is recognized in the matrix mineral assemblage of the host Sykesville Formation where calculated average pressure-temperature has been estimated to be 5.5 kb and 460 °C (Tamburro, ms, 1986). Other tonalite-granodiorites of this group have major element abundances that are also compatible with dehydration

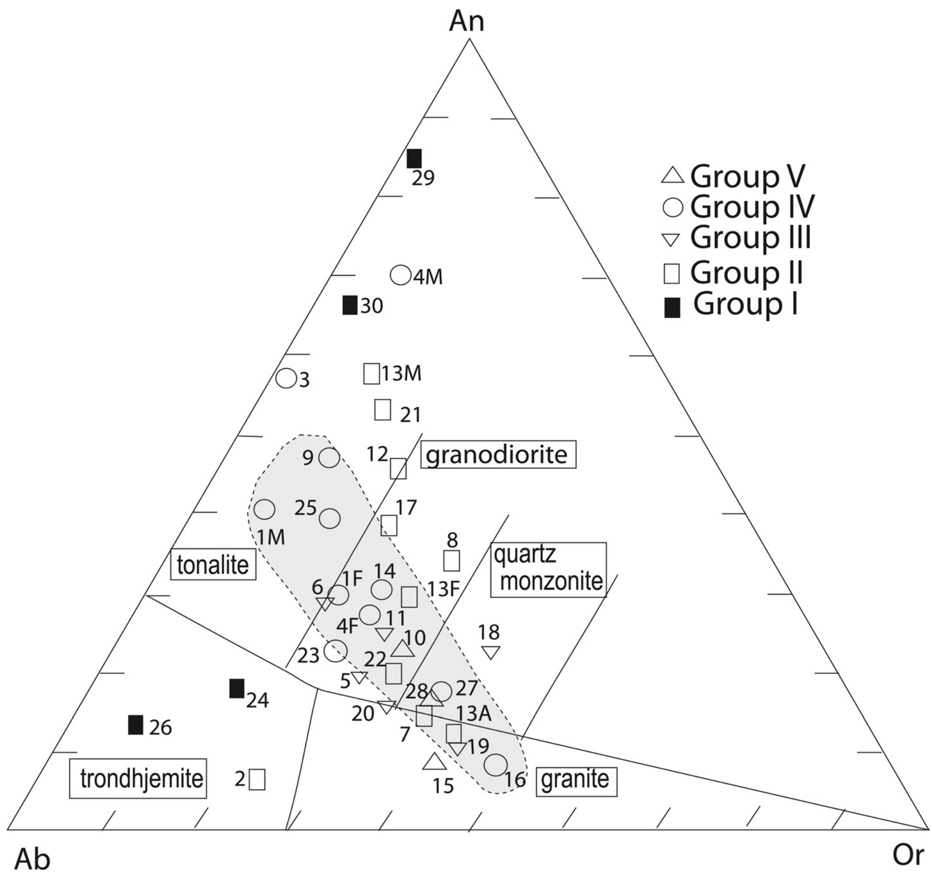

Fig. 6. Normative Ab-An-Or classification diagram of Barker (1979) showing compositional range of plutons in the area of study. Numbers used in the plot refer to plutons listed in table 3. Shaded region highlights the compositional diversity observed for Group IV plutons.

melting with no residual garnet in the source (fig. 9). Other syntectonic plutons (Occoquan, Bear Island, and Dalecarlia) range in composition from tonalite to monzogranite (Seiders and others, 1975; Drake, 1989, 1998), are peraluminous (A/CNK >1.1) and suggest melting of a volcaniclastic source. Primitive mantle normalized trace element data for all plutons in this group, including peraluminous Bear Island and Dalecarlia, exhibit typical arc geochemical signature of negative Nb, P, and Ti anomalies (fig. 8C), and suggesting that these magmas were derived from melting of sources dominated by arc composition protoliths.

Group II plutons have chondrite-normalized La/Lu ratios between 4 to 13; the highest value is from a siliceous phase of the Georgetown pluton the measurable positive Eu anomaly of which suggests a cumulate mineralogy (table 3, this article). The Kensington pluton has a very limited range in composition (shaded field in fig. 8D) and suggests a relatively uniform source involved in melting, accompanied by fractionation. Although the Dalecarlia pluton, including monzogranite and trondjhemite (Drake and Fleming, 1994), shows a decrease in La/Yb ratios as a function of increasing silica content the average La/Yb ratio of 6.2 is very similar to other plutons in this group. Brophy (2008) noted a similar trend with increasing liquid SiO_2 content, if hornblende is a residual phase during melting.

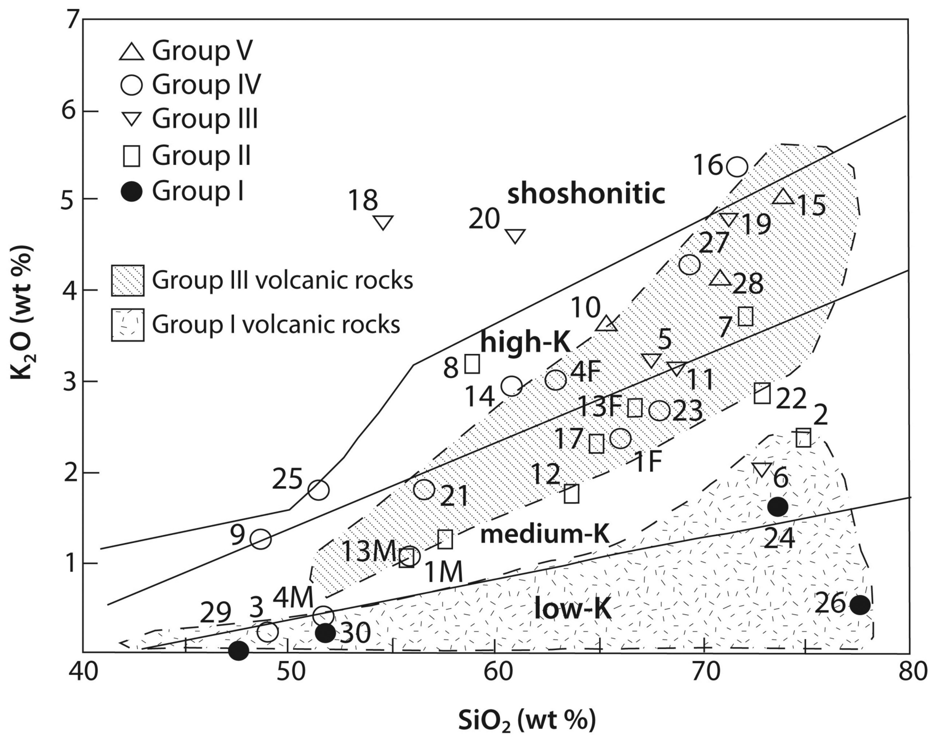

Fig. 7. SiO_2-K_2O classification diagram of Le Maitre (1989) with shoshonitic/high-K boundary from Peccerillo and Taylor (1976). Numbers used in the plot refer to plutons listed in table 3. Group I volcanic rocks are dominantly low-K with tholeiitic affinities, and contrast with Group III volcanic rocks from the Milton Belt that are mostly calc-alkaline with medium-K to high-K affinities. Group II plutons are primarily of medium-K affinity, whereas Group IV and V plutons are mostly of high-K affinity.

Group III.—The plutons in this group, ranging in composition from tonalites to monzonites and granodiorites, were emplaced after regional deformation that is constrained to be older than the 450 Ma Lahore pluton, which intrudes deformed schists of Melange Zone III of Pavlides and others (1994). Farther south, where similar age volcanic rocks of the Milton belt have been preserved, the deformation and metamorphism are related to Neoacadian to Alleghanian orogenesis (Hibbard and others, 1998; Hatcher, 2010), which is also recognized east of the Long Branch thrust in central Virginia (Pavlides and others, 1994). We consider the type example of this group to be the Ellisville pluton, which is dominantly a granodiorite with magmatic epidote and co-existing hornblende and biotite (Pavlides, 1989; Pavlides and others, 1994). The pluton intrudes deformed Mine Run Complex and Chopawamsic Formation volcanic rocks and is chemically homogeneous with calc-alkaline affinities (Pavlides and others, 1994). On the basis of REE modeling and initial $^{87}Sr/^{86}Sr$ ratio of 0.7067, the pluton is considered to have a silicic crustal source (garnet, plagioclase, and amphibole as restites), but with no significant input from mafic magmas (Pavlides and others, 1994). Primitive mantle normalized abundances for Group III rocks are enriched in Th, Ba and Pb suggesting involvement of sediments during magma genesis (Hawkesworth and others, 1991). Chondrite-normalized La/Yb ratios range from 20 to 50 and are negatively correlated with silica content suggesting fractionation of La by removal of a low-silica phase such as biotite or hornblende as suggested by Brophy

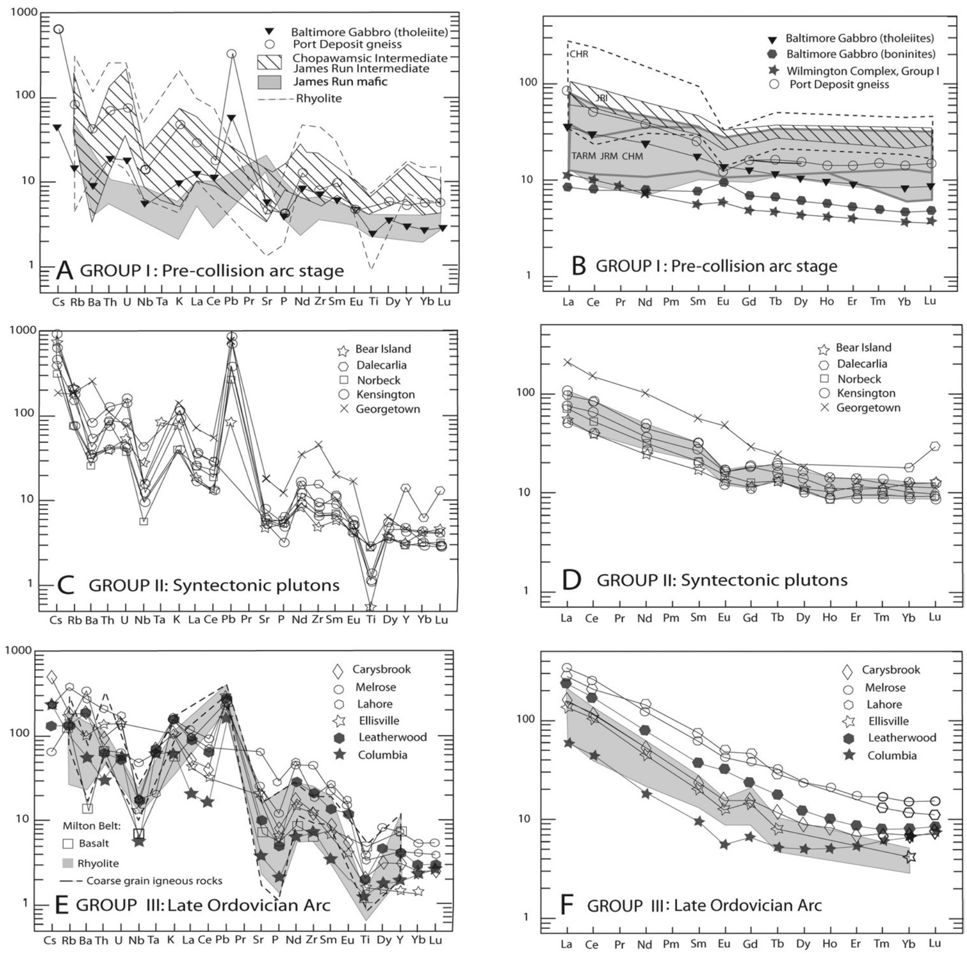

Fig. 8. (A)–(J). Multi-element variation diagram: data normalized to primitive mantle concentrations (left column) and chondrite normalized rare earth (REE) diagram (right column) for Group I through V igneous rocks. Available data have been sorted to emphasize similarities in trace element behavior across a broad range of chemical compositions. REE diagrams (B), (D), (F), (H), (J) show ranges in values across major element compositions based on silica content, where mafics are <55 wt %, intermediate range from 56–69 wt % and felsics are >70 wt %. TARM = Ta River mafics; JRM = James Run mafics; CHM = Chopawamsic mafics; JRI = James Run intermediate; CHR = Chopawamsic felsics (rhyolites). Data from Coler and others (2000) are shown as shaded area in (E). All samples from Ellisville pluton are included in shaded area (F). No REE data from volcanic rocks of Group III are available; note the positive Gd anomaly of Group III, which is distinctly different from Group I igneous rocks as shown in (B).

(2008). Other plutons in Group III also have La/Yb ratios that are similar to Ellisville pluton (fig. 8F), with the exception of Lahore and Melrose monzonitic plutons which have a lower ratio of ~20 and perhaps reflect shoshonitic affinities (fig. 7). The Lahore pluton with an initial Sr isotopic composition of 0.7046 has been modeled as a partial melt of continental lithosphere (Pavlides and others, 1994). The positive Gd anomaly coupled with a negative Eu anomaly (range 0.7 to 0.85 for all plutons except Leatherwood which has a positive anomaly of 1.3) is a very distinctive geochemical marker of this group (fig. 8F).

These observations, combined with high-K_2O/Na_2O (0.6 to 1.8) for the plutons, suggests that remelting of mantle-derived magmas emplaced at mid-crustal levels

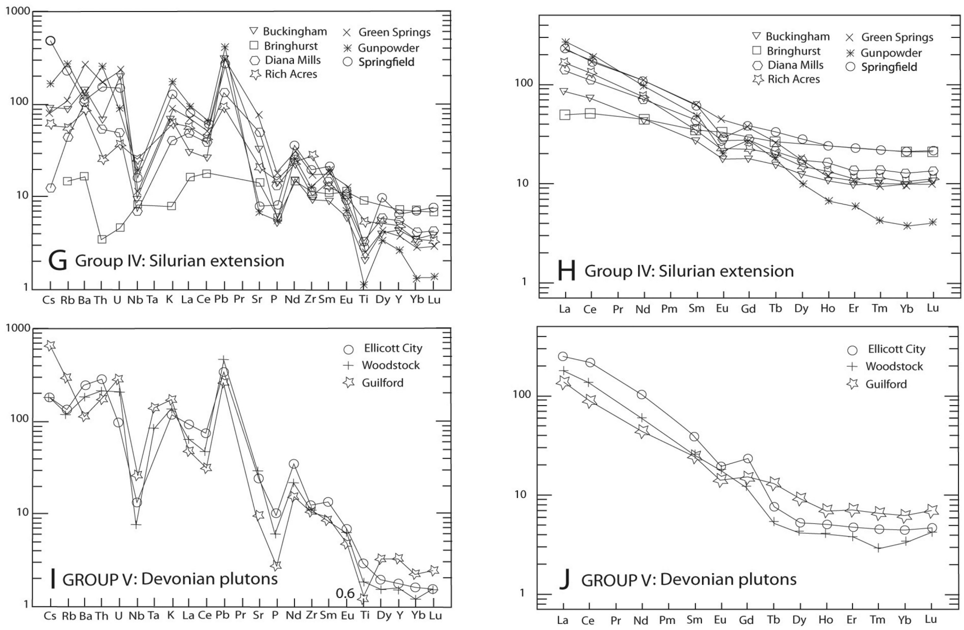

Fig. 8 (continued)

(Vogel and others, 2006; Deering and others, 2007) could support the observations for the geochemical properties of this group. The high alkali content of the temporally equivalent volcanic rocks of the Milton belt (fig. 7) suggests the availability of intermediate to high-K basalt derived plutons during the construction of the arc. Calculated ε_{Nd} values range from 3.7 to -7.2 for Milton belt volcanic rocks (Wortman and others, 1996; Coler and others, 2000) and are only broadly similar to values for Group I igneous rocks where the highest positive ε_{Nd} has a value of $+0.4$ (Shaw and Wasserburg, 1984; Rooney and others, 2006). The data however, underscore the need to recognize that isotopic similarities are probably the result of emplacement of both magma series (Groups I and III) through arc-related processes within either the same or similar continental lithosphere, albeit separated in time.

Group IV.—These plutons are compositionally diverse (see fig. 6) and are dominated by mafic compositions in the southern and central part of the study area, whereas the northern part is dominated by felsic compositions. We consider the type example of felsic magmatism in this group to be the Gunpowder pluton (fig. 4), which is a high SiO_2 (72-75 wt %) peraluminous granite (Hammarstrom and others, 1995). The trace element patterns, however, mimic those of arc-derived magmas (fig. 8G) and can only be the result of remelting of older felsic volcanic protoliths of Group I that are common in the area. Sr isotopic initial ratio of 0.709 would support a model of remelting earlier arc-dominated volcaniclastic rocks as the initial Sr isotopic ratio for the felsic James Run Formation (Group I) has a similar value of 0.708 (Lesser, ms, 1982). Strong depletion in HREE (fig. 8H) reflects extraction of garnet leading to an average normalized La/Lu ratio of 65. The Springfield pluton has a similar trace element signature and initial Sr isotopic ratio as the Gunpowder pluton, even though it is a well-documented epidote-bearing granodiorite (Becker, ms, 1996). Unlike the Gunpowder granite, the lower La/Lu ratio of 10.5 for the Springfield pluton suggests limited garnet in the restite phase. In contrast to these two bodies, the Ardentown

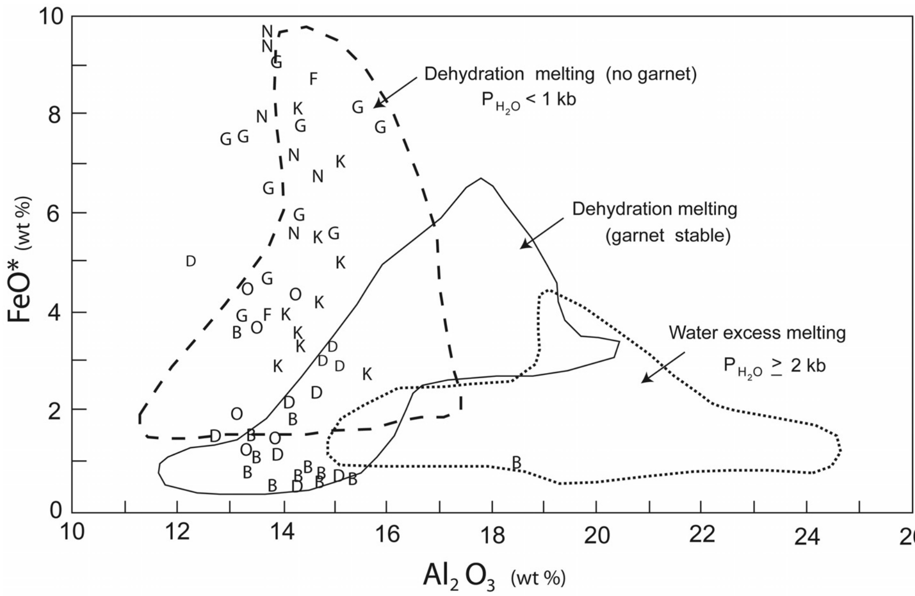

Fig. 9. FeO* (total) versus Al_2O_3 comparison of tonalitic compositions produced by experimental melting of amphibolites at various conditions (from Beard, 1997), with observed compositional ranges for plutons of Group II. B = Bear Island; D = Dalecarlia; F = Falls Church; G = Georgetown; K = Kensington; N = Norbeck. Samples with high SiO_2 and low FeO (total) content from Bear Island and Dalecarlia plutons are shown for reference only, and are unlikely to be related to dehydration melting in garnet stable field. Data sources are given in table 3.

complex is composed of comagmatic pyroxene-bearing quartz diorite, granodiorite, and granite that co-existed with contemporaneous basaltic magmas at depths of 17 to 25 km (Srogi and Lutz, 1997). Co-existing basaltic and felsic magmas support the likelihood of extensional structures facilitating the emplacement of mafic magmas into an overthickened crust, resulting in anatexis and co-mingling of liquids. Neodymium and strontium isotopic data from a gabbronorite from the Ardentown complex (ε_{Nd} of +3.3; ε_{Sr} of +1.2) suggests derivation from a mantle source with limited crustal contamination (Srogi, ms, 1988). Farther south, the Rich Acres gabbroic suite can be considered as a type example of mafic magmatism associated with this group. It is comprised of an alkali-rich diorite, as well as norite and quartz gabbro (Conley and Henika, 1973; Ragland and others, 1997). Geochemical data suggest that the Rich Acres Suite is dominantly cogenetic, and the geochemical trends are the result of clinopyroxene fractionation and interaction with interstitial liquid (Ragland and others, 1997). The alkaline nature of Rich Acres pluton, for example based on high Na + K contents for a range of SiO_2 values yield volcanic equivalent compositions that are mostly trachybasalt and trachyandesite of Le Bas and others (1986) and commonly associated with an extensional environment (Crawford and others, 1997). Based on Nb-Zr-Y abundances these rocks are compatible with emplacement as within plate basalts in a tensional setting (Meschede, 1986). Calculated initial strontium isotopic ratio of 0.7046 similar to the Arden gabbronorite suggests minimal interaction with an evolved crust (Wilson, ms, 2001). Other mafic rocks of this group also have trace element signatures similar to the plutons described earlier with pronounced depletion in Nb, P, and Ti (fig. 8G). REE data (fig. 8H) exhibit a range in La/Lu ratios (range from 2.3-24.3): the Bringhurst gabbro has the lowest La/Lu value. The close abundance pattern for the heavy REE for the mafic plutons suggests that fractionation of clinopyroxene, as was proposed for the Rich Acres gabbro (Ragland and others, 1997), is perhaps the dominant mechanism for the abundance of HREE.

Group V.—These plutons are of small areal extent in the region of study, and have trace element patterns similar to those of all other groups (figs. 8I and 8J). Although compositionally diverse, the REE patterns yield normalized La/Lu ratios that range from 20 to 58; the highest value recorded is from Ellicott City pluton (table 3). This pluton is compositionally zoned from granodiorite at the margin to porphyritic granite in the core. All facies of the pluton have primary epidote, which commonly coexists with hornblende (Hopson, 1964). Geochemical data show that the pluton is metaluminous with I-type characteristics (Hammarstrom and others, 1995). The pluton shows unusual enrichment in Sr (600 to 900 ppm) with no measurable Eu anomaly (Hammarstrom and others, 1995) suggesting that the high Sr content probably reflects source region compositions. Although Guilford and Woodstock plutons are classified as monzonites (Hopson, 1964), they have similar geochemical signatures similar to those of Ellicott City granodiorite (figs. 8I and 8J) suggesting very similar sources for magma generation.

INTERPRETATION: GEOCHEMICAL SIMILARITIES AND DIFFERENCES BETWEEN GROUPS

Multi-element diagrams, especially primitive mantle-normalized element abundances and chondrite-normalized rare earth patterns provide a template to compare and contrast sources and petrogenetic processes between the igneous rocks representing the five age groups. In primitive mantle-normalized diagrams the most striking pattern for all plutons in the study area regardless of age, is the depleted signature for Nb, P, and Ti with enrichment in Pb (figs. 8A, 8C, 8E, 8G, and 8I). These are patterns observed in modern island arcs (Rollinson, 1993) and suggest either subduction-related magmatic activity, or remelting of an older arc crust (see Tarney and Jones, 1994 for discussion of such anomalies in orogenic igneous rocks).

The distinction in alkalinity between Group I and Group III volcanic rocks (fig. 7) is also seen in higher abundances for Ba, Th, and Sr in all Group III rocks, suggesting their formation in an arc system chemically different from that represented by Group I. Assuming fractional crystallization induced differences in Ba and Sr abundances for the felsic rocks in Groups I and III, the differing slopes (shown as bounding boxes in fig. 10A) imply amphibole $\pm$ K-spar control for Group III, and plagioclase $\pm$ biotite control for Group I. We infer these differences to imply compositionally different primary melts for the two groups. We also utilize the magnitude of the Gd anomaly (fig. 10B), in ways similar to the more commonly used Eu anomaly (Rollinson, 1993) to show that in modern arcs Gd anomalies are commonly associated with partial melting of amphibole-rich plutons formed from high-K basalts (Vogel and others, 2006). Gadolinium abundances in igneous rocks are dominated by modal abundance of amphibole, garnet, apatite, and allanite, all of which have high partition coefficients for Gd (Rollinson, 1993). In a partial melting model, the lack of correlation between P and Ce abundances and the magnitude of Gd anomaly precludes apatite and allanite control on the anomaly. Similarly, garnet is also unlikely to control this anomaly as normalized La/Lu ratios do not reveal a positive correlation with the calculated Gd anomaly. Melting of amphibole-bearing intermediate- to high-K basalts (Sisson and others, 2005), however, can readily explain the large positive Gd anomalies, as well as the bulk composition of Group III rocks (fig. 11). The similarity in alkali content of melts produced from intermediate- and high-K basalts and rocks of Group III is striking, and the differences from Group I rocks confirm our suggestion that two very distinctive arc environments are represented by these two groups.

The data from all groups exhibit a range of Ba/Nb ratios (10 to 200); values greater than 100 are represented by mafic rocks of Group IV (except Rich Acres) and two plutons of Group V. These values are similar to those seen in continental-margin

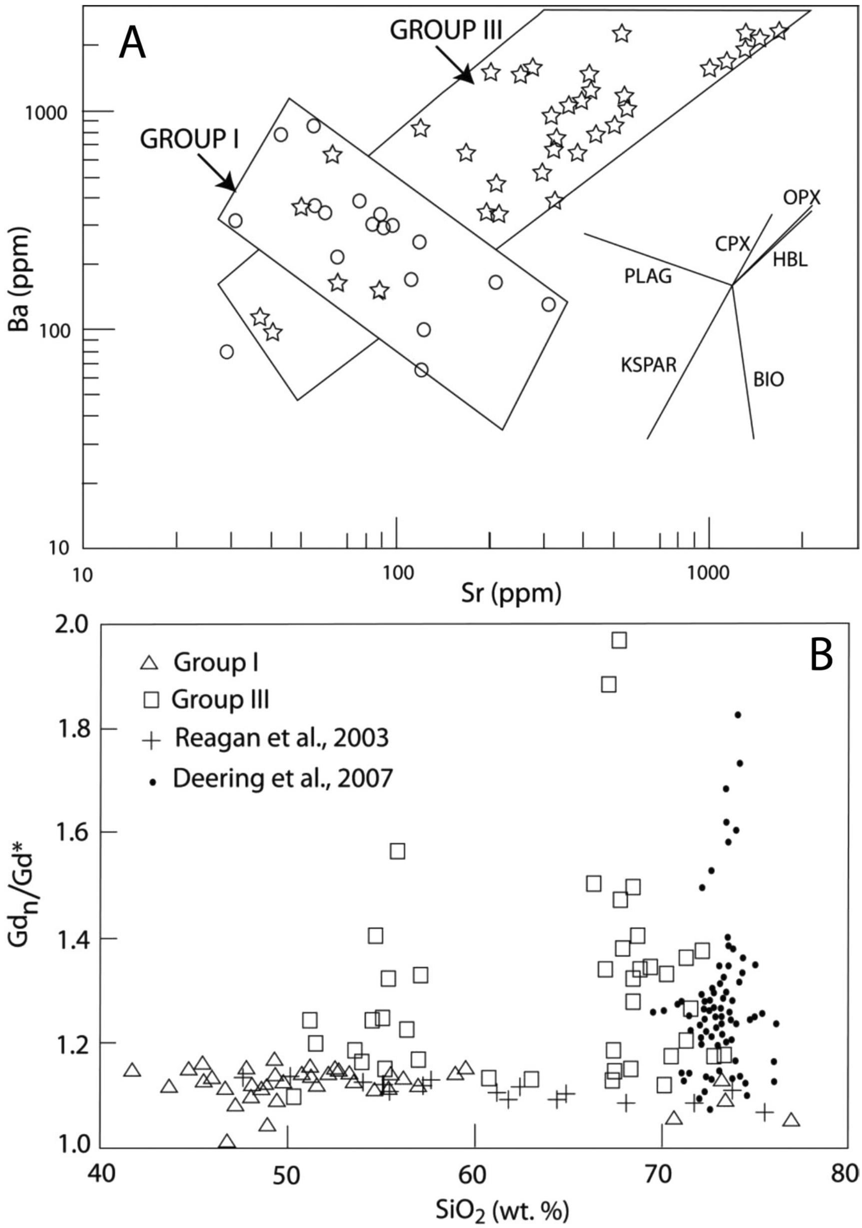

Fig. 10. (A) Sr-Ba abundances for Group I and III rocks show significant differences in fractionating assemblages. Group III rocks are dominated by hornblende accumulation/fractionation, whereas Group I rocks show plagioclase controlled geochemical abundances. Data suggest differences in mineralogies associated with source areas for the two groups. (B) Silica versus Gd anomaly where Gd (n) is measured Gd abundance normalized to primitive mantle values. Gd* is derived from interpolating between Eu* and Tb abundance normalized to primitive mantle. Note that simple fractionation from basalt to rhyolite (Reagan and others, 2003) does not change the Gd anomaly. In contrast partial melting of amphibole bearing basalts or derivatives (Deering and others, 2007) may yield the enrichment observed in Group III samples.

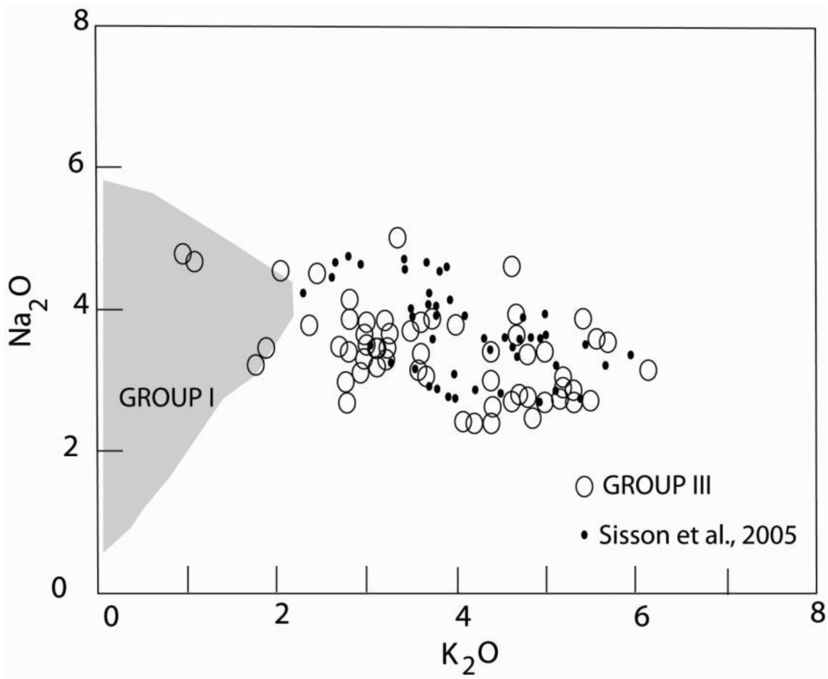

Fig. 11. Measured K_2O and Na_2O abundances from partial melting of intermediate to high-K amphibolites (Sisson and others, 2005). The volcanic and plutonic rocks of Group III are very similar in composition to those observed in experimental melts.

arcs (Pearce, 1982; Weaver and others, 1986) and are weakly but positively correlated with silica values suggesting that differentiation may have increased Ba concentrations. The enrichment in LREE through time to values greater than the average continental crust (Rudnick and Fountain, 1995) suggests fractionation as a mechanism for Groups II, IV, and V plutons. Limited fractionation is also apparent from a negative correlation between TiO_2 and Zr as observed in modern arc systems (Pearce, 1982). Th/Nb versus Y plot shows that all groups have Th/Nb $<$7.4 (primitive mantle ratio) and are within an arc field (Jenner and others, 1991). In rare earth element diagrams, we note that positive Eu anomalies observed in some of the plutons (for example, Columbia and Ellisville from Group III) indicating plagioclase accumulation does not mask the characteristics of arc affinities for this group. This correlation suggests that felsic rocks, such as those for Groups II, IV, and V are likely to have been derived from a crustal source that itself was derived from an arc crust or remelted volcanic materials, an observation similar to one made by Kemp and others (2009) and Cawood and others (2011).

It is interesting to note that three epidote-bearing granodiorites belonging to three different groups (Ellisville: Group III; Springfield: Group IV; and Ellicott City: Group V) have very dissimilar REE patterns. The most HREE depleted body is Ellisville (La/Lu = 35) and the least depleted is Springfield (La/Lu = 11) with Ellicott City at 35. With similar observed mineralogies, partial melting must have been accompanied by significant amphibole and allanite fractionation.

Tectonic discriminant diagrams such as Nb vs. Y or Y + Nb vs. Rb show that all plutons plot within the VAG field of Pearce and others (1984), and only Melrose and

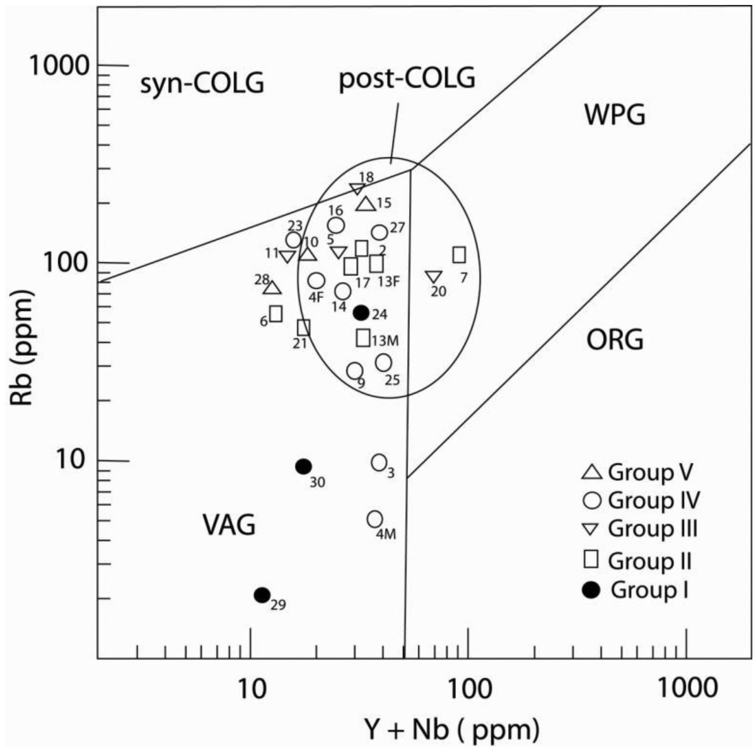

Fig. 12. Tectonic classification diagram of Pearce and others (1984) with post-collisional field adapted from Pearce (1996). VAG = volcanic arc granite; syn-COLG = syn-collisional granite; post-COLG = post collisional granite; WPG = within plate granite; ORG = ocean ridge granite. Numbers refer to plutons listed in table 3.

Dalecarlia plot in the WPG field (fig. 12). Most plutons interpreted to be emplaced in an extensional regime also plot within the post-collisional field (fig. 9).

rifted margin geometry and compositional diversity of silurian (group iv) igneous rocks

Neoproterozoic through Cambrian rifting of eastern North America was accompanied by the deposition of both synrift and passive-margin-shelf sediments (Thomas, 1977, 1993). Accumulations of synrift sediments associated with both lower- and upper-plate rift geometries include complex facies relationships and laterally variable thickness, but are dominated by siliciclastic sediments and mafic volcanic rocks (Thomas, 2006). Thickness distributions are related to the rift-controlled Tennessee and Pennsylvania embayments (fig. 13). The availability of a thick sedimentary succession along a rifted margin to form both the source of fluids and fertile zones for magma genesis, as well as traps for mantle-derived magmas, plays the most critical role in defining the unusual compositional diversity of Silurian magmatism: plutons in the southern part of the region of the proposed extensional setting are mafic, whereas those farther north are bimodal. A key attribute of our model is the recognition that the distribution of fertile sources (metavolcanic and metasedimentary rocks) requires an assessment of the pre-collisional structural and stratigraphic framework for the accumulation of synrift sediments and volcanics and early post-rift sediments. We recognize no significant change in the structure along strike of the rifted margin from

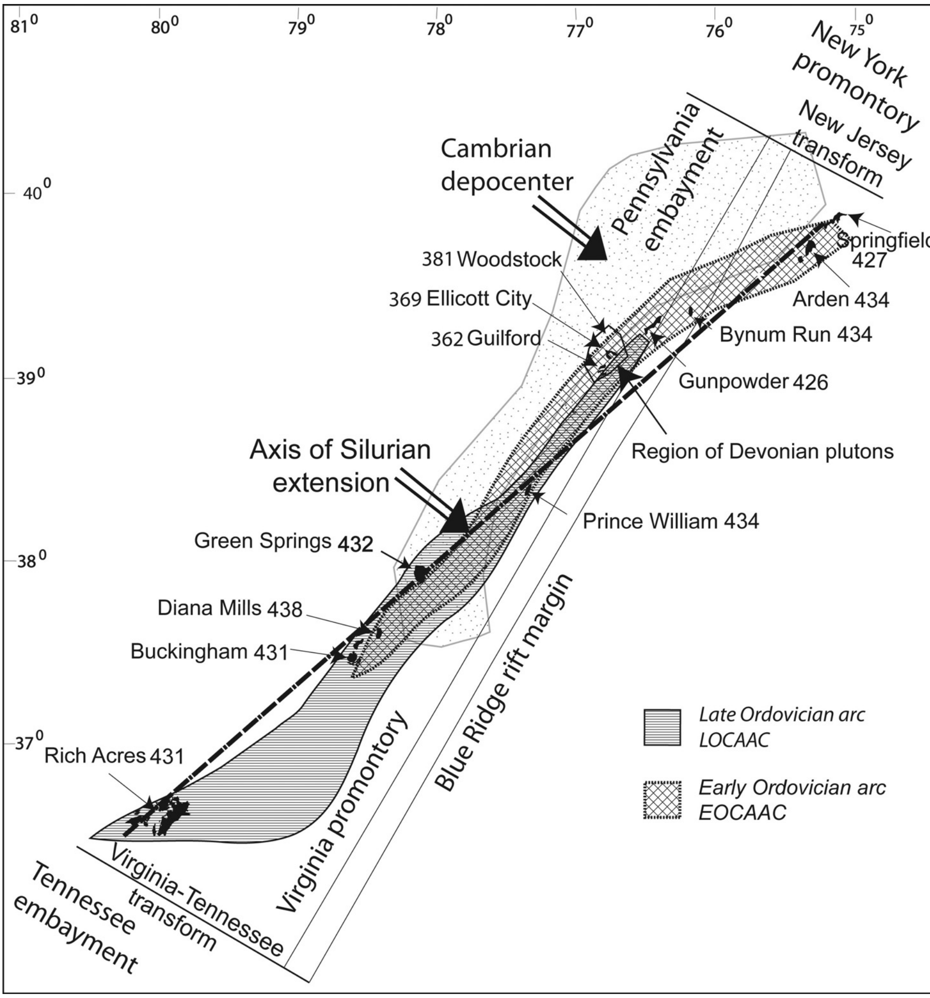

Fig. 13. The distribution and composition of Silurian igneous rocks reflect an extensional tectonic environment. Abundant mafic plutons in the central and southern parts of the study area yield to dominantly felsic plutons in the region of the Pennsylvania embayment of Thomas (2006). These plutons are considered to be partial melts of volcanic rocks associated with emplacement of mafic magmas at depth, as well as availability of fluids from buried sediments of the depocenter. Devonian age felsic magmatism is restricted to the depocenter, and is modeled as result of distal thermal anomaly associated with the accretion of peri-Gondwanan elements. Figure adapted from Thomas (2006) and Read (1989).

the Virginia promontory northward into the Pennsylvania embayment, where the margin is considered to be located in an upper-plate rift regime (fig. 13) (fig. 2 of Thomas, 1993). As recognized by Thomas (1993), there is no apparent along-strike change in dip of the detachment from the Virginia promontory to the Pennsylvania embayment to accommodate a very thick synrift succession of fertile lithologies similar to that in the Tennessee embayment in a lower-plate extensional regime (fig. 13). We suggest that, although relatively thin synrift sediments are associated with the volcanic Catoctin Formation on the Virginia promontory, thick sediment accumulation is likely only along tectonic depressions adjacent to the transform fault (for example, Poole and others, 2005) in the Pennsylvania embayment (fig. 13) (Thomas, 2006). Such an environment, coupled with differences in post-rift thermal histories, may have contributed to the evolution of a thick sedimentary depocenter, including passive-margin shelf deposition in an embayment with upper-plate geometry. Across the New Jersey transform, the rift margin of the upper-plate New York promontory is offset dextrally from the rift margin of the upper-plate Pennsylvania embayment (fig. 13) (Thomas, 1993). Because of the offset, at any point along the transform, lithosphere on the New York promontory is farther from the New York rift axis than lithosphere directly across the transform in the Pennsylvania embayment is from the Blue Ridge rift in Pennsylvania. The juxtaposed lithospheres on opposite sides probably led to different levels of thermal subsidence because of varying distances from the axis of the rift. The more mobile crust nearer the rift margin (in the Pennsylvania embayment) may have subsided more than the crust directly across the transform (which was farther from the rift axis on the New York promontory), leading to a thick accumulation of sedimentary rocks in the embayment.

Our new data, as well as those compiled from the literature (tables 2 and 3) show a strong cluster of ages between 423 and 438 Ma that we interpret as melting associated within an extensional stage, although no coeval basins of similar age and tectonic setting have been identified in the region of study. Closer examination of the mineralogy and chemistry of these plutons shows only mafic plutons on the Virginia promontory, whereas similar age bodies in Delaware, Maryland, and Pennsylvania (region of depocenter) are generally granitic in composition, although hybrid plutons are also present (fig. 13, table 2). Following well-demonstrated post-collisional extension in continent-scale collision zones (Dewey and others, 1993), and the rapid reversal from compression to extension in less than 5 m.y., as suggested by Charlton (1991) for the eastern Indonesian region and Cawood and others (2011) for eastern Australia, to perhaps less than 50 m.y. for the Irish Dalradian collision zone (Alsop and Hutton, 1993), the Silurian mafic plutons reflect magmatic conduits from the mantle to mid-crustal levels (fig. 12). Discovery of an olivine melilite (432 Ma) of the Clear Springs Volcanic Suite in the basal part of the Silurian Tuscarora Formation in Maryland also supports an extensional geometry pre-dating development of the Silurian Appalachian basin (Smith and others, 2004). Unlike the well-recognized Silurian extensional structures farther north in the Upper Connecticut Valley (Rankin and others, 2007), no structural studies in the central Appalachians have recognized Early Silurian extensional fabrics. Our data, however suggest that such structures might exist.

We also argue that the distribution and ages of pegmatites in the Maryland Piedmont (Wetherill and others, 1966), although ignored by most geologists undertaking tectonic reconstructions, are good markers for extension. These pegmatite swarms are in two groups. One is associated primarily with basement gneisses, Baltimore mafic complex and Glenarm Series metasedimentary rocks; the other group lies within plutons (Hopson, 1964). Rb-Sr mineral ages range from 387 to 416 Ma for the first group and 334 Ma for the second group (Wetherill and others, 1966; ages recalculated with ^{87}Rb decay constant of 1.42×10^{-11} yr^{-1}). The older group is mostly coincident with our proposed time of extension, although Hopson (1964) considered tension fractures associated with basement remobilization to be the emplacement mechanism. We suggest that the presence of these rocks in regions with thick sedimentary accumulations and the broad similarity in age with Silurian ages of plutons are permissive evidence of an extensional tectonic heritage. The absence of Silurian mafic magmas in such environments may reflect lithologic traps perhaps related to density contrasts (for example, Glazner and Ussler, 1988; Hogan and others, 1998) within thick sedimentary columns contained in such environments or structural traps generated during overthrusting (for example, Rocchi and others, 2002). Heating of these sedimentary columns through emplacement of mafic magmas would provide the temperatures for partial melting to produce felsic plutons of similar age, for example, Springfield, Ardentown, and Gunpowder.

Interpretation of tectonic framework of magma genesis through time

Plate tectonic models summarizing the Ordovician igneous record in the Appalachian orogen (van Staal and Hatcher, 2010) have been correlated with geodynamic processes such as changes in polarity of subduction (Miller and others, 2006; Horton and others, 2010) or multiple subduction and associated suprasubduction zones (Hibbard and others, 2007) followed by collision of arc or microcontinent tracts, leading to Taconic orogenesis (Rodgers, 1982; Stanley and Ratcliffe, 1985; Drake and others, 1989; MacNiocaill and others, 1997; Karabinos and others, 1998; van Staal and others, 1998). On the basis of the ages and geochemical data of igneous rocks from the central Appalachians, we suggest that the history of the Iapetus ocean basin is recorded in the sequential development of an arc (EOCAAC) followed by an episode of mid-Ordovician syntectonic magmatism associated with an arc-continent collisional event (Taconic orogeny) leading to a change in polarity of subduction and the development of a second arc (LOCAAC) during the Late Ordovician (fig. 14). The cessation of subduction through closing the Rheic ocean marking the arrival of peri-Gondwanan tracts led to slab delamination and Silurian magmatism within an extensional regime.

The geologic evidence for the breakup of supercontinent Rodinia in the region of study is well constrained by late Neoproterozoic rift-related volcanic and sedimentary rocks along the margin of Laurentia (Rankin, 1975, 1976; Thomas, 1977, 1991, 2006; Glover and others, 1997; Allen and others, 2009; Bradley, 2009; Cawood and others, 2011). Although the exact timing of the rift-to-drift transition is not known, estimates range from 574 Ma (age of rift related volcanic rocks of the Catoctin Formation) and the early Cambrian drift stage estimated by Glover (1992) to be ~550 Ma and very similar to the age of 540 Ma suggested by Cawood and others (2001) and Bradley (2009). Specifically, post-rift onlap at the beginning of Cambrian time indicates rift-to-drift transition at 542 Ma along the Virginia promontory (Thomas, 1991). The development of tholeiitic EOCAAC suggests subduction of Iapetus oceanic lithosphere underneath continental fragments (ribbon continent?) at 489 to 470 Ma. Utilizing an average sea-floor spreading rate of 3 cm/yr, the width of the ocean basin (drift stage to Early Ordovician arc stage) would have been approximately 1800 km, and arc activity developed late in the drift history. The closing of this basin is marked by the collision of EOCAAC and the Laurentian margin by 472 Ma (oldest syntectonic pluton of Group II) or by 461 Ma if the average age is used. The Rheic ocean basin developed in the Early Ordovician via the separation of Gondwanan terranes from the continental margin of Gondwana (Nance and others, 2010), and westward movement was accommodated through subduction of the Rheic oceanic crust under Laurentia including the already accreted arc (EOCAAC), causing the development of the second proposed calc alkalic arc (Group III; 441-459 Ma). The timing and composition of this episode of volcanism is consistent with ages and distribution of K-bentonites in the Appalachian basin (Thomas and others, 2002). Group IV igneous activity (423-438 Ma; average age of 430 Ma) is adequately modeled to be the result of lithosphere delamination because of discontinued subduction associated with accretion of peri-Gondwanan tracts to Laurentia, and provides a time stamp for the end of the Rheic ocean basin. Late Devonian Neoacadian (Group V) plutons with an average age of 365 Ma are more enigmatic in tectonic setting, but perhaps are related to local melting caused by post-closure shortening associated with accretion of the peri-Gondwanan tracts and transpressive subduction of pre-Acadian Laurentian and peri-Laurentian elements beneath the Carolina superterrane.

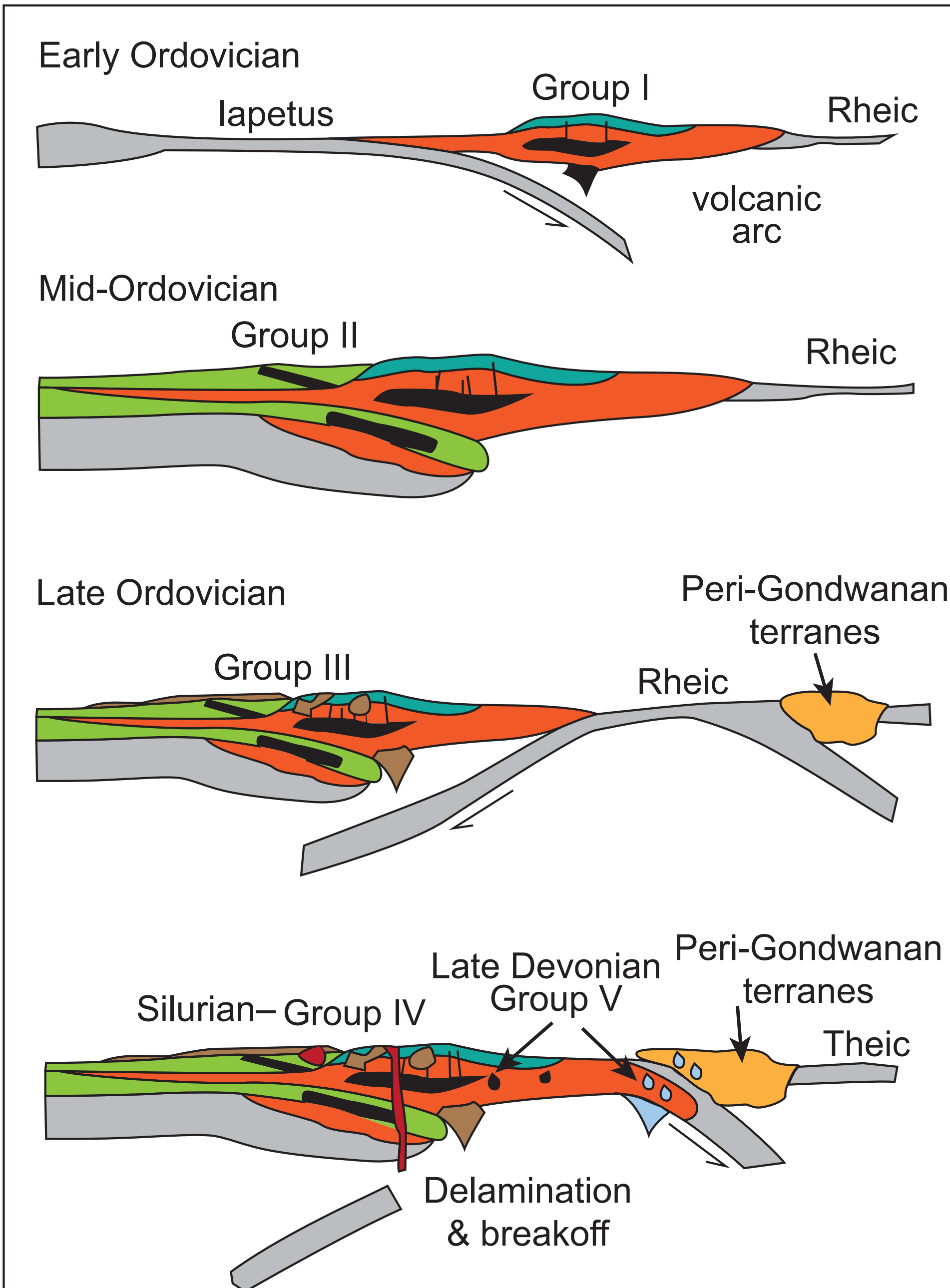

Fig. 14. Schematic representation of proposed geodynamic settings that enable linkage between age and composition of igneous rocks in the central Appalachians. Group I rocks are generated in a low-K tholeiitic arc environment where subduction is directed eastward. Syntectonic plutons of Group II are emplaced in mélange complexes. Continued convergence of Rheic ocean basin forms a second arc with west-dipping subduction. This Late Ordovician event generates intermediate to high-K calc-alkaline magmas of Group III. Group IV magmas are modeled to be the result of slab delamination and breakoff caused by accretion of peri-Gondwanan tracts, marking the terminal stage of the Rheic ocean basin. Group V plutons are likely to have been produced by post-closure shortening related to mid-Paleozoic accretion of Carolina superterrane.

Summary of Conclusions

Geochronologic and geochemical data for igneous rocks in the central Appalachian orogen provide a geodynamic template for the collision of a rifted margin with an outboard Early Ordovician tholeiitic arc. The resulting Taconic orogeny is accompanied by syntectonic intrusions of tonalitic plutons derived by partial melting of arc crust. Subduction of the Rheic ocean basin under the composite mid-Ordovician arc-continental margin generated a Late Ordovician calc-alkaline arc characterized by a Gd anomaly suggesting remelting of amphibole-rich sources. The early stages of accretion of peri-Gondwanan tracts led to delamination of the subducting plate and extension in the overlying lithosphere and Silurian-age bimodal magmatism. Mafic plutons are dominant only in the southern part of the region that is not underlain by a synrift depocenter formed during rifting of Rodinia. Continued post-accretion shortening in the region, as the Carolina superterrane was transpressionally accreted provided the thermal instability for minor Late Devonian magmatism. Our results emphasize that all tectonic events recognized in the region will continue to require high precision ages as we seek to unravel rates of tectonic processes.

Acknowledgements

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Appendix 1

Sample Locations

Zircon Samples

James Run Formation: split of same zircon sample (B-83) as analyzed by Tilton and others, 1970; from Gatch Quarry, lat 39.52 and long −76.26

Port Deposit Gneiss: lat 39.61 and long −76.12

Columbia granodiorite: lat 37.75 and long −78.15

Leatherwood granite: lat 36.69 and long −79.83

Shelton granite 1: lat 36.32 and long −79.28 (type area)

Shelton granite 2: lat 36.39 and long −79.28

Carysbrook granite: lat 37.82 and long −78.22

Ellisville granodiorite: split of zircon sample P-80-36 analyzed by Pavlides and others, 1994; lat 38.05 and long −77.99

Lahore monzonite: split of zircon sample P-81-12 analyzed by Pavlides and others, 1994; lat 38.15 and long −77.97

Melrose granodiorite: lat 37.03 and long −79.04

Gretna granodiorite: lat 36.93 and long −79.25

Poor Creek gabbro/diorite: lat 38.03 and long −78.13

Green Springs: lat 38.00 and long −78.13

Diana Mills gabbro: lat 37.67 and long −78.42

Buckingham gabbro: lat 37.55 and long −78.59

Rich Acres gabbro: lat 36.65 and long −79.87

Ardentown granite: lat 39.81 and long −75.47

Gunpowder granite: lat 39.42 and long −76.50

Woodstock granite: split of zircon sample B-6 analyzed by Wetherill and others, 1966; lat 39.34 and −76.82

Ellicott City granodiorite 8136: lat 39.26 and long −76.79
Ellicott City granodiorite 8112: lat 39.27 and long −76.80

Geochemistry Samples

Kensington KS-3: lat 38.96 and long −77.06
Kensington KS-4: lat 38.95 and long −77.05
Kensington KS-9: lat 38.92 and long −77.05

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