Grenvillian magmatism in the northern Virginia Blue Ridge: Petrologic implications of episodic granitic magma production and the significance of postorogenic A-type charnockite

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Abstract

Grenvillian (1.2 to 1.0 Ga) plutonic rocks in northern Virginia preserve evidence of episodic, mostly granitic magmatism that spanned more than 150 million years (m.y.) of crustal reworking. Crystallization ages determined by sensitive high resolution ion microprobe (SHRIMP) U–Pb isotopic analyses of zircon and monazite, combined with results from previous studies, define three periods of magmatic activity at 1183–1144 Ma (Magmatic Interval I), 1120–1111 Ma (Magmatic Interval II), and 1078–1028 Ma (Magmatic Interval III). Magmatic activity produced dominantly tholeiitic plutons composed of (1) low-silica charnockite, (2) leucogranite, (3) non-leucocratic granitoid (with or without orthopyroxene (opx)), and (4) intermediate biotite-rich granitoid. Field, petrologic, geochemical, and geochronologic data indicate that charnockite and non-charnockitic granitoids were closely associated in both space and time, indicating that presence of opx is related to magmatic conditions, not metamorphic grade. Geochemical and Nd isotopic data, combined with results from experimental studies, indicate that leucogranites (Magmatic Intervals I and III) and non-leucocratic granitoids (Magmatic Intervals I and II) were derived from parental magmas produced by either a high degree of partial melting of isotopically evolved tonalitic sources or less advanced partial melting of dominantly tonalitic sources that also included a more mafic component. Post-orogenic, circa 1050 Ma low-silica charnockite is characterized by A-type compositional affinity including high FeOt/(FeOt + MgO), Ga/Al, Zr, Nb, Y, and Zn, and was derived from parental magmas produced by partial melting of potassic mafic sources in the lower crust. Linear geochemical trends defined by leucogranites, low-silica charnockite, and biotite-rich monzogranite emplaced during Magmatic Interval III reflect differences in source-related characteristics; these features do not represent an igneous fractionation sequence. A compositional gap between circa 1160 Ma magnesian low-silica charnockite and penecontemporaneous higher silica lithologies likewise precludes a fractionation relationship among plutons intruded during Magmatic Interval I. Correspondence in timing of magmatic activity between the Blue Ridge and neighboring Mesoproterozoic terranes underscores the widespread nature of Grenvillian processes in the region.

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1. Introduction

Orogenic belts typically contain abundant evidence of the extended sequence of tectonic processes that result in their formation. Deciphering this geological record is an important means of elucidating tectonic mechanisms and, especially for Precambrian orogens, reconstructing the geologic history of early Earth. However, in areas where cyclic plate tectonic processes locally superpose the effects of subsequent orogenic and other events such as rifting on previously activated crust, geologic evidence of the earliest tectonic activity can be obscured. Nevertheless, investigations involving detailed field studies and application of modern analytical techniques (e.g. Frost et al., 2000; Slagstad et al., 2004) have demonstrated the efficacy of multidisciplinary studies of the oldest rocks in polydeformed orogenic belts to produce useful insight into the nature of ancient tectonic processes.

This study presents results of detailed field mapping and petrologic, geochemical, and geochronologic investigations of Mesoproterozoic crust in the northern Blue Ridge. It expands the findings of Tollo et al. (2004a) by presenting results from a much larger field area encompassing previously unreported rock types. This report includes 135 major- and trace-element analyses of samples from all lithologic units and new geochronologic data from 12 additional samples. The research is designed to elucidate the nature and sequence of Mesoproterozoic tectonomagmatic events involved in the geologic evolution of Blue Ridge basement and to evaluate the significance of these events within the wider context of the Grenville orogen. A major emphasis is the application of detailed geochronologic data to temporally calibrate and improve understanding of petrologic and tectonic processes. In this paper, the terms “Grenville orogeny” and “Grenvillian orogenesis” refer to largely compressional tectonism that occurred at 1.2–1.0 Ga and which, in the Adirondacks and Grenville province of southeastern Canada, involved multiple pulses including Ottawa activity which is most closely correlative temporally to events recorded in the northern Blue Ridge.

The largely granitic Mesoproterozoic rocks of the northern Blue Ridge record an interval of magmatism and tectonic activity spanning more than 150 million years (m.y.) (Aleinikoff et al., 2000; Tollo et al., 2004a). Field relations and results from geochronologic investigations indicate that magmatic activity both predated and postdated a major episode of deformation. As a result, these rocks offer a rare perspective on Grenvillian geodynamic activity and shed light on the role of granitic magmatism in the evolution of orogens.

2. Regional geology

The Blue Ridge province is an inlier of Grenville-age basement located within the Paleozoic Appalachian orogen of central and northern Virginia (Fig. 1). This area preserves evidence of multiple tectonic cycles spanning more than 1 billion year and includes collisional orogens of both Mesoproterozoic (Grenvillian) and Paleozoic (Appalachian) age. Mesoproterozoic rocks of the Blue Ridge and other Appalachians inliers are especially noteworthy because they occur in an area where rocks of the Grenville orogen are otherwise buried beneath Phanerozoic sediments in eastern North America south of the Adirondacks (Fig. 1).

The Blue Ridge in Virginia is a fault-bounded allochthonous thrust sheet that was transported northwestward to its present location during the Carboniferous–Permian Alleghenian orogeny (Rankin et al., 1989). This sheet is the largest of about 12 external (allochthonous) and internal (autochthonous) massifs that contain Grenvillian basement within the Appalachian orogen from Alabama to Newfoundland (Fig. 1). Mesoproterozoic basement rocks in Virginia occur within the core of the northeast-trending, northwest-vergent Blue Ridge anticlinorium (Fig. 2). They are locally intruded by numerous Neoproterozoic extension-related A-type plutons such as the 735–700 Ma Robertson River batholith (Tollo and Aleinikoff, 1996), and are structurally overlain by the circa 570 Ma extension-related metavolcanic and metasedimentary Catoclin Formation and underlying metasedimentary units (Rankin et al., 1989; Aleinikoff et al., 1995).

The igneous and metamorphic basement rocks of the Virginia Blue Ridge were formed at 1.2–1.0 Ga (Aleinikoff et al., 2000; Tollo et al., 2004a) during Grenvillian orogenesis associated with tectonic assembly of Rodinia (Dalziel, 1997; Karlstrom et al., 2001). The Grenville orogeny in Virginia involved polyphase deformation, high-grade metamorphism, and abundant, largely granitic plutonism, resulting in construction of a terrane composed primarily of granitoids and charnockites that locally enclose isolated screens and inliers of granitic gneiss (Bartholomew and Lewis, 1984; Tollo et al., 2004a). Orthopyroxene (opx) + garnet assemblages occurring in Blue Ridge gneisses (Sinha and Bartholomew, 1984; Tollo et al., 2004b) indicate that ambient conditions of Grenvillian orogenesis locally reached granulite facies (Spear, 1993). Most rocks also display mineralogic evidence of limited retrograde recrystallization at greenschist-facies conditions resulting from multiple Paleozoic orogenies (Kunk and

Fig. 1. Map showing locations of major occurrences of Grenville-age basement in eastern North America. Map modified after Rankin et al. (1990).

Burton, 1999). Paleozoic orogenesis also resulted in widespread ductile deformation manifested by numerous high-strain zones (Fig. 3) that affected basement rocks throughout the Blue Ridge (Bailey and Simpson, 1993) but involved displacement on the order of only a few kilometers (Bailey et al., 1994).

3. Previous studies

Basement rocks of the northern Virginia Blue Ridge are dominated by granitic gneisses and compositionally

variable granitoids that include abundant opx-bearing (charnockitic) types (Bartholomew and Lewis, 1984). Early studies indicated that charnockitic rocks ("Pedlar Formation" of Bloomer and Werner, 1955) were concentrated in western portions of the area, whereas amphibole $\pm$ biotite-bearing rocks of presumably lower metamorphic grade dominated eastern regions ("Lovingston Formation" of Jonas, 1928). Bartholomew (1977) and Bartholomew et al. (1981) subdivided the Blue Ridge into two massifs: (1) the upper granulite facies Pedlar massif located west of the northeast-trending Rock-

Fig. 2. Generalized geologic map of the Blue Ridge anticlinorium in northern Virginia showing location of study area included in Fig. 3. Modified after Virginia Division of Mineral Resources (1993). Faults shown only in Mesoproterozoic rocks. Insert map shows location of Shenandoah National Park.

fish Valley fault zone (Fig. 2) and (2) the lower granulite to upper amphibolite facies Lovingson massif located east of the fault. In this model, the Rockfish Valley fault zone represents a significant structural boundary in central Virginia along which the two massifs were juxtaposed by Paleozoic thrusting (Sinha and Bartholomew, 1984). Evans' (1991) alternative model attributes lithologic differences to hydration and retrograde metamorphism of Lovingson rocks resulting from fluid migration associated with Neoproterozoic extension and Paleozoic orogenesis. Subsequent studies suggest that (1) rocks of the two massifs are grossly similar in geochemical composition and thus unlikely to represent greatly disparate crustal blocks (Hughes et al., 2004), (2) movement along the fault zone is likely insufficient to juxtapose crustal blocks (Bailey

and Simpson, 1993), and (3) most lithologic variation in northern Virginia reflects primary mineralogy of igneous plutons (this study).

Field-based petrologic and structural studies indicate that northern Blue Ridge basement is composed of a complex array of granitic rocks that preserve evidence of over 150 m.y. of magmatic and metamorphic processes (Aleinikoff et al., 2000; Tollo et al., 2004a,c). The oldest rocks are represented by strongly foliated granitoids and granitic gneisses that are locally intruded by, and enclosed within, younger magmatic rocks. The older rocks range from quartz diorite to syenogranite (Table 1) and are characterized by (1) deformed compositional layering that commonly is defined by discontinuous leucosomes, (2) pervasive alignment of primary minerals, and (3) open to isoclinal folds (e.g. Burton et al., 1995; Bailey

Fig. 3. Generalized geologic map of the study area. Geology of the Madison quadrangle is from Bailey et al. (2003).

et al., 2003; Burton and Southworth, 2004; Southworth, 1995). Younger rocks range from quartz monzodiorite to syenogranite (Table 1); these rocks are variably foliated but do not display fabrics indicative of deformation at high-grade conditions.

Results from previous U–Pb geochronologic studies of zircon and monazite indicate that igneous crystallization ages range from circa 1160 to 1050 Ma (Aleinikoff et al., 2000; Tollo et al., 2004a), defining three episodes of magmatic activity occurring at circa 1160–1140 Ma

(Magmatic Interval I), circa 1112 Ma (Magmatic Interval II), and 1078–1050 Ma (Magmatic Interval III). Field relations and ages of crosscutting igneous units indicate that a major deformational event occurred between 1078 and 1050 Ma (Tollo et al., 2004a), approximately contemporaneous with the Ottawa orogeny documented elsewhere (McLelland et al., 2001; Rivers, 1997). New mapping and analytical data of this study refine the previous three-fold temporal division of Grenvillian igneous activity in the northern Blue Ridge.

Table 1
Lithologic characteristics of northern Blue Ridge basement rocks

Magmatic Interval	Map symbol	Lithologic nomenclature ^a and group ^b	Fabric and rock type	Primary Fe-Mg minerals ^c	Field relations
III (1078–1028 Ma)	Ybg	Biotite-rich monzogranite to quartz monzodiorite (BM)	Variably foliated, bt-rich; local compositional layering; granitoid	bt	Intrudes and includes xenoliths of Ylg
	Yfqj	Monzogranite (<i>farsundite</i>) to quartz monzodiorite (<i>quartz jotunite</i>) (LSC)	Non-foliated; charnockite	opx ± amph ± cpx	Intruded by Ygr; intrudes Ylgg
	Ygr	Old Rag magmatic series (garnetiferous leucogranite) (LG)	Non-foliated to weakly foliated; leucogranite	bt ± grt ± opx	Intrudes Yfqj and Ycf
	Ygg	Garnetiferous syenogranite (LG)	Weakly foliated; leucogranite	grt + bt ± opx (ps) ^d	Intrudes Ypqd
	Ylgg	Megacrystic leucogranite gneiss (LG)	Strongly foliated; leucogranite	bt	Intruded by Yfqj
II (1120–1111 Ma)	Yfe	Equigranular pyroxene monzogranite (<i>farsundite</i>) (NLG)	Weakly to moderately foliated; charnockite	opx ± bt ± grt	–
	Yfpg	Foliated pyroxene monzogranite (<i>farsundite</i>) (NLG)	Strongly foliated; charnockite	opx ± amph ± bt ± grt	Contact truncates foliation in Yfh
I (1183–1144 Ma)	Yfh	Flint Hill Gneiss (syenogranite) (NLG)	Strongly foliated; granitoid	bt	–
	Ycf	Megacrystic syenogranite and monzogranite (<i>charnockite</i> and <i>farsundite</i>) (NLG)	Strongly foliated; charnockite	opx ± amph ± cpx	Intruded by Ygr; encloses screen of Yg
	Ypqd	Pyroxene quartz diorite (<i>orthopyroxene quartz diorite</i>) (LSC)	Strongly foliated; charnockite	opx + bt	Intrudes Ylgn; intruded by Ygg
	Yg	Garnetiferous granite (<i>charnockite</i> to <i>farsundite</i>) gneiss (NLG)	Strongly foliated, compositional layering; charnockite	opx + grt + bt ± cpx	Forms screen within Ycf
	Ylgn	Layered granodiorite (<i>opdalite</i>) gneiss (NLG)	Strongly foliated, compositional layering; charnockite	opx + amph	Intruded by Ypqd
	Ylg	Leucocratic granitoid (Ylg2) (LG) and foliated megacrystic leucocratic granite (Ylg1) (LG)	Strongly to weakly foliated; leucogranite	bt	Intruded by Ybg; Ylg2 intrudes Ylg1; leucogranite pegmatite intrudes both Ylg1 and Ylg2

^a Nomenclature for charnockitic rocks are italicized in parentheses, following recommendations of Le Maitre et al. (1989).

^b Lithologic groups: LG: leucogranite, NLG: non-leucocratic granitoid (includes charnockites), LSC: low-silica charnockite; BM: biotite monzogranite.

^c Abbreviations after Kretz (1983): bt, biotite; opx, orthorhombic pyroxene; amph, amphibole; cpx, monoclinic pyroxene; grt, garnet.

^d ps: pseudomorphed by retrograde metamorphic mineral assemblage.

4. Lithologic characteristics and field relations

The study area includes six contiguous 7.5-min quadrangles located in the core of the Blue Ridge anticlinorium in northern Virginia (Figs. 2 and 3). Previous studies demonstrated the existence of multiple lithologies, including granitic gneisses, charnockite, and leucocratic granitoids of Grenvillian affinity (Gathright, 1976; Virginia Division of Mineral Resources, 1993; Lukert, 1982; Sinha and Bartholomew, 1984).

4.1. Normative compositions and nomenclature

All rocks are interpreted to be igneous in origin based on (1) primary mineral assemblages (Table 1); (2) chemical compositions compared to experimental data and compositions of granitic rocks of igneous origin from other orogens (e.g. Rämö, 1991; Kilpatrick and Ellis, 1992; Landenberger and Collins, 1996; Smith et al., 1999); (3) igneous-type textures observed in the least deformed rocks; (4) field relations including crosscutting contacts, incorporation of xenoliths, and local development of cogenetic pegmatite; (5) systematic variation trends in chemical compositions indicative of igneous processes, and (6) concentric oscillatory compositional zoning patterns of zircon from most rocks. Normative compositions, calculated assuming $\text{Fe}^{2+}/\text{Fe}_{\text{total}} = 0.9$, are used in place of modal data for determining lithologic nomenclature because of the very coarse grain size and strongly anisotropic fabrics of some rocks. Standard International Union of Geological Sciences (IUGS) nomenclature (Streckeisen and Le Maitre, 1979;

Le Maitre et al., 1989) is used for all rocks (Table 1; Fig. 4). However, specialized nomenclature, recommended for opx-bearing rocks of inferred igneous origin (i.e. charnockites, *sensu lato*), is employed for some units and is included in italics. Such terms include *charnockite* (opx-bearing syenogranite), *farsundite* (opx-bearing monzogranite), *opdalite* (opx-bearing granodiorite), and *quartz jotunite* (opx-bearing quartz monzodiorite). The term “charnockitic” is used to refer to all opx-bearing granitoid rocks of inferred igneous origin.

Normative compositions define a broad range extending from alkali feldspar granite to quartz diorite (Fig. 4); however, the extent of compositional variation is strongly dependent on age. Rocks emplaced during Magmatic Intervals I and II are dominantly monzogranite and syenogranite; a notable exception are rocks from a small body of pyroxene quartz diorite (Ypqd) that occurs as an inlier within younger leucogranitoid (Fig. 3). In contrast, rocks emplaced during Magmatic Interval III define a broad and continuous span of compositions, ranging from alkali feldspar granite to quartz monzodiorite (Fig. 4).

4.2. Field relations

Geologic mapping indicates that the present erosional surface is a crustal cross section characterized by repeated emplacement of Mesoproterozoic magmas. Supracrustal rocks are rare throughout the Virginia Blue Ridge (Bartholomew and Lewis, 1984; Rankin et al., 1989). Field relations and geochronologic data define an intrusive sequence for rocks of the study area (Table 1;

Fig. 4. Plot of normative [anorthite/(orthoclase + anorthite)] $\times 100$ vs. normative [quartz/(quartz + orthoclase + albite + anorthite)] $\times 100$ (ANOR vs. Q' , after Streckeisen and Le Maitre, 1979). Normative compositions calculated with $\text{Fe}^{2+}/\text{Fe}_{\text{total}} = 0.9$. See Table 1 for explanation of map symbols for lithologic units. Rocks emplaced during Magmatic Interval I are indicated by filled symbols, Magmatic Interval II by line symbols, and Magmatic Interval III by unfilled symbols. Numbered field labels include (1) alkali feldspar granite, (2) syenogranite, (3) monzogranite, (4) granodiorite, (5) tonalite, (6) quartz syenite, (7) quartz monzonite, (8) quartz monzodiorite, (9) quartz diorite, and (10) monzodiorite.

Fig. 3). Rocks of Magmatic Intervals I and II predate regional high-grade deformation and typically display strong foliation and/or gneissosity. Younger rocks lack ductile fabrics, exhibiting instead variably developed foliation due to waning stages of Grenvillian activity. All rocks were affected by low-grade Paleozoic metamorphism and structural overprinting. The rocks are divisible on the basis of mineralogic and geochemical composition into four lithologic types including (1) leucogranites (feldspar + quartz >90 modal %; units Ylg, Ylgg, Ygg, and Ygr), (2) non-leucocratic granitoids that include both orthopyroxene-bearing types (charnockites, *sensu lato*) and non-orthopyroxene-bearing types (units Ylgn, Yg, Ycf, Yfh, Yfe, and Yfpg), (3) low-silica (<65% SiO₂) charnockites (units Ypqd and Yfqj), and (4) biotite-rich monzogranite (Ybg). Charnockitic rocks were emplaced during nearly the full range of local Mesoproterozoic igneous activity. Such plutons typically include co-magmatic dikes and, in some instances (e.g. Yfqj), pegmatite. Leucogranite plutons emplaced during Magmatic Intervals I and III are typically internally complex, characterized by multiple crosscutting lithologies including leucogranitic pegmatites (Bailey et al., 2003; Tollo et al., 2004c). Biotite-rich monzogranite (Ybg) (Magmatic Interval III) is intermediate between the silica-rich and silica-poor rocks (Fig. 4).

Some gneissic units (e.g. Yg and Ylgg) occur as large xenoliths within younger plutons (Fig. 3). Tollo et al. (2004a) reported an igneous crystallization age of 1078 ± 9 Ma for strongly deformed leucogranite gneiss (Ylgg) that occurs as xenoliths within relatively undeformed low-silica charnockite (Yfqj) (1050 ± 8 Ma). These relations define the timing of a local pulse of Grenvillian deformation that corresponds to the age of Ottawa orogenesis in the Adirondacks (McLelland et al., 2001) and southeastern Canada (Rivers, 1997). Locally, peak deformation affected rocks as young as the oldest pluton of Magmatic Interval III (Ylgg), developing strong ductile fabrics; waning stages affected rocks as young as 1028 Ma, typically imparting weak foliation.

5. Geochronology

5.1. Analytical methods

Relatively unweathered samples of about 10 kg were collected from outcrops of nine lithologic units (Fig. 3). Zircon and monazite were extracted by routine mineral separation processes, including crushing, pulverizing, Wilfley table concentration, and purification using magnetic separation and methylene iodide. Individual

grains were handpicked under a binocular microscope, mounted in epoxy, ground to nearly half thickness, and polished using 6 and 1 μ m diamond suspension. All grains were digitally imaged in both transmitted and reflected light to discern areas free from inclusions, cracks, and other imperfections. Using the scanning electron microscope, zircons were imaged by cathodoluminescence (CL), whereas monazites were imaged by back-scattered electrons (BSE).

Zircons in these rocks preserve multiple age zones indicative of complex histories involving igneous origin, inheritance from source materials, and episodes of metamorphic overprinting (Tables 2 and 3). To decipher these events, we determined U–Pb ages of small, homogeneous areas of grains by *in situ* microanalysis using the sensitive high resolution ion microprobe (SHRIMP II) at the Research School of Earth Sciences, Australian National University, following the methods of Williams (1998). The area excavated by the primary oxygen ion beam is about 25–30 μ m in diameter for zircon and about 15–20 μ m for monazite. $^{206}\text{Pb}/^{238}\text{U}$ ages were corrected for instrument fractionation using zircon standard R33 (419 ± 1 Ma; Black et al., 2004) or monazite standard 44069 (424 ± 1 Ma; Aleinikoff et al., 2006). Uranium concentrations are considered accurate to $\pm 20\%$. Monazite was analyzed using energy filtering (Rubatto et al., 2001) to avoid isobaric interference at mass 204 (Ireland et al., 1999). Raw data were reduced using Squid 1 (Ludwig, 2001) and plotted using Isoplot 3 (Ludwig, 2003). All isotopic data (shown as 2-sigma error ellipses) are plotted on concordia diagrams to visually determine coherent age groups. Ages are calculated using the weighted average of $^{207}\text{Pb}/^{206}\text{Pb}$ ages. A Concordia Age (Ludwig, 1998) was calculated in cases where several analyses form a concordant age group.

Age data are reported for 12 new samples from nine lithologic units: (1) biotite-rich monzogranite to quartz monzodiorite (Ybg), (2) garnetiferous syenogranite (Ygg), (3) equigranular pyroxene monzogranite (Yfe), (4) foliated pyroxene monzogranite (Yfpg), (5) Flint Hill Gneiss (Yfh), (6) orthopyroxene quartz diorite (Ypqd), (7) garnetiferous granite gneiss (Yg), (8) layered granodiorite gneiss (Ylgn), and (9) leucocratic granitoid and foliated megacrystic leucocratic granite (Ylg2 and Ylg1, respectively). U–Pb geochronologic data obtained by conventional isotopic techniques were previously reported for the Flint Hill Gneiss (Lukert et al., 1977). However, because of internal compositional complexity of zircons from this unit, we decided to analyze another sample collected from a different locality in order to make use of the high spatial resolution of the SHRIMP technique.

Table 2

SHRIMP U–Th–Pb data for zircon and monazite from rocks of the northern Blue Ridge, Virginia

Sample ^a (location)	Measured ²⁰⁴ Pb/ ²⁰⁶ Pb	Measured ²⁰⁷ Pb/ ²⁰⁶ Pb	% Common ²⁰⁶ Pb	U (ppm)	Th/U	²⁰⁶ Pb ^b / ²³⁸ U (Ma)	Err ^c (Ma)	²⁰⁷ Pb ^b / ²⁰⁶ Pb (Ma)	Err ^c (Ma)	Disc. %	²⁰⁷ Pb ^d / ²³⁵ U	Err ^c (%)	²⁰⁶ Pb ^d / ²³⁸ U	Err ^c (%)	Err corr
SNP-02-186 biotite monzogranite (Ybg), Madison quadrangle, UTM coordinates: Easting ^c : 0735 611, Northing ^c : 4259 886															
02-186-1.1c	0.000105	0.0759	0.34	30	0.68	1017.3	15.5	1054	55	3	1.76	3.2	0.1712	1.6	0.501
02-186-2.1c	−0.000646	0.0736	−0.12	19	0.71	1058.3	20.5	1262	103	16	2.05	5.6	0.1801	2	0.361
02-186-2.2r	0.00011	0.0751	0.12	75	0.24	1045.8	11.4	1030	47	−2	1.79	2.6	0.176	1.1	0.445
02-186-3.1c	0.000321	0.0736	0	30	0.7	1030.3	16.4	899	97	−15	1.64	5	0.1724	1.7	0.336
02-186-4.1c	0.000186	0.075	0.07	23	0.72	1053.6	18.7	996	76	−6	1.77	4.2	0.1771	1.8	0.443
02-186-5.1c	0.000028	0.0753	0.18	52	0.45	1036.7	13.8	1066	57	3	1.8	3.1	0.1747	1.4	0.433
02-186-6.1c	0.00083	0.0772	0.44	28	0.83	1029.3	17.1	783	124	−31	1.54	6.2	0.1714	1.8	0.286
02-186-7.1c	0.00012	0.0735	0.12	29	0.64	1000.6	16.3	980	64	−2	1.66	3.6	0.1678	1.7	0.475
02-186-8.1c	−0.000097	0.0759	0.32	27	0.88	1020.5	17.1	1128	44	10	1.84	2.8	0.1724	1.7	0.618
02-186-9.1c	−0.000385	0.0717	−0.13	18	0.87	1006.8	20	1125	84	11	1.81	4.7	0.1699	2.1	0.443
02-186-10.1c	−0.000035	0.0766	0.42	31	0.73	1017.9	16.1	1125	39	10	1.83	2.5	0.1719	1.6	0.644
02-186-11.1c	−0.000314	0.0774	0.52	22	0.8	1014.2	18.9	1241	64	18	1.94	3.8	0.1722	1.9	0.508
02-186-12.1c	0.000007	0.0753	0.29	69	0.29	1010.8	11.9	1074	34	6	1.76	2.1	0.1702	1.2	0.58
02-186-13.1c	0.000486	0.0759	0.25	24	0.69	1036.3	18.1	896	137	−16	1.65	6.9	0.1734	1.9	0.272
02-186-13.2r	0.000379	0.0743	0.2	56	0.34	1004.4	12.6	895	64	−12	1.59	3.4	0.1678	1.3	0.39
02-186-14.1c	0.000336	0.0735	0.04	34	0.73	1018.7	15.4	889	92	−15	1.61	4.7	0.1703	1.6	0.336
02-186-14.2r	0.000459	0.0756	0.38	51	0.38	997.4	13.1	900	69	−11	1.59	3.6	0.1667	1.4	0.381
02-186-15.1c	0.000011	0.072	−0.07	69	0.3	1002.3	11.8	982	28	−2	1.67	1.8	0.1681	1.2	0.666
02-186-16.1c	0.000123	0.0746	0.06	17	0.5	1044.4	21.7	1010	73	−3	1.76	4.2	0.1756	2.2	0.513
02-186-16.2r	−0.000011	0.0739	−0.03	67	0.32	1046.7	12.2	1043	26	0	1.8	1.7	0.1763	1.2	0.687
SNP-02-197 garnetiferous syenogranite (Ygg), Chester Gap quadrangle, UTM coordinates: Easting: 0740 365, Northing: 4304 228															
02-197-1.1r	0.000009	0.0749	0.01	1272	0.01	1027.4	9.3	1062	10	3	1.78	1.1	0.173	0.9	0.889
02-197-2.1r	0.000009	0.0765	0.02	1073	0.01	1075	12.4	1105	11	3	1.91	1.3	0.1817	1.2	0.91
02-197-3.1r	0.000002	0.0736	0	1430	0.03	1015.7	6.8	1029	7	1	1.73	0.8	0.1708	0.7	0.899
02-197-4.1c	0.000018	0.0754	0.03	1031	0.28	1073.1	6.5	1071	8	0	1.88	0.7	0.1811	0.6	0.846
02-197-2.2c	0.000007	0.0776	0.01	1089	0.41	1115.8	6.7	1134	7	2	2.02	0.7	0.1891	0.6	0.857
02-197-3.2c	0.000032	0.0775	0.05	1283	0.27	1151.3	6.8	1121	7	−3	2.07	0.7	0.1953	0.6	0.865
02-197-4.2c	0.000051	0.0759	0.09	1787	0.27	987.6	5.8	1074	7	8	1.72	0.7	0.1662	0.6	0.872
02-197-5.1r	0.000054	0.0736	0.09	878	0.03	1000.5	6.1	1009	10	1	1.69	0.8	0.1679	0.6	0.778
02-197-5.2c	0.000152	0.0794	0.26	1188	0.29	1076.7	6.4	1128	10	5	1.94	0.8	0.1822	0.6	0.781
02-197-6.1c	0.000006	0.0749	0.01	1818	0.28	1055.7	6.2	1063	6	1	1.84	0.7	0.178	0.6	0.899
02-197-7.1c	0.000003	0.0777	0	989	0.31	1136.9	6.8	1137	7	0	2.06	0.7	0.1929	0.6	0.858
02-197-7.2c	0.000004	0.0784	0.01	1244	0.29	1154.3	6.8	1156	7	0	2.12	0.7	0.1961	0.6	0.882
02-197-8.1c	0.000006	0.0755	0.01	1561	0.16	1076.6	7	1080	12	0	1.89	0.9	0.1818	0.7	0.755
02-197-9.1c	0.000015	0.0781	0.03	843	0.24	1142.8	7	1144	8	0	2.08	0.8	0.194	0.6	0.836
02-197-10.1c	0.00002	0.0774	0.03	1563	0.39	1103.4	6.5	1125	7	2	1.99	0.7	0.1869	0.6	0.864
02-197-11.1c	0.000056	0.075	0.09	1191	0.26	1004.6	6	1048	9	4	1.73	0.8	0.169	0.6	0.81
02-197-12.1c	0.000002	0.0764	0	1219	0.2	1111.2	6.7	1106	10	0	1.98	0.8	0.1881	0.6	0.788
02-197-13.1c	0.000011	0.076	0.02	1982	0.25	1087.7	6.3	1092	7	0	1.92	0.7	0.1838	0.6	0.873
02-197-14.1c	0.000007	0.0764	0.01	1430	0.35	1079.7	6.4	1104	6	2	1.92	0.7	0.1825	0.6	0.888
02-197-15.1c	0.000061	0.077	0.1	820	0.23	1038.8	6.3	1098	11	5	1.84	0.8	0.1753	0.6	0.751
02-197-16.1r	0.000012	0.0742	0.02	452	0.04	1025.9	6.7	1043	12	2	1.76	0.9	0.1726	0.7	0.757
02-197-17.1r	0.000314	0.0781	0.53	408	0.05	1007.8	6.7	1033	25	2	1.72	1.4	0.1694	0.7	0.492
02-197-18.1r	0.000026	0.0748	0.04	496	0.04	1140	7.8	1054	12	−8	1.98	0.9	0.1927	0.7	0.758
02-197-19.1r	−0.000047	0.0745	−0.08	436	0.04	1044.6	6.9	1074	16	3	1.83	1	0.1761	0.7	0.654
02-197m-1.1	0.000027	0.0733	0.05	398	22.8	1116.9	16.1	1011	17	−10	1.89	1.7	0.1883	1.5	0.866
02-197m-1.2	−0.000023	0.0748	−0.04	634	15	1054.1	13	1071	12	2	1.84	1.4	0.1778	1.3	0.908
02-197m-1.3	0.000006	0.0741	0.01	479	13.7	1040.5	15.7	1043	16	0	1.79	1.8	0.1752	1.6	0.887
02-197m-2.1	−0.00003	0.0738	−0.05	463	19.5	1057.9	13.2	1048	16	−1	1.82	1.5	0.1783	1.3	0.847
02-197m-2.2	−0.000028	0.0748	−0.05	504	15.1	1070.4	13.7	1074	14	0	1.87	1.5	0.1807	1.3	0.88

02-197m-3.1	0.000027	0.0745	0.05	547	9.6	1097.2	13	1043	14	−5	1.89	1.4	0.1851	1.2	0.868
02-197m-3.2	0.000011	0.0749	0.02	827	10.2	1076.2	12	1062	14	−1	1.87	1.3	0.1816	1.2	0.861
02-197m-4.1	0	0.0774	0	1261	5.1	1160.6	12	1132	16	−3	2.1	1.4	0.197	1.1	0.791
02-197m-4.2	0.000012	0.0741	0.02	556	14.7	1040.7	12.4	1040	14	0	1.79	1.4	0.1752	1.2	0.869
02-197m-4.3	0.000029	0.075	0.05	898	11	1046.6	11.4	1057	11	1	1.81	1.3	0.1764	1.1	0.892
02-197m-5.1	−0.000009	0.0756	−0.02	732	13.9	1054.4	17.9	1087	12	3	1.86	1.9	0.178	1.8	0.946
02-197m-5.2	0.000035	0.0744	0.06	430	23.8	1001.4	12.9	1038	17	4	1.71	1.6	0.1683	1.3	0.847
02-197m-6.1	0	0.0748	0	795	7.8	1097	12.2	1062	12	−3	1.91	1.3	0.1852	1.2	0.896
02-197m-6.2	0.000015	0.0741	0.03	417	23.1	1024.1	13.2	1039	18	1	1.76	1.6	0.1723	1.3	0.831
02-197m-7.1	−0.000007	0.0742	−0.01	855	9.8	1054.1	11.7	1049	11	0	1.82	1.3	0.1776	1.1	0.897
02-197m-7.2	−0.000021	0.0757	−0.04	541	11.2	1048	12.9	1096	15	4	1.85	1.5	0.1769	1.3	0.86
02-197m-8.1	0	0.0757	0	534	17.5	1109.7	13.6	1087	14	−2	1.96	1.5	0.1877	1.3	0.87
02-197m-8.2	0.000021	0.0732	0.04	627	13.4	1025.3	14.7	1012	14	−1	1.73	1.6	0.1723	1.5	0.907
02-197m-9.1	0.000012	0.0743	0.02	409	27.3	1033.9	21.7	1044	18	1	1.78	2.3	0.174	2.2	0.928
02-197m-9.2	0.000015	0.0748	0.03	693	10.5	1055.8	12.3	1056	13	0	1.83	1.4	0.178	1.2	0.882
02-197m-9.3	0.000017	0.075	0.03	770	8.6	1138.4	12.9	1062	12	−7	1.98	1.3	0.1925	1.2	0.894
02-197m-10.1	0.000058	0.0735	0.1	461	19.2	1032.4	14.9	1005	22	−3	1.74	1.9	0.1735	1.5	0.804
02-197m-10.2	0.000042	0.0752	0.07	716	13.7	1060	12.4	1057	15	0	1.84	1.4	0.1787	1.2	0.851
02-197m-11.1	0.000009	0.075	0.02	1092	6.7	1067.5	11.4	1065	10	0	1.86	1.2	0.1801	1.1	0.908
02-197m-11.2	0	0.0731	0	577	15.4	1049.3	12.6	1018	14	−3	1.78	1.4	0.1765	1.2	0.871
02-197m-12.1	0.000019	0.0754	0.03	1065	16.4	1051	11.4	1072	12	2	1.84	1.3	0.1772	1.1	0.888
02-197m-12.2	0	0.0725	0	430	17.5	1007.6	13	999	17	−1	1.69	1.6	0.1691	1.3	0.854

SNP-01-170 garnetiferous syenogranite (Ygg), Chester Gap quadrangle, UTM coordinates: Easting: 0739 690, Northing: 4295 280

01-170-1.1c	0.004467	0.1329	7.4	516	1.34	961.6	11.5	894	293	−8	1.52	14.2	0.1604	1	0.069
01-170-2.1c	0.000387	0.0816	0.83	124	1.06	1059.1	9.5	1098	46	4	1.88	2.5	0.1789	0.9	0.381
01-170-3.1c	0.005663	0.158	9.88	327	1.18	1071.6	18.2	1139	330	6	1.94	16.7	0.1814	1.3	0.079
01-170-3.2r	0.000365	0.0775	0.81	2072	0.06	949.8	11.6	993	22	4	1.58	1.7	0.159	1.3	0.755
01-170-4.1c	0.001034	0.0957	1.98	147	0.41	1171.2	16.1	1224	61	4	2.23	3.4	0.1997	1.4	0.413
01-170-5.1c	0.000023	0.0798	−0.06	461	0.26	1206.1	10.3	1185	8	−2	2.25	1	0.2055	0.9	0.911
01-170-6.1r	0.000323	0.075	0.96	2089	0.06	838.3	6.1	939	22	11	1.35	1.3	0.1394	0.7	0.576
01-170-7.1r	0.000226	0.0748	0.98	2671	0.06	825.7	6.6	972	14	15	1.36	1.1	0.1375	0.8	0.762
01-170-8.1r	0.000187	0.0733	0.63	1972	0.07	871.5	9.8	946	14	8	1.41	1.4	0.1452	1.2	0.857

SNP-03-204 equigranular pyroxene monzogranite (farsundite) (Yfe), Big Meadows quadrangle, UTM coordinates: Easting: 0727 990, Northing: 4275 420

03-204-1.1c	0.000084	0.0767	0.3	133	0.3	1045.4	9.2	1082	17	3	1.84	1.3	0.1763	0.9	0.723
03-204-2.1c	0.000014	0.0768	−0.35	179	0.3	1191.5	22.8	1110	48	−7	2.14	3.1	0.2022	2	0.631
03-204-3.1c	0.000001	0.0824	−0.18	172	0.4	1290.1	11.2	1254	21	−3	2.51	1.4	0.2212	0.9	0.647
03-204-4.1c	0.000007	0.0821	0.17	116	0.73	1213.3	14.1	1246	41	3	2.35	2.4	0.2074	1.2	0.489
03-204-5.1c	0.00001	0.0861	−0.51	163	0.48	1434.2	16.1	1336	45	−7	2.94	2.6	0.2479	1.1	0.439
03-204-6.1c	0.00002	0.0799	0.32	241	0.42	1125.5	10.8	1187	11	5	2.1	1.1	0.1913	1	0.869
03-204-7.1c	0.000043	0.0744	−0.15	169	0.34	1085.5	14.8	1035	21	−5	1.86	1.8	0.183	1.4	0.8
03-204-8.1c	0.000025	0.0766	0.17	162	0.36	1072.9	10.2	1100	16	2	1.9	1.3	0.1813	1	0.772
03-204-9.1c	0.000008	0.0774	0.24	208	0.37	1077.7	10.7	1128	14	4	1.94	1.2	0.1824	1	0.832
03-204-9.2r	0.000014	0.0748	0.27	803	0.23	1003.1	7.7	1059	24	5	1.74	1.4	0.1688	0.8	0.545
03-204-10.1c	0.000025	0.0781	0.22	208	0.45	1100.3	15.1	1140	13	3	2	1.6	0.1865	1.4	0.911
03-204-11.1c	0.000069	0.0786	0.38	168	0.34	1080.7	10	1138	27	5	1.96	1.7	0.183	1	0.569
03-204-12.1r	−0.000003	0.0754	−0.07	423	0.23	1095.5	16.6	1081	15	−1	1.93	1.7	0.1851	1.6	0.904
03-204-12.2c	−0.000014	0.0743	0.12	161	0.23	1021.2	15.6	1054	14	3	1.77	1.7	0.1719	1.6	0.911
03-204-13.1c	0.000017	0.0775	0.25	144	0.32	1079.7	10.2	1129	20	4	1.95	1.4	0.1827	1	0.698
03-204-14.1c	0.000018	0.0762	0.42	108	0.39	1006.7	9.7	1094	32	8	1.78	1.9	0.1697	1	0.521
03-204-15.1c	0.000003	0.0767	0.07	752	0.23	1097.6	15.5	1111	19	1	1.96	1.8	0.1857	1.5	0.833
03-204-15.2c	0.000015	0.0853	0.83	151	0.26	1153.6	45.9	1318	86	12	2.32	6	0.1976	4.1	0.681
03-204-16.1c	0.000012	0.0748	0.18	86	0.33	1020.5	9.9	1057	31	3	1.77	1.8	0.1718	1	0.547

Table 2 (Continued)

Sample ^a (location)	Measured ²⁰⁴ Pb/ ²⁰⁶ Pb	Measured ²⁰⁷ Pb/ ²⁰⁶ Pb	% Common ²⁰⁶ Pb	U (ppm)	Th/U	²⁰⁶ Pb/ ^b ²³⁸ U (Ma)	Err ^c (Ma)	²⁰⁷ Pb/ ^b ²⁰⁶ Pb (Ma)	Err ^c (Ma)	Disc. %	²⁰⁷ Pb/ ^d ²³⁵ U	Err ^c (%)	²⁰⁶ Pb/ ^d ²³⁸ U	Err ^c (%)	Err corr
03-204-17.1c	0.000053	0.0772	0.02	155	0.34	1120.3	9.9	1106	24	−1	2	1.5	0.1897	0.9	0.601
03-204-18.1c	0.000058	0.076	−0.13	157	0.39	1122.2	24.2	1072	23	−5	1.97	2.5	0.1897	2.2	0.894
SNP-02-177 foliated pyroxene monzogranite (farsundite) (Yfpg), Chester Gap quadrangle, UTM coordinates: Easting: 0747 420, Northing: 4293 520															
02-177-1.1c	0.000041	0.0798	0.07	334	0.31	1132.5	7.8	1178	17	4	2.1	1.1	0.1925	0.7	0.628
02-177-2.1c	−0.000003	0.0761	0	656	0.3	1074.7	6.7	1100	19	2	1.91	1.2	0.1816	0.6	0.55
02-177-3.1c	−0.000005	0.0799	−0.01	279	0.33	1079.6	7.7	1196	26	10	2.02	1.5	0.1833	0.7	0.482
02-177-4.1c	0.000022	0.0775	0.04	594	0.31	1162.5	8.3	1125	27	−3	2.1	1.5	0.1973	0.7	0.479
02-177-5.1c	0.000373	0.0848	0.62	299	0.39	1128.3	7.7	1186	45	5	2.1	2.4	0.1918	0.7	0.294
02-177-5.2c	0.000015	0.0753	0.02	295	0.77	1047	10.2	1071	21	2	1.83	1.4	0.1765	1	0.696
02-177-6.1c	0.000026	0.0774	0.04	627	0.31	1147.6	9	1122	14	−2	2.07	1.1	0.1946	0.8	0.764
02-177-7.1r	0.000104	0.0752	0.18	275	0.77	1055	7.6	1035	21	−2	1.81	1.3	0.1776	0.7	0.592
02-177-7.2c	0.000062	0.0764	0.1	220	0.35	1133.1	10.7	1083	20	−5	2	1.4	0.1917	1	0.706
02-177-8.1r	0.00001	0.075	0.02	630	0.3	1026.6	8.1	1066	12	4	1.79	1	0.1729	0.8	0.8
02-177-8.2c	0.000015	0.079	0.02	455	0.46	1144	7.3	1168	11	2	2.11	0.9	0.1944	0.7	0.779
02-177-9.1c	0.00003	0.0775	0.05	561	0.29	1115.8	15.2	1123	31	1	2.01	2.1	0.189	1.4	0.674
02-177-9.2c	0.000053	0.078	0.09	251	0.35	1046.1	7.6	1128	17	7	1.88	1.2	0.1768	0.8	0.653
02-177-10.1c	0.000013	0.0784	0.02	451	0.36	1093.8	9.3	1151	22	5	2	1.4	0.1854	0.9	0.623
02-177-10.2c	0.000042	0.077	0.07	354	0.32	1142.7	12	1105	25	−3	2.04	1.6	0.1936	1.1	0.658
02-177-11.1c	0.000061	0.0799	0.1	274	0.33	1098.3	13.7	1172	34	6	2.03	2.2	0.1864	1.3	0.595
02-177-11.2r	0.000001	0.0742	0	289	0.95	1014.5	7	1047	17	3	1.75	1.1	0.1707	0.7	0.639
02-177-12.1c	0.000023	0.0768	0.04	699	0.31	1178	9.5	1108	22	−6	2.11	1.4	0.1999	0.8	0.601
02-177-13.1c	0.000018	0.0799	0.03	710	0.34	1148.7	7.2	1189	14	3	2.15	0.9	0.1954	0.6	0.686
02-177-14.1c	0.000019	0.0783	0.03	687	0.24	1069.2	7	1148	42	7	1.95	2.2	0.181	0.7	0.292
02-177-15.1c	0.000042	0.0778	0.07	434	0.28	1087.5	13.8	1127	52	4	1.96	2.9	0.1841	1.3	0.448
02-177-16.1c	0	0.0765	0	484	0.28	1092.3	8.2	1109	32	2	1.95	1.8	0.1848	0.8	0.425
02-177-17.1c	−0.00001	0.077	−0.02	934	0.29	1068.6	6.5	1125	17	5	1.92	1.1	0.1808	0.6	0.592
02-177-18.1r	0.000055	0.0736	0.09	346	0.8	1028	6.8	1008	14	−2	1.73	1	0.1727	0.7	0.7
02-177-19.1r	0.000037	0.0743	0.06	315	1.01	1018.5	6.9	1036	18	2	1.74	1.1	0.1713	0.7	0.619
02-177-20.1r	0.000022	0.0744	0.04	459	0.65	1010.8	6.5	1043	13	3	1.74	0.9	0.17	0.7	0.708
SNP-01-146 Flint Hill Gneiss (Yfh), Chester Gap quadrangle, UTM coordinates: Easting: 0747 760, Northing: 4296 630															
01-146-1.1c	0.000024	0.0769	−0.11	462	0.31	1141.3	8.9	1109	44	−3	2.04	2.3	0.1934	0.8	0.339
01-146-2.1c	0.000005	0.0762	−0.04	327	0.34	1109.7	8.9	1099	14	−1	1.97	1.1	0.1878	0.8	0.758
01-146-2.2r	0.000095	0.0748	−0.94	266	0.5	1265.6	10.5	1027	32	−23	2.17	1.8	0.2146	0.9	0.48
01-146-3.1c	0.000021	0.0794	0.36	625	0.31	1105.1	8.1	1175	22	6	2.05	1.3	0.1876	0.8	0.565
01-146-4.1c	0.000034	0.0784	0.01	329	0.33	1154.8	9.4	1145	25	−1	2.11	1.5	0.1961	0.8	0.558
01-146-4.2c	0.000013	0.0783	−0.11	511	0.63	1178	8.7	1151	9	−2	2.16	0.9	0.2002	0.8	0.863
01-146-5.1c	0.000004	0.0776	−0.03	392	0.34	1143.1	15	1135	23	−1	2.07	1.8	0.194	1.4	0.765
01-146-5.1c	0.000011	0.0809	0.31	597	0.35	1153.7	8.4	1216	13	5	2.19	1	0.1966	0.8	0.758
01-146-6.1c	0.000013	0.0786	−0.02	488	0.37	1166.9	8.9	1157	14	−1	2.14	1.1	0.1983	0.8	0.751
01-146-8.1c	0.000017	0.0791	0.26	427	0.33	1118.1	8.8	1168	11	4	2.06	1	0.1898	0.8	0.83
01-146-9.1c	−0.000001	0.0768	−0.22	570	0.31	1161.9	11.8	1115	23	−4	2.09	1.5	0.1971	1	0.677
01-146-10.1c	0.000019	0.0781	0.09	503	0.33	1129.3	8.7	1142	23	1	2.06	1.4	0.1916	0.8	0.565
01-146-11.1c	0.00001	0.0804	0.46	542	0.32	1108.1	8.5	1202	21	8	2.08	1.3	0.1884	0.8	0.603
01-146-12.1c	−0.000009	0.0783	0.19	382	0.32	1112.4	12.5	1157	44	4	2.04	2.5	0.1887	1.1	0.463
01-146-13.1c	0.000001	0.0772	0.25	415	0.3	1071.4	8.4	1127	14	5	1.93	1.1	0.1813	0.8	0.749
01-146-14.1c	0.000055	0.0754	−0.14	283	0.34	1110.9	9	1059	23	−5	1.93	1.4	0.1876	0.8	0.595
01-146-15.1c	0.00006	0.0746	0.24	289	0.37	1001.6	8.1	1034	15	3	1.71	1.1	0.1683	0.8	0.756
01-146-16.1c	0.000018	0.076	−0.18	513	0.34	1132.9	8.8	1087	35	−4	2	1.9	0.1917	0.8	0.416
01-146-17.1r	0.000374	0.0829	0.81	1489	0.29	1096.8	7.7	1137	22	4	1.99	1.3	0.1858	0.7	0.545
01-146-17.2c	0.000005	0.0762	−0.11	590	0.33	1124.4	12.8	1098	17	−2	2	1.5	0.1903	1.2	0.814
01-146-18.1r	0.000027	0.0784	0.08	1050	0.21	1141.3	8.3	1148	16	1	2.09	1.1	0.1937	0.7	0.691
01-146-18.2c	−0.000002	0.0808	0.7	366	0.34	1065.6	12.8	1216	10	12	2.02	1.4	0.181	1.2	0.921
01-146-19.1r	0.000074	0.0793	0.85	1766	2.02	990.2	7.6	1153	14	14	1.8	1.1	0.1672	0.8	0.743
01-146-19.2c	0.000021	0.0775	0.24	396	0.33	1080.8	15.4	1125	16	4	1.95	1.7	0.1829	1.5	0.878

SNP-01-175 pyroxene quartz diorite (orthopyroxene quartz diorite) (Ypqd), Chester Gap quadrangle, UTM coordinates: Easting: 0740 412, Northing: 4302 664

01-175-1.1c	0.000013	0.076	−0.04	162	0.75	1101.8	9.7	1089	22	−1	1.95	1.4	0.1863	0.9	0.643
01-175-2.1c	0.000073	0.0748	0.13	95	0.47	1033.3	12.1	1035	32	0	1.77	2	0.1739	1.2	0.605
01-175-3.1c	−0.000005	0.0783	0.02	205	0.76	1151.2	13.6	1157	11	1	2.11	1.4	0.1956	1.2	0.906
01-175-4.1c	−0.000001	0.0801	0.17	158	0.75	1164.7	20.3	1200	13	3	2.19	1.9	0.1984	1.8	0.94
01-175-5.1c	−0.000039	0.0789	−0.01	169	0.76	1171.7	11.1	1183	13	1	2.18	1.2	0.1994	1	0.838
01-175-6.1c	−0.000041	0.0724	−0.06	56	0.42	1011.7	10.9	1013	24	0	1.71	1.6	0.1699	1.1	0.679
01-175-7.1c	0.000109	0.0813	0.2	109	0.78	1188.8	10.8	1192	20	0	2.23	1.4	0.2025	0.9	0.686
01-175-8.1c	0.000032	0.0782	0.02	141	0.63	1148.1	13.8	1141	16	−1	2.09	1.5	0.1949	1.2	0.846
01-175-8.2c	−0.000029	0.0787	0.09	170	0.4	1144.4	11.9	1175	56	3	2.12	3	0.1945	1.1	0.351
01-175-9.1c	0	0.08	0.43	119	0.74	1107	10	1198	24	8	2.08	1.5	0.1881	0.9	0.611
01-175-10.1c	0.000089	0.0772	−0.01	88	0.6	1128.7	16.8	1093	41	−3	2	2.5	0.191	1.5	0.602
01-175-10.2r	0.001779	0.0768	0.25	17	0.39	1060	17.9	231	344	−359	1.22	15	0.1738	1.9	0.127
01-175-11.1c	0.000043	0.0757	0	100	0.58	1086.4	10.3	1071	27	−1	1.9	1.7	0.1834	1	0.581
01-175-12.1c	0.000038	0.082	−0.02	120	0.71	1250	11.3	1233	23	−1	2.4	1.5	0.2138	0.9	0.618
01-175-13.1c	0.000037	0.0821	0.01	146	0.77	1245.8	30	1236	30	−1	2.4	2.9	0.2131	2.5	0.851
01-175-14.1c	0.000051	0.0786	0.06	120	0.74	1148.8	15.5	1144	18	0	2.09	1.7	0.195	1.4	0.846
01-175-15.1c	−0.000009	0.0843	0.04	149	0.75	1291	18.8	1302	15	1	2.58	1.7	0.2218	1.5	0.895
01-175-16.1c	0.000007	0.0765	−0.05	145	0.62	1118.8	10.2	1106	16	−1	2	1.2	0.1894	0.9	0.758
01-175-17.1c	0.000074	0.0794	0.24	133	0.76	1131.3	13.5	1156	20	2	2.08	1.6	0.1921	1.2	0.779
01-175-18.1c	0.000052	0.0785	0	170	0.76	1159.9	9.7	1141	16	−2	2.11	1.2	0.197	0.9	0.736
01-175-19.1c	0.000101	0.0735	0.06	91	0.66	1016	10.2	989	31	−3	1.69	1.8	0.1705	1	0.566
01-175-20.1c	0.000105	0.0726	−0.08	88	0.61	1020.9	15	960	29	−6	1.68	2.1	0.1711	1.5	0.729
01-175-20.2r	0.000222	0.0711	−0.07	27	0.84	978.2	13.7	867	119	−13	1.53	5.9	0.1631	1.5	0.248

SNP-96-1 garnetiferous granite (charnockite to farsundite) gneiss (Yg), Thornton Gap quadrangle, UTM coordinates: Easting: 0734 425, Northing: 4281 017

96-1-1Z-1.1c	0.00174	0.1039	2.91	195	0.41	1180.5	10.8	1179	135	0	2.2	6.9	0.2009	1.1	0.16
96-1-1Z-1.2c	0.000629	0.0856	1.06	210	0.4	1155.9	10.3	1112	64	−4	2.07	3.3	0.196	0.9	0.277
96-1-1Z-2.1c	0.000053	0.0768	0.09	366	0.44	1138.8	7.6	1096	18	−4	2.02	1.1	0.1928	0.7	0.608
96-1-1Z-2.2c	0.001334	0.0939	2.26	386	0.35	1156.8	8.4	1068	64	−8	2.02	3.3	0.1958	0.8	0.239
96-1-1Z-3.1r	0.000016	0.0737	0.03	1447	0.07	1090.5	4	1026	11	−6	1.86	0.7	0.1838	0.4	0.584
96-1-1Z-3.2r	0.000058	0.0746	0.1	593	0.63	1069.4	6.3	1035	18	−3	1.83	1.1	0.1802	0.6	0.561
96-1-1Z-4.1c	0.000086	0.0807	0.14	178	0.39	1220.3	12.9	1185	45	−3	2.28	2.5	0.208	1.1	0.433
96-1-1Z-5.1c	0.000238	0.0754	0.41	134	0.3	1068.7	11.8	987	46	−8	1.78	2.5	0.1797	1.1	0.453
96-1-1Z-6.1c	0.000088	0.0771	0.15	194	0.33	1108.3	10.1	1091	26	−2	1.96	1.6	0.1874	0.9	0.58
96-1-1Z-7.1c	0.000144	0.0814	0.24	168	0.75	1209.5	13.1	1182	30	−2	2.26	1.9	0.2061	1.1	0.597
96-1-1Z-8.1c	0.00007	0.0804	0.12	309	0.36	1185.5	8.5	1183	20	0	2.21	1.3	0.2019	0.7	0.588
96-1-1Z-9.1c	0.000158	0.0806	0.27	407	0.18	1079	7.7	1155	32	7	1.97	1.8	0.1828	0.7	0.418
96-1-1Z-10.1c	0.000054	0.0796	0.09	468	0.32	1175.4	10.6	1168	15	−1	2.17	1.2	0.1999	0.9	0.77
96-1-1Z-11.1c	0.000059	0.08	0.1	561	0.19	1263.8	7.7	1175	27	−8	2.35	1.5	0.2157	0.6	0.416
96-1-1Z-11.2r	0.000046	0.074	0.08	528	0.51	1053.1	6	1024	14	−3	1.79	0.9	0.1772	0.6	0.636
96-1-1Z-12.1c	0.000014	0.0813	0.02	413	0.37	1239.6	7.8	1223	18	−1	2.37	1.1	0.2119	0.6	0.576
96-1-1Z-13.1c	0.00009	0.0801	0.15	393	0.27	1183.8	8.5	1167	21	−1	2.19	1.3	0.2014	0.7	0.567
96-1-1Z-14.1c	0.000147	0.0807	0.25	242	0.38	1188.3	9.8	1163	35	−2	2.19	1.9	0.2022	0.9	0.44
96-1-1Z-15.1c	−0.000005	0.0853	−0.01	315	0.27	1385.7	9.7	1324	14	−5	2.81	1	0.239	0.7	0.716
96-1-1Z-16.1c	0.000088	0.0796	0.15	246	0.37	1110.4	10.3	1157	37	4	2.04	2.1	0.1884	0.9	0.455
96-1-1Z-17.1r	0.000086	0.0742	0.15	361	0.65	1044.3	7.3	1014	24	−3	1.77	1.4	0.1756	0.7	0.523
96-1-1Z-17.2c	0.000034	0.0804	0.06	218	0.65	1147	9.9	1194	24	4	2.15	1.5	0.1952	0.9	0.588
96-1-1Z-18.1c	0.000196	0.0801	0.33	579	0.3	1092.1	6.6	1131	28	3	1.97	1.5	0.1849	0.6	0.405
96-1-1Z-19.1c	0.000162	0.0793	0.27	148	0.35	1083.3	23.7	1122	32	3	1.95	2.8	0.1833	2.3	0.816
96-1-1Z-20.1c	0.000153	0.0796	0.26	210	0.36	1139.7	10.1	1132	27	−1	2.06	1.7	0.1933	0.9	0.555
96-1-1Z-21.1c	0.000036	0.0783	0.06	262	0.67	1182.3	9.3	1141	19	−4	2.15	1.3	0.2009	0.8	0.642

Table 2 (Continued)

Sample ^a (location)	Measured ²⁰⁴ Pb/ ²⁰⁶ Pb	Measured ²⁰⁷ Pb/ ²⁰⁶ Pb	% Common ²⁰⁶ Pb	U (ppm)	Th/U	²⁰⁶ Pb/ ²³⁸ U (Ma)	Err ^c (Ma)	²⁰⁷ Pb/ ²⁰⁶ Pb (Ma)	Err ^c (Ma)	Disc. %	²⁰⁷ Pb/ ²³⁵ U	Err ^c (%)	²⁰⁶ Pb/ ²³⁸ U	Err ^c (%)	Err corr
96-1-1Z-22.1c	0.000164	0.0796	0.28	117	0.51	1160	13.9	1127	35	−3	2.1	2.1	0.1968	1.2	0.582
96-1-1Z-23.1c	0.000224	0.0795	0.38	205	0.34	1116.7	11.3	1103	38	−1	1.99	2.2	0.189	1.1	0.483
96-1-1Z-24.1c	0.000015	0.0788	0.02	154	0.42	1080.5	11.4	1162	23	7	1.99	1.6	0.1832	1.1	0.681
SNP-03-198 garnetiferous granite (charnockite to farsundite) gneiss (Yg), Thornton Gap quadrangle, UTM coordinates: Easting: 0734 711, Northing: 4282 659															
03-198-1.1r	0.000003	0.0736	−0.05	244	1.56	1042.7	8.8	1031	27	−1	1.78	1.6	0.1755	0.9	0.539
03-198-2.1r	0.000054	0.0768	0.34	251	1.69	1040.8	8.5	1096	17	5	1.84	1.2	0.1757	0.8	0.713
03-198-3.1r	−0.000012	0.075	0.07	260	1.8	1053.7	8.8	1074	24	2	1.84	1.5	0.1777	0.9	0.579
03-198-4.1c	0.000026	0.0741	−0.13	707	0.14	1072.9	7.9	1033	9	−4	1.84	0.9	0.1808	0.8	0.873
03-198-5.1c	0.000005	0.0768	0.16	400	0.09	1080.2	8.6	1113	24	3	1.93	1.5	0.1827	0.8	0.557
03-198-6.1r	0.000001	0.075	0.14	240	1.49	1038.1	8.7	1069	17	3	1.81	1.2	0.175	0.9	0.711
03-198-6.2c	−0.000006	0.0761	0.12	565	0.34	1069.5	8	1099	26	3	1.9	1.5	0.1807	0.8	0.503
03-198-7.1r	0.000063	0.0755	0.14	308	1.39	1049.8	8.4	1058	25	1	1.82	1.5	0.1769	0.8	0.549
03-198-8.1c	−0.000004	0.0825	0.57	344	0.17	1141.4	17.9	1260	61	9	2.22	3.5	0.1948	1.6	0.454
03-198-10.1c	0.000016	0.0817	0.38	520	0.45	1158.1	10.2	1232	37	6	2.22	2.1	0.1975	0.9	0.425
03-198-11.1c	−0.000006	0.0758	−0.24	278	1.62	1142.4	9.3	1092	12	−5	2.02	1	0.1935	0.8	0.814
03-198-9.2c	0.000014	0.076	−0.7	325	0.15	1245.3	24.4	1091	41	−14	2.21	2.9	0.2116	2	0.699
03-198-12.1c	0.000025	0.0726	−0.14	462	0.3	1034.2	7.7	993	21	−4	1.73	1.3	0.1737	0.8	0.588
03-198-12.2r	0.000013	0.073	−0.11	743	0.2	1038.6	7.4	1009	10	−3	1.75	0.9	0.1746	0.7	0.82
03-198-13.1c	0.000105	0.0812	0.18	218	0.59	1190.3	12.2	1191	17	0	2.23	1.4	0.2028	1.1	0.771
03-198-13.1r	−0.000019	0.0777	0.15	265	1.55	1104.6	9.2	1145	28	4	2.01	1.7	0.1873	0.9	0.519
03-198-14.1c	0.000042	0.0788	−0.21	295	0.47	1213.3	9.5	1153	15	−5	2.23	1.1	0.2065	0.8	0.722
03-198-14.2r	0.000001	0.073	−0.23	308	0.92	1067.4	11.1	1014	15	−5	1.81	1.3	0.1797	1.1	0.83
03-198-15.1c	0.000042	0.076	−0.19	161	0.57	1138.5	10.6	1080	18	−5	2	1.3	0.1927	1	0.726
03-198-15.2r	0.000071	0.0727	−0.1	248	1.37	1028.7	8.4	977	16	−5	1.71	1.1	0.1726	0.8	0.738
03-198-16.1c	0.000057	0.0767	−0.26	178	0.29	1169.1	10.3	1093	48	−7	2.07	2.5	0.1981	0.9	0.352
03-198-17.1c	0.000012	0.081	−0.42	507	0.4	1304.2	13.1	1216	17	−7	2.49	1.3	0.2233	1	0.772
SNP-01-150 layered granodiorite (opdalite) gneiss (Ylgn), Chester Gap quadrangle, UTM coordinates: Easting: 0744 658, Northing: 4301 678															
01-150-1.1c	0.000006	0.0789	0.19	253	0.44	1131.2	19.7	1169	14	3	2.09	1.9	0.1921	1.8	0.931
01-150-2.1c	0.000047	0.0801	0.28	175	0.37	1138.7	10.7	1182	14	4	2.12	1.2	0.1936	1	0.807
01-150-3.1c	0.000009	0.0784	0.07	543	0.49	1142.9	26.8	1155	8	1	2.1	2.5	0.1941	2.4	0.986
01-150-4.1c	0.000022	0.0781	−0.02	204	0.43	1154.7	10.3	1142	14	−1	2.1	1.2	0.1961	0.9	0.799
01-150-5.1c	0.000019	0.0789	0.06	346	0.49	1156.1	9.1	1162	9	1	2.13	0.9	0.1965	0.8	0.866
01-150-6.1c	0.000027	0.0783	0.08	217	0.44	1136.2	13.8	1144	17	1	2.07	1.5	0.1928	1.3	0.823
01-150-7.1c	0.000032	0.0788	−0.02	172	0.52	1170.4	9.8	1155	15	−1	2.15	1.2	0.1989	0.9	0.747
01-150-8.1c	0.000039	0.0799	0.55	211	0.29	1076.5	9.2	1182	15	9	2	1.2	0.1826	0.9	0.766
01-150-9.1r	0.000022	0.0753	0.02	1125	0.18	1071.1	7.8	1067	10	0	1.87	0.9	0.1807	0.8	0.846
01-150-10.1c	−0.000045	0.0768	0.01	116	0.34	1113.3	10.4	1132	29	2	2.01	1.7	0.1887	1	0.554
01-150-11.1c	0.000127	0.077	−0.04	135	0.38	1129.9	11.9	1073	23	−5	1.98	1.6	0.1911	1.1	0.692
01-150-12.1c	0.000053	0.0807	0.25	191	0.41	1160	10.4	1195	22	3	2.18	1.4	0.1975	0.9	0.641
01-150-13.1c	0.000022	0.0787	0.13	127	0.33	1137.6	10.1	1158	18	2	2.09	1.3	0.1932	0.9	0.716
01-150-14.1c	0.000036	0.0793	−0.15	397	0.3	1212.1	9.8	1167	20	−4	2.24	1.3	0.2064	0.8	0.638
01-150-15.1c	0.000023	0.0795	−0.22	190	0.37	1228.8	11.8	1175	33	−5	2.29	1.9	0.2095	1	0.507
01-150-16.1c	−0.000006	0.0794	−0.12	298	0.42	1205.5	9.5	1183	19	−2	2.25	1.2	0.2054	0.8	0.653
01-150-17.1c	0.000037	0.08	0.28	188	0.35	1138.6	9.5	1185	24	4	2.12	1.5	0.1936	0.9	0.584
01-150-18.1c	−0.000005	0.0793	−0.24	270	0.43	1228.6	45.6	1181	32	−4	2.29	4.2	0.2095	3.9	0.922
01-150-19.1c	0.00004	0.08	0.06	230	0.42	1184.8	17	1184	14	0	2.21	1.7	0.2017	1.5	0.9
01-150-20.1c	0.000011	0.0822	0.01	186	0.39	1246.2	49.7	1246	22	0	2.41	4.3	0.2133	4.1	0.965
SNP-03-199 biotite-bearing leucocratic granitoid (Ylg2), Madison quadrangle, UTM coordinates: Easting: 0733 654, Northing: 4256 241															
03-199-1.1c	0.000014	0.0794	0.38	737	0.24	1101.1	17.6	1177	38	6	2.04	2.5	0.1869	1.7	0.653
03-199-2.1c	0.000118	0.0792	0.19	1406	0.24	1136.2	7.9	1134	24	0	2.06	1.4	0.1927	0.7	0.51
03-199-3.1c	0.000011	0.092	2.83	408	0.3	881.9	12.4	1174	49	25	1.62	2.9	0.1485	1.4	0.506
03-199-4.1c	0.000003	0.0799	−0.12	761	0.34	1219	16.4	1193	16	−2	2.29	1.6	0.2079	1.4	0.863
03-199-5.1r	0.000214	0.0777	0.36	3740	0.04	1057.8	7.3	1058	11	0	1.83	0.9	0.1783	0.7	0.796
03-199-6.1r	0.000003	0.0731	−0.07	5498	0.06	1033.6	7.1	1017	3	−2	1.75	0.7	0.1738	0.7	0.98

03-199-6.2r	0.001297	0.0924	1.85	3033	0.04	1117.1	12.2	1039	117	–8	1.92	5.9	0.1885	1.1	0.195
03-199-7.1c	–0.000006	0.0789	0.11	717	0.27	1145.6	8.4	1172	7	2	2.12	0.8	0.1947	0.8	0.902
03-199-8.1r	0.000022	0.074	–0.03	903	0.4	1049.8	7.4	1034	11	–2	1.8	0.9	0.1767	0.7	0.814
03-199-9.1c	0.000001	0.0775	–0.44	1412	0.76	1227.3	8.6	1135	5	–8	2.23	0.8	0.2088	0.7	0.943
03-199-10.1c	0.000003	0.0776	–0.11	683	0.37	1160.7	8.5	1135	7	–2	2.11	0.8	0.197	0.8	0.897
03-199-11.1c	0.000014	0.0789	0.09	740	0.33	1149.9	8.3	1165	28	1	2.12	1.6	0.1954	0.7	0.462
03-199-12.1r	0.000017	0.0742	–0.08	941	0.4	1063	7.5	1039	9	–2	1.83	0.9	0.1791	0.7	0.847
03-199-13.1c	0.000979	0.0896	0.52	518	0.27	1320.6	10.9	1089	92	–21	2.35	4.7	0.2248	0.8	0.174
03-199-14.1c	–0.000001	0.079	0.1	565	0.32	1149.7	9.9	1171	15	2	2.13	1.2	0.1954	0.9	0.756
03-199-15.1r	0.000012	0.077	–0.19	912	0.27	1162.8	8.3	1117	9	–4	2.09	0.9	0.1973	0.7	0.85
03-199-16.1c	0.000016	0.0775	–0.15	579	0.34	1166.5	11.6	1129	20	–3	2.11	1.4	0.198	1	0.721
03-199-17.1r	0.000011	0.075	0.02	891	0.41	1062.5	7.5	1064	13	0	1.85	1	0.1792	0.7	0.761
03-199-18.1c	0.000655	0.0858	2.01	585	1.03	900.8	6.6	1107	24	19	1.6	1.4	0.1513	0.8	0.531
03-199-19.1r	0.000317	0.079	0.66	417	0.4	1028.7	8.2	1056	34	3	1.78	1.9	0.1732	0.8	0.43
SNP-02-189 foliated megacrystic leucocratic granite (Ylg1), Madison quadrangle, UTM coordinates: Easting: 0733 654, Northing: 4256 241															
02-189-1.1c	0.000046	0.0806	0.08	196	0.34	1099.4	16.8	1195	60	8	2.06	3.4	0.1868	1.6	0.454
02-189-2.1c	0.000032	0.0779	0.05	318	0.34	1187.3	15.8	1134	33	–5	2.16	2.1	0.2017	1.4	0.64
02-189-3.1c	0	0.079	0	246	0.33	1195.8	21.1	1172	41	–2	2.22	2.8	0.2036	1.8	0.66
02-189-3.2c	0.000024	0.0785	0.04	340	0.57	1198.6	7.8	1151	11	–4	2.2	0.9	0.2039	0.7	0.775
02-189-4.1c	0.000007	0.0784	0.01	547	0.32	1168.4	9	1154	16	–1	2.14	1.2	0.1986	0.8	0.693
02-189-4.2r	0.000156	0.0787	0.26	802	0.24	1206.8	9.6	1108	31	–9	2.16	1.7	0.2049	0.8	0.466
02-189-5.1c	0.000113	0.0782	0.19	182	0.31	1081.7	8	1111	25	3	1.93	1.5	0.1829	0.8	0.52
02-189-5.2c	0.00004	0.0811	0.07	215	0.32	1133.9	8.1	1209	27	6	2.14	1.6	0.193	0.7	0.465
02-189-5.3r	0.000013	0.0748	0.02	497	0.17	951	9.6	1059	18	10	1.64	1.4	0.1597	1	0.766
02-189-6.1c	0.000028	0.0804	0.05	435	0.39	1152.5	7.5	1196	10	4	2.16	0.8	0.1962	0.7	0.794
02-189-7.1c	0.000016	0.0806	0.03	747	0.31	1141.3	7.9	1207	19	5	2.15	1.2	0.1943	0.7	0.596
02-189-8.1c	–0.000007	0.0778	–0.01	548	0.14	1137.2	12.1	1143	43	1	2.07	2.4	0.193	1.1	0.444
02-189-8.2r	0.0001	0.0772	0.17	676	0.14	1095.4	7	1089	36	–1	1.93	1.9	0.1852	0.6	0.337
02-189-9.1c	0.000037	0.0802	0.06	322	0.31	1143.9	7.9	1189	32	4	2.14	1.8	0.1946	0.7	0.393
02-189-10.1r	0.000064	0.0738	0.11	168	0.22	1026.5	7.8	1012	24	–1	1.73	1.4	0.1725	0.8	0.553
02-189-11.1c	0.000014	0.0801	0.02	296	0.31	1082.2	7.3	1194	17	9	2.02	1.1	0.1837	0.7	0.636
02-189-12.1c	–0.000021	0.0791	–0.04	389	0.31	1108.5	12.6	1182	33	6	2.06	2.1	0.1883	1.2	0.572
02-189-13.1c	0.000014	0.0806	0.02	495	0.31	1146.9	16	1207	26	5	2.17	2	0.1953	1.4	0.735
02-189-13.2r	0.000023	0.0777	0.04	482	0.31	1183.1	12.1	1132	29	–5	2.15	1.8	0.201	1.1	0.583
02-189-14.1c	0	0.0785	0	343	0.36	1124.9	10.8	1159	24	3	2.07	1.5	0.1909	1	0.642
02-189-15.1c	0.000038	0.0809	0.06	276	0.38	1143	8.1	1205	27	5	2.15	1.5	0.1946	0.7	0.468
02-189-16.1r	0.000012	0.0736	0.02	1309	0.07	1002.2	6	1027	19	2	1.71	1.1	0.1684	0.6	0.538
02-189-16.2c	0.000009	0.0877	0.01	526	1.26	1333.4	8.3	1372	8	3	2.78	0.8	0.2303	0.6	0.846
02-189-16.3c	0	0.0788	0	224	0.35	1138.1	13.4	1167	25	2	2.1	1.7	0.1933	1.2	0.695
02-189-17.1r	0.00001	0.0743	0.02	503	0.62	1003.7	6.6	1045	12	4	1.72	0.9	0.1688	0.7	0.76
02-189-17.2c	0.000044	0.0792	0.07	223	0.41	1116.7	11	1162	24	4	2.05	1.6	0.1895	1	0.646
02-189-17.3r	0.003651	0.1208	6.31	83	1.22	989.5	9.3	881	184	–12	1.56	9	0.1652	1.2	0.132

^a Sample names containing the suffix “m” are monazite; all other samples are zircon.

^b ²⁰⁶Pb/²³⁸U ages corrected for common Pb using the ²⁰⁷Pb-correction method; ²⁰⁷Pb/²⁰⁶Pb ages corrected for common Pb using the ²⁰⁴Pb-correction method. Decay constants from Steiger and Jäger (1977).

^c 1-Sigma errors.

^d Radiogenic ratios, corrected for common Pb using the ²⁰⁴Pb-correction method, based on the Stacey and Kramers (1975) model.

^e All coordinates refer to UTM Grid Zone 17 NAD 27.

Table 3

Summary of U–Pb SHRIMP geochronologic data for the Virginia Blue Ridge province in northern Virginia

Magmatic Interval	Lithologic unit	Sample	Sample location (Fig. 3)	Figure	Igneous crystallization age (Ma)	Metamorphic recrystallization age (Ma)	Inheritance (Ma)
III	Ybg	SNP-02-186	15	Fig. 5B	1028 ± 9		~1.2 Ga
	Yfqj ^a	SNP-99-93	14	–	1050 ± 8	1018 ± 14	
	Ygr ^a	OR-97-35	13	–	1060 ± 5	1027 ± 9 (m ^b)	~1.2–1.3 Ga
					1059 ± 8 (m)	1019 ± 15	
	Ygg	SNP-02-197	12	Fig. 5D	1063 ± 8	979 ± 11	
					1059 ± 6 (m)	1010 ± 14 (m)	~1090–1160
II	Ygg	SNP-01-170	11	Fig. 5F	Undetermined	0.94–0.99 Ga	~1.2 Ga
	Ylgg ^a	SNP-99-90	10	–	1078 ± 9	1028 ± 10	
						997 ± 19	
	Yfe	SNP-03-204	9	Fig. 6B	1111 ± 16	1051 ± 20	~1.2–1.3 Ga
	Yfpg	SNP-02-177	8	Fig. 6D	1120 ± 12	1050 ± 12	1178 ± 14
	Yfh	SNP-01-146	7	Fig. 6F	1144 ± 8	–	~1.2 Ga
I	Ycf ^a	SNP-96-10	6	–	1159 ± 14	1052 ± 14	~1.2 Ga
	Ypqd	SNP-02-175	5	Fig. 7B	1161 ± 10	1095 ± 22	1.2–1.3 Ga
						0.96–1.04 Ga	
	Yg	SNP-96-1	4	Fig. 7D	1164 ± 8	1.03–1.06 Ga	~1.2–1.3 Ga
	Yg	SNP-03-198	3	Fig. 7F	Undetermined	0.98–1.04 Ga	~1.2 Ga
	Ylgn	SNP-01-150	2	Fig. 8B	1165 ± 7	ca. 1200	~1.2 Ga
	Ylg2	SNP-03-199	1	Fig. 8D	1175 ± 11	1131 ± 7	~1.2–1.3 Ga
						1045 ± 11	
	Ylg1	SNP-02-189	1	Fig. 8F	1183 ± 11	1.01–1.09 Ga	~1.2–1.3 Ga

^a Data from Tollo et al. (2004a).^b Monazite; all other ages from zircon.

5.2. Results from U–Pb geochronology

5.2.1. Biotite-rich monzogranite to quartz monzodiorite, sample SNP-02-186

Biotite-rich monzogranite to quartz monzodiorite (Ybg) was collected for isotopic analysis in the Madison quadrangle (locality 15, Fig. 3). The outcrop is composed of foliated, medium- to coarse-grained, biotite-rich granitoid that contains several meter-scale xenoliths of leucocratic granite from the neighboring Ylg complex (Bailey et al., 2003; Tollo et al., 2004c). Zircons from this rock are light brown to colorless, elongate (length-to-width ratio (l/w) of 3–5), and typically clear with few inclusions or imperfections. Most grains have unusual CL zoning that is indistinct and irregular; a few zircons show faint oscillatory zoning (Fig. 5A). This pale CL zoning is reflective of the very low uranium concentrations (about 17–75 ppm) of the zircons which result in relatively imprecise $^{207}\text{Pb}/^{206}\text{Pb}$ ages (Table 2). SHRIMP results indicate that 16 of 20 analyses (14 cores and 2 overgrowths) are concordant and yield a Concordia Age

of 1028 ± 9 Ma (Fig. 5B) that we interpret as the time of igneous crystallization. Three analyses of overgrowths are slightly younger (ages of about 1.0 Ga) and two analyses of cores are older (ages ~1.25 Ga).

5.2.2. Garnetiferous syenogranite, samples SNP-02-197 and SNP-01-170

Two samples of garnetiferous syenogranite (Ygg) were collected in the Chester Gap quadrangle (localities 12 and 11, Fig. 3). The outcrop at locality 12 is composed of weakly foliated, medium-grained, garnet + biotite leucogranite. The outcrop at locality 11 is composed of weakly foliated, medium- to coarse-grained garnet + biotite syenogranite that is typical of the main pluton.

Zircons from both samples occur as two distinct morphologies (Fig. 5C and E). Elongate ($l/w=3-4$) grains are medium to dark brown and typically contain numerous fractures that are mostly concentrated in core regions. CL imaging shows that most of these grains are composed of partially resorbed cores of igneous ori-

Fig. 5. CL images of zircons (left) and Concordia and weighted averages plots of SHRIMP isotopic data (right) obtained by analyses of zircons from biotite-rich monzogranite (Ybg, A and B) and garnetiferous syenogranite (Ygg, sample SNP-02-197, C and D; sample SNP-01-170, E and F). Solid lines in C separate observed cores and overgrowths.

gin with remnant oscillatory zoning and large, dark (in CL), unzoned metamorphic overgrowths. The darkness of the CL images is indicative of the high U content (mostly 1000–2000 ppm) of zircons from both samples. Core material has Th/U of 0.16–0.41, typical of

igneous zircon, whereas overgrowths have lower Th/U (0.01–0.05) typical of metamorphic origin. Metamorphic material occurs both around and within the damaged older cores (Fig. 5C and E). The proportion of igneous cores generally ranges from about 10 to 50%; some

grains contain no apparent core material. Because the cores are small, resorbed, fractured, and locally invaded by metamorphic zircon, it was difficult to locate pristine areas for SHRIMP analysis. Also present are equant grains ($l/w=1$), each of which is composed of a fragment of an oscillatory-zoned zircon overgrown by a thick metamorphic rim (Fig. 5C).

Monazite from SNP-02-197 is pale yellow and anhedral to subhedral. In BSE, most grains show patchy- or oscillatory-zoned cores and broad, unzoned rims. The zoning distinctions are also reflected in chemical data. Although cores and rims have similar ranges of Th concentrations (~ 6000 – $10,000$ ppm), concentrations of U in cores (~ 500 – 1100 ppm) is higher than in rims (~ 400 – 600 ppm). Th/U in cores (~ 6 – 16) is somewhat lower than in rims (~ 13 – 28).

Ten analyses of zircon from sample SNP-02-197 yield a coherent age of 1063 ± 8 Ma (Fig. 5D). Some zircons contain inherited cores with ages ranging from 1.09 to 1.16 Ga. Primary, oscillatory-zoned regions are crosscut by relatively unzoned material (analogous to overgrowths) two analyses of which yielded ages of about 1.01 and 1.03 Ga. The second sample (SNP-01-170) produced very poorly preserved zircons from which it was impossible to obtain a magmatic age due to the very small size of the remnant igneous cores (Fig. 5E). Overgrowths have typically low Th/U (0.06–0.07) and yielded metamorphic ages of about 0.94–0.99 Ga (Fig. 5F).

Isotopic data from 11 cores of monazite from sample SNP-02-197 result in a Concordia Age of 1062 ± 5 Ma, in agreement with data from cores of co-existing zircon (Fig. 5D). Somewhat older ages (~ 1090 – 1130 Ma) were obtained from three oscillatory-zoned cores, indicating the occurrence of inherited material in some of the monazites. Two ages (1046 ± 13 and 1010 ± 14 Ma, based on five analyses each) of rims are in agreement with very limited data from rims of co-existing zircon.

5.2.3. Equigranular pyroxene monzogranite (*farsundite*), sample SNP-03-204

Weakly foliated, medium-grained, equigranular, opx-bearing monzogranite (Yfe) was collected in the Big Meadows quadrangle (locality 9, Fig. 3). Zircons are medium brown and elongate ($l/w=3$ – 4). CL imaging shows that the cores are broadly oscillatory-zoned (Fig. 6A); a few grains contain very small, dark overgrowths. Uranium content of oscillatory-zoned cores is low (mostly 100–200 ppm) and yielded relatively imprecise $^{207}\text{Pb}/^{206}\text{Pb}$ ages (Table 2). Sixteen analyses overlap in an array between about 1.0 and 1.2 Ga (Fig. 6B). The weighted average of these analyses is 1098 ± 18 Ma

(MSWD = 3.1). However, subdividing this group solely on the basis of age (most grains have similar morphologies) results in ages of 1111 ± 16 Ma (MSWD = 1.7; 12 analyses) and 1051 ± 20 (MSWD = 0.24; 4 analyses). Further complicating the interpretation is that each subgroup contains data from an apparent overgrowth. We cautiously interpret a crystallization age of 1111 ± 16 Ma. Inherited material is also present, ranging in age from about 1.19 to 1.34 Ga.

5.2.4. Foliated pyroxene monzogranite (*farsundite*), sample SNP-02-177

Strongly foliated, medium- to coarse-grained, pyroxene monzogranite (Yfpg) was collected in the Chester Gap quadrangle (locality 8, Fig. 3). Zircons from this sample are dark brown and stubby to elongate ($l/w=2$ – 4). Many grains contain partially resorbed cores (presumably inherited), broad igneous mantles showing fine oscillatory zoning in CL, and moderate-sized, dark (in CL), unzoned overgrowths (Fig. 6C). Uranium concentrations of both mantles and overgrowths is intermediate (mostly 200–700 ppm) (Table 2). Fourteen analyses of the oscillatory-zoned mantles yield an age of 1120 ± 12 Ma, interpreted as the time of crystallization (Fig. 6D). An older (1178 ± 14 Ma) generation of oscillatory-zoned zircon is locally similar in appearance to the 1120 Ma mantles. However, a few resorbed cores are also this age, suggesting that this 1178 Ma material was inherited from the source. Overgrowths are dated at 1050 ± 12 Ma.

5.2.5. Flint Hill Gneiss, sample SNP-01-146

Strongly foliated, medium-grained, syenogranite gneiss (Yfh) that locally displays centimeter- to decimeter-scale compositional layering oriented parallel to foliation was collected in the Chester Gap quadrangle (locality 7, Fig. 3). Zircons are light to medium brown and stubby to somewhat elongate ($l/w=2$ – 3). Most grains are composed of igneous mantles of finely oscillatory-zoned material overgrown by thin, dark (in CL) rims of metamorphic origin; some grains contain inherited cores (Fig. 6E). Uranium concentrations are intermediate (mostly 300–600 ppm) (Table 2). Sixteen analyses (13 cores and 3 overgrowths) yield an age of 1144 ± 8 Ma, interpreted as the time of protolith crystallization (Fig. 6F). Inherited material of circa 1.2 Ga age also is present in some grains. Four young ages (about 1.03–1.10 Ga) are from oscillatory-zoned grains that are similar in appearance to the older grains. These analyses are excluded from the age calculation because of their significantly younger age.

Fig. 6. CL images of zircons (left) and Concordia and weighted averages plots of SHRIMP isotopic data (right) obtained by analyses of zircons from equigranular pyroxene monzogranite (Yfe, A and B), foliated pyroxene monzogranite (Yfpg, C and D), and Flint Hill Gneiss (Yfh, E and F).

5.2.6. Pyroxene quartz diorite (*orthopyroxene quartz diorite*), sample SNP-02-175

Strongly foliated, medium-grained, opx + biotite-bearing quartz diorite (Ypqd) was collected in the Chester Gap quadrangle (locality 5, Fig. 3). The road-cut exhibits weak compositional layering that is locally deformed into tight folds with axial planes oriented parallel to foliation. Zircons are light to medium brown and either elongate ($l/w=3-4$) or equant ($l/w=1$). Igneous cores exhibit broad oscillatory zoning; overgrowths appear either very light or medium dark in CL (Fig. 7A). Cores contain relatively low U contents (mostly 100–200 ppm); most overgrowths are even lower in U (mostly 25–100 ppm). Both cores and overgrowths have similar Th/U values (0.39–0.84).

Age data from this unit define multiple populations. Nine analyses result in a Concordia Age of 1161 ± 10 Ma, interpreted as the time of protolith crystallization (Fig. 7B). Four broadly zoned zircons of generally similar appearance yield an apparent age of 1095 ± 22 Ma; however, this age may be due to Pb-loss, not new growth of zircon. Three other grains yield older ages of about 1.23–1.30 Ga, and are considered to be inherited. Also present are distinctly younger grains with ages about 0.96–1.04 Ga that are interpreted to have formed during regional metamorphism.

5.2.7. Garnetiferous granite (*charnockite to farsundite*) gneiss, samples SNP-96-1 and SNP-03-198

Two samples of strongly foliated, opx + garnet-bearing syeno- to monzogranite (*charnockite to farsundite*) gneiss (Yg) were collected within an elongate inlier in the Thornton Gap quadrangle (localities 4 and 3, Fig. 3). Zircons from locality 4 are medium to dark brown and elongate ($l/w=2-4$) (Fig. 7C). Most grains include oscillatory-zoned igneous mantles and wide, dark metamorphic overgrowths. Zircons from locality 3 are similar in shape and color (Fig. 7E). However, the proportion of overgrowth is much greater; in many grains, only a tiny remnant core remains, overgrown by extensive dark (in CL) rims. Uranium content of cores and overgrowths is intermediate (mostly about 150–600) (Table 2); both have relatively high Th/U values (mostly 0.2–0.7). Meaningful isotopic data indicative of the igneous age of the gneiss were obtained only from zircons from locality 4.

Twelve analyses from sample SNP-96-1 result in a Concordia Age of 1164 ± 8 Ma (Fig. 7D), interpreted as the time of crystallization of the protolith. Several other analyses have similar $^{207}\text{Pb}/^{206}\text{Pb}$ ages but are slightly discordant; these data were excluded from the

Concordia Age calculation. Ages of 1.22 and 1.32 Ga from two oscillatory-zoned grains suggest that these zircons are xenocrysts. Also present are some dark (in CL) metamorphic overgrowths that yielded ages of 1.01–1.04 Ga. In zircons from sample SNP-03-198, Th/U varies widely (0.09–1.8) in both cores and overgrowths. Small, resorbed cores in sample SNP-03-198 did not yield a coherent age population (Fig. 7F). Metamorphic overgrowths from this sample are about 0.98–1.04 Ga.

5.2.8. Layered granodiorite (*opdalite*) gneiss, sample SNP-01-150

Strongly foliated, medium- to locally coarse-grained, opx + amphibole-bearing granodiorite (*opdalite*) gneiss (Ylgn) was collected in the Chester Gap quadrangle (locality 2, Fig. 3). Zircons are light to medium brown and elongate ($l/w=3-4$) (Fig. 8A). Most grains are composed of oscillatory-zoned igneous mantles and small, dark (in CL) metamorphic overgrowths. The light color of the zircons is due to the relatively low U content (mostly 100–300 ppm). Seventeen analyses yield an age of 1165 ± 7 Ma, interpreted as the time of protolith crystallization (Fig. 8B). One overgrowth, with low Th/U of 0.18, was dated at about 1.07 Ga; an inherited core yielded an age of about 1.25 Ga.

5.2.9. Leucocratic granitoid and foliated megacrystic leucocratic granite (Ylg2 and Ylg1), samples SNP-03-199 and SNP-02-189, respectively

Two samples were collected from the leucogranite complex (Ylg) in the Madison quadrangle (locality 1, Fig. 3). Sample SNP-03-199 was collected from medium-grained, equigranular biotite leucogranite (Ylg2) that occurs as dikes which crosscut associated coarser-grained granitoid. Sample SNP-02-189 was collected from foliated megacrystic biotite-bearing leucocratic granite (Ylg1) exposed nearby.

Zircons from the medium-grained leucogranite (Ylg2) are medium to dark brown and either elongate ($l/w=3-4$) or equant ($l/w=1$) (Fig. 8C). All elongate grains are composed of highly fractured mantles that show fine oscillatory zoning and thin to moderate, dark (in CL), unzoned overgrowths. Some grains contain small, inherited cores. Uranium contents of mantles are moderate (mostly about 500–900 ppm) (Table 2). Ten analyses of oscillatory-zoned mantles yield two apparently distinct age groupings: 1175 ± 11 and 1131 ± 7 Ma (Fig. 8D). These groups are distinguished on the basis of age only; all grains in both groups have similar morphology. Overgrowths, some of which have low Th/U of 0.04–0.06, are dated at 1045 ± 11 Ma. Two possible

Fig. 7. CL images of zircons (left) and Concordia and weighted averages plots of SHRIMP isotopic data (right) obtained by analyses of zircons from orthopyroxene quartz diorite (Ypqd, A and B) and garnetiferous granitic gneiss (Yg, sample SNP-96-1, C and D; sample SNP-03-198, E and F).

interpretations of the age data from the mantles are that the rock: (1) crystallized at about 1175 Ma and was metamorphosed at about 1131 Ma, or (2) crystallized at about 1131 Ma and contains xenocrystic 1175 Ma zircons possibly derived from Ylg1.

Zircons from the megacrystic granite (Ylg1) are medium brown and elongate ($l/w = 3-4$) (Fig. 8E). Most grains are composed of broad mantles showing fine oscillatory zoning and dark (in CL) overgrowths. Uranium contents (mostly about 200–500 ppm) of igneous

Fig. 8. CL images of zircons (left) and Concordia and weighted averages plots of SHRIMP isotopic data (right) obtained by analyses of zircons from layered granodiorite gneiss (Ylgn, A and B), leucocratic granitoid (Ylg2, C and D) and foliated megacrystic leucocratic granite (Ylg1, E and F).

mantles are lower than in zircons from Ylg2. Seventeen analyses yield a coherent age group at $1183 \pm 11 \text{ Ma}$ (Fig. 8F), interpreted as the igneous crystallization age. Five of six metamorphic overgrowths have relatively low

Th/U values and have ages of about 1.01–1.09 Ga. The significantly different U contents of circa 1175–1185 Ma zircons in Ylg2 and Ylg1 (Table 2) suggest that the older population of zircon in Ylg2 are not inherited from Ylg1.

Thus, the combination of field relations, petrologic characteristics, and zircon systematics suggests that the leucocratic granitoid (Ylg2) formed at about 1175 Ma (i.e. shortly after emplacement of Ylg1). Zircons of 1131 Ma age in Ylg2 record a younger event, perhaps related to local generation of undated pegmatite.

5.3. Summary of geochronologic data

The new geochronologic data (Table 3), combined with ages reported by Aleinikoff et al. (2000) and Tollo et al. (2004a), indicate that Grenvillian magmatism in the Blue Ridge occurred during three major periods: Magmatic Interval I, 1183–1144 Ma; Magmatic Interval II, 1120–1111 Ma; and Magmatic Interval III, 1078–1028 Ma. A major episode of deformation peaked at 1078–1050 Ma but continued to affect rocks for 20 m.y. Isotopic evidence further suggests that temperatures remained elevated until about 980 Ma.

6. Major- and trace-element geochemistry

A total of 135 samples were analyzed for major- and trace-element compositions. Data for representative samples from each lithologic unit shown in Fig. 3 are presented in Table 4.

6.1. Analytical methods

Powders were prepared from samples weighing 20–40 kg by crushing using a steel jaw apparatus and grinding in a shatterbox. Powder subsplits were analyzed for major elements and trace elements including Rb, Ba, Sr, Pb, Zr, Nb, Ni, Zn, Cr, Ga, V, and Y by X-ray fluorescence (XRF) techniques at the Gilmore Laboratory at the University of Massachusetts in Amherst using methods modified from Norrish and Chappell (1967) and Norrish and Hutton (1969). All samples were analyzed in duplicate. Abundances of rare-earth elements (REE) and Th, U, Hf, Ta, and Sc were determined using instrumental neutron activation techniques at Oregon State University.

6.2. Major-element characteristics

Whole-rock compositions define a broad data array encompassing a range of ~30% in SiO₂ content (Fig. 9). Compositional variation defines steep gradients in TiO₂ and P₂O₅ contents (Fig. 9A and B, respectively) which, together with relatively low CaO contents at low silica concentrations (Fig. 9E), are features characteristic of igneous charnockites (Kilpatrick and Ellis, 1992). Most

lithologic units are silica-rich with SiO₂ contents >65%. Considered in terms of lithologic types, all leucogranites are silicic, including the most silica-rich rocks in the region (Fig. 9). Non-leucocratic granitoids are broadly similar to the leucogranites but with generally lower SiO₂ contents (Fig. 9). The petrologically unrelated low-silica charnockites (Ypqd and Yfqj) are characterized by silica contents <65% and by typically high concentrations of compatible major elements (Fig. 9). Biotite-rich monzogranite (Ybg) spans the compositional gap between high- and low-silica rocks (Fig. 9). The only other lithologic unit of broadly intermediate composition, layered opx-bearing granodiorite gneiss (Ylgn), shares many chemical characteristics with the non-leucocratic granitoids and is considered part of that group (Table 1).

Nearly all rocks are subalkaline (Fig. 9F), and over 90% of the analyses plot within the ferroan field of Frost et al. (2001) (Fig. 9G), indicating strong tholeiitic affinity. However, samples of the circa 1160 Ma low-silica charnockite (Ypqd) plot within the magnesian field and thus display compositional similarity to arc-related Cordilleran granites. Most Blue Ridge granitoids are characterized by marked K enrichment (Fig. 9H) regardless of age, presence or absence of opx, and degree of alteration. Low-silica charnockite of Magmatic Interval I (Ypqd) is compositionally distinct in this regard as well, characterized by only moderate K enrichment.

Aluminum saturation indices (ASI) vary considerably with rock type (Fig. 10). All leucogranitic units are peraluminous (ASI > 1.0) (Fig. 10A and C), whereas non-leucocratic granitoids (with or without opx) are borderline metaluminous to weakly peraluminous (ASI = 0.95–1.1) (Fig. 10B and C). Low-silica charnockites are borderline to strongly metaluminous (ASI ≤ 0.7–1.1) (Fig. 10A and C) and the intermediate biotite monzogranite (Ybg) is transitional between the high- and low-silica groupings (Fig. 10A). Considered in terms of age, granitoids of Magmatic Interval III show the greatest compositional variation, defining a continuum of compositions ranging from strongly metaluminous to moderately peraluminous and spanning the entire silica spectrum of the regional suite (Fig. 10A). Granitoids emplaced during Magmatic Intervals II and I are borderline metaluminous (dominantly charnockites) to moderately peraluminous (leucogranites) (Fig. 10B and C).

6.3. Trace-element characteristics

Mesoproterozoic rocks of the northern Blue Ridge display systematic variation in trace-element concen-

Table 4
Geochemical compositions of representative samples

Map unit sample	Ylg1 (z) SNP-02-189Z	Ylg2 (z) SNP-03-199	Ylgn SNP-01-148	Ylgn (z) SNP-01-150	Yg SNP-96-5	Yg (z) SNP-03-198	Ypqq SNP-01-154	Ypqq (z) SNP-01-175
SiO ₂ ^a	72.01	75.67	64.89	66.67	68.77	72.09	56.68	55.29
TiO ₂	0.39	0.14	0.94	0.80	0.61	0.41	1.45	1.71
Al ₂ O ₃	14.28	12.65	15.86	15.53	14.67	14.28	17.81	16.49
Fe ₂ O ₃ ^b	2.71	0.85	5.73	4.97	4.19	3.00	8.35	9.33
MnO	0.04	0.02	0.07	0.08	0.06	0.04	0.09	0.14
MgO	0.42	0.01	1.22	0.85	0.63	0.43	3.53	4.78
CaO	1.58	0.61	4.13	3.49	2.33	1.76	5.40	6.54
Na ₂ O	2.63	3.02	3.13	2.96	2.94	2.53	3.50	3.00
K ₂ O	5.41	6.73	3.91	4.21	5.19	5.48	2.25	2.00
P ₂ O ₅	0.09	0.02	0.23	0.20	0.17	0.13	0.52	0.52
Total	99.55	99.71	100.10	99.76	99.57	100.16	99.58	99.80
Rb	199.0	237.1	139.4	186.7	179.2	177.1	53.7	57.9
Ba	675	126	732	935	960	911	787	1030
Sr	130	60	218	209	169	145	987	993
Pb	30	46	24	25	28	30	16	11
Th ^c	8.13	34.64	3.18	3.78	10.6	1.14	11.86	<0.59
U	0.7	15.3	0.7	1.4	n.d.	n.d.	0.7	<0.63
Zr	147	75	396	369	295	215	338	188
Hf	7.24	4.53	11.88	11.16	10.2	8.17	10.60	6.55
Nb	7.7	3.9	13.1	10.5	8.9	6.9	9.7	6.7
Ta	0.49	0.16	1.22	1.20	0.80	0.40	0.57	0.70
Ni	4	1	5	4	5	5	24	32
Zn	42	20	86	80	62	53	138	130
Cr	23	19	46	35	31	28	95	144
Ga	20	17	23	22	21	19	26	25
Sc	6.474	3.19	15.80	13.16	9.68	6.64	17.83	20.24
V	27	1	51	43	28	18	134	161
La	54.3	81.7	49.0	48.1	59.5	58.0	84.6	39.2
Ce	93.3	144.4	115.5	97.5	107.0	93.8	177.0	79.4
Nd	38	58.7	58.1	52	51	42.5	85	47
Sm	6.83	11.25	11.74	10.17	9.84	8.22	13.19	8.43
Eu	1.27	0.52	2.03	1.84	1.75	1.59	3.40	2.66
Tb	0.89	0.96	1.85	1.89	1.22	1.20	1.23	1.04
Yb	1.81	1.22	5.0	4.87	2.4	3.77	1.7	1.80
Lu	0.24	0.15	0.69	0.71	0.26	0.58	0.23	0.28
Y	19.1	10.6	56.6	48.7	25	32.5	23.4	21.8
10 ⁴ × Ga/Al	2.65	2.54	2.74	2.68	2.70	2.51	2.76	2.86
FeOt/(FeOt + MgO)	0.85	0.98	0.81	0.84	0.86	0.86	0.68	0.64
A.S.I. (m)	1.10	0.95	0.96	1.00	1.01	1.09	1.03	0.90

Table 4 (Continued)

Map unit sample	Ycf SNP-96-4A	Ycf SNP-97-20	Yfh SNP-99-70	Yfh (z) SNP-01-146	Yfpg SNP-02-176	Yfpg (z) SNP-02-177	Yfe (z) SNP-03-204	Yfe SNP-03-205
SiO ₂ ^a	71.80	69.48	69.92	69.69	67.83	67.36	66.88	67.44
TiO ₂	0.55	0.64	0.50	0.58	0.74	0.78	0.79	0.76
Al ₂ O ₃	13.05	14.47	14.78	15.21	14.97	14.73	14.55	14.62
Fe ₂ O ₃ ^b	3.48	4.04	3.07	3.80	4.86	5.34	6.19	6.03
MnO	0.06	0.07	0.04	0.05	0.06	0.08	0.10	0.10
MgO	0.49	0.43	0.92	0.68	0.90	0.95	0.98	0.90
CaO	1.71	2.26	2.16	1.87	2.73	2.72	2.76	2.75
Na ₂ O	2.45	2.52	3.53	2.34	2.71	2.73	2.58	2.64
K ₂ O	5.87	5.68	4.21	6.13	4.85	4.83	4.90	4.85
P ₂ O ₅	0.11	0.16	0.18	0.15	0.19	0.22	0.24	0.22
Total	99.56	99.75	99.29	100.49	99.84	99.74	99.96	100.31
Rb	270.5	187.8	120	166.7	191.9	186.2	153.8	164.4
Ba	424	806	841	951	841	863	1034	977
Sr	79	118	363	170	165	161	171	176
Pb	32	27	23	28	28	28	24	28
Th ^c	6.0	2.3	17.9	3.19	6.5	15.00	0.38	2.03
U	0.6	0.6	2.18	n.d.	0.7	1.5	0.7	0.9
Zr	271	264	187	239	277	336	308	315
Hf	8.1	10.1	5.63	9.26	11.16	13.07	11.61	11.21
Nb	7.4	7.7	8.8	8.6	8.9	10.4	14.3	12.8
Ta	0.46	0.87	0.64	0.50	1.10	1.10	0.98	1.16
Ni	3	3	7	5	6	8	8	7
Zn	49	71	53	64	68	77	105	110
Cr	33	28	36	27	34	39	40	33
Ga	21	21	19	20	22	22	22	22
Sc	6.88	8.37	7.29	10.84	11.88	12.57	16.12	16.04
V	21	25	33	33	44	49	45	40
La	55.3	48.4	41	46.2	55.8	69.5	43.0	66.0
Ce	112.4	86.3	94.5	100.4	107.5	129.2	91.1	111.5
Nd	52	41	39.1	42.9	49	61	46.4	55.8
Sm	12.72	9.16	8.6	7.06	9.56	10.82	10.08	12.52
Eu	1.35	1.93	1.49	1.83	1.76	1.72	2.16	2.27
Tb	1.50	1.43	0.99	0.85	0.00	0.00	1.58	1.65
Yb	4.3	3.8	1.92	1.9	3.87	3.9	4.74	5.53
Lu	0.58	0.43	0.36	0.27	0.54	0.57	0.74	0.87
Y	48	41.5	26.5	20.5	39.5	40.1	45.8	48.9
10 ⁴ × Ga/Al	3.04	2.74	2.43	2.48	2.78	2.82	2.86	2.84
FeOt/(FeOt + MgO)	0.86	0.90	0.75	0.83	0.83	0.84	0.85	0.86
A.S.I. (m)	0.98	1.02	1.05	1.11	1.04	1.03	1.08	1.02

Table 4 (Continued)

Map unit sample	Ylgg SNP-99-90A	Ylgg (z) SNP-99-90B	Ygg (z) SNP-01-170	Ygg (z) SNP-03-197	Ygr OR-97-36	Ygr OR-97-59	Yfqj SNP-00-121	Yfqj SNP-03-200
SiO ₂ ^a	75.35	74.26	75.18	64.10	73.64	71.89	62.37	59.27
TiO ₂	0.04	0.20	0.28	0.23	0.24	0.45	1.83	1.94
Al ₂ O ₃	13.74	13.93	12.84	18.44	13.88	14.23	13.90	14.77
Fe ₂ O ₃ ^b	0.47	1.94	2.16	6.59	1.86	2.87	8.04	9.53
MnO	0.01	0.02	0.04	0.26	0.05	0.06	0.11	0.13
MgO	0.02	0.22	0.14	0.28	0.24	0.48	1.54	1.30
CaO	0.36	0.79	0.94	2.92	1.08	1.54	4.10	5.26
Na ₂ O	2.59	3.15	2.27	4.13	2.49	2.44	2.69	2.79
K ₂ O	7.35	6.16	5.71	2.71	6.16	6.08	4.43	3.53
P ₂ O ₅	0.02	0.04	0.06	0.11	0.06	0.13	0.81	0.98
Total	99.95	100.71	99.61	99.77	99.70	100.16	99.83	99.50
Rb	177.4	161.5	229.3	65.9	272.1	245.1	139	101.7
Ba	1302	1009	638	786	350	777	1281	1553
Sr	111	157	115	511	76	248	383	510
Pb	32	28	60	39	57	44	25	29
Th ^c	9.05	33.4	23.42	38.20	53.6	35.1	26.8	2.83
U	0.04	1.2	2.8	3.2	9.6	0.0	7.8	0.9
Zr	31	169	222	331	148	216	839	866
Hf	1.5	6.8	9.45	10.38	7.3	4.7	4.2	27.37
Nb	0.5	6.7	6.0	7.8	5	7	26.5	28.9
Ta	0.08	0.72	0.32	0.42	0.45	0.50	0.18	1.74
Ni	2	4	3	1	2	2	3	3
Zn	5	18	62	41	41	61	193	226
Cr	20	30	23	20	31	23	22	31
Ga	19	22	20	27	23	22	26	29
Sc	0.64	3.75	6.18	5.04	3.95	5.01	2.437	18.41
V	2	5	7	1	6	14	64	64
La	64.3	94	67.7	103.2	75.2	73.0	97	99.8
Ce	93.1	190.0	147.4	323.4	130.0	141.0	133.8	252.0
Nd	25	64	64	121.4	50	53	52	142.1
Sm	2.78	8.35	10.92	16.83	11.10	12.00	10.49	27.53
Eu	1.27	1.65	1.09	2.02	0.95	1.95	0.921	4.65
Tb	0.18	0.62	1.58	1.65	1.29	1.10	0.76	2.07
Yb	0.54	1.38	6.0	5.21	5.3	2.9	0.99	7.09
Lu	0.08	0.2	0.87	0.79	0.61	0.22	0.13	1.03
Y	2.8	8.1	45.1	38.8	27.8	33.7	103.4	86.5
10 ⁴ × Ga/Al	2.61	2.98	2.94	2.77	3.13	2.92	3.53	3.71
FeOt/(FeOt + MgO)	0.96	0.89	0.93	0.95	0.88	0.84	0.82	0.87
A.S.I. (m)	1.07	1.05	1.11	1.24	1.10	1.07	0.89	0.88

Table 4 (Continued)

Map unit sample	Ybg OR-97-65	Ybg (z) SNP-02-186	USGS G-2 mean ^d	USGS G-2 average dev ^e
SiO ₂ ^a	67.06	62.41	70.14	0.225
TiO ₂	0.75	1.44	0.49	0.005
Al ₂ O ₃	15.11	13.87	15.40	0.088
Fe ₂ O ₃ ^b	4.91	9.13	2.64	0.009
MnO	0.07	0.15	0.04	0.003
MgO	0.96	0.81	0.70	0.033
CaO	2.62	3.97	1.94	0.006
Na ₂ O	2.89	2.80	4.08	0.079
K ₂ O	5.05	4.43	4.50	0.018
P ₂ O ₅	0.33	0.69	0.14	0.002
Total	99.75	99.70	100.06	
Rb	199.9	109.1	169.4	0.24
Ba	929	2112	1874.8	7.04
Sr	266	314	483.6	1.12
Pb	40	28	30.6	0.48
<i>Th</i> ^c	31.7	1.40		
<i>U</i>	3.2	<0.83		
Zr	561	1354	321.6	3.28
<i>Hf</i>	19.6	43		
Nb	13	25.2	11.8	0.25
<i>Ta</i>	0.70	1.40		
Ni	3	1	2.6	0.48
Zn	106	249	92.6	0.48
Cr	27	11	7.8	0.32
Ga	26	25	22.0	0.0
<i>Sc</i>	7.31	20.0		
V	31	39	33.2	0.64
<i>La</i>	112.7	83.6		
<i>Ce</i>	235.2	170.0		
<i>Nd</i>	91	106		
<i>Sm</i>	15.35	18.87		
<i>Eu</i>	2.195	5.0		
<i>Tb</i>	1.34	1.90		
<i>Yb</i>	1.85	4.6		
<i>Lu</i>	0.26	0.73		
Y	23.1	58.6	7.9	0.62
10 ⁴ × Ga/Al	3.25	3.41		
FeOt/(FeOt + MgO)	0.82	0.91		
A.S.I. (m)	1.04	0.88		

A.S.I. (m) (modified aluminum saturation index) = molar Al₂O₃/[(CaO – 1.67 × P₂O₅) + Na₂O + K₂O], (z) zircon analyzed for geochronology (this study); n.d.: not detected.

^a Major elements expressed in weight percent; trace elements in parts per million.

^b Total iron expressed as Fe₂O₃.

^c Elements in italics were analyzed by neutron activation; others by X-ray fluorescence.

^d Mean of 103 (majors) and 5 (traces) replicate analyses of USGS G-2 standard.

^e Average deviation from mean.

Fig. 9. Plots of SiO_2 vs. TiO_2 (A), P_2O_5 (B), FeOt (C), MgO (D), CaO (E), $\text{Na}_2\text{O} + \text{K}_2\text{O}$ (F), $\text{FeOt}/(\text{FeOt} + \text{MgO})$ (G), and K_2O (H) for rocks of the study area. All data are expressed in weight percent. Symbols are the same as in Fig. 4. Data fields for lithologies include: LSC, low-silica charnockites (Ypqd and Yfqj); BM, biotite-rich monzogranite (Ybg); NLG, non-leucocratic granitoids (Ylgn, Yg, Ycf, Yfh, Yfe, Yfpg); and LG, leucogranites (Ylg, Ylgg, Ygg, Ygr). FeOt refers to total iron expressed as FeO . Dash-dot lines in A, B, and E outline compositional fields of charnockitic rocks of igneous origin from Kilpatrick and Ellis (1992). Boundary separating ferroan (tholeiitic) and magnesian (calc-alkaline) fields in E is from Frost et al. (2001). Dashed lines separating medium-K, high-K, and ultra-K fields in H are modified from Gill (1981).

Fig. 10. Plots of SiO_2 vs. modified aluminum saturation index ($A/CNK = \text{molar } \text{Al}_2\text{O}_3 / [(\text{CaO} - 1.67 \times \text{P}_2\text{O}_5) + \text{Na}_2\text{O} + \text{K}_2\text{O}]$) for rocks emplaced during Magmatic Intervals III (A), II (B), and I (C) separated by lithology. Symbols are the same as in Fig. 4. Data fields for lithologies include: LSC, low-silica charnockites (Ypqd (Magmatic Interval I) and Yfqj (III)); BM, biotite-rich monzogranite (Ybg (III)); NLG: non-leucocratic granitoids (Ylgn, Yg, Ycf, Yfh (I), and Yfe, Yfpg (II)); and LG, leucogranites (Ylg (I) and Ylgg, Ygg, Ygr (III)). Filled and unfilled stars in A and C indicate the compositions of melts produced from tonalite in the experiments of Patiño-Douce (1997) at 4 and 8 kbar, respectively.

trations and ratios that bear directly on their igneous origin (Fig. 11). The low-silica charnockites, characterized by low Rb concentrations (Fig. 11A), represent the chemically least evolved rocks. In contrast, the higher silica granitoids, especially the leucogranites, exhibit relatively evolved compositions, including characteristics such as low Sr concentrations and high Rb/Ba and K/Ba ratios (Fig. 11B and D) that likely result from feldspar

fractionation. Compositional distinctions between rock types are further supported by differences in concentrations of source-sensitive, compatible, high-field-strength elements (HFSE) such as Nb, Zr, Ta, and Y that are generally higher in the low-silica charnockites and lower in the higher silica granitoids (Fig. 11E–H). Significantly, HFSE concentrations illuminate differences between the two low-silica charnockites; 1160 Ma pyroxene quartz diorite (Ypqd) consistently displays lower concentrations than ca. 1050 Ma farsundite-quartz jotunite (Yfqj). The biotite-rich monzogranite (Ybg) is compositionally transitional between Yfqj and the higher silica rocks. Elemental concentrations in samples of low-silica charnockite (Yfqj) and biotite-rich monzogranite (Ybg) of Magmatic Interval III show the greatest variation in HFSE because of internal fractionation and inclusion of dikes (Yfqj), large-scale compositional layering (Ybg), and local alteration. Y concentrations in leucogranites Ygr and Ygg are generally low; however, high values in some samples are probably caused by local accumulation of garnet.

7. Nd isotopic characteristics

Twenty-one samples were analyzed for Nd and Sm concentrations and Nd isotopic compositions. Data for representative samples from each lithologic unit are presented in Table 5 and include 13 of the 14 samples for which crystallization ages are reported in Table 3.

7.1. Analytical methods

Sm–Nd analysis followed procedures described in Holmden and Dickin (1995). After dissolution using HF and HNO_3 , samples were split and one aliquot spiked with a mixed ^{150}Nd – ^{149}Sm spike. Standard cation and reverse phase column separation methods were used. Nd isotope analyses were performed on a VG isomass 354 mass spectrometer at McMaster University using double filaments and a four collector peak switching algorithm, and were normalized to a $^{146}\text{Nd}/^{144}\text{Nd}$ ratio of 0.7219. An average value of 0.51185 ± 2 (2-sigma) was determined for the La Jolla standard. Analysis by this technique yielded $\text{Sm}/\text{Nd} = 0.2280 \pm 2$ for U.S. Geological Survey standard BCR-1. Average within-run precision for samples was ± 0.000012 (2 sigma). Reproducibilities of model ages and initial Nd ratios are estimated at ± 20 m.y. and ± 0.4 epsilon units, respectively (2 sigma), based on experience analyzing duplicate dissolutions.

Fig. 11. Plots of SiO_2 vs. Rb (A), Sr (B), Rb/Ba (C), K/Ba (D), Nb (E), Zr (F), Ta (G), and Y (H) for rocks of the study area. All elemental data are expressed in parts per million. Symbols are the same as in Fig. 4. Labels of data fields for lithologies are the same as in Fig. 9.

7.2. Nd isotope results

Nd isotope compositions and Sm–Nd concentration data (Table 5) were used to calculate a T_{dm} model age for each sample using the depleted mantle model of DePaolo

(1981). Model ages (significantly older than zircon crystallization ages for all samples) range from 1.37 to 1.62 Ga, indicating that none of the samples are juvenile. The granitoids must therefore have been derived by melting of older enriched sources such as continental crust.

Table 5

Sm–Nd isotopic data for Grenvillian rocks of the northern Virginia Blue Ridge

Sample	Unit	Igneous crystallization age (Ma)	Nd (ppm)	Sm (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	ϵ_{Nd}	T_{DM} (Ga)
Magmatic Interval III								
SNP-02-186	Ybg	1028 ± 9	108	20.9	0.1171	0.512106	0.0	1.59
SNP-99-93	Yfqj	1050 ± 8 ^a	144	27.4	0.1146	0.512075	0.0	1.49
SNP-99-89	Yfqj		161	32.1	0.1206	0.512119	0.1	1.51
SNP-03-200	Yfqj		146	28.1	0.1163	0.512103	0.3	1.47
OR-97-35	Ygr	1060 ± 5 ^a	88.8	18.35	0.1248	0.512117	−0.5	1.58
SNP-02-197	Ygg	1063 ± 8	144.5	18.4	0.0770	0.511769	−0.7	1.42
SNP-01-170	Ygg		55.5	10.0	0.1087	0.512012	−0.3	1.49
SNP-99-90	Ylgg	1078 ± 9 ^a	60.4	7.89	0.0789	0.511836	0.5	1.37
Magmatic Interval II								
SNP-03-204	Yfe	1111 ± 16	47.3	9.85	0.1258	0.512108	−0.3	1.62
SNP-02-177	Yfpg	1120 ± 12	58.8	10.9	0.1121	0.512020	0.0	1.53
Magmatic Interval I								
SNP-01-146	Yfh	1144 ± 8	39.3	7.18	0.1105	0.512002	0.2	1.54
SNP-96-10	Ycf	1159 ± 14 ^a	52.5	10.4	0.1193	0.512047	−0.1	1.61
SNP-96-4	Ycf		66	12.9	0.1184	0.512107	1.2	1.49
SNP-02-175	Ypqd	1161 ± 10	46.4	8.80	0.1146	0.512136	2.4	1.39
SNP-01-154	Ypqd		81.3	13.2	0.0979	0.511980	1.9	1.40
SNP-03-198	Yg	ca. 1180	39.4	7.41	0.1138	0.512039	0.8	1.53
SNP-01-150	Ylgn	1165 ± 7	51.8	11.0	0.1284	0.512159	0.8	1.58
SNP-02-184	Ylgn		51.2	10.7	0.1261	0.512143	0.8	1.56
SNP-03-199	Ylg2	1175 ± 11	49.9	9.09	0.1101	0.512031	1.1	1.49
SNP-02-189	Ylg1	1183 ± 11	38.4	6.82	0.1074	0.511977	0.5	1.53
SNP-02-193	Ylg1		49.6	9.60	0.1168	0.512071	1.0	1.53

^a Ages from Tollo et al. (2004a).

U–Pb ages for each unit were used to calculate initial Nd isotope ratios at the time of crystallization in the form of $\epsilon_{\text{Nd}(t)}$ (part per 10,000 deviation from Bulk Earth at time t) (Table 5). Plotted in terms of Nd isotope evolution against time (Fig. 12), all values fall well below the depleted mantle (T_{dm}) growth curve, fur-

Fig. 12. Plot of Nd isotope evolution against time, showing initial ratios for analyzed units relative to evolution curves for the depleted mantle (dashed line, after DePaolo (1981)) and for the oldest unit in the study area (Ylg) (dash-dot line). Symbols are the same as in Fig. 4. Error bars are estimated analytical reproducibilities (2 sigma). Shaded field represents 2-sigma isotopic evolution of lithologic unit Ylg.

ther indicating that sources were enriched relative to depleted mantle. Most samples lie relatively close to a Bulk Earth evolution line ($\epsilon_{\text{Nd}} = 0$), with a small range from -0.7 to $+1.2$ indicating that they are unlikely to be derived from a primordial undepleted mantle source. Instead, the magmas were most likely produced by melting of an old crustal source. The Nd evolution of the Ylg unit is considered an approximation of crustally derived parental magmas that gave rise to most lithologic units because this pluton was among the first to be emplaced and is compositionally similar to magmatic sources inferred in the central Virginia Blue Ridge (Hughes et al., 2004). This source has a present-day value (ϵ_0) of -11.1 . Two samples of unit Ypqd have $\epsilon_{\text{Nd}(t)}$ values of $+1.9$ and $+2.4$, significantly different from the rest of the suite. These rocks probably sampled a slightly more primitive source but are nonetheless not mantle derived. Fullagar et al. (1997) likewise demonstrated that Grenville-age rocks from the southern Appalachians were derived from recycled Laurentian crust of Middle Proterozoic age. Pettingill et al. (1984) and Owens and Samson (2004) reported initial ϵ_{Nd} values and depleted mantle model ages (T_{dm}) from Grenville-age rocks elsewhere in Virginia that are similar to the rocks of this study.

8. Petrogenesis

Mesoproterozoic rocks of the Virginia Blue Ridge constitute a granitoid–charnockite association that is comparable to other suites worldwide (e.g. Emslie et al., 1994; Vander Auwera et al., 2003). The occurrence of minor anorthosite of circa 1045 Ma age (Pettingill et al., 1984) further suggests that Blue Ridge crust has much in common with anorthosite–mangerite–charnockite–granite (AMCG) suites that are a widespread component of Earth's Proterozoic orogens (Emslie, 1978). The dominance of granitoids in the Blue Ridge suggests that the present erosion level is more shallow than in areas such as Labrador and the Grenville Province of Canada, where granitic rocks and anorthosites occur in more equal proportions (Emslie et al., 1994).

8.1. Petrogenetic relationships

The petrogenesis of charnockitic rocks has received considerable attention in recent decades as researchers have documented the igneous heritage of many opx-bearing suites. In the Virginia Blue Ridge, the close proximity of both charnockitic and non-charnockitic rocks of similar age and likely igneous parentage suggests that the presence of opx results from intrinsic characteristics of the original magmas and therefore, in most cases, is not a direct manifestation of metamorphic recrystallization. Similar juxtaposition of opx-bearing and opx-free igneous rocks of granitic composition was observed by Frost et al. (2000) in the 2.6 Ga Louis Lake batholith in Wyoming where the occurrence of pyroxene was restricted to high pressure zones where CO₂ was enriched in magmatic fluids at the expense of H₂O. Liogys and Tracy (2004) documented igneous temperatures of equilibration (920–980 °C) for coexisting pyroxenes in charnockitic rocks from the Blue Ridge, providing additional evidence for magmatic origin.

The extended compositional range characterizing Blue Ridge granitoids emplaced during Magmatic Intervals I and III suggests that the rocks preserve evidence of differentiation processes. In each case the relatively unevolved low-silica charnockites could represent an approximation of magmas parental to contemporaneous higher silica rocks. However, for Magmatic Interval I, the broad compositional gap between low-silica magnesian charnockite (Ypqqd) and associated, exclusively tholeiitic granitoids (Fig. 9) precludes a cogenetic relationship, especially fractionation. Among the higher silica rocks, crystallization ages of most non-leucocratic granitoids are statistically irresolvable from the age range of associated Ylg leucogranites (Table 3), suggesting that

a petrogenetic relationship is possible. Moreover, the leucogranites display compositional features consistent with greater fractionation, as illustrated by higher SiO₂, La/Yb, Rb/Ba, and Rb/Sr (Table 4; Figs. 9 and 11), in addition to lower Eu/Eu* (ratio of measured Eu concentration divided by the value derived through interpolation of adjacent REE) in some samples (Tollo et al., 2004a). However, considerable overlap in data suggest that it is unlikely that the non-leucocratic granitoids fractionated to produce the leucogranite magmas. The preponderance of data implies that leucogranites and non-leucocratic granitoids of Magmatic Interval I represent products of fractionation processes in which removal of feldspar was important; however, rocks representing parental magmas have not been recognized.

The considerable range in SiO₂, FeOt/(FeOt + MgO), and total alkali content of granitoids emplaced during Magmatic Interval III (Fig. 9) could define a cogenetic association in which low-silica charnockite (Yfqj) is an approximation of parental magma that ultimately produced penecontemporaneous leucogranites. Low Sr concentrations and elevated Rb/Ba and K/Ba ratios in leucogranites (Fig. 11) suggest that any such mechanism likely involved feldspar fractionation. However, the chemically least evolved leucogranite samples have Eu/Eu* ratios that exceed the average value for Yfqj, arguing against a parental role for the latter. A possible relationship involving fractionation of ferromagnesian silicate minerals also is precluded by similar FeOt/(FeOt + MgO) ratios of Yfqj and associated leucogranites (Fig. 9G). In addition, the relative abundance of leucogranites is inconsistent with an origin involving differentiation of low-silica charnockite. Finally, the widespread biotite monzogranite (Ybg), which is compositionally transitional between penecontemporaneous low-silica charnockite (Yfqj) and associated leucogranites (Ygr and Ygg), is resolvably younger (circa 1030 Ma) than the latter (1050–1063 Ma). As a result, the range in compositional data characterizing plutons of Magmatic Interval III is unlikely to represent a sequence in which low-silica charnockite, biotite-rich monzogranite, and leucogranites represent successive stages of differentiation.

8.2. Source characteristics and production of parental magmas

Most Blue Ridge Mesoproterozoic rocks display compositions that are transitional between I- and A-type granitoids (Fig. 13); however, geochemical features of the low-silica charnockite (Yfqj) and biotite monzogranite (Ybg) of Magmatic Interval III are more indicative

Fig. 13. Plots of $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y}$ vs. FeOt/MgO (A) and $\text{Ga/Al} \times 10^4$ vs. Zn (B) for rocks of the study area. Diagrams modified after Whalen et al. (1987). Symbols are the same as in Fig. 4. Data fields are outlined for biotite monzogranite (Ybg) and low-silica charnockite (Yfqi) emplaced during Magmatic Interval III. Dashed and shaded field encloses data (34 analyses) for metaluminous A-type granitoids of the Neoproterozoic Robertson River batholith from Virginia (Tollo and Aleinikoff, 1996).

of A-type affinity. Similar variation is characteristic of other Mesoproterozoic suites in eastern North America, including examples from the Central Gneiss Belt of the Canadian Grenville Province (Slagstad et al., 2004), Adirondack Highlands (McLelland and Whitney, 1990), and New Jersey Highlands (Volkert, 2004). Like the Blue Ridge rocks, these suites span a considerable age range and were produced in an evolving tectonic framework. HFSE concentrations of most Blue Ridge rocks are comparable, at lower FeOt/MgO and Ga/Al ratios, to values characteristic of metaluminous A-type granitoids from the extension-related circa 735–700 Ma Robertson River

Fig. 14. Plots of $(\text{Y} + \text{Nb})$ vs. Rb for rocks emplaced during Magmatic Intervals I and II (A) and III (B). Diagrams modified after Pearce et al. (1984). All data are expressed in parts per million. Symbols are the same as in Fig. 4. Data fields are outlined for leucogranites (LG, units Ylgi, Ygg, and Ygr), biotite monzogranite (BM; unit Ybg) and low-silica charnockite (LSC, unit Yfqi) emplaced during Magmatic Interval III.

batholith that intruded the Blue Ridge core east of the study area (Fig. 2) (Tollo and Aleinikoff, 1996). However, only the low-silica charnockite (Yfqi) and biotite monzogranite (Ybg) are also characterized by moderately high Ga/Al ratios and elevated concentrations of $\text{Y} + \text{Nb}$ and Zn (Figs. 13B and 14), compositional features typical of A-types (Whalen et al. (1987)). Such geochemical variation likely results from a combination of differentiation (Collins et al., 1982) and source-related characteristics (Eby, 1992).

Compositionally transitional Blue Ridge rocks plot in an equivocal region of the tectonic discrimination diagrams of Pearce et al. (1984) (Fig. 14). Data for nearly all

rocks of Magmatic Intervals I and II plot near the triple-point intersection defined by compositional fields of collisional, volcanic-arc, and within-plate granites; however, samples of the circa 1160 Ma low-silica charnockite (Ypqd) plot solely in the volcanic-arc field. Similar to most older rocks, leucogranites of Magmatic Interval III plot near the triple-point intersection; however, less evolved biotite monzogranite (Ybg) and low-silica charnockite (Yfqj) exhibit increasing HFSE enrichment and Rb depletion. Förster et al. (1997) concluded that tectonic discrimination diagrams such as the Nb + Y versus Rb plot (Fig. 14), while useful in many cases for identifying the tectonic environment of granitoid emplacement, are more likely to reflect compositional characteristics of sources involved in magma generation. Geochemical characteristics of granitoids of Magmatic Intervals I and II, and the leucogranites emplaced during Magmatic Interval III, correspond closely to those of syn- to post-collisional granitoids (Förster et al., 1997). This chemical signature is a result of the mixed sources involved in magma generation within recently developed (or still developing) orogens, where both continental crust and arc-related materials are commonly present (Förster et al., 1997). Data for the circa 1050 Ma low-silica charnockite (Yfqj) plot well inside the within-plate granite field (Fig. 14), distinct from nearly all other Blue Ridge rocks. Such compositions are especially characteristic of post-collisional granitoids emplaced within extensional, encratonic environments (Förster et al., 1997). A post-collisional setting is consistent with field and geochronologic characteristics of this undeformed charnockite that intruded Blue Ridge crust about 30 m.y. after initiation of widespread orogenic activity (Tollo et al., 2004a). Sources for such A-type magmas range from lower crustal to mantle-derived but petrogenesis appears in most cases to involve a mantle contribution through either direct (e.g. source of primary magmas) or indirect (e.g. source of heat responsible for melting) processes (Turner et al., 1992a; Nédélec et al., 1995; Landenberger and Collins, 1996; Frost et al., 1999). Geochemical data for 1028 ± 9 Ma biotite monzogranite (Ybg) are transitional between the penecontemporaneous leucogranites and low-silica charnockite.

Association of fractionated I-type and A-type granites is not unusual worldwide (e.g. Landenberger and Collins, 1996). Although A-types are characterized by lower Eu/Eu*, higher Ga/Al, and higher Th, features typically indicative of igneous differentiation, Eby (1992) did not observe a continuum of compositions and proposed that A-types are not derived from I-types through fractionation. This conclusion is supported by the Blue Ridge example where A-type charnockite (Yfqj) is less

chemically evolved than associated transitional granitoids. Lack of petrologic relationship between transitional Blue Ridge granitoids and A-type charnockite could therefore result from differences in sources. The influence of sources on the geochemistry of A-types and fractionated I-types has been the subject of numerous multidisciplinary studies including various combinations of experimental, geochemical, and isotopic investigations. Models concerning generation of A-types and associated transitional granitoids involve the following mechanisms: (1) partial melting of, or fractionation from, a mafic source derived directly or indirectly from the mantle (Frost et al., 2001; Nédélec et al., 1995; Turner et al., 1992a), (2) partial melting of a residual crustal source (Landenberger and Collins, 1996; Whalen et al., 1987; Clemens et al., 1986), and (3) partial melting of an intermediate crustal source (Menuge et al., 2002; Patiño-Douce, 1997; Creaser et al., 1991).

Frost and Frost (1997) proposed that some metaluminous A-type granitoids characterized by high K₂O contents and FeOt/(FeOt + MgO) ratios are produced through either extreme differentiation of mantle-derived tholeiitic basalts or through partial melting of underplated basalts and their differentiates. The presence of ilmenite is a critical feature because it indicates that crystallization proceeded under relatively reducing redox conditions (Ishihara, 1977). Because some tholeiite-derived suites include chemically unevolved rocks (e.g. Frost et al., 1999; Anderson et al., 2003), this model is an attractive option to explain the origin of the Fe-rich, low-silica charnockite (Yfqj) of Magmatic Interval III. However, this pluton likely crystallized at relatively high $f(\text{O}_2)$ because it contains abundant primary magnetite. Moreover, ϵ_{Nd} values for multiple samples of Yfqj (Table 5) range from 0.0 to +0.3, indicating that this charnockite is unlikely to be derived from isotopically juvenile sources. Likewise, ϵ_{Nd} values of 0.7 to +1.2 (Table 5) rule out an origin involving juvenile sources for all of the other more evolved, ilmenite-bearing, transitional granitoids.

The dominance of relatively silica-rich Mesoproterozoic rocks produced repeatedly throughout a ~150 m.y. period in the Blue Ridge suggests that these rocks were derived from crustal sources. Emslie et al. (1994) proposed a similar origin for granitoids of the Nain AMCG Plutonic Suite in Labrador. Compositions of the least chemically evolved siliceous rocks indicate that parental magmas must have had SiO₂ contents <65% and were probably mildly metaluminous (Figs. 9 and 10). Landenberger and Collins (1996) considered crustal sources in evaluating possible relationships between older I-type and younger A-type granitoids of Trias-

sis age that are closely associated in eastern Australia, proposing that water-undersaturated partial melting of K-rich, mafic to intermediate lower crust produced magmas that were parental to both types. An important aspect of this model is that an earlier melting episode that gave rise to parental magmas for the I-types resulted in dehydration of the residue so that subsequent melting produced water-undersaturated A-type magmas. However, Cullers et al. (1993) noted that such melting will deplete or significantly reduce alkali feldspar and quartz in the source, making it unlikely that such sources would generate parental magmas suitable to produce the chemically evolved granitoids of the Blue Ridge. In addition, Patiño-Douce (1997) noted that partial melting of such residues cannot produce granitic liquids with the high TiO_2/MgO ratios that are typical of A-type granitoids in general and which are characteristic of virtually all samples analyzed in this study (Table 4).

Patiño-Douce (1997) and Skjerlie and Johnston (1993) demonstrated that granitoids similar in composition to the Blue Ridge rocks could be derived by partial melting of calc-alkaline sources and that previous production of I-type magma was not necessary to develop A-type features. Patiño-Douce (1997) performed melting experiments on tonalite and granodiorite at 950 °C and both 4 and 8 kbar. Results from the tonalite indicate that mildly metaluminous melt produced at 4 kbar, and weakly peraluminous melt formed at 8 kbar, are similar in composition to the silicic granitoids of this study, especially the leucogranites (Fig. 10). Moreover, Patiño-Douce (1997) demonstrated the importance of reactions involving plagioclase and orthopyroxene in developing compositional characteristics similar to the Blue Ridge silicic granitoids, including high Fe/Mg and TiO_2/MgO , moderately elevated Ga/Al , depletion in Sr and Eu, and enrichment in HFSE. We propose that compositional similarity between Blue Ridge granitoids and run products of Patiño-Douce (1997) constitutes strong evidence that comparable calc-alkaline lithologies served as an important component of sources that produced parental magmas for the more siliceous rocks of this study. However, such experimental results offer only approximations of the mixed, compositionally complex sources that likely exist at depth within long-lived orogenic zones formed by progressive amalgamation and tectonic juxtaposition of heterogeneous lithospheric components. Parental magmas for Blue Ridge rocks likely were somewhat less siliceous than the experimental products, and therefore were derived either through a greater degree of melting of a tonalitic source or involved lithologically complex tonalitic sources that also included a more mafic component. Menuge et al. (2002) likewise proposed that

Fig. 15. Primitive mantle-normalized elemental variation diagram comparing the composition of a representative Blue Ridge leucogranite (Ygg) of Magmatic Interval III to A-type rhyolites from the St. Francois Mountains in Missouri (Menuge et al., 2002) (A) and low-silica charnockite (Yfqj) of Magmatic Interval III to A-type granitoids from the Svöfjell massif in southern Norway (Vander Auwera et al., 2003) (B).

1.45–1.60 Ga A-type rhyolites of the St. Francois Mountains in Missouri, which are compositionally similar to leucogranites of this study (Fig. 15A), were derived from dominantly calc-alkaline source materials by processes that likely involved large degrees of melting. Compositional affinities between the Blue Ridge and St. Francois rocks include similar fractionation-related depletions in Ba (feldspar), P (apatite), and Ti (ilmenite), as well as probable source-related depletion in Nb (Fig. 15A). Similarly, Daly and McLelland (1991) determined that melting of largely calc-alkaline sources was responsible for production of some AMCG and Ottawan magmatism in the Adirondack Highlands. Collectively, these rocks are compositionally similar and temporally comparable to the Blue Ridge granitoids.

Melts produced in the Patiño-Douce (1997) study do not replicate the average composition of low-silica charnockite (Yfqj) and biotite monzogranite (Ybg) of Magmatic Interval III, suggesting that similar tonalitic

sources are unsuitable precursors to parental magmas for these rocks. These relatively unevolved plutons have low to moderate silica concentrations (Table 4) and ε_{Nd} values that are similar to those of the more silica-rich granitoids and leucogranites (Table 5), suggesting derivation by melting of chemically less evolved crustal sources of comparable age. Vander Auwera et al. (2003) described post-collisional biotite + hornblende-bearing granitoids from the Svöfjell massif in southern Norway that correspond closely to the ~1050 Ma low-silica A-type charnockite of this study (Fig. 15B). They proposed that gabbroic parental magmas were derived by partial melting of relatively undepleted mafic sources that were both hydrated and potassic. We envision similar sources for the low-silica charnockite which, like the Svöfjell granitoids, contains primary amphibole and a relatively oxidized mineral assemblage. Such lower crustal sources likely melted in response to increased temperatures following the onset of major deformation at about 1080 Ma.

Zircons in Magmatic Interval III granitoids support separate origins for granitic and jotunitic members of the Blue Ridge suite. Lack of inherited zircon in the low-silica charnockite is a likely result of the high temperatures and high solubility of Zr in such melts, characteristics that would result in enhanced dissolution of entrained zircon (Watson and Harrison, 1983). Less likely, lack of inherited component could indicate absence of zircon in the source. In either case, the common presence of inherited zircon in the non-leucocratic granitoids and leucogranites emphasizes their probable derivation from sources different from those of the charnockite, and suggests that the former are unlikely differentiation products of the latter. Zircons in biotite monzogranite (Ybg) contain evidence of inherited component, suggesting a petrologic lineage similar to the granitic rocks. Compositional and mineralogical characteristics of this chemically less evolved, more hydrous granitoid suggest that it formed from crustal sources that were more mafic than those that produced the associated granitoids.

The geodynamic model of Turner et al. (1992b) suggests that increased temperatures responsible for production of parental magmas for the post-tectonic charnockite (Yfqj) may have resulted from thinning of the lithospheric mantle. Removal of part or all of the lithospheric mantle could have been achieved by either delamination or convective thinning but, in either case, would likely have been accompanied by increased temperatures and intrusion of potassic magmas (Turner et al., 1996). Emplacement of the low-silica charnockite may thus mark the onset of a new melting regime in the underlying source regions. As a consequence, Magmatic Interval

III includes plutons derived from at least two types of sources: (1) tonalitic crustal sources that produced non-leucocratic granitoids and leucogranites episodically in response to crustal thickening over ~150 m.y., and (2) potassic mafic sources that melted only in the post-kinematic environment in response to increased thermal input from the asthenosphere. High temperatures that accompanied production of mafic parental magmas probably resulted in increased solubility of accessory phases that, in turn, led to higher concentrations of HFSE and enhanced A-type affinity of the low-silica charnockite (Collins et al., 1982).

The ~1161 Ma low-silica charnockite (Ypqd), characterized by magnesian compositions (Fig. 9D and E), low HFSE concentrations (Fig. 11), possible volcanic-arc affinity (Fig. 14A), and the least evolved ε_{Nd} values of the Blue Ridge suite (Fig. 12), probably was not produced from sources comparable to those that gave rise to other Blue Ridge rocks. The unique compositional characteristics of this body raise the possibility that it formed from different crustal sources, perhaps involving greater volcanic-arc component.

9. Tectonic significance

The three episodes of Blue Ridge magmatic activity span over 150 m.y. (Fig. 16; Table 3) of tectonic evolution. A major period of deformation, probably correlative to the regional Ottawa orogeny (McLelland et al., 2001; Rivers, 1997), occurred at 1078–1050 Ma. A similar time frame is recorded by largely granitic rocks of the Adirondacks where Ottawa deformation and metamorphism occurred at 1090–1045 Ma (McLelland et al., 2001) (Fig. 16).

The timing of episodic Blue Ridge igneous activity corresponds to periods of magmatism in the Adirondack Highlands where dominantly granitic plutonism occurred at 1175–1140, 1103–1093, and 1060–1040 Ma (Fig. 16) (McLelland et al., 1996, 2001). This correspondence in magmatic timing, together with temporal overlap of Ottawa orogenesis, provides strong evidence for the widespread nature of Grenvillian processes. The recurrence of magmatism in the Blue Ridge implies the existence of episodic thermal flux. Significantly, Magmatic Interval I ended about 60 m.y. prior to major deformation and, presumably, crustal thickening in the Blue Ridge. As a result, this magmatism does not appear to be directly related to Ottawa orogenesis. McLelland et al. (2004) proposed that Adirondack AMCG magmatism, which shares many compositional features with Magmatic Interval I granitoids including tholeiitic affinity and A-type characteristics (McLelland and Whitney,

Fig. 16. Comparison of igneous and orogenic histories of the northern Virginia Blue Ridge (this study) and the Adirondack Highlands. Igneous crystallization ages for the latter are based on zircon U–Pb data from McLelland et al. (1996, 2001, 2004).

1990), occurred in response to lithospheric delamination following the 1200–1150 Ma Shawinigan orogeny, and it is therefore possible that some or all of the Magmatic Interval I plutonism in the Blue Ridge could have a similar origin involving an older orogenic episode. However, because there is presently no evidence for

Shawinigan orogenic activity in the Virginia Blue Ridge, the relevance of the Adirondack model is difficult to assess. The occurrence of mafic, ~1160 Ma low-silica charnockite (Ypqd) indicates that the Magmatic Interval I sequence is, like the Adirondack AMCG interval, compositionally bimodal but dominated by granitoids. The

presence of such mafic rocks points to the existence of high-temperature magmas that might have served as heat sources responsible for crustal melting that ultimately produced contemporaneous granitoids.

Charnockites of Magmatic Interval II are compositionally indistinguishable from similar rocks of Magmatic Interval I and were therefore likely derived from similar calc-alkaline sources. McLelland et al. (1996) noted that emplacement of the 1100–1090 Ma Hawkeye Granite suite in the Adirondacks coincided with magmatism in the Mid-Continent rift (MCR) (Van Schmus et al., 1993) and suggested that Adirondack plutonism was related to MCR activity. Magmatic Interval II, which may also include leucogranites of 1112 Ma age (Aleinikoff et al., 2000), occurred immediately prior to initiation of major magmatism in the MCR. However, it is unlikely to be related to MCR activity because the latter is linked to mantle plume activity for which evidence is lacking within the Grenville orogen. Considering compositional similarities with older Blue Ridge granitoids, we view the Magmatic Interval II activity as indicating reinvigoration of Magmatic Interval I processes following an apparent 24 m.y. hiatus.

The age range of Magmatic Interval III plutons overlaps that of the Adirondack Lyon Mountain Granite suite (Fig. 16) and, like the latter, the Blue Ridge rocks are late- to post-tectonic. However, whereas the Lyon Mountain suite is dominantly felsic and derived from similar crustal sources (McLelland et al., 1996), the Blue Ridge plutons include significant volumes of low-silica rocks that were derived from more primitive sources. The apparent compositional continuity of the Blue Ridge suite is produced by penecontemporaneous plutons including relatively unevolved rocks derived from mafic sources and more chemically evolved counterparts derived from intermediate sources. In this way, insight provided by geochronologic data, demonstrating that the evolved leucogranites are considerably older than compositionally transitional rocks, provides a critical constraint on possible petrogenetic models.

The interval 1200–1000 Ma is likewise marked by abundant magmatism in the Grenville province of Canada (Rivers, 1997). This plutonism, which occurs along the full length of the province but is concentrated in the southeastern sector, includes mafic rocks, AMCG complexes of varying size, and granitoid bodies that are not associated with AMCG rocks. Most of this syn- to post-tectonic plutonic activity bears “within-plate” compositional characteristics similar to the majority of Blue Ridge rocks described in this study, and likely resulted from similar delamination-related processes that accompanied and followed two major orogenic episodes

(Corrigan and Hanmer, 1995; Rivers, 1997). As a result, these rocks collectively signify a tectonically important transition from pre-1190 Ma, dominantly calc-alkaline magmatism related to arc convergence and subduction. The compositional and temporal similarities between the oldest Blue Ridge rocks (i.e. Magmatic Interval I and, possibly, II) and those of the Adirondacks and Canadian Grenville province may foreshadow future recognition of a pre-Ottawan orogenic event in the basement terrane of northern Virginia.

10. Conclusions

The observations and data of this study support the following conclusions regarding the Grenvillian geology of the northern Virginia Blue Ridge.

1. Grenvillian intrusive activity produced plutons composed of: (1) low-silica charnockite, (2) leucogranite, (3) non-leucocratic granitoid (including charnockite), and (4) intermediate granitoid. Crystallization ages define three periods of plutonic activity occurring at 1183–1144 Ma (Magmatic Interval I), 1120–1111 Ma (Magmatic Interval II), and 1078–1028 Ma (Magmatic Interval III). High-temperature, ductile deformation occurred at 1078–1050 Ma and likely corresponds to the regional Ottawan orogeny. The timing of episodic igneous activity and orogenesis corresponds to similar periods in the Adirondack Highlands.
2. Chemically evolved non-leucocratic granitoids (Magmatic Intervals I and II) and leucogranites (Magmatic Intervals I and III) are compositionally transitional between I- and A-type granitoids. Comparison with experimental data suggests that parental magmas were produced either by partial melting of mixed mafic and tonalitic sources or by relatively high degrees of melting of dominantly tonalitic sources.
3. The circa 1050 Ma low-silica charnockite (Yfqj) was emplaced following peak deformation and is chemically distinctive in displaying A-type characteristics. These magnetite-bearing rocks were likely derived from relatively oxidized parental magmas produced by partial melting of potassic, dominantly mafic, lower crustal sources. In contrast, associated intermediate biotite monzogranite was probably derived from sources similar to those of the more silicic granitoids.
4. Linear major-element compositional trends defined by plutons of Magmatic Interval III involve magmas that were emplaced episodically over ~30 m.y. and

which were derived from different crustal sources. These apparent trends do not result from differentiation and thus underscore the importance of applying precise geochronology for interpretation of geochemical characteristics of ancient igneous terranes.

5. Differences in geochemical composition and apparent tectonic affinity of Blue Ridge Grenvillian rocks reflect source characteristics, modified by differentiation. In long-lived orogenic regions composed at depth of heterogeneous source materials, such rocks may define continuous compositional spectra, making distinction between source-related I- and A-types difficult. Without precise geochronologic data, geochemical data are of limited value in developing an enhanced understanding of the tectonic significance of local magmatism.

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