Space-Time Analysis of Magmatism: The Igneous Record for an Early Cryogenian Plume Track in Central Appalachian Orogen

by

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Space-Time Analysis of Magmatism: Evidence for an Early Cryogenian Plume Track in Eastern Laurentia

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(Abstract)

In the Grenville age basement rocks of Virginia and North Carolina, nearly thirty Cryogenian volcanic/plutonic complexes have been recognized. A-type granites and rhyolites dominate the igneous complexes within the Cryogenian Magmatic Province (CMP), but compositional variations range from gabbro through syenites. The mineralogy, chemical composition and field data including microstructural emphasis suggests emplacement of these igneous complexes in an extensional setting.

In this study U/Pb zircon ages of several plutons were determined using secondary ion mass spectrometry. The ages suggest two episodes of magmatism. An older episode (739 to 745 Ma) of magmatism includes White Oak Creek, Suck Mountain, and Amisville plutons. The younger episode (613 to 694 Ma) includes Dillons Mill, Stewartsville, Mobley Mountain, Rockfish River, and Fine Creek Mills plutons.

These two age groups also display differences in geochemistry. In contrast to the older group of plutons, the younger plutons are characteristically more metaluminous, lower in silica, higher in aluminum and phosphate, lower agpatic index, less REE enrichment, minimal K-feldspar and accessory mineral fractionation.

The distribution of the older group of plutons over a distance of nearly 600km requires the development of a crustal scale zone of extension. A space-time analysis suggests that these plutons represent a continental plume track similar to the White Mountain Magma Series. Plume head arrival ages of 765 to 754 Ma in the southern part of the region are measurably older than 735 to 705 Ma observed in the north, and yield a plate motion rate of ~2 cm/year.

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Introduction

The thermo-tectonic evolution of the continental crust is often best preserved in the magmatic record (Bayly, 1968; McBirney, 1993). Igneous rocks provide information on both the paleotectonic environment and the timing of a thermal event, as recognized through production of melts (Zen, 1992). Utilizing relatively young igneous rocks, significant correlations in geochemical, isotopic, and petrologic characteristics have been developed between igneous rocks and tectonic setting (Pitcher, 1982; Pearce et. al, 1984; Whalen et. al, 1987; Eby, 1990, 1992; Rogers and Greenberg, 1990; Barker et al., 1975). It is clear from these and numerous other studies that petrochemical and isotopic character of igneous rocks is strongly dependent on the nature of the source involved in the production of the melt, the extent of wall rock interaction, and mixing of compositionally distinct magmas (Foland and Allan, 1991; Eby et al., 1992, Barker et al., 1975). Through integration of field observations, geochemical and isotopic data, as well as theoretical models it is possible to use information from a suite of igneous rocks to identify both the tectonic setting and the geochemical evolution of a magma (Foland and Allen, 1991; Heaman and Kjarsgaard, 2000, Lee et al., 2003).

The Appalachian Orogen has been traditionally divided into lithotectonic belts (Hatcher, 1985) and more recently separated into terranes (Williams and Hatcher, 1983; Horton et al., 1991). The oldest rocks exposed in the central and southern Appalachians are ~1 Ga and are considered part of the Grenville Orogenic Belt (Rankin, 1975; Rankin et al., 1989). In the study region Grenville aged rocks are exposed as discrete massifs called the Pedlar and Lovingston massifs (Figure 1) (Bartholomew et al., 1981; Sinha and Bartholomew, 1984). Further east, rocks of similar age are referred to as the Goochland terrane (Glover et al., 1978; Farrar, 1984). In northern North Carolina and Virginia these massifs are host to Cryogenian (AGSO timescale) plutons and volcanic rocks (Rankin 1968, 1970, 1975, 1976; Rankin et al, 1969; Bryant and Reed, 1970) first named the Crossnore Volcanic-Plutonic group by Rankin (1970). This group has since been expanded to include other peralkaline complexes (Figure 1) to the north (Rankin et al., 1983). These rocks have been interpreted as magmatism associated with a failed rifting event preceding the breakup of Rodinia (examplified by the Catoctin volcanics, parts of which have been interpreted to represent oceanic crust, and the Moneta gneiss) (Rankin, 1975; Odom and Fullagar, 1984; Badger and Sinha, 1988; Wang, 1991; Aleinikoff et al., 1995; Goldberg et

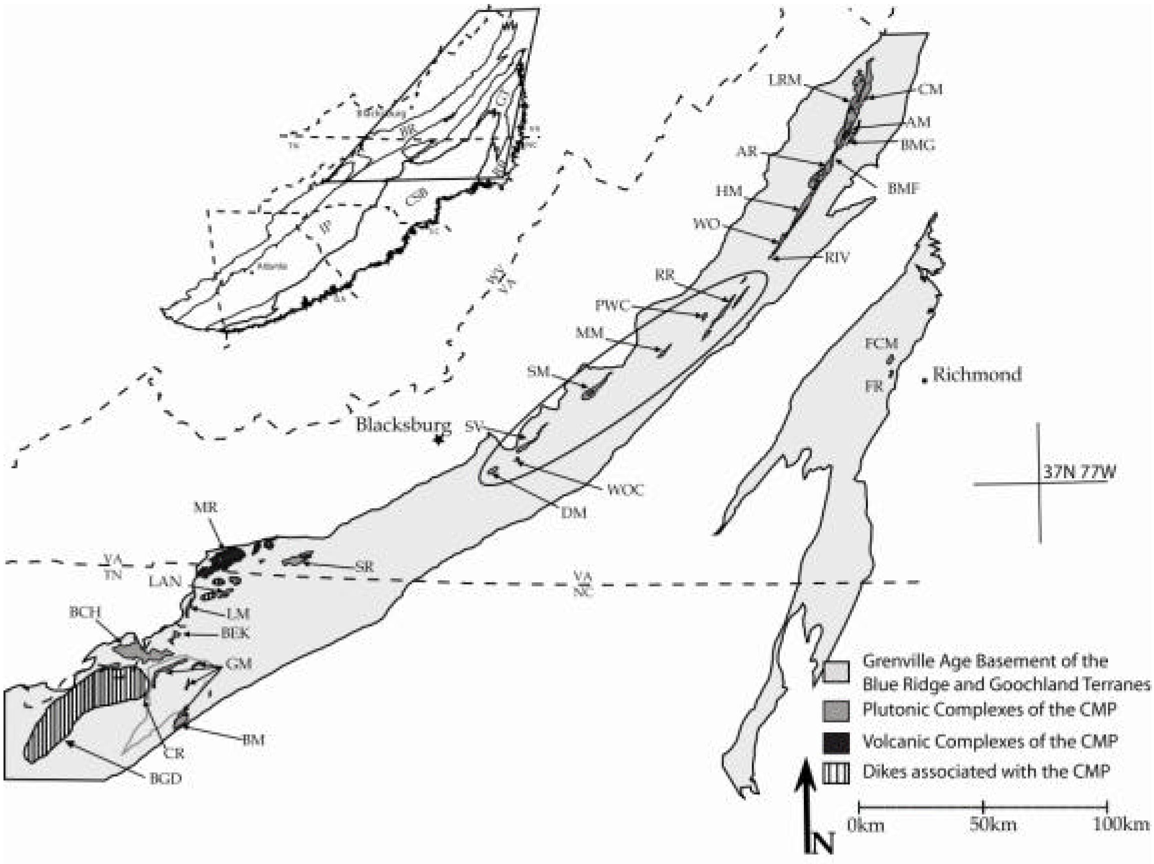


Figure 1. Simplified geologic map of the LPMP plutonic and volcanic complexes of northern North Carolina and Virginia compiled from Brock (1981), Essex (1992), Glennie (1993), Tollo (1994), Henika (1997a), Geological map of North Carolina (1985) and the Geological map of Virginia (1993). Area represented in the larger figure is outlined in the smaller figure. The abbreviations are : IP - Inner Piedmont terrane, CSB - Carolina Slate belt, RB - Raleigh Belt, GT - Goochland Terrane, BR - Blue Ridge terrane in the smaller figure and BGD - Backersville gabbro dikes, CR - Crossnore pluton, BM - Brown Mountain pluton, BCH - Beech pluton, GM - Grandfather Mountain volcanics, BEK - Buck Eye Knob pluton, LM - Leander Mountain pluton, LAN - Lansing pluton, MR - Mount Rogers volcanics, SR - Striped Rock pluton, DM - Dillons Mill pluton, WOC - White Oak Creek pluton, SV - Stewartsville Pluton, SM - Suck Mountain pluton, MM - Mobley Mountain pluton, PWC - Polly Wright Cove pluton, RR - Rockfish River pluton, RV - Rivanna pluton, WO - White Oak pluton, HM - Hitt Mountain pluton, AR - Arrington pluton, BMF - Battle Mountain Felsite, BMG - Battle Mountain Granite, AM - Amissville pluton, LRM - Laurel Mill pluton, CM - Cobble Mountain pluton, FCM - Fine Creek Mills pluton, FR - Flat Rock pluton in the larger figure. The plutons located within the oval in the larger figure have no previous U/Pb SIMS ages.

al., 1995; Tollo and Aleinikoff, 1996). This failed rifting event has been suggested to be the failed arm of a triple junction (Rankin, 1976), gravitational collapse (Sinha, 1992), and extension along the flanks of a continental rift (Tollo and Aleinikoff, 1996). Despite extensive geochronologic studies focusing on these igneous rocks (conducted mostly using TIMS methods) (Essex, 1992; Abbey et al., 1995; Su, 1994; Su et al., 1994; Tollo and Aleinikoff, 1996; Fetter and Goldberg, 1995; Goldberg et al., 1986; Aleinikoff et al., 1995; Owens, 2000), a large gap (Figure 1) in data exists within the central region of the province. A younging northward age trend is also observed for the CMP published TIMS ages. In this paper we present new geochemical and SIMS geochronologic data for the plutons located in the central region of this province, and through integration with published data, propose a fourth mechanism of crustal extension and the associated igneous activity.

Regional Setting and the Geology of the Cryogenian plutons of the Blue Ridge

Regional Setting

The CMP (Cryogenian Magmatic Province) includes Cryogenian bimodal volcanic and plutonic rocks occurring over ~600 km length and from the Bakersville Dike Swarms in western North Carolina to the Robertson River Igneous Suite in northern Virginia (Bryant and Reed, 1970; Davis, 1974; Luckert and Banks, 1984; Sinha and Bartholomew, 1984; Goldberg et al., 1986; Brock et al., 1987; Tollo and Arav, 1988; Essex, 1992; Goldberg et al., 1992; Glennie, 1993; Bailey, 1994; Su, 1994; Su et al., 1994; Tollo, 1994; Tollo and Aleinikoff, 1996; Bailey and Tollo, 1998). Most of the ECMP bodies intrude the basement rocks of the Lovingston massif of the Blue Ridge Anticlinorium and are closely associated with the Rockfish Valley Fault and Fries Fault zones (Bartholomew et al., 1981; Bartholomew and Lewis, 1984; Glennie, 1993; Hughes et al., in press). The volcanic complexes of the CMP include Mt. Rogers, Grandfather Mountain, and Battle Mountain rhyolites and are located within the southern and northern sections of the province (Figure 1). They are dominated by interbedded sedimentary and rhyolitic lavas and tuffs, with some basaltic members (Bryant and Reed, 1970; Alinikoff et al., 1995). The plutonic bodies are roughly elongate in surface exposure with the longest dimension parallel to the axis of the Blue Ridge. Many of the well-mapped plutonic rocks of the CMP occur in close proximity to or are bounded by normal faults (e.g. Striped Rock Pluton, Polly Wright Cove Pluton, Suck Mt. Pluton and Robertson River Igneous Suite (Essex, 1992; Glennie, 1993; Bailey, 1994; Tollo and Arav, 1988; Su, 1994; Su et al., 1994; Tollo, 1994; Tollo and Aleinikoff, 1996; Bailey and Tollo, 1998)). These bodies range in surface exposure size from ~2 km^2 to as much as 125 km^2 with no apparent correlation between size and location within the igneous province.

Central Virginia plutons

Geochronologic and geochemical studies have been published for the plutons and volcanic complexes of the southern and northern ends of the CMP (Bryant and Reed, 1970; Davis, 1974; Luckert and Banks, 1984; Sinha and Bartholomew, 1984; Goldberg et al., 1986; Brock et al., 1987; Tollo and Arav, 1988; Essex, 1992; Goldberg et al., 1992; Glennie, 1993; Bailey, 1994; Su, 1994; Su et al., 1994; Tollo, 1994; Tollo and Aleinikoff, 1996; Bailey and Tollo, 1998). However, for many of the igneous bodies within the central area of the province, no geochronologic or geochemical data is available. The plutons extend along a distance of ~150 km and include White Oak Creek, Dillons Mill, Stewartsville, Mobley Mountain, Suck Mountain, Rockfish River plutons. Amissville pluton, within the Robertson River Igneous Suite, and Fine Creek Mills, of the Goochland terrane, were also analyzed.

Dillons Mill Pluton is a fine to medium grained alkali-feldspar granite, which intrudes layered biotite granulite and gneisses of the Lovingston Massif (Henika, personal communication). White Oak Creek Pluton is a coarse-grained biotite granite (Henika, 1997b). Stewartsville Pluton is a medium to coarse-grained biotite granite (Bartholomew, 1981; Henika, personal communication). It is a steeply SW dipping sheet stretching over ~10 km aligned with the axis of the CMP as well as the local foliation (Henika, personal communication). It intrudes granulites and gneisses of the Lovingston Massif and is located in close proximity to the Fries Fault Zone (Bartholomew, 1981; VA state map, 1993). Suck Mountain pluton is an elongate body, which intrudes basement granulite gneisses of the Pedlar massif (Glennie, 1993). Two distinctive igneous facies have been identified within the Pluton (Glennie, 1993). The core of the pluton is a medium to coarse-grained biotite granite, with a distinct NE trending foliation (Glennie, 1993). The arealy dominant rock occurs as a rim and is a medium grained, equigranular biotite to alkali feldspar granite. Suck Mountain pluton is bounded to the SE by Fries Fault and to the NW by an unnamed normal fault (Glennie, 1993). Mobley Mountain pluton is located NE of Suck Mountain, is elongate in shape, and intrudes the Grenville aged Turkey Mountain pluton (Brock et al., 1987). Mobley Mountain pluton is a weakly foliated, medium to coarse-grained, two feldspar biotite granite (Herz and Force, 1984; Brock et al., 1987). Rockfish River pluton is a coarse grained granodiorite exhibiting a weak foliation (Davis, 1974; Sinha and Bartholomew, 1984). Ammisville pluton is a medium-grained porphyritic alkali feldspar granite and is part of the Robertson River Igneous Suite (Tollo and Arav, 1988). It intrudes the basement gneisses and granulites of the Lovingston Massif and has been interpreted as representing the upper crustal roots of a volcanic center (Tollo and Arav, 1988; Tollo and Aleinikoff, 1996).

Cryogenian plutons have also been recognized within the Goochland terrane (Ferrar, 1984; Owens, 2000) and include the Fine Creek Mills and Flat Rock plutons.

Petrography

The dominant mineralogy of the CMP plutons includes quartz, alkali feldspar, plagioclase, ±biotite, and ±amphibole. Metamorphic overprint is weak and recognized by secondary development of sericite, epidote, and garnet. Accessory minerals present in most of the bodies include zircon, sphene, fluorite, allanite, and apatite with less abundant garnet, illmenite, tourmaline, calcite, and magnetite (Bryant and Reed, 1970; Davis, 1974; Luckert and Banks, 1984; Sinha and Bartholomew, 1984, Brock et al., 1987; Tollo and Arav, 1988; Essex, 1992; Tollo, 1992; Glennie, 1993; Bailey, 1994; Goldberg et al., 1992; Su, 1994; Su et al., 1994; Tollo and Aleinikoff, 1996; Bailey and Tollo, 1998, Henika, personal communication).

Analytical Methods

Geochemistry

The samples were reduced, crushed, and powdered using a titanium-carbide shatterbox. Splits of ~5 g were analyzed for major elements and trace elements using ICP/MS methods at Activation Laboratories Ltd. in Ancaster, Canada. Details of techniques and reproducibility are given in Jerden (2001).

Geochronology

Zircons were extracted from samples of White Oak Creek, Stewartsville, Dillons Mill, Mobley Mountain, Suck Mountain, Amissville, and Rockfish River plutons using standard heavy liquids and magnetic separation procedures. The zircons were optically characterized, and crystals representing the dominant populations were hand picked for ion probe work. Twenty to thirty zircons from each pluton, as well as fragments of zircon standard AS-3 (1099±5 Ma (Paces and Miller, 1993; Quidelleur et al., 1997)), were mounted in epoxy resin, polished to expose as much surface area as possible, and coated with ~100Å of gold. Both SEM and optical images were made prior to gold coating. SIMS U/Pb dating methods were used. Although most published ages were calculated using TIMS methods, in cases were both techniques were used the ages agree within error. SIMS Ion probe analysis was performed at the UCLA Ion Microprobe facility using a Cameca ims 1270. Analyses of at least ten spots per sample were completed, with five to ten cycles per spot. The primary beam was focused to ~30 µm with a mass resolving power of ~5500, an energy window of 50 eV, and a ^{238}U offset of 15 eV. Lead ionization efficiencies were enhanced by O_2 flooding (Quidelleur et al., 1997). The data collected by the ion probe was processed using the ZIPS program, version 2.4 (Coath, personal communication). Ages of the unknowns were calculated utilizing a ^{204}Pb correction. The results were imported into Microsoft Excel spreadsheet, and further calculations were made with Isoplot/EX software (Ludwig, 1999). Final crystallization ages were calculated by the weighted average method where the ages with the lowest errors were given the most weight. U ppm concentrations were calculated by comparing the peak intensities of $UO+/ZrO_2$ in the unknowns and the standard (Miller et al., 2000).

Zircon Morphology

The zircons separated from samples of Dillons Mill, White Oak Creek, Stewartsville, Suck Mountain, Mobley Mountain, Rockfish River, and Fine Creek Mills plutons are dominantly euhedral, with length to width ratios ranging from 1:1 to 6:1 and averaging between 150-300 µm in length. They vary in color from clear to dark brown, with some of the crystals exhibiting darker color pyramids. Dillons Mill and Suck Mountain plutons also contain substantial populations of >200 µm, subhedral to anhedral crystals of yellow to brown color. The crystals exhibit first-order and first-order and second-order prisms and first-order pyramids and range from {110}-type face dominant to {100}-type face dominant. These geometries correlate with Pupin and others (1978) classes G1, P1-5 and S10, 5 and D. Differences in crystallization temperatures of the melt (ranging from 750 to 1200ºC for these morphologies (Pupin and Turco, 1972, 1975)) or U, Th, Y, or P contents of the melt (Benisek and Finger, 1993) are possible reasons for the observed variations.

Zircons from White Oak Creek and Suck Mountain plutons contain predominantly {110}-dominated crystals, correlating with P1-2, G1, S5, and 10 of Pupin et al. (1978) and corresponding to presumably lower crystallization temperatures (<850ºC (Pupin and Turco, 1972, 1975)) or higher U, Th, Y, and P contents (Benisek and Finger, 1993). In contrast, zircon populations from other plutons contain predominantly {100}-dominated morphologies, correlating with P3-5 and D of (Pupin et al., 1978) and corresponding to crystallization temperatures of ~850-1200ºC (Pupin and Turco, 1972, 1975) and/or lower U, Th, Y, and P contents (Benisek and Finger, 1993).

Zircons of White Oak Creek, Suck Mountain and Amissville also contain abundant fractures, inclusions, and inherited cores (Figures 2a, b, and c) relative to zircons from other plutons with the exception of Fine Creek Mills pluton (Figure 2d, e, and f). Zircons from Fine Creek Mills pluton are similar to those of White Oak Creek and Suck Mountain plutons containing abundant inclusions that are concentrated within both cores and rims (Figure h).

The zircons from Amissville pluton show extensive heterogeneity in backscatter SEM images characterized by variously sized patches of different average atomic number (possibly multimineralic domains), as compared to very homogeneous of zircons from other plutons (Figure 2d,e and f). Possible dissolution features in SEM images (Figure 2i) of Amissville pluton crystals as well as irregular crystal surfaces of White Oak Creek and Amissville plutons are also observed.

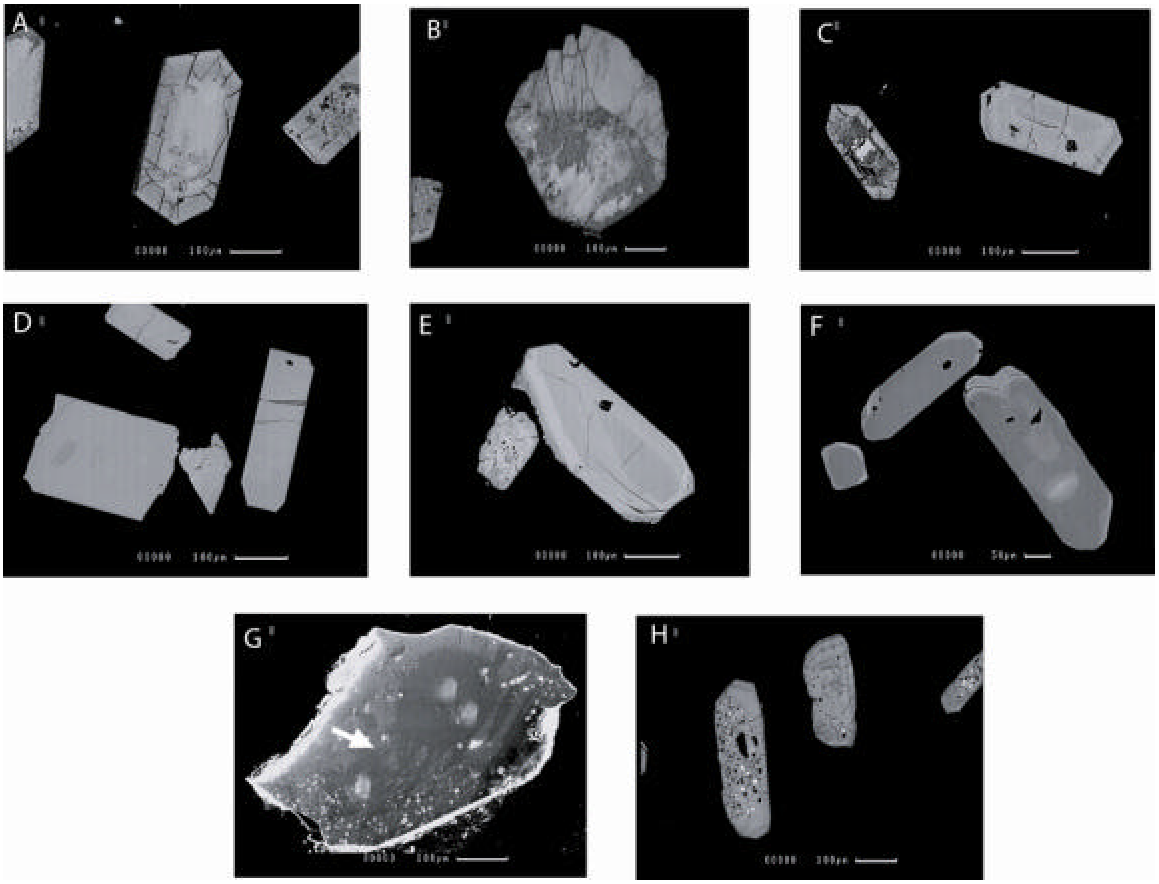


Figure 2. All images above except image G, which is a secondary electron SEM image, are backskatter electron SEM images. The first three images (A, B and C) are of representative zircons from White Oak Creek, Amissville, and Suck Mountain plutons, respectively. These three plutons have zircons with {110} dominant morphologies. The next three images (D, E and F) are of representative zircons from Dillons Mill, Rockfish River, and Mobley Mountain plutons, respectively. Zircons from these as well as, Stewartsville pluton, have {100} dominant morphologies. Image C is of a zircon from Amissville pluton with the core exhibiting possible dissolution features, identified with an arrow. Image H is of a representative zircon from Fine Creek Mills pluton, the only pluton analyzed from the Goochland terrane.

Geochronology

Calculated U/Pb ages for the eight plutons range from 625 to 745 Ma (Table 1) and form two distinct groups. The older of the two groups includes White Oak Creek, Suck Mountain, and Amissville Plutons, which range in age from 739 to 745 Ma and is similar to other published ages in the province (ranging from 765 to 705 Ma). The zircons from this group are very complex, having abundant zoning, inclusions, and cores, and have high U contents (~2000 ppm) (Table 1). The second group includes Dillons Mill, Stewartsville, Mobley Mountain, and Rockfish River plutons, which range in age from 695 to 625 Ma, and are measurably younger than the majority of the plutons in the province. The zircons from these younger plutons are less complex, display less inheritance, and have lower U (average ~250 ppm) (Table 1).

The U/Pb ages show complex Concordia relationships, interpreted to be due to large internal variations (Table 2). Notably, reverse discordancy was observed for analyses from White Oak Creek, Mobley Mountain, and Amissville plutons and may be the result of imperfect centering on the ^{207}Pb peak during analyses (Miller et al., 2000) or anomalously high U and Th content perhaps related to multimineralic domains.

Older Group

White Oak Creek pluton

Zircons from White Oak Creek pluton (sample QCY-863) yield calculated ^{206}Pb/^{238}U ages from 689 Ma to 794 Ma. An Pb^{206}/U^{238} age of 745±9 Ma and an Pb^{207}/U^{235} age of 736±13 Ma (Figure 3a) were obtained by using the weighted average method in Isoplot (Ludwig, 1999). Two analyses yielded significantly older ages (^{206}Pb/^{238}U) ranging from 800Ma to 1538Ma. These analyses contained very high ^{204}Pb (as high as 200cps versus <1 for other samples) and Th (~14,000 cps on average) and may represent presence of impurities such as thorite. As such, we do not ascribe these results any geologic significance. Three ^{206}Pb/^{238}U ages (689 to 710 Ma) were interpreted to represent lead loss, possibly the result of extensive fracturing of the crystals in associated with metamictization (Lee and Troup, 1995). All the zircons from this sample have high U (~3000 ppm on average). Reverse discordancy observed in the data may be the result of a high number of microscopic, U-rich inclusions in the crystals.

Table 1 U/Pb zircon data

					Age (Ma)		Age (Ma)		Age (Ma)	% Radiogenic		
analyses[2]	^{207}Pb*/^{235}U	errors[1]	^{206}Pb*/^{238}U	errors[1]	^{206}Pb*/^{238}U	errors[1]	^{207}Pb*/^{235}U	errors[1]	^{207}Pb/^{206}Pb	errors[1]	^{206}Pb[3]	Uppm[4]
White Oak Creek pluton, sample QCY-863 (analysis used to calculate crystalization age)												
WOCc1r4g1	1.083	0.0092	0.1265	0.0011	768	6	745	4	676	13	99.96	2953
WOCc1r4g2	1.103	0.0164	0.1238	0.0014	752	8	755	8	762	19	98.72	2617
WOCc1r4g3	1.095	0.0140	0.1246	0.0013	757	7	751	7	734	21	98.95	3289
WOCc1r4g4s3@	1.064	0.0276	0.1250	0.0025	759	14	736	14	665	38	96.13	3067
WOCc1r4g5@3	1.095	0.0113	0.1264	0.0011	767	6	751	5	702	13	99.73	2846
WOCc1r4g6@5	1.035	0.0176	0.1208	0.0019	735	11	721	9	679	20	99.94	2536
WOCc1r4g8	1.051	0.0159	0.1221	0.0015	743	8	729	8	688	21	99.83	2672
WOCc1r4g9	1.041	0.0153	0.1209	0.0013	736	7	725	8	691	21	99.99	2416
WOCc1r4g10a	1.042	0.0177	0.1214	0.0017	738	10	725	9	684	15	99.94	2980
inheritance (analysis not used to calculate crystalization age)												
WOCc1r4g4s2@	1.726	0.1648	0.1311	0.0030	794	17	1018	61	1538	159	72.81	3794
WOCc1r4g11	1.294	0.0593	0.1210	0.0020	736	11	843	26	1136	84	87.23	4195
lead loss (analysis not used to calculate crystalization age)												
WOCC1R4G4	0.988	0.0143	0.1165	0.0014	710	8	698	7	658	14	99.95	3064
WOCc1r4g6@4	0.939	0.0212	0.1129	0.0021	690	12	672	11	614	18	99.85	3781
WOCc1r4g10	0.983	0.0128	0.1128	0.0010	689	6	695	7	715	22	99.47	1965
Suck Mountain pluton, samples SM-5-95 and SM-16-95 (analysis used to calculate crystalization age)												
SMc1r6g1A	1.039	0.0584	0.1187	0.0033	723	19	723	29	724	86	99.71	51
SMc1r6g2a	1.051	0.0145	0.1230	0.0015	748	8	729	7	672	18	99.94	5197
SMc1r7g4	1.021	0.0236	0.1186	0.0023	722	13	714	12	688	23	99.81	1247
SMc1r7g4a	1.057	0.0130	0.1244	0.0013	756	8	733	6	661	18	99.94	1310
SMc1r7g6a	1.027	0.0122	0.1195	0.0012	728	7	717	6	685	17	99.77	1741
SMc1r7g6@	1.024	0.0238	0.1188	0.0026	724	15	716	12	691	19	99.81	1485
inheritance (analysis not used to calculate crystalization age)												
SMc1r6g4	1.816	0.0753	0.1655	0.0048	987	26	1051	27	1187	53	97.8	259
SMc1r7g1	1.733	0.0997	0.1741	0.0081	1034	44	1021	37	992	60	99.55	60
SMc1r6g2	1.171	0.0139	0.1362	0.0013	823	7	787	7	686	16	99.18	4720
SMc1r7g5@1	3.889	0.2157	0.1349	0.0041	816	24	1611	45	2899	65	62.34	5109
SMc1r6g3	1.267	0.0792	0.1264	0.0030	767	17	831	35	1006	108	92.78	241
SMc1r7g7@1	1.205	0.0934	0.1228	0.0018	747	10	803	43	963	154	94.4	1210
SMc1r7g2	0.984	0.0287	0.1130	0.0019	690	11	695	15	712	54	96.97	543
SMc1r7g8	0.992	0.0124	0.1146	0.0013	700	8	700	6	700	21	99.9	1383
lead loss (analysis not used to calculate crystalization age)												
SMc1r7g3	0.890	0.0239	0.1036	0.0014	636	8	647	13	685	38	99.84	1115
discordant (analysis not used to calculate crystalization age)												
SMc1r6g1	1.089	0.0719	0.1307	0.0062	792	35	748	35	619	118	99.09	75
Amissville pluton, sample R-4-95 (analysis used to calculate crystalization age)												
Amc1r9g1	1.078	0.0159	0.1226	0.0013	745	7	743	8	734	25	99.2	1465
Amc1r9g2a	1.056	0.0141	0.1221	0.0014	743	8	732	7	699	26	99.93	1073
Amc1r9g5	1.095	0.0214	0.1246	0.0016	757	9	751	10	734	35	99.22	1162
Amc1r9g6	1.050	0.0143	0.1213	0.0015	738	9	729	7	701	17	99.83	2633
Amc1r9g6c	1.059	0.0145	0.1236	0.0012	751	7	733	7	679	18	99.25	2668
Amc1r9g2b	1.076	0.0129	0.1234	0.0010	750	6	742	6	717	15	99.97	1147
Amc1r9g1b	1.072	0.0247	0.1197	0.0015	729	8	740	12	774	37	97.28	1447
inheritance (analysis not used to calculate crystalization age)												
Amc1r9g6a	1.225	0.0157	0.1391	0.0011	840	6	812	7	737	25	99.65	1038
lead loss (analysis not used to calculate crystalization age)												
Amc1r9g1a	0.839	0.0142	0.1007	0.0013	619	7	619	8	619	29	99.56	1445
Amc1r9g6b	0.749	0.0147	0.0934	0.0014	576	8	568	9	537	29	99.66	2540
Amc1r9g3	0.959	0.0145	0.1123	0.0011	686	6	683	8	673	26	99.71	733
Amc1r9g4	0.954	0.0550	0.1101	0.0025	673	15	680	29	704	102	99.24	114
Amc1r9g2	1.007	0.0188	0.1178	0.0015	718	9	707	10	674	32	99.59	1082
Dillons Mill pluton, samples MF-02-2 and MF-02-3 (analysis used to calculate crystalization age)												
DMc1r2g1	0.934	0.0768	0.1208	0.0049	735	28	670	40	455	147	98.77	41
DMc1r2g2	0.971	0.0356	0.1146	0.0042	699	25	689	18	656	90	99.71	52
DMc1r2g3@	0.967	0.0359	0.1143	0.0040	698	23	687	19	652	47	99.89	100
DMc1r2g4	0.943	0.0488	0.1118	0.0051	683	30	675	25	646	70	99.76	69
DMc1r2g5@1	1.025	0.1299	0.1209	0.0052	736	30	717	65	656	236	98.37	22
DMc1r2g5a@2	1.039	0.1491	0.1176	0.0070	717	41	723	74	744	288	98.69	21
DMc1r2g9	0.898	0.0690	0.1075	0.0077	658	45	650	37	624	115	99.52	56
DMc1r2g8a	0.882	0.1184	0.1094	0.0065	669	38	642	64	547	253	98.65	41
DMc1r2g2a	0.969	0.0606	0.1097	0.0031	671	18	688	31	744	100	99.58	49
inheritance (analysis not used to calculate crystalization age)												
DMc1r3g1	1.670	0.0606	0.1642	0.0054	980	30	997	23	1035	54	99.82	78
DMc1r3g2	1.857	0.0577	0.1810	0.0041	1072	22	1066	21	1053	43	99.88	178
DMc1r3g3	1.640	0.0454	0.1662	0.0026	991	14	986	17	974	36	99.83	165
DMc1r3g4	1.571	0.0905	0.1631	0.0088	974	49	959	36	924	50	99.36	124
DMc1r2g1a	1.061	0.0745	0.1112	0.0037	680	21	735	37	905	125	99.39	42
DMc1r2g7a	1.185	0.1653	0.1222	0.0097	743	56	794	77	938	199	99.1	17
DMc1r2g7@4	1.153	0.1521	0.1225	0.0102	745	59	779	72	876	202	99.06	16
lead loss (analysis not used to calculate crystalization age)												
DMc1r2g6@3	0.932	0.0597	0.1040	0.0040	638	23	669	31	774	118	99.58	40
DMc1r2g8@5	0.831	0.1018	0.1061	0.0040	650	23	614	56	483	248	98.91	34

Table 1 continued…

					Age (Ma)		Age (Ma)		Age (Ma)		% Radiogenic	
analyses [2]	^{207}Pb*/^{235}U	errors [1]	^{206}Pb*/^{238}U	errors [1]	^{206}Pb*/^{238}U	errors [1]	^{207}Pb*/^{235}U	errors [1]	^{207}Pb/^{206}Pb	errors [1]	^{206}Pb [3]	Uppm [4]
Stewartsville pluton, samples MF-02-1 and s-ville 1 (analysis used to calculate crystalization age)												
SVc1r5g2	0.873	0.0422	0.1052	0.0041	645	24	637	23	611	89	98.89	216
SVc1r5g4	0.914	0.0550	0.1072	0.0027	657	16	659	29	667	109	99.46	190
SVc1r5g4a	0.930	0.0354	0.1117	0.0037	682	22	668	19	618	47	99.66	196
SVc1r5g5	0.988	0.0370	0.1153	0.0048	704	28	698	19	678	46	99.85	214
SVc1r5g6	0.926	0.0397	0.1085	0.0033	664	19	666	21	670	63	99.87	209
SVc1r5g7	0.929	0.0337	0.1112	0.0023	680	13	667	18	625	73	99.61	226
SVc1r5g9	0.943	0.0246	0.1095	0.0018	670	11	674	13	690	50	99.8	183
SVc3r8g1	0.983	0.0255	0.1092	0.0021	668	12	695	13	785	34	98.65	1439
SVc1r5g5a	0.902	0.0215	0.1056	0.0021	647	12	653	11	672	50	99.78	180
inheritance (analysis not used to calculate crystalization age)												
SVc1r5g3	1.037	0.0445	0.1241	0.0033	754	19	723	22	627	79	99.7	118
lead loss (analysis not used to calculate crystalization age)												
SVc1r5g8	0.876	0.0254	0.1030	0.0016	632	9	639	14	664	56	99.86	248
discordant (analysis not used to calculate crystalization age)												
SVc1r5g1	0.821	0.0471	0.1124	0.0031	687	18	609	26	327	93	99.5	187
Mobley Mountain pluton, sample CL-12-95 (analysis used to calculate crystalization age)												
MMc2r6g1	0.801	0.0793	0.1061	0.0038	650	22	597	45	402	201	98.79	74
MMc2r6g2	0.954	0.0786	0.1051	0.0070	644	41	680	41	803	102	100	15
MMc2r6g3	0.886	0.1077	0.1009	0.0052	620	31	644	58	732	240	99.29	19
MMc2r6g4	0.945	0.0408	0.1093	0.0028	669	16	675	21	698	80	99.85	20
MMc2r6g6	0.942	0.0873	0.1143	0.0057	698	33	674	46	594	165	99.19	11
MMc2r6g6a	0.931	0.0668	0.1027	0.0037	630	22	668	35	798	147	99.64	11
inheritance (analysis not used to calculate crystalization age)												
MMc2r6g2a	1.119	0.2855	0.1114	0.0131	681	76	763	137	1010	353	99.54	14
MMc2r6g5	1.165	0.0967	0.1105	0.0043	676	25	784	45	1106	144	99.33	9
MMc2r6g2b	0.718	0.1885	0.0718	0.0143	447	86	549	111	999	391	98.75	12
lead loss (analysis not used to calculate crystalization age)												
MMc2r6g7	0.661	0.1738	0.0927	0.0052	571	31	515	106	273	561	97.29	8
Rockfish River pluton, sample JR-75-19 (analysis used to calculate crystalization age)												
RRc3r9g2	0.944	0.0330	0.1138	0.0021	695	12	675	17	609	65	99.69	88
RRc3r9g3	0.904	0.0549	0.1064	0.0045	652	26	654	29	660	113	99.65	47
RRc3r9g4	0.996	0.0373	0.1107	0.0018	677	11	702	19	782	67	98.58	235
RRc3r9g5	0.979	0.0435	0.1116	0.0038	682	22	693	22	729	64	100	75
RRc3r9g6	0.991	0.0324	0.1106	0.0025	676	14	699	17	775	54	99.87	58
RRc3r9g7	0.928	0.1012	0.1130	0.0041	690	24	667	53	588	210	99.07	24
RRc3r9g7a	0.941	0.0353	0.1055	0.0064	647	37	673	18	763	98	99.97	143
RRc3r9g8	0.939	0.0344	0.1107	0.0022	677	13	672	18	658	58	99.76	133
RRc3r9g9	0.930	0.0364	0.1087	0.0039	665	22	667	19	674	43	99.79	150
RRc3r9g9a	0.896	0.0391	0.1082	0.0028	662	16	650	21	606	81	99.79	100
RRc3r9g101	0.980	0.0242	0.1143	0.0023	698	13	694	12	682	26	99.86	280
inheritance (analysis not used to calculate crystalization age)												
RRc3r9g1	1.050	0.0299	0.1236	0.0017	751	10	729	15	661	57	99.92	186
Fine Creek Mills pluton (analysis used to calculate crystalization age)												
FCc3r3g3	0.849	0.0104	0.0993	0.0007	610	4	624	6	675	27	99.3	657
FCc3r3g4	0.828	0.0126	0.0988	0.0007	607	4	612	7	631	31	96.6	1320
FCc3r3g6	0.870	0.0178	0.1020	0.0010	626	6	635	11	667	31	99.8	704
FCc3r3g8s1	0.844	0.0239	0.0980	0.0019	603	11	621	13	689	40	99.2	958
FCc3r3g1s2@1	0.882	0.0299	0.1060	0.0020	649	12	642	16	616	56	99.4	736
inheritance (analysis not used to calculate crystalization age)												
FCc3r3g1	2.506	0.1955	0.1120	0.0034	685	20	1274	57	2479	113	71.4	806
FCc3r3g2@1	0.932	0.0115	0.1080	0.0008	661	5	669	6	693	11	99.8	996
FCc3r3g7@1	0.972	0.0311	0.1054	0.0017	646	10	690	16	834	57	98.4	627
lead loss (analysis not used to calculate crystalization age)												
FCc3r3g5s1	0.770	0.0240	0.0883	0.0017	546	10	580	14	716	48	99.1	1022
FCc3r3g5s2@1	0.744	0.0308	0.0832	0.0017	515	10	565	18	771	74	97.7	740

* radiogenic lead was corrected for common Pb

[1] all errors are 1s

[2] each analysis represents and individual spot on a zircon, spot name consists of: pluton name, location of zircon on bead (column, row, grain), additional spots on the same zircon are labeled with either a lowercase letter or "@1"

[3] % radiogenic ^{204}Pb calculated using uncorrected ^{206}Pb/^{204}Pb; common Pb ratios used for correction were ^{206}Pb/^{204}Pb = 17.59, ^{207}Pb/^{204}Pb = 15.56

[4] Uppm were calculated using method described by Miller et al., 2000

Table 2 Average U/Pb ages of zircons from plutons in the central region of the neoproterozoic province. The ^{206}Pb/^{238}U age (in bold) is considered to represent the best estimate of the crystallization event.

	Age (Ma)	Age (Ma)	Age (Ma)
Pluton Name	**^{206}Pb/ ^{238} U**	^{207}Pb/^{235}U	^{207}Pb/^{206}Pb
LCMP			
White Oak Creek Pluton	**745±9**	736±13	703±31
Suck Mountain Pluton	**727±20**	718±11	683±15
Amissville Pluton	**745±9**	737±6	710±22
ECS			
Dillons Mill Pluton	**695±16**	689±18	674±58
Stewartsville Pluton	**666±10**	671±14	693±50
Mobley Mountain Pluton	**653±19**	665±28	709±100
Rockfish River Pluton	**680±9**	682±11	690±32
Fine Creek Mills Pluton	**613±15**	623±12	661±29
all errors 2s			

Suck Mountain pluton

Data was collected from two samples of Suck Mountain pluton (SM-5-95 and SM-16-95). The Pb^{206}/U^{238} ages range from 636 Ma to 767 Ma. Calculated crystallization Pb^{206}/U^{238} age is estimated at 739±16 Ma and Pb^{207}/U^{235} age at 724±7 Ma (Figure 3b). The spots considered for the crystallization age had average ^{204}Pb of ~2 cps, with average U and Th concentrations of ~1600 ppm and ~3,000 cps, respectively, and radiogenic ^{206}Pb above 99%. Two inherited spots, of Grenville age, located in both samples, on subhedral, yellow zircons, were not used in the final age. Four additional spots exhibiting inherited components were excluded from the average crystallization age. These spots have a wide range of U (~20-5000 ppm) and high ^{204}Pb concentrations (~0.03 – 520 cps). Additionally, one young age (636 Ma) appeared to have suffered lead loss, and was also not considered in the crystallization age.

Amissville pluton

Analyses of sample R-4-95 from Amissville pluton give a calculated Pb^{206}/U^{238} age of 745±9 Ma and a Pb^{207}/U^{235} age of 737±6 Ma (Figure 3c) and are considered concordant within error limits. The analyzed zircons are characterized by multimineralic domains, as can be seen in backscatter SEM images (Figure 2b), have an average ^{204}Pb cps of ~1.5, and average U and Th concentrations of ~1400 ppm and ~23000 cps, respectively. When plotted on a Concordia diagram the data show a lead loss pattern, which may be the result of abundant fracturing of the crystals. All points with Pb^{206}/U^{238} ages younger than 720 Ma were not used in the weighted average. One inherited analyses (Pb^{206}/U^{238} age of 840 Ma) was also observed and not included in the weighted average.

Younger Group

Dillons Mill pluton

^{206}Pb/^{238}Pb ages of zircons from Dillons Mill Pluton (sample MF-02-3) range from 638 Ma to 745 Ma. The final weighted average of ^{206}Pb /^{238}U and ^{207}Pb /^{235}U ages yield ages of 695±16 and 689±18 Ma, respectively (Figure 3d), which are considered significantly younger than pluton ages discussed earlier. No reverse discordance was observed in this pluton. Average U and Th concentrations are ~ 60 ppm and 180 cps, respectively. Four zircons from a second Dillons Mill pluton sample, MF-02-4, give ^{206}Pb /^{238}U ages of 980-1072 Ma, and are interpreted to represent inheritance from the Grenville basement. Spots with calculated Pb^{206}/U^{238} ages of

650 Ma and younger were attributed to lead loss and not considered. The low Pb yield of these zircons (~90 cps of ^{206}Pb on average relative to several thousand for other plutons) is interpreted as the cause of the higher error on these analyses.

Stewartsville pluton

The calculated ^{206}Pb /^{238}U ages of zircons from Stewartsville pluton (MF-02-1 and sville-1) range from 632 to 754Ma. Analyzed spots were weighted and averaged to give an overall crystallization ^{206}Pb /^{238}U age of 666±10 Ma and an ^{207}Pb /^{235}U age of 671±14 Ma (Figure 3e). With a few exceptions, the zircons from sample MF-02-1 (from which most of the data were gathered) have average ^{204}Pb cps of ~0.35, average U and Th concentrations of ~300 ppm and ~700 cps, respectively. Three outliers, one attributed to inheritance, one to lead loss and one very discordant, were not used in weighted average calculations. One analysis from sample s-ville1 was collected. Zircons from this sample were characterized by much higher Pb cps (~10 times) as well as much higher average U and Th concentrations (~1400ppm and ~3000 cps, respectively) than those of sample MF-02-1, but gave a very similar age confirming the final crystallization age.

Mobley Mountain pluton

Data from sample CL-12-95 yielded ^{206}Pb/^{238}U ages that range from 447 to 698 Ma. The calculated crystallization ages are 653±19 (^{206}Pb/^{238}U) and 665±28 (^{207}Pb/^{235}U) (Figure 3f). Average U and Th concentration for the zircons is very low (~ 20 ppm and 80cps, respectively) with the lead content being significantly lower than the average for most other plutons. The larger errors of the calculated ages may be the result of low counts encountered in the analyses. Three analyses displaying extreme discordance, with ^{207}Pb/^{206}Pb ages of 1010 Ma, 1106 Ma, and 999 Ma, and one attributed to lead loss (with a ^{206}Pb/^{238}U age of 571) were not averaged.

Rockfish River pluton

Calculated ^{206}Pb /^{238}U ages for sample JR-75-19 of Rockfish River pluton range from 647 to 698 Ma. Eleven spots were weighted and averaged to give a ^{206}Pb /^{238}U age of 680±9 Ma and a ^{207}Pb /^{235}U age of 682±11 Ma (Figure 3g). The data for this pluton are very concordant and yield an average U and Th concentration of ~120 ppm and ~580cps, respectively, and ^{204}Pb ~0.1

cps. One analysis, with a ^{206}Pb /^{238}U age of 751 Ma, was eliminated from further calculations and attributed to inheritance.

Fine Creek Mills

The calculated ^{206}Pb /^{238}U ages for Fine Creek Mills Pluton varied between 516 Ma and 685 Ma. A preliminary crystallization Pb^{206}/U^{238} age of 613±15 Ma was calculated (Figure 3h). This age agrees within error with a published age of Fine Creek Mills Pluton of 629±5 Ma (Owens, 2000). Both inheritance and lead loss has been experienced by the zircons analyzed. Several of the spots have exceedingly high Pb^{204} cps (as high as 65) and high average U and Th concentrations (~800 ppm and ~1700 cps, respectively). The abundance of inclusions in many of the crystals may be the cause of the high Pb^{204} cps.

Summary of Geochronology

Based on calculated crystallization ages two groups of plutons can be distinguished (Table 2). The older group includes White Oak Creek, Suck Mountain, and Amissville plutons with ages ranging 739 to 745 Ma. These ages correlate well with published ages in the CMP (Essex, 1992; Abbey et al., 1995; Su, 1994; Tollo and Aleinikoff, 1996; Fetter and Goldberg, 1995; Goldberg et al., 1986; Aleinikoff et al., 1995; Owens, 2000). The plutons of this group are characterized by high Pb cps (^{204}Pb ~10 cps, ^{206}Pb ~2000 cps, ^{207}Pb ~250 cps, ^{208}Pb ~3600 cps on average), U concentrations (~2000 ppm), and Th cps (1000s), evidence of both inheritance and lead loss, complex zircon (containing cores, inclusions and fractures), and occasional reverse discordancy. Although the main cause for the reverse discordance observed in these plutons is probably related to the centering of the ^{207}Pb peak (e.g. Miller et al., 2000), another possibility is the unusually high U and Th contents of the zircons. A positive correlation between U content and reverse discordancy of the ^{206}Pb/^{238}U ages has been observed in these plutons (Suck Mountain, White Oak Creek, and Amissville plutons) suggesting such a relationship. The high Th content of zircons from Amissville and White Oak Creek plutons, resulting from thorite exsolution (Pointer et al., 1988), possibly seen as multimineralic domains in SEM images of Amissville pluton (Figure 2a) and supported by zircon morphologies (Benisek and Finger, 1993), could also have played a role in the slight reverse discordance of ages.

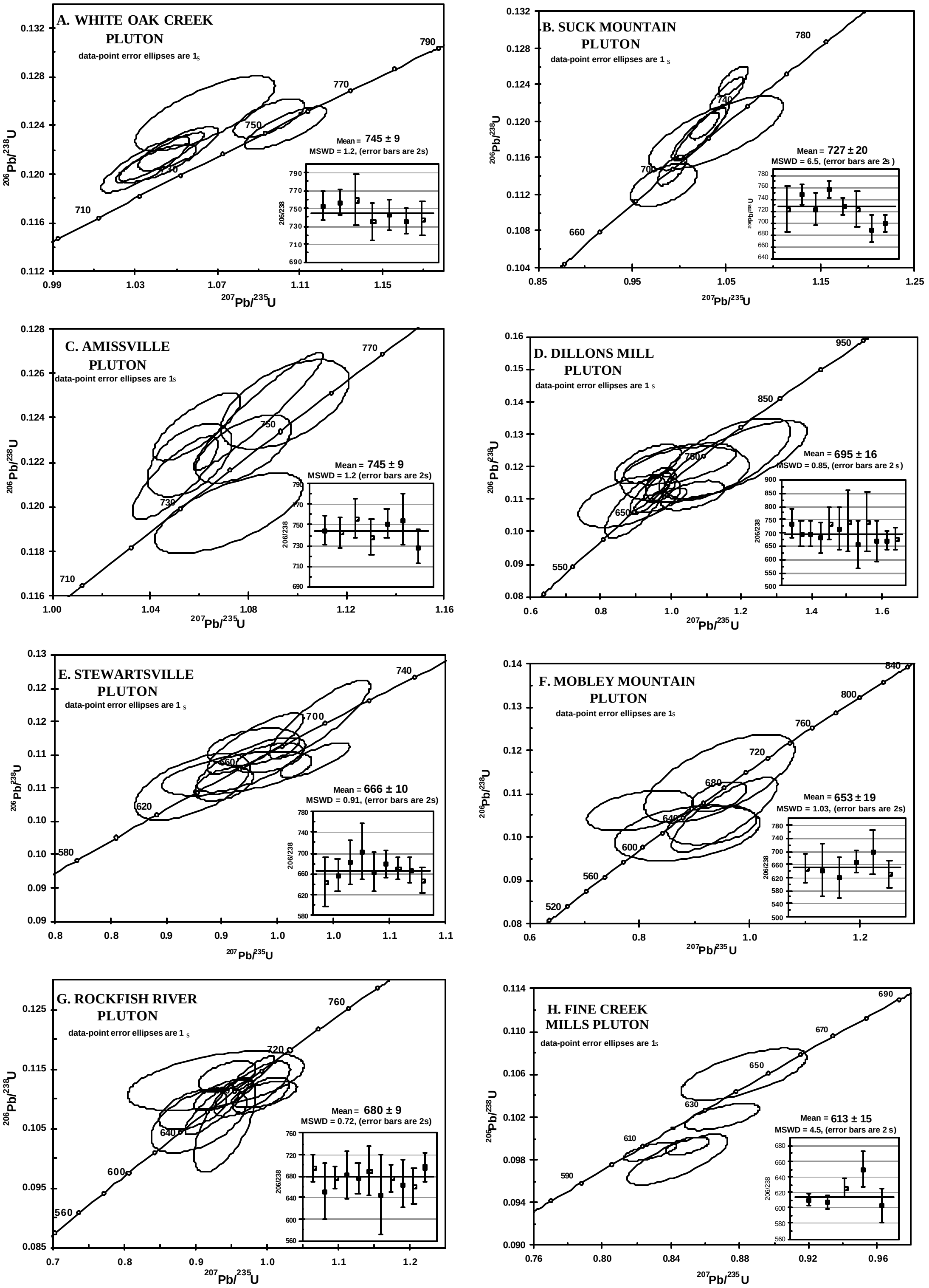


Figure 3. Concordia and weighted ^{206}Pb /^{238}U average diagrams for A – White Oak Creek pluton, B - Suck Mountain pluton, C – Amissville pluton, D – Dillons Mill pluton, E – Stewartsville pluton, F – Mobley Mountain pluton, G – Rockfish River pluton, and h – Fine Creek Mills pluton. The error bars of ellipses are 1s and correspond to 95% confidence. The weighted averages are taken as the crystallization ages and have 2s error bars. From these ages a younger group of plutons (LCMP – late Cryogenian magmatic province) emerges with an average age of approximately 670 Ma, which is measurably younger than the ECMP (late Cryogenian magmatic province) with an average age of 743 Ma.

The younger group includes Dillons Mill, Stewartsville, Mobley Mountain, and Rockfish River plutons with ages ranging from 695 to 625 Ma. These ages are measurably younger then the well-recognized 720 to 750 Ma plutons of the ECMP, and are likely to represent a unique igneous province. These plutons have much lower Pb cps (^{204}Pb ~5 cps, ^{206}Pb ~3000 cps, ^{207}Pb ~300 cps, ^{208}Pb ~600 cps on average) and U concentrations (~674 ppm), no inheritance or lead loss and are characterized by zircons with very little zoning, inclusions or cores. Fine Creek Mills Pluton, belonging to the younger group, is an exception. Similar to the older group, this zircons from the pluton have high U concentrations (~2000 ppm average), high Pb cps, abundant inclusions, and show evidence of lead loss. However, unlike the older group, no reverse discordance was observed.

Geochemistry

Major elements

The average major element chemistry of igneous rocks from the province is reported in Table 3 and includes both published (Brock, 1981; Goldberg et al., 1986; Zmoda, 1987; Arav, 1989; Tollo et al., 1991; Glennie, 1993; Tollo and Aleinikoff, 1996) and new chemical data. The igneous rocks of the ECMP are bimodal, with silica peaks at 49.2 and 72.9 wt% (Figure 4a). The felsic members of the province have a range of SiO_2 from 64-77 wt%, are high in Na_2O+K_2O (average 9 wt%), Fe/Mg (average ~23), and low in CaO (<1.5 wt%), typical of A-type granites (Whalen et al., 1987; Pearce et al., 1984; Eby 1990; Loiselle and Wones, 1979).

The felsic plutons and volcanic complexes can be divided into two groups, coincident with their age subdivision (Table 4). Based on Shand’s classification (Manian and Piccoli, 1989), the older plutons are dominantly peralkaline, while the younger bodies are metaluminous (Figure 4b). In addition, the ~650 Ma plutons exhibit lower agpatic index values (average of 0.83, versus 0.91 for the older suite), lower silica content, and higher Al_2O_3 and P_2O_5 concentrations (Figure 4c). The calculated CIPW norms for the younger plutons are also more hypersthene rich and lacking acmite.

Table 3 geochemical data for the LcMP and ECS																
	Felsic members of the ECMP															
	BM	Cross	BCM	BEK	LM	Lans	MR(R)	SR	WOC	SMG[1]	SMFG[1]	Riv[2]	WO[2]	HM[2,3]	Arr[2,3]	BtMF[2,3]
wt%	major oxides															
SiO_2	76.6	71.3	72.8	73.2	74.0	75.9	75.0	72.3	74.3	77.2	75.7	66.4	71.8	64.6	76.3	73.6
TiO_2	0.1	0.3	0.2	0.3	0.3	0.1	0.3	0.3	0.1	0.0	0.1	0.5	0.3	0.4	0.1	0.2
Al_2O_3	12.0	13.1	13.5	13.0	12.4	12.0	11.6	13.3	12.8	12.6	12.2	14.3	13.4	16.3	12.3	12.7
Fe_2O_3	1.6	3.5	2.3	3.0	3.1	2.2	2.9	2.8	2.3	0.7	2.6	5.0	3.7	5.6	2.3	4.0
FeO*	1.4	3.1	2.1	2.7	2.8	2.0	2.6	2.5	2.0	0.6	2.3	4.5	3.4	5.1	2.0	3.6
MnO	0.0	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.1	0.0	0.1
MgO	0.1	0.0	0.2	0.1	0.0	0.0	0.2	0.3	0.0	0.0	0.1	1.4	0.1	0.2	0.1	0.2
CaO	0.6	1.0	1.0	0.7	0.7	0.9	0.5	1.2	0.9	0.4	0.8	2.5	1.2	1.9	0.4	0.1
Na_2O	3.7	4.1	3.6	4.4	3.7	3.0	3.6	3.6	4.1	4.7	3.0	3.6	4.0	5.7	3.6	4.4
K_2O	5.2	5.6	5.5	5.0	5.4	5.2	4.6	5.3	4.4	3.8	5.3	4.6	5.5	4.8	5.2	4.4
P_2O_5	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.2	0.0	0.1	0.0	0.0
LOI	0.3	0.4	0.7	0.2	0.2	0.5	0.9	0.7	0.6	0.4	0.5	0.8	-	0.9	-	-
Total	100.2	99.3	99.8	100.0	100.0	99.9	99.7	99.9	99.4	99.9	100.4	99.4	100.3	100.7	100.4	99.5
[£]agpatic in	0.98	0.98	0.88	0.98	0.96	0.88	0.94	0.87	0.89	0.94	0.87	0.76	0.93	0.89	0.94	0.94
ppm	trace elements															
Rb	215.0	75.0	156.0	75.0	116.5	168.0	136.4	142.5	169.0	156.5	169.9	109.7	105.0	117.0	184.5	220.0
Sr	9.0	32.5	68.5	27.3	15.0	6.0	24.9	83.3	9.0	16.5	37.5	220.0	84.0	303.5	18.5	1.5
Ba	31.5	191.0	533.5	145.0	82.5	11.0	472.4	768.0	23.0	62.5	135.1	974.4	490.0	689.0	198.3	37.0
Zr	289.0	684.5	328.5	331.7	734.5	237.0	495.0	316.8	157.0	87.0	257.0	292.5	638.5	306.5	411.0	2041.3
Y	126.0	94.0	65.0	82.0	113.0	132.0	129.3	69.5	322.0	169.5	258.1	39.6	79.5	91.5	134.5	60.5
Hf	13.9	21.1	11.4	10.1	21.6	12.0	17.5	10.0	8.7	7.3	10.5	8.6	18.7	11.4	13.1	46.1
U	4.3	1.9	3.1	1.4	1.9	1.6	3.4	2.9	6.2	2.5	4.1	1.8	1.5	5.4	3.9	4.8
Th	23.7	25.4	29.7	12.2	18.3	20.4	16.2	24.1	25.9	6.3	17.7	11.3	13.3	19.2	17.9	26.4
Ta	8.5	5.5	7.2	6.3	6.1	11.0	7.3	6.0	15.3	7.5	7.1	4.0	4.1	34.8	5.5	17.6
Ga	42.0	35.0	29.0	46.0	33.5	31.0	27.2	21.8	44.0	38.5	33.1	22.7	30.5	40.0	33.5	56.0
La	81.6	240.0	108.5	185.7	169.5	61.7	65.5	67.9	46.0	5.1	81.1	49.8	184.5	50.6	82.5	125.5
Ce	181.0	542.0	213.0	259.0	344.5	155.0	134.0	129.8	125.0	12.5	202.0	82.9	368.5	146.0	174.0	202.3
Nd	82.1	216.0	81.9	153.0	148.0	95.3	64.8	54.2	88.2	9.8	105.5	43.7	179.0	57.1	83.0	93.4
Sm	20.2	40.1	15.2	27.4	28.0	27.8	16.7	11.3	33.9	5.4	34.7	9.5	36.5	13.1	23.0	19.1
Eu	0.3	2.1	1.3	2.2	0.7	0.5	0.8	1.5	0.8	0.2	1.5	1.8	2.5	2.2	0.9	0.7
Gd	20.3	32.3	13.0	24.3	25.1	28.8	17.5	10.2	37.7	8.0	44.2	8.0	-	13.6	-	-
Tb	3.7	4.3	2.1	3.3	3.7	4.8	3.4	1.9	8.6	2.2	7.7	1.5	3.8	2.6	4.2	2.4
Dy	24.4	23.4	13.0	18.7	22.8	29.7	21.1	11.7	56.3	15.7	65.9	8.8	-	15.3	-	-
Ho	4.5	3.8	-	3.1	4.2	5.2	4.5	2.5	12.2	3.8	13.9	1.8	-	3.1	-	-
Er	13.8	10.4	7.3	8.7	12.8	15.1	13.7	8.0	35.7	13.5	40.2	5.6	-	9.0	-	-
Tm	2.1	1.5	1.1	1.2	2.0	2.2	2.1	1.2	4.9	2.4	5.6	0.8	-	1.4	-	-
Yb	11.1	8.5	6.0	6.7	11.2	11.9	12.3	7.2	25.6	15.6	22.9	5.2	8.0	8.1	12.6	8.6
Lu	1.6	1.4	0.9	1.0	1.8	1.8	1.7	1.1	3.3	2.3	2.9	0.8	1.1	1.0	1.6	1.2
Pb	16.0	11.0	-	9.0	10.5	30.0	10.9	19.5	31.0	39.5	30.5	19.9	40.5	33.0	18.0	25.0
[§]T(C)	834	908	847	841	928	821	895	840	782	736	830	820	902	813	877	1073

Table 3 continued….

	Felsic members of the ECMP						mafic members of the ECMP				LCMP			
	BtMG^2	BtMR^2	A-ville^{2,4}	LMill^2	CM^{2,4}		B-ville^5	GM^6	MR(B)		DM	SV	MM^7	RR
wt%							major oxides							
SiO_2	72.2	75.6	74.5	70.4	70.9		50.1	46.8	47.7		66.7	74.5	68.5	70.7
TiO_2	0.2	0.2	0.1	0.3	0.3		3.1	2.7	3.2		0.6	0.2	0.4	0.2
Al_2O_3	12.6	11.1	12.1	14.0	13.7		12.0	15.0	13.3		15.0	11.7	13.7	14.9
Fe_2O_3	3.9	4.3	3.9	3.6	4.1		10.8	13.5	16.3		5.4	2.9	5.1	1.4
FeO*	3.5	3.9	3.5	3.2	3.7		14.9	14.7	14.7		4.8	2.6	4.6	2.5
MnO	0.1	0.0	0.0	0.1	0.1		0.2	0.2	0.2		0.1	0.0	0.1	0.0
MgO	0.4	0.3	0.1	0.2	0.1		5.1	5.3	4.7		0.4	0.0	0.3	0.3
CaO	0.8	0.6	0.2	1.2	0.7		8.5	7.8	6.7		2.1	1.0	1.2	1.1
Na_2O	4.3	3.7	4.5	3.9	4.9		2.8	2.4	3.6		3.4	2.4	3.3	4.6
K_2O	4.5	3.8	4.5	5.6	5.0		1.8	1.4	1.6		5.5	5.7	5.2	5.1
P_2O_5	0.0	0.0	0.0	0.1	0.0		-	0.6	0.4		0.1	0.0	0.2	0.1
LOI	0.9	-	0.6	0.4	-		-	3.2	2.3		0.7	0.5	0.1	0.2
H_2O+							0.7	-	-		-	-	-	-
Total	99.9	99.7	100.5	99.6	99.7		95.0	98.8	99.9		99.9	98.9	98.1	98.7
^{1}AGP. IND	0.95	0.92	1.01	0.89	0.98						0.77	0.87	0.80	0.88
ppm							trace elements							
Rb	250.5	260.5	246.5	70.5	109.6		24.4	97.0	30.0		141.5	134.0	99.2	104.0
Sr	13.5	10.5	5.5	91.0	23.5		358.8	616.8	162.0		163.5	43.0	176.5	60.0
Ba	97.5	-	57.0	870.5	170.0		760.0	-	717.0		1700.0	177.0	138.2	245.5
Zr	851.5	1980.0	1505.0	675.5	707.2		291.7	128.7	242.5		939.0	357.0	387.9	199.5
Y	175.0	200.5	220.0	63.5	114.8		-	61.0	50.0		58.0	243.0	29.4	45.0
Hf	27.2	50.4	34.2	17.3	17.5		-	-	6.9		21.4	13.7	1.3	10.9
U	6.0	10.8	6.4	1.0	2.1		-	-	0.7		1.0	2.5	1.1	6.3
Th	22.8	34.8	15.7	6.5	9.7		-	-	4.2		2.4	11.7	7.9	15.6
Ta	13.5	23.9	14.3	3.8	4.8		-	-	1.9		3.5	4.8	0.5	8.3
Ga	42.0	51.0	46.5	36.5	41.8		-	-	25.5		29.0	35.0	9.2	37.0
La	202.4	145.5	118.5	117.0	257.0		-	-	31.2		48.3	141.0	6.8	44.5
Ce	338.5	297.0	229.5	258.0	387.2		-	-	69.4		100.7	318.0	64.5	82.1
Nd	139.6	135.5	125.2	127.5	214.5		-	-	38.3		54.0	191.0	46.8	33.6
Sm	27.0	35.4	29.1	23.7	44.6		-	-	9.4		12.2	53.2	1.3	7.3
Eu	0.8	0.7	1.1	4.6	3.7		-	-	2.7		3.9	2.8	0.3	1.1
Gd	27.9	-	31.1	21.7	-		-	-	9.3		10.3	50.1	1.1	6.5
Tb	4.7	5.9	5.8	3.0	5.0		-	-	1.6		1.8	9.2	0.2	1.2
Dy	26.6	-	34.3	14.4	-		-	-	9.5		10.4	51.6	1.2	7.6
Ho	5.3	-	7.2	2.6	-		-	-	1.8		2.2	9.9	0.2	1.4
Er	15.7	-	21.7	7.0	-		-	-	5.5		6.6	26.6	0.7	4.6
Tm	2.5	-	3.4	0.9	-		-	-	0.8		1.0	3.5	0.1	0.8
Yb	14.8	19.2	18.9	5.8	10.3		-	-	4.6		6.0	18.6	0.6	4.9
Lu	2.0	2.4	2.5	0.8	1.4		-	-	0.7		0.9	2.5	0.1	0.8
Pb	16.5	32.5	58.0	10.0	21.0		-	-	7.0		33.5	26.0	8.3	20.0
^{2}T(C)	942	1064	1018	914	915						946	859	867	796

BM - Brown Mountain pluton, Cross - Crossnore pluton, BCM - Beech Mountain pluton, BEK - Buck Eye Knob pluton, LM - Leander Mountain pluton,
Lans - Lansing pluton, MR(R) - Mount Rogers Complex (rhyolite), SR - Striped Rock pluton, WOC - White Oak Creek pluton,
SMG - Suck Mountain pluton (granite), SMFG - Suck Mountain pluton (foliated granite), Riv - Rivanna pluton, WO - White Oak pluton,
HM - Hitt Mountain pluton, Arr - Arrington pluton, BtMF - Battle Mountian pluton (felsite), BtMG - Battle Mountian pluton (granite),
BtMR - Battle Mountain pluton (rhyolite), A-ville - Amissville pluton, LMill - Laurel Mill pluton, CM - Cobbler Mountain pluton, B-ville - Backersville Gabbro Dikes,
GM - Grandfather Mountain Formation, MR(B) - Mount Rogers Complex (basalt), DM - Dillons Mill pluton, SV - Stewartsville pluton,
MM - Mobley Mountain pluton, RR - Rockfish River pluton

* FeO was calculated using 0.8998*Fe2O3

£ calculated using (Na+K)/Al (Hall, 1996)

§ calculated using formulas of Watson and Harrison (1983)

[1] Glennie, 1993;

[2] Tollo and Aleinikoff, 1996

[3] Tollo et al., 1991

[4] Arav, 1989

[5] Goldberg et al., 1986

[6] Zmoda, 1987

[7] Brock, 1981

Table 4 ECMP vs.LCMP

	Older Group (ECMP)	**Younger Group (LCMP)**
Major Element	SiO_2 ~77, CaO ~.8, P_2O_5 ~.5, agpatic index ~.91, Fe/Mg ~114	SiO_2 ~70, CaO ~1.3, P_2O_5 ~.1, agpatic index ~.83, Fe/Mg ~4.7
Trace Elements	more enriched in REE (La ~105ppm, Yb ~12ppm), lower Eu anomaly(~.21), Ba ~356, Sr ~46	less REE enriched (La ~68ppm, Yb ~ 8ppm), higher Eu anomaly (~.6), Ba ~895, Sr ~118
Zircon Morphology	very complex; fractures, cores, zoning abundant, {110} faces dominant	few overgrowths or cores, inclusions present in great amounts only in Fine Creek Mills pluton, {100} faces dominant

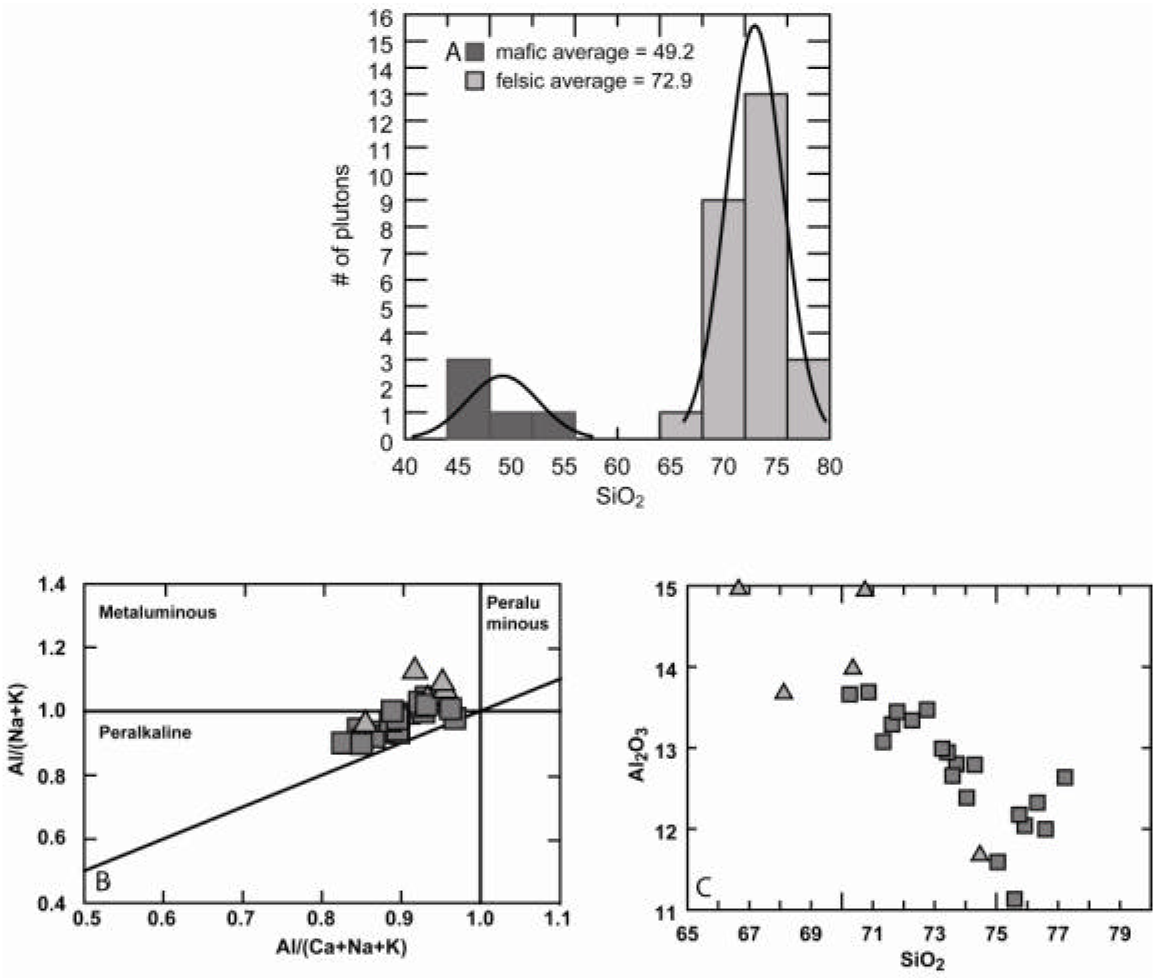


Figure 4. The average major element geochemistry per pluton of the ECMP (squares) and the LCMP (triangles) of published as well as new data. (A) shows the bimodal nature of the Cryogenian rocks of the Blue Ridge and mean values for the two peaks (B) Shand's index showing the dominantly peralkaline ECMP and metaluminous LCMP; (C) demonstrated the significantly more silicious nature of the ECMP as compared to the LCMP.

Trace elements

In general, felsic rocks of the province are high in Ga/Al, F, Zr, Nb, Ga, Sn, Y, Ce, and REE (except Eu), and low in Ba and Sr, and can be classified as within-plate, A-type granites (Figure 5a, b) (Whalen et al. 1987; Pearce et al. 1984). Based on partition coefficients of Ce and La in allanite and Hf in zircon, the Ce/La (Figure 5c) and Hf/Zr (Figure 5d) ratios of the plutons suggest both zircon and allanite fractionation as contributing to the REE concentrations of the melt. However, because the heavy REE are incorporated into the zircon structure more readily than the allanite structure the slope of the average REE pattern of ~7 suggest a dominance of zircon fractionation (Figure 5e). High Eu anomalies as well as low Ba and Sr suggest K-feldspar controlled fractionation. Despite similar classification and fractionation and REE removal control patterns, geochemical distinctions can be made between the ECMP and the younger group. The younger members of the suite exhibit less REE enrichment (average La and Yb for LCMP are 68 and 8 ppm, respectively, and for ECMP are 105 and 12 ppm respectively), lower Eu anomalies (Figure 5f), and are higher in Ba and Sr (Figure 5g) (with the exception of Stewartsville Pluton, which has a REE pattern identical to the ECMP plutons). Half of the younger plutons have Rb/Sr ratios below 1 and all except one of the older bodies have ratios significantly higher than one (Figure 5h). Two exceptions to the general REE patterns include White Oak Creek and Suck Mountain plutons. The REE patterns of these two plutons are flat with a ratio of light to heavy REE of ~1 (Figure 5i), suggesting minimal zircon or allanite removal from the melt.

Summary of Geochemistry

The major and trace element data for the ECMP and the younger plutons show significant similarities and differences between the two age groups. Both can be classified as A-type groups have experienced K-feldspar fractionation and have REE patterns controlled by zircon granites, although the younger group does not have any recognizable mafic end-members. Both plutons are measurably higher in silica, less Al and P rich, have experienced more K-feldspar fractionation, and are more enriched in REE. Anomalous plutons include Stewartsville pluton, which has the geochemical signature of the ECMP while of younger age, and White Oak Creek and Suck Mountain plutons. The latter two plutons show little to no geochemical modification to the liquid as represented by a light to heavy REE ratio of ~1.8 (excluding K-feldspar

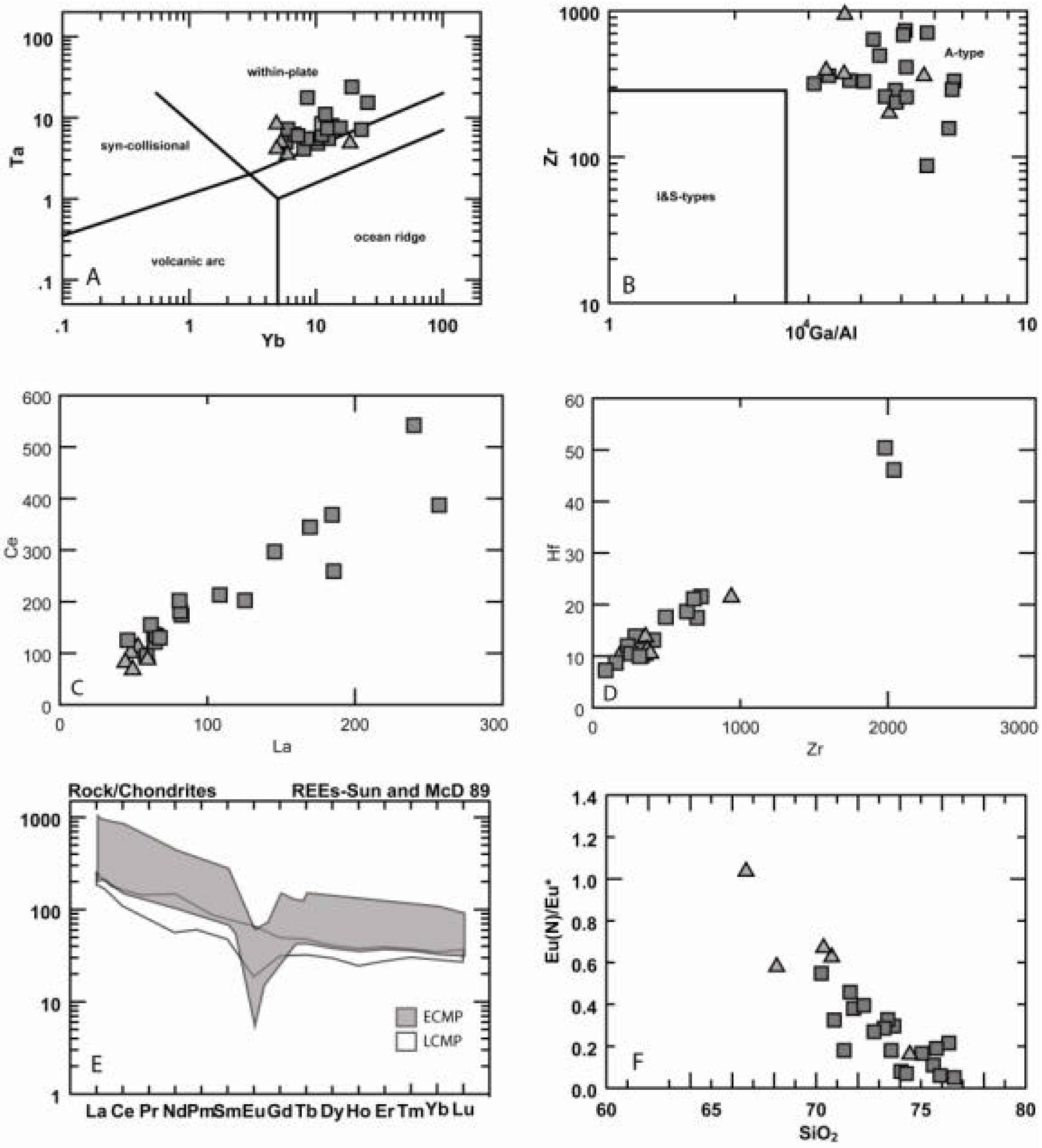


Figure 5. caption on next page

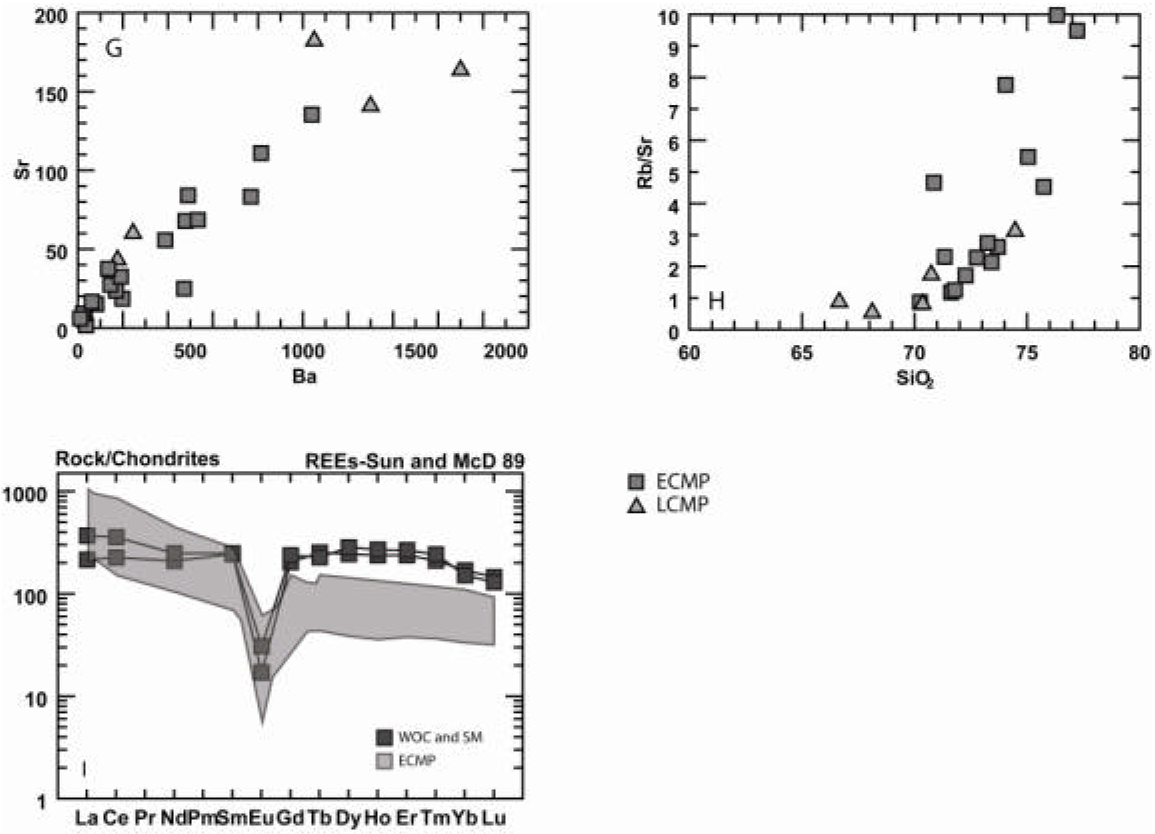


Figure 5. continued... Trace element geochemistry of the ECMP and LCMP. The shaded fields represent ranges of values for the two suites. One anomalous analysis for the ECMP was not included. (A) and (B) classification diagrams of Pearce et al. (1984) and Whalen et al.(1987) respectively; (C) and (D) show patterns of allanite and zircon removal from the liquid, both zircon and allanite control the REE paterns of the ECMP bodies while for the LCMP only zircon contributes; (E) shows fields of typical REE patterns for the ECMP and LCMP; (F) and (G) show the dominance of K-feldspar fractionation for both suites with Eu, Ba and Sr removal from the liquid. The LCMP shows very minimal fractionation with the ECMP being much more evolved; (H) all of the ECMP and about half of the LCMP have Rb/Sr ratios greater than one, characteristic of mantle input to the melt; (I) anamolous (WOC - White Oak Creek and SM - Suck Mountain) plutons of the ECMP showing minimal allanite or zircon removal from the liquid.

fractionation), and are slightly more K_2O-rich. These differences may be responsible for the difficulty of geochronologic interpretation for these two plutons.

Discussion

Evidence for two provinces within the CMP

When the calculated as well as published ages for the ECMP are plotted versus distance along strike of the province from south to north, two clusters become apparent (Figure 6). The older spans the length of the province, displaying an apparent decreasing age trend (~760 to ~720Ma) and corresponds in age to the previously dated ECMP bodies. The younger cluster, however, is concentrated within the center of the province, displays little recognizable age variation with distance, and is significantly younger than the ECMP with an average age of ~670 Ma (Figure 7).

Both clusters show extensive Sr_i variation (Essex, 1992) as well as a K-feldspar fractionation trend, as evidenced by high Eu anamolies and Ba and Sr depletion (Figure 5f, g). Similar REE pattern slope and Ce to La and Hf to Zr ratios of the ECMP and the younger plutons suggest that the REE concentrations are controlled dominantly by zircon removal from the melt, with minor contribution of allanite for the older suite (Figure 5 c, d, e). This semblance suggests a similar mode of origin for the ECMP and LCMP. However, the higher SiO_2 and Al_2O as well as higher Eu anomalies and lower REE enrichments suggest that the younger cluster has experienced significantly less K-feldspar fractionation. This leads to the proposal that although both have a mantle component, these clusters may represent distinct magmatic events. Stewartsville pluton, with REE and major element abundances very similar to those of the ECMP but temporally similar to the LCMP is the only anomoly. However, because no published petrogenetic work on Stewartsville pluton exists, a discussion of the reasons for this seemingly anomalous character of this pluton is beyond the scope of this study.

Petrogenesis

Several petrogenetic models have been proposed for A-type magmas. These models include (1) liquid state thermogravitational diffusion, (2) liquid immiscibility, (3) melting of the lower crust under the influence of mantle derived volatiles, and (4) fractionation of mantle derived alkaline

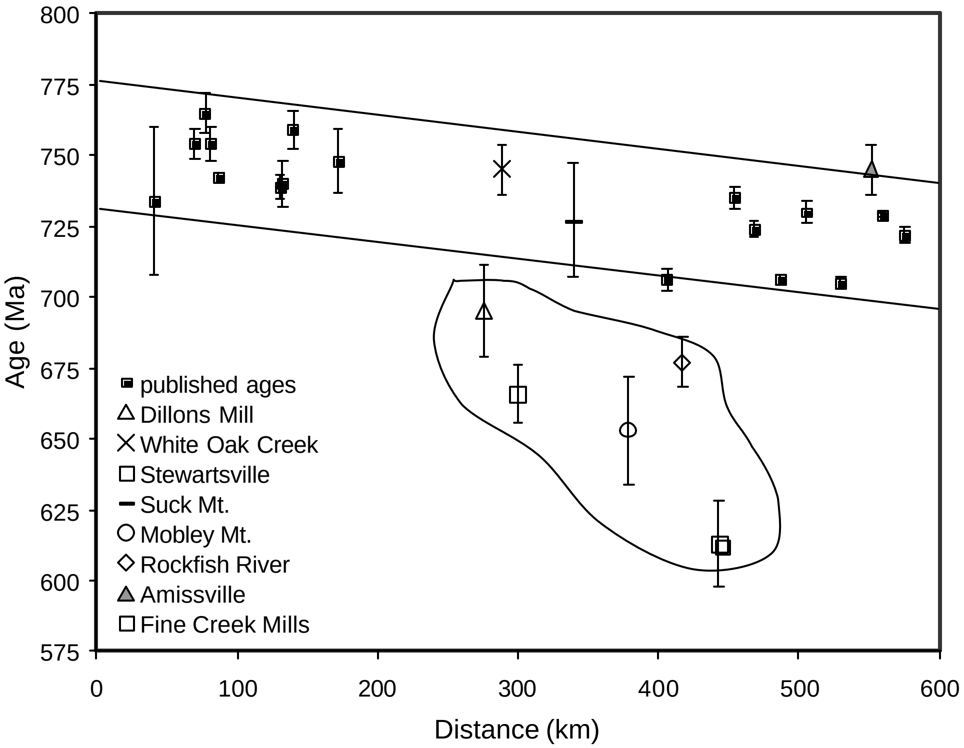


Figure 6. New as well as published ages for the ECMP and plotted versus distance north along strike of the province from Ashville, NC. The location of Fine Creek Mills pluton has been projected perpendicular to the axis of the ECMP. The split between the older and younger plutons is very apparent. The older ECMP shows a north-younging trend and is clearly distinct from the cluster of younger ages of the LCMP towards the center of the province. Using a regression a plate motion rate based on the LCMP ages has been calculated to be ~2 cm/yr. The apparent trend of the LCMP plutons is not considered to reflect plate motion rate.

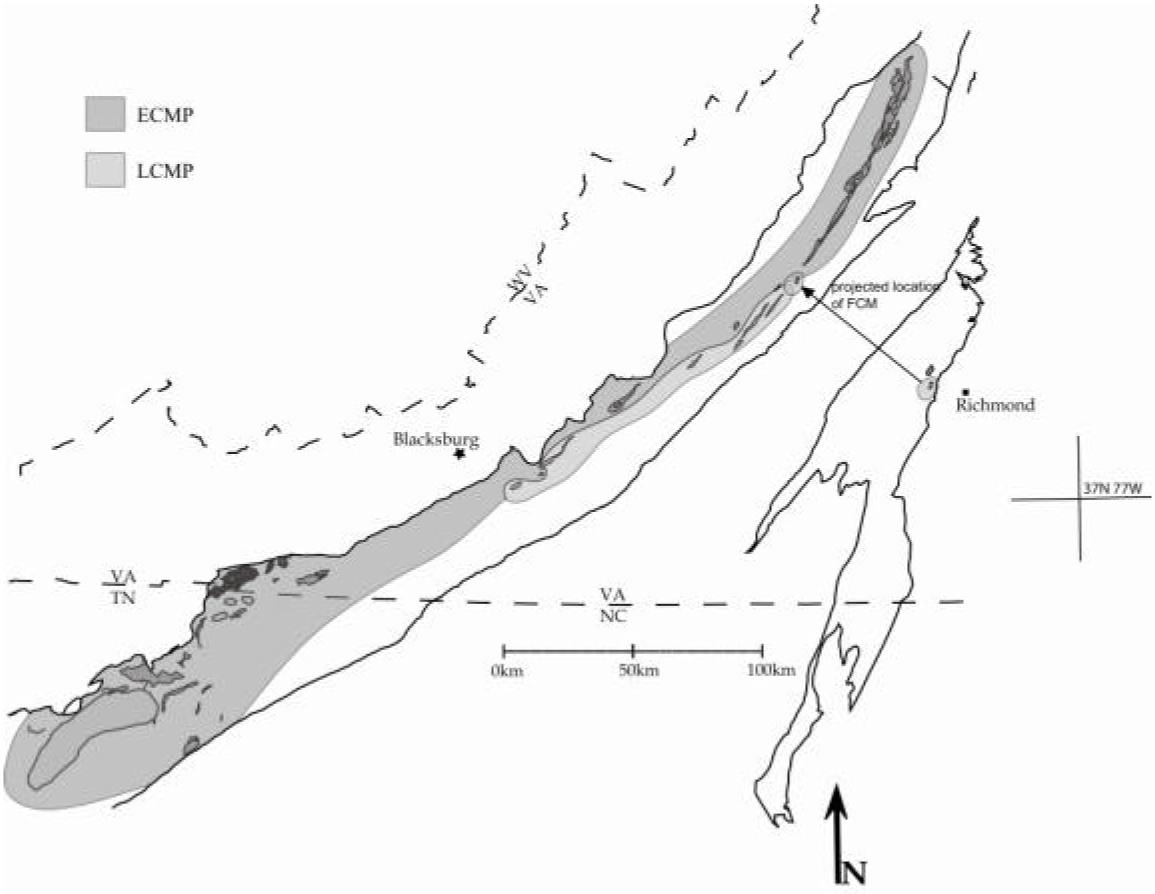


Figure 7. Geologic map of the ECMP and the LCMP. The LCMP is localized in the central area of the ECMP and to the west possibly extending into the Goochland terrane. To correct for post grenville rotation the location of Fine Creek Mills pluton (FCM) was projected perpendicular to the axis of the LCMP.

magmas (Clemens et al., 1986), (5) fractionation of an I-type magma (Collins et al., 1982), (6) partial melting of a restitic source including granulites, tonalities, and granitoids from which I-type magmas have been extracted (Rushmer, 1991; Clemens et al., 1986; Creaser at al., 1991; Beard et al., 1994), and (7) reaction melting involving a series of fractionation and contamination events (Barker et al., 1975). Because A-type classification does not imply a specific source or mode of origin, these theories are not mutually exclusive.

Two of the above models have been proposed for the CMP; partial melting of granulite basement and reaction melting (Essex, 1992; Glennie, 1993). Two experimental studies applicable towards ascertaining the first of these models have been conducted by Rushmer (1991) and Beard et al., (1994). In the first of these studies granulites of the Cucamonga Granulite Terrain in the San Gabriel Mountains of CA were melted, successfully producing an A-type melt. These results suggest that it may indeed be possible to produce A-type magmas from granulites however, because of the inconclusive nature of this study, more work needs to be done before this can be confirmed (Rushmer, 1991). More recently, Beard et al. (1994) conducted melting experiments and found that partial melting of the Blue Ridge lithologies could not reproduce higher Na and Fe, lower K and the REE pattern characteristic of A-type magmas. This suggests that although the partial melting of granulites may in certain conditions produce A-type melts it was not what produced the rocks of the ECP.

The second model described by Barker et a;., (1975) involves reaction melting involving a series of fractionation and contamination events with the first event involving the interaction of a basaltic liquid with the lower crust producing a syenitic magma which then may produce small amounts of Na-rich magmas through direct differentiation and K-rich magmas through interaction with granulite facies crust. Several of the bodies of the CMP have low Sr_i ratios including Bakersville gabbro at 0.7044 (Goldberg et al., 1986), Beech Pluton at 0.707 (Odom and Fullagar, 1984) and Striped Rock at 0.7077 (Essex, 1992). Modeling results of Essex (1992) suggest that in order to reproduce these low Sr_i ratios interaction with a less evolved source (.g. mantle) is necessary. The reaction-melting model of Barker et al. (1975) not only provides this primitive source, but an explanation for the presence of syenitic melts in the province. This model has been found by several authors (Essex, 1992; Glennie, 1993) to be the most applicable to the ECP and is the preferred model in this study.

White Mountain batholith (WMB), Figure 8, is qualitatively very similar to the ECMP in both major and trace element geochemistry. Substantial overlap is apparent in Shand's index (Figure 8a) and discrimination diagrams of Pearce et al. (1984) and Whalen et al. (1987) (Figure 8b, c). The most significant similarity between the two provinces, however, is in the REE trend. Identical REE concentrations, zircon controlled light to heavy REE ratio (~8) and a range of Eu anomalies (Figure 8d) of the ECMP and WMB in contrast to the LCMP suggest a similar petrogenetic history for the ECMP and the White Mountain Magma Series (WMMS), to which WMB belongs. The WMMS has been suggested to be the end product of crustal contamination and fractionation of a mantle derived source (Eby et al., 1992; Foland and Allen, 1991) a model similar to that proposed by Barker et al. (1975) for the Pikes Peak batholith and considered the most likely model for the ECMP. The primitive source necessary in this model has been suggested to represent a mantle plume (Eby et al., 1992) and, although still under debate, has since been linked to the Great Meteor hot spot track (Heaman and Kjarsgaard, 2000). In light of the similarities between the two provinces, a similar plume related model for the ECMP might be a possibility.

Inheritance

The REE patterns controlled by zircon extraction and high Zr concentrations within the ECMP plutons suggest liquids oversaturated in respect to Zr. This would result in minimal dissolution of inherited zircons incorporated into the melt (Watson and Harrison, 1983). The presence of inherited zircons is characteristic of ECMP plutons. The plutons dated in this study, ranging in age from 765±7 to 722±3 Ma, exhibit inherited ages between 800 to 2400 Ma. Inherited components in zircons within ECMP plutons have also been recognized by Su (1994), Odom and Fullagar (1984), and Fetter and Goldberg (1995). Su (1994) dated inherited zircons within Beech Pluton at 1424±29 Ma. These pre-Grenville ages suggest the possibility of an even older source to the melts of ECMP plutons. When plotted on a ternary diagram of the system, $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2, most ECMP compositions plot close to the A-type granites of the Southern Oklahoma Aulocogen (McConnell and Gilbert, 1990). McConnell and Gilbert (1990) suggested that Southern Oklahoma Aulocogen is the product of partial melting of a feldspathic-rich, "continental", crustal layers most likely represented by the Eastern Granite-Rhyolite Province

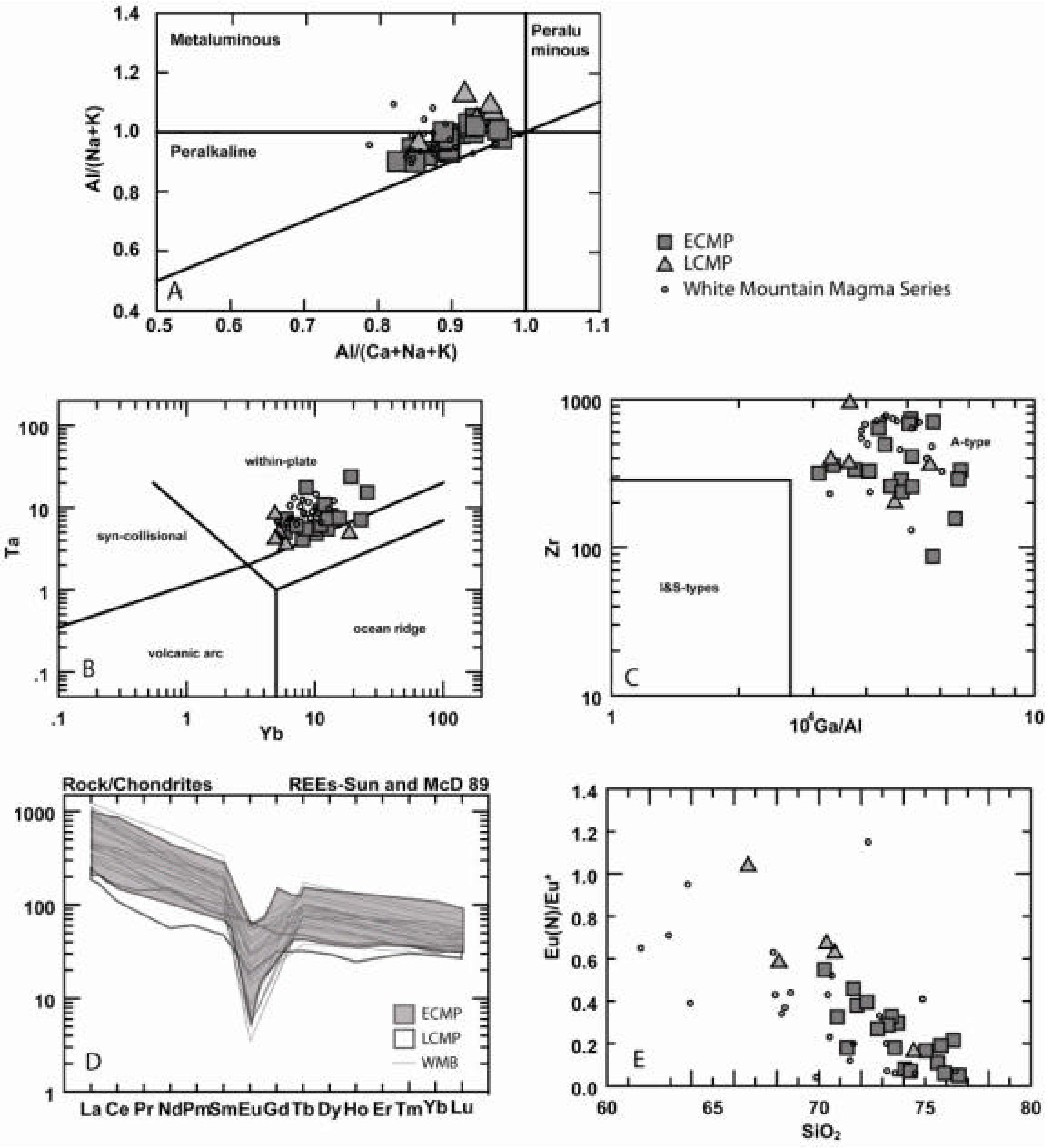


Figure 8. Major and trace element geochemistry of the Cryogenian rocks of the Blue Ridge as compared to the White Mountain Batholith (WMB) which is part of the White Mountain Magma Series. Figure A is Shand's index, B and C are Pearce et al. (1984) and Whalen et al. (1987) discrimination diagrams for granites and D and E are trace element distribution diagram and Eu anamoly versus SiO_2 diagram, respectively. In all the above diagrams a significant overlap between the ECMP, LCMP and WMB is apparent. Of the two Cryogenian provinces, the ECMP is significantly more similar to the WMB in trace element concentrations.

which has been dated at ~1500 Ma (Van Schmus et al., 1996). It is possible that the pre-Grenville inheritance observed within the ECMP may come from the same source as the rocks of the Southern Oklahoma Aulocogen, Eastern Granite-Rhyolite province (Hatcher, 2002). Among the plutons belonging to the younger province, no inheritance was observed. More isotopic (Sr and Nd) data is necessary in order to ascertain whether this difference in inheritance represents a difference in source regions.

Tectonic Models

Mechanisms of extension leading to rift formation have been summarized and classified by Sengör and Natal'in (2001). In this classification, mechanisms of extension are split into active and passive, which are then further subdivided based on tectonic environment. Of these mechanisms, several can result in interplate extensional regimes and two, both passive, have been proposed to be applicable to the ECMP; triple junction, and convergence-related extension. These tectonic models include (1) a failed rift associated with a triple junction (Rankin 1976), (2) gravitational collapse of crustal regions overthickened by Grenville orogenesis, (Sinha, 1992) and (3) flanks of an active within plate rift zone similar to the Red Sea region (Tollo and Aleinikoff, 1996).

Rankin (1976) was the first to discuss the possible tectonic mechanisms for extension leading to the formation of the ECMP. He suggested that the Catoctin and Mt. Rogers rhyolites were developed within a triple junction leading to the breakup of Rodinia with the Catoctin volcanics representing an active rift arm and the Mt. Rogers volcanics a failed arm. With the recognition that the Mt. Rogers and the Catoctin Volcanics were the result of two different rifting events (Badger and Sinha, 1988; Aleinikoff et al., 1995) this theory is unlikely.

The ECMP was also modeled by Sinha (1992) to be the result of gravitational collapse and associated crustal extension as a result of Grenville orogenesis and crustal thickness. The time lapse between maximum thickening and the onset of extension has been shown to depend on the strength of the crustal block, the temperature of the underlying lithosphere, and the maximum thickness during orogenesis. Depending on these parameters, the time lapse can vary from almost instantaneous to 100 Ma (Sonder et al., 1987). The time lapse between the

Grenville orogenesis and the onset of extension represented by the ECMP, however, is in excess of 220 Ma, making erosion a more likely method of restoring isostatic balance.

Tollo and Aleinikoff (1996) compared the ECMP to A-type silicic rocks exposed along the flanks of an active encratonic rift zone in the Red Sea region. Similar to the ECMP, the plutonic bodies in the Red Sea region are A-type granites to syenites of metaluminous to peralkaline composition and are found in close associated with volcanic bodies. The igneous rocks are oriented parallel to the rift zone in a narrow corridor and are considered directly related the rift system. Unlike the Red Sea region, the plutons within the ECMP predate the development of oceanic crust, represented by the Catoctin volcanics and the Moneta gneiss (Badger and Sinha, 1988; Wang, 1991; Aleinikoff et al., 1995; Goldberg et al., 1995), by almost 200 Ma.

Based on a space-time analysis of the ECMP we propose a mechanism of extension for the province fitting into the k22 (active extension without previous doming) category of Sengör and Natal'in (2001); a plume.

When the calculated as well as published U/Pb ages of the ECMP plutons are plotted versus distance along strike of the province from Ashville, NC to Bloomfield, VA (Figure 6), a negative slope becomes apparent. It is likely that this age progression is the record of a continental plume track similar to the White Mountain magma series of the Great Meteor hot spot track (supported by geochemical similarities described above) (Heaman and Kjarsgaard, 2000). The age variation of ~30 Ma on average at any given spot along the province is similar to that observed by Heaman and Kjarsgaard (2000) for the continental section of the Great Meteor hot spot track. Such variation could result from several factors including delayed melting and magma ponding due to crustal heterogeneities (Beard et al., 1994) and normal faults acting as conduits propelling melt towards the surface (Figure 9). Furthermore, the ~2 cm/yr plate motion rate calculated from the plot of U/Pb ages versus distance along the province from south to north is in agreement with predicted plate motion rates within a supercontinent (Meert, in press; Gurnis, 1988).

In addition, zircon saturation temperatures, calculated using the method developed by Watson and Harrison (1983) for the plutonic (and volcanic) rocks of the ECMP, range between

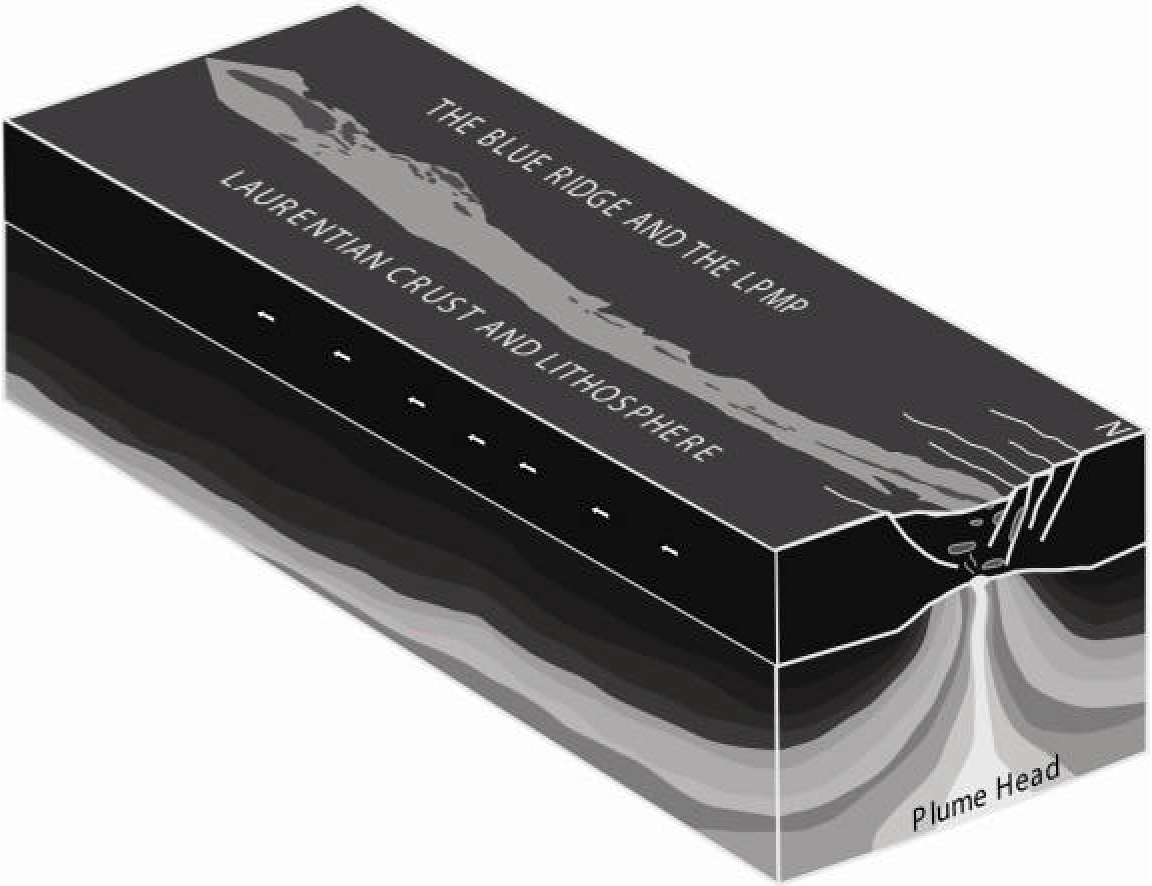


Figure 9. Three dimensional representation of plume induced rifting of the Blue Ridge (not to scale). Plutons rising at different rates or produced as a result of plume tail interaction with the crust represent the youngest bodies at any given spot. Only the ECMP plutons are represented.

800ºC and 1100ºC, requiring an extracrustal heat source. Such a heat source can be supplied through underplating of continental crust by basaltic magma (Clemens and Vielzeuf, 1987) or superplume formation, resulting from insulation tendencies of supercontinents (Gurnis, 1988) such as Rodinia. Such a superplume, as much as ~6000 km in diameter, has been suggested to have formed beneath the supercontinent of Rodinia (Meert, in press; Li and Li, 2003). Such a superplume may act as a magma source for the formation of smaller plume events (Li and Li, web). Several such smaller events, originating from the transition zone or mid-mantle (Zhao, 2001), have been identified on both coasts of Laurentia as well as Australia and China (Heaman et al., 1992; Wingate et al., 1998; Park, 1995; Li et al., 1999; Li and Li, 2002; Li et al., 2003). We propose that the ECMP is also such an event.

Furthermore, the failure of this event to produce successful rifting may have lead to the development of a zone of weakness along which later successful extension, possibly resulting from a superplume (Puffer, 2002), could be focused culminating with the extrusion of the Catoctin volcanics and the formation of the Iapetus ocean.

Conclusions

Based on geochemical as well as geochronologic data it is concluded that the Late Cryogenian Magmatic Province of the Blue Ridge Geologic Province of northern North Carolina and Virginia is in fact two distinct provinces, the ECMP and the Early Cryogenian Suite (LCMP) (Figure 7). Although sharing similar source materials the two provinces have undergone different amounts of fractionation with the LCMP the less evolved of the two. In addition the LCMP appears to be less extensive and lacking an age trend which is one of the distinguishing features of the older province (Figure 6).

Published as well as new ages of ECMP bodies display a younging trend towards the north that closely resembles the continental section of the great Meteor Hot Spot Track (Heaman and Kjarsgaard, 2000). Geochemical similarity between the plutons of the ECMP and the White Mountain Magma Series (Figure 6), stratigraphic evidence (Fetter and Goldberg, 1995) and agreement with the predicted plate motion rate at the time (Meert, in press; Gurnis, 1988) supports the model of the ECMP as a continental plume track. The recognition of such plume tracks and their relationship to rift margins is crucial to deciphering the dynamics of supercontinetal breakup.

References:

Abbey, W.J., Tollo, R.P., and Aleinikoff, J.N., 1995, Petrology and geochemistry of the Polly Wright Cove Pluton, Blue Ridge Province, Virginia; perspectives on late Neoproterozoic anorogenic magmatism, central Laurentian Appalachians, in Brown, M., and Picoli, P.M. (Editors), The origin of granites and related rocks: US Geologic Survey Circular 1129, p.7

Arav, S., 1989, Geology, geochemistry, and gelative age of two plutons from the Robertson River formation in Northern Virginia, MS thesis, George Washington University

Aleinikoff, J.N., Zartman, R.E, Walter, M., Rankin, D.W., Lyttle, P.T., and Burton, W.C., 1995, U-Pb ages of the metarhyolites of the Catoctin and Mount Rogers formations, central and southern Appalachians: evidence for two pulses of Iapetan rifting, American Journal of Science, v. 295, pp. 428-454

Badger, R.L. and Sinha A.K., 1988, Age and Sr isotopic signature of the Catoctin Volcanic province: implications for subcrustal mantle evolution, Geology, v.16, pp. 692-695

Bailey, C.M., 1994, Temporal, kinematic, and strain analyses of granitic tectonites from the central Appalachians, PhD thesis, Johns Hopkins University

Bailey, C.M. and Tollo, R.P., 1998, Late-Neoproterozoic extension-related magma emplacement in the central Appalachians: an example from the Polly Wright Cove pluton, The Journal of Geology, v.106, pp. 347-359

Barker, F., Wones, D.R., Sharp, W.N., and Desborough, G.A., 1975, The Pikes Peak batholith, Colorado Front Range, and a model for the origin of the gabbro-anorthosite-syenite-potassic granite suite, Precambrian Research, v2, pp. 97-160

Bartholomew, M.J., 1981, Geology of the Roanoke and Stewartsville quadrangles, Virginia: Virginia Division of Mineral Resources, Publication 34, p.23

Bartholomew, M.J., Gathright, T.M., and Henika, W.S., 1981, A tectonic model for the Blue Ridge in central Virginia, American Journal of Science, v. 281, pp. 1164-1183

Bartholomew, M.J. and Lewis, S.E., 1984, Evolution of Grenville massifs in the Blue Ridge geologic province, southern and central Appalachians, in M.J. Bartholomew (Editor), The Grenville Event in the Appalachians and Related Topics: Geological Society of America Special Paper , v.194, pp.229-254

Bayly, B., 1968, Introduction to petrology, Prentice Hall, Engelwood Cliffs, New Jersey

Beard, J.S., Lofgren, G.E., Sinha, A.K., and Tollo, R.P., 1994, Partial melting of apatite-bearing charnokite, Granulite, and diorite: melt compositions, restite mineralogy, and petrologic implications, Journal of Geophysical Research, vol. 99, #B11, pp. 21591-21603

Benisek, A., and Finger, F., 1993, Factors controlling the development of prism faces in granite zircons: a microprobe study, Contributions to Mineralogy and petrology, v. 114, pp. 441-451

Brock J.C., 1981, Petrology of the Mobley Mountain granite, Amherst Co., Virginia, MS thesis, University of Georgia, Athens

Brock, J.C., Herz, N., Mose, D., and Nagel, S., 1987, Geology of the Mobley Mountain granite, Piney River quadrangle, Virginia Blue Ridge, Contributions to Virginia Geology-V, Virginia Division of Mineral resources Publication, v. 74, pp 69-80

Bryant B., and Reed Jr. J.C., 1970, Geology of the Grandfather Mountain window and vicinity, North Carolina and Tennessee, Geological Survey professional paper #615, pp. 12-115

Clemens, J.D., Holloway, J.R., White A.J.R., 1986, Origin of an A-type granite, American Mineralogist, v. 71, pp. 317-324

Clemens, J.D., and Vielzeuf, D., 1987, Constraints on melting and magma production in the crust, Earth and Planetary Science Letters, v. 86, pp. 287-306

Collins W.J., Beams, A.J., White, A.J.R., and Chappell, B.W., 1982, Nature and origin of A-type granites with particular reference to southeastern Australia, Contribution to Mineralogy and Petrology, v. 80, pp. 189-200

Creaser, R.A., Price, R.C., and Wormald, R.J., 1991, A-type granites revisited: assessment of a residual-source model, Geology, pp.163-166

Davis, R.G., 1974, Pre-Grenville ages of basement rocks in central Virginia: a model for interpretation of zircon ages, M.S. Thesis, Virginia Tech

Eby, G.N., 1990, The A-type granitoids: a review of their occurrence and chemical characteristics and speculation on their petrogenesis, Lithos, v. 26, pp. 115-134

Eby, G.N., Krueger, H.W., and Creasy, J.W., 1992, Geology, geochronology, and geochemistry of the White Mountain batholith, New Hampshire, Geological Society of America Special Paper #268, pp. 379-397

Essex, R.M., 1992, Age and petrogenesis of the Striped Rock granite pluton: Blue Ridge province, southwest Virginia: MS thesis, Virginia Tech, Virginia

Farrar, S.S., 1984, The Goochland granulite terrane: remobilized Grenville basement in the eastern Virginia Piedmont, in Bartholomew, M.J. (Editor), The Grenville Event in the Appalachians and related Topics, Geological Society of America Special Paper 194, pp. 215-227

Fetter, A.H, and Goldberg, S.A., 1995, Age and geochemical characteristics of bimodal magmatism in the Neoproterozoic Grandfather Mountain rift basin, Journal of Geology, v. 103, pp. 313-326

Foland, K.A., and Allen, J.C., 1991, Magma sources for Mesozoic anorogenic granites of the White Mountain magma series, New England, USA, Contributions to Mineralogy and Petrology, v. 109, #2, pp. 195-211

Glennie, S.P., 1993, The geology of Suck Mountain pluton, Blue Ridge province, Virginia: MS thesis, Columbian College

Glover, L., III, Mose, D.G., Poland, F.B., Bobyarchick, A.R., and Bourland, W.C., 1978, Grenville basement in the eastern Piedmont of Virginia: implications for orogenic models, Geologic Society of America Abstracts with Programs, v. 10, p. 169

Goldberg, A.G., Butler, J.R., Fullagar, P.D., 1986 The Backersville Dike swarm: geochronology and petrogenesis of late Proterozoic basaltic magmatism in the southern Appalachian Blue Ridge, American Journal of Science, vol. 286, pp.403-429

Goldberg, S.A., Butler, J.R. Trupe, C.H., and Adams, M.G., 1992, The Blue Ridge thrust complex northwest of the Grandfather Mountain window, North Carolina and Tennessee, in Dennison, J.M. and Stewart, K.G. (Editors), Geologic field guides to North Carolina and vicinity: Chapel Hill, North Carolina, department of geology, Geologic Guidebook no.1

Goldberg, S.A., Wang, P., and Glover, L., III, 1995, U-Pb zircon age for the Moneta gneiss, Blue Ridge of Virginia, GSA Abstracts with Programs, Southeastern Section, v. 27, p. 57

Gurnis, M., 1988, Large-scale mantle convection and the aggregation and dispursal of supercontinents, Nature, v. 332, pp. 695-699

Hall, A., 1996, Igneous petrology, second edition, Longman Group Limited, London, pp 421-423

Hatcher, R.D.Jr, 1985, The North American Appalachian orogen, in Gayer, R.A. (Editor), The tectonic evolution of the Caledonide-Appalachian orogen, Friedr. Vieweg & Sohn, Braunschweig, Germany, pp. 48-56

Hatcher, R.D., Jr., 2002, Hints of the mid-continent beyond the Grenville orogen and Gondwanan inheritance in Appalachian terranes, GSA Abstracts with Programs, v. 34, # 6, p.78

Heaman, L.M. and Kjarsgaard, B.A., 2000, Timing of eastern North American kimberlite magmatism: continental extension of the Great Meteor hotspot track?, Earth and Planetary Science Letters. V. 178, pp. 253-268

Heaman, L.M., Le Cheminant, A.N., and Rainbird, R.H., 1992, Nature and timing of the Franklin igneous events, Canada: Implications for the late Proterozoic mantle plume and the break-up of Laurentia, Earth and Planetary Science Letters, v. 109, pp. 117-131

Henika, W.S., 1997a, Geologic Map of the Roanoke 30 x 60minute quadrangle, Virginia: Virginia Division of Mineral Resources Publication 148, 1:100000 scale, colored geologic map w/explanation.

Henika, W.S., 1997b, Economic and environmental geology across the boundary between the Blue Ridge and Valley and Ridge, near Roanoke, Virginia, Twenty seventh annual Virginia Geologic Field Conference Guide.

Herz N.M, and Force, E.R., 1984, Rock suites in Grenvillian terrane of the Roseland District, Virginia: Part1. Lithologic relationships, Geological Society of America Special Paper #194, pp. 187-200

Horton, J.W., Jr., Drake, A.A., Jr., Rankin, D.W., Dallmeyer, R.D., 1991, Preliminary tectonostratigraphic terrane map of the central and southern Appalachians, Miscellaneous Investigations Series – US Geological Survey, Report: I-2163, 1sheet

Hughes, S.S., Lewis, S.E., Bartholomew, M.J., Sinha, A.K., Hudson, T.A., Herz, N., 1997, Chemical diversity and origin of Precambrian Charnokitic rocks of the central Pedlar massif, Grenvillian Blue Ridge Terrane, Virginia, Precambrian Research, v. 84, pp. 37-62

Hughes, S.S., Lewis, S.E., Bartholomew, M.J., Sinha, A.K., and Herz, N., in press, Geology and geochemistry of Fe-Ti-rich granitic and charnokitic rocks in the central Lovingston massif of the Grenvillian Blue Ridge terrane, USA, in Tollo, R.P., Corriveau, L., McLelland, J.B., and

Bartholomew, M.J. (Editors), Proterozoic tectonic evolution of the Grenville orogen in eastern North America

Jerden, J.L., 2001, Origin of uranium mineralization at Coles Hill Virginia (USA) and its natural attenuation within an oxidizing rock-soil-ground water system, PhD thesis, Virginia Tech, Virginia

Lee, J.K.W., and Tromp, J., 1995, Self-induced fracture generation in zircon, Journal of Geophysical Research, B, Solid Earth and Planets, v. 100, n. 9, pp. 17753-17770

Lee, R.L., Cho, M., Cheong, C.-S., Kim, H., Wingate, M.T.D., 2003, Age, Geochemistry, and tectonic significance of Neoproterozoic alkaline granitoids in the northwestern margin of the Gyeoniggi massif, South Korea, Precambrian Research, v. 122, pp. 297-310

Li, X.H., Li, Z.X., Zhou, H., Liu, Y., and Kinny, P.D., 2002, U-Pb zircon geochronology, geochemistry and Hd isotopic study of Neoproterozoic bimodal volcanic rocks in the Kangdian Rift of South China: implications for the initial rifting of Rodinia, Precambrian Research, v. 113, pp. 135-154

Li, Z.X., and Li, X.H., 2003, Did a mantle superplume bring down the Neoproterozoic supercontinent Rodinia? Geophysical research Abstracts, v. 5, 08113

Li, Z.X., Li, X.H., Kinny, P.D., and Wang, J., 1999, The breakup of Rodinia: did it start with a mantle plume beneath South China?

Loiselle, M.C. and Wones, D.R., 1979, Characteristics and origin of anorogenic granites, Geologic Society of America Abstracts with Programs, v.11, p.468

Luckert, M.T., and Banks, P.O., 1984, Geology and age of the Robertson River pluton, in Bartholomew, M.J. (Editor), The Grenville event in the Appalachians and related topics: Geological Society of America Special Paper, v. 194, pp. 161-166

Ludwig, 1990, ISOPLOT: A plotting and regression program for radiogenic isotope data, for IBM-PC compatible computers Version 211, US Geological Survey Open –file Report, p.88-557

Manian, P.D. and Piccoli, P.M., 1989, Tectonic discrimination of granitoids, Geological Society of America Bulletin, v.101, #5, pp. 635-643

McBirney, A.R., 1993, Igneous petrology, Second Edition, Jones and Baertlett Publishers, Boston

McConnell, D.A., and Gilbert, M.C., 1990, Cambrian extensional tectonics and magmatism within the southern Oklahoma Aulocogen, Tectonophysics, v. 174, pp. 147-157

Meert, J.G., and Tamrat, E., 2003, A mechanism for explaining continental motion in the late Neoproterozoic, in: Eriksson et al., (Editors), The Precambrian Earth: Tempos and Events, Elsevier Publications, in press

Miller, C.F., Hatcher, R.D. Jr., Ayes, J.C., Coath, C.D., and Harrison, T.M., 2000, Age and zircon inheritance of eastern Blue Ridge plutons, southwestern North Carolina and northeastern Georgia, with implications for magma history and evolution of the southern Appalachian orogen, American Journal of Science, v. 300, pp. 142-172

North Carolina Division of Land Resources, 1985, Geologic map of North Carolina, Division of Land Resources, scale 1:500,000

Odom, A.L. and Fullagar, P.D., 1984, The time of opening of the Iapetus ocean: Rb-Sr whole-rock and inherited zircon ages of the Crossnore Plutonic-Volcanic group, Southern Appalachians: Geological Society of America Special Paper 194, pp. 255-262

Owens, B.E., 2000, Late Proterozoic plutonism in the Goochland terrane, Virginia: Laurentian or Avalonian connection?, GSA Abstracts with Programs, SE section, v. 32, # 2, p. A-65

Paces, J.B., and Miller, J.D., 1993, Precise U-Pb ages of Duluth Complex and related mafic intrusions, northeastern Minnesota: geochronological insights into physical, petrogenetic, paleomagnetic, and tectonomagnetic processes associated with the 1.1Ga midcontinent rift system, Journal of Geophysical Research, v. 98, pp. 13997-14103

Park, J.K., Buchan, K.L., and Harlan, S.S., A proposed giant radiating dyke swarm fragmented by the separation of Laurentia and Australia based on paleomagnetism of ca. 780 Ma mafic intrusions in western North America, Earth and Planetary Science Letters, v. 132, pp. 129-139

Pearce, J.A., Nigel, B.W., and Tindle, A.G., 1984, Trace element discrimination diagrams for the tectonic interpretation of granitic rocks, Journal of Petrology, v. 25, pp. 956-983

Pitcher, W.S., 1982, Granite type and tectonic environment, in Hsu, K.J. (Editor): Mountain building processes, Academic Press, London, pp. 19-40

Pointer, C.M., Ashworth, J.R., and Ixer, R.A., 1988, The zircon-thorite mineral group in metasomatized granite, Ririwai, Nigeria, 2.Zoning, alteration and exsolution in zircon, Mineralogy and Petrology, v. 39, pp. 21-37

Puffer, J.H., 2002, A late Neoproterozoic eastern Laurentian superplume: location, size, chemical composition, and environmental impact, American Journal of Science, v. 302, pp. 1-27

Pupin, J.P., and Turco, G., 1972, La zircon accessoire en geothermometrie, C.R. Ac. Sc., Paris, D, v.274, pp. 2121-2124

Pupin, J.P., and Turco, G., 1975, Typologie du zircon accessoire dans les roches plutoniques dioritiques, granitiques et syenitiques. Factures essentials determinant les variations typologiques, Petrol., v. I, pp. 139-156

Pupin, J.P., Bonin, P., Tessier, M., and Turco, G., 1978, Rôle de l’eau sur les caractères morphologiques et la cristallisation du zircon dans les granitoïds, Bull. Soc. Geol. France, (7), T. XX, #5, p. 721-725

Quidelleur, X., Grove, M., Lovera, O.M., Harrison, T.M., Yin, A., and Ryerson, F.J., 1997, Thermal evolution and slip history of the Renbu Zedong thrust, southeastern Tibet, Journal of Geophysical Research, vol.102, #B2, pp 2659-2679

Rankin, D.W., 1968, Magmatic activity and orogeny in the Blue Ridge province of southern Appalachian mountain system in northwestern North Carolina and southwestern Virginia, Gological Sciety of America Special Paper 115, p. 181

Rankin, D.W., 1970, Stratigraphy and structure of Precambrian rocks in northwestern North Carolina, in Studies of Appalachian geology: central and southern, in Fisher, G.W., Pettijohn, F.J., Reed, J.C. Jr., and Weaver, K.N. (Editors), Interscience Publishers, New York, pp. 227-245

Rankin, D.W., 1975, The continental margin of eastern North America in the southern Appalachians: The opening and closing of the proto-Atlantic, American Journal of Science, v.275-A, pp. 298-336

Rankin, D.W., 1976, Appalachian salients and recesses: late Precambrian continental breakup and the opening of the Iapetus ocean, Journal of Geophysical Research, v. 81, # 32, pp. 5605-5619

Rankin, D.W., Stern, T.W., Reed, J.C., Jr., and Newell, M.F., 1969, Zircon ages of felsic volcanic rocks in the upper Precambrian of the Blue Ridge central and southern Appalachian Mountains: Science, v. 166, # 3906, pp. 741-744

Rankin, D.W., Stern, T.W., McLelland, J., Zartman, R.E., and Odom, A.L., 1983, Correlation chart for Precambrian rocks in the eastern United States, in Harrison, J.E., and Peterman, Z.E., (Editors), Correlation of Precambrian rocks of the United States and Mexico. US Geological Survey Professional Paper 1240-E, pp. E1-E18

Rankin, D.W., and nine others, 1989, Pre-orogenic terranes, in Hatcher, R.S., Jr., et al., (Editors), The Appalachian Ouachta orogen in the United States, Boulder, Colorado, Geological Society of America, Geology of North America, v. F-2, p. 7-100

Rogers, J.J.W., and Greenberg, J.K., 1990, Late-orogenic, post-orogenic, and anorogenic granites: distinction by major-element and trace-element chemistry and possible origins, The Journal of Geology, v. 98, # 3, pp. 291-309

Rushmer, T., 1991, The chemical and rheological behavior of amphibolite rocks during fluid-absent partial melting, PhD thesis, Swiss Federal Institute of Technology, Zurich, Switzerland

Sengör, A.M.C., and Natal'in, B.A., 2001, Rifts of the world, in Ernst, R.E. and Buchan, K.L. (Editors), Mantle plumes: their identification through time, Geological Society of America Special Paper 352, pp. 389-482

Simpson, C., and Kalaghan, T., 1989, Late Precambrian crustal extension preserved in Fries fault zone mylonites, Southern Appalachians, Geology, v. 17, pp. 148-151

Sinha, A.K., 1992, The latest Precambrian magmatic record of extensional tectonics in the central and southern Appalachians: response to Grenville compressions, Geological Society of America Abstracts with Programs, Southeastern Section, v.24, #2, p.65

Sinha, A.K., and Bartholomew, M.J., 1984, Evolution of the Grenville terrane in the central Virginia Appalachians, Bartholomew, M.J. (Editor), The Grenville event in the Appalachians and related topics: Geological Society of America Special Paper 194, pp. 175-186

Sonder, L.J., England, P.C., Wernicke, B.P., and Christiansen, R.L., 1987, A physical model for Cenozoic extension of western North America, in Continental extensional tectonics, Geological Society Special Publication, 28, pp. 187-201

Su Q., 1994, Geochronological and isotopic studies of late Proterozoic Crossnore-Type plutons in the southern Appalachian Blue Ridge, North Carolina and Tennessee, PhD thesis, University of North Carolina at Chapel Hill.

Su Q., Goldberg S.A., Fullagar, P.D., 1993, Precise U-Pb zircon ages of Neoproterozoic pPlutons in the southern Appalachian Blue Ridge and their implications for the initial rifting of Laurentia, Precambrian Research, v.68, pp. 81-95

Tollo, R.P., 1994, Definition and nomeclature of the Robertson River igneous suite, Blue Ridge province, Virginia, in Stratigraphic Notes, USGS Bulletin 2060, pp. 19-24

Tollo, R.P. and Aleinikoff, J.N., 1996, Petrology and U-Pb geochronology of the Robertson River igneous suite, Blue Ridge province, Virginia - evidence for multistage magmatism associated with an early episode of Laurentian rifting; American Journal of Science, vol. 296, p 1045-1090

Tollo, R.P. and Arav S., 1988, The Robertson River igneous suite (Blue Ridge province, Virginia); late Proterozoic anorogenic (A-Type) granitoids of unique petrochemical affinity, in: Proceedings of the international conference on basement tectonics, vol. 18, pp. 425-441

Tollo, R.P., Lowe, T.K., Arav, S., Gray, K.J., 1991, Geology of the Robertson River igneous suite, Blue Ridge province, Virginia, in Schultz, A., and Compton-Gooding, E. (Editors), Guidebook (Virginia Museum of Natural History), v.2, pp.229-262

Tollo, R.P., Zartman, R.E., Walter, M., Rankin, D.W., Lyttle, P.T., and Burton, W.C., 1995, U-Pb ages of metarhyolites of the Catoctin and Mount Rogers formations, central and southern Appalachians: evidence for two pulses of Iapetan rifting, American Journal of Science, vol. 295, pp. 428-454

Van Schmus, W.R., Bickford, M.E., and Turek, A., 1996, Proterozoic geology of the east-central midcontinent basement, in: van der Pluijm, B.A., Catacosinos, P. (Editors), Basement and basins of eastern North America, Geological Society of America Special Paper 308, pp. 7-32

Virginia Division of Mineral Resources, 1993, Geologic map of Virginia: Virginia Division of Mineral Resources, scale 1:500,000

Wang, P., 1991, Geology and tectonic significance of the late Precambrian eastern Blue Ridge cover sequence in central Vieginia, PhD thesis, Virginia Tech, Blacksburg, Va

Watson, E.B. and Harrison, T.M., 1983, Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types, Earth and Planetary Science Letters, v. 64, pp. 295-304

Whalen., J.B., Currie, K.L., and Chappell, B.W., 1987, A-type granites: geochemical characteristics, discrimination and petrogenesis, Contributions to Mineralogy and Petrology, v. 95, pp. 407-419

Williams, H., and Hatcher, R.D., Jr., 1983, Appalachian suspect terranes, in Hatcher, R.D., Jr., Williams, H., and Zietz, I. (Editors), Contributions to the tectonics and geophysics of mountain belts, Geological Society of America Memoir 158, pp. 33-54

Wingate, M.T.D., Campbell, I.H., Compston, W., and Gibson, M.G., 1998, Ion microprobe U-Pb ages for Neoproterozoic basaltic magmatism in south-central Australia and implications for the breakup of Rodinia, Precambrian Research, v. 87, pp. 135-159

Zen, E., 1992, Using granite to image the thermal state of the source terrane, in Brown, P.E and Chappell, B.W. (Editors), The second Hutton symposium on the origin of granites and related rocks, Geological Society of America Special Paper 272, pp. 107-114

Zhao, D., 2001, Seismic structure and origin of hotspots and mantle plumes, Earth and Planetary Science Letters, v. 192, pp.251-265

Zmoda, A.J., 1987, Geochemistry of volcanic rocks from the Grandfather Mountain window, northwestern North Carolina, MS thesis, University of North Carolina at Chapel Hill

Appendix A: Sample Locations

MF-02-3 (Dillons Mill pluton) was collected from an extensively weathered outcrop on the bank of a stream a few hundred feet from route 742 in the Callaway quadrangle. The GPS coordinates of the sample location 37 13.687N 80 02.452E. The collected hand sample is a medium grained granite.

MF-02-4 (Dillons Mill pluton) was collected from a small, extensively weathered outcrop on the side of route 742 near the fence of a horse pasture. The hand sample is a medium grained granite exhibiting a weak foliation.

GCY-863 (White Oak Creek pluton) was received from Bill Henika of the Division of Mineral Resources who collected it along white oak creek off of route 684.

MF-02-1 (Stewartsville pluton) was collected from an outcrop located on the northern side of the railroad tracks east of the intersection of the tracks with route 634 in the Hardy quadrangle. The GPS coordinates of the sample location are 37 13.687N, 79 49.210E. The sample is a coarse-grained granite exhibiting steeply dipping foliation.

Sville-1 Stewartsville pluton, was collected at the southern end of the pluton

SM-5-95 (Suck Mountain pluton) rim, granite, collected along a road cut beginning at bench mark 1133 and Antioch Church

SM-16-95 (Suck Mountain pluton) core, foliated granite, collected from the ridge of the pluton

CL-12-95 (Mobley Mountain pluton), light colored, medium grained granite sampled along the ridge of Mobley Mountain

JR–75-19 (Rockfish River pluton), granodiorite, 37º48’52”N, 78º46’31”W

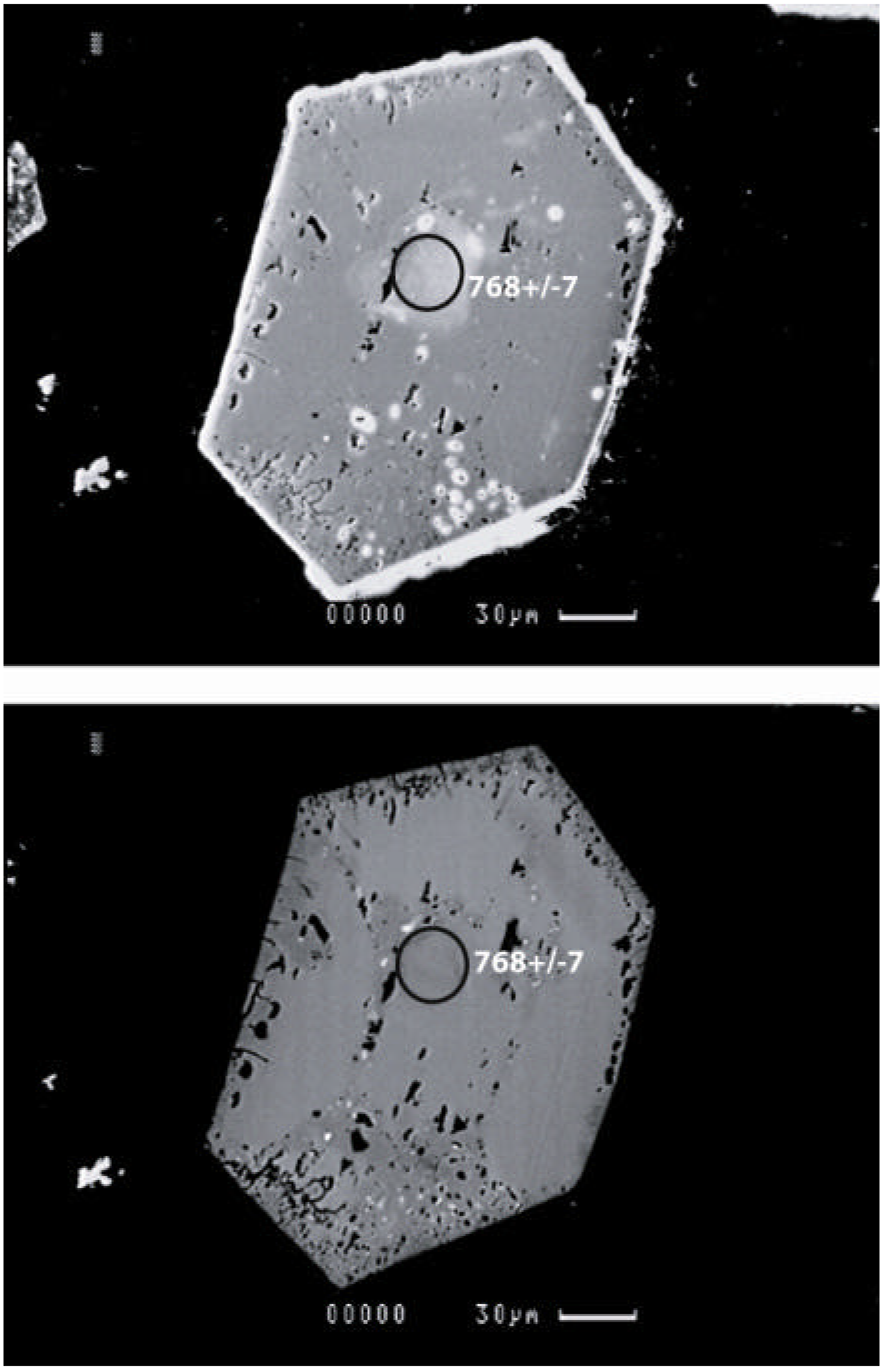
R-4-95 (Amissville pluton) near the intersection of Virginia Rt. 637 and Rt. 647

FP5-42 (Fine Creek Mills pluton) 350m northeast of intersection of RT. 711 and 628, Fine Creek Mills quadrangle

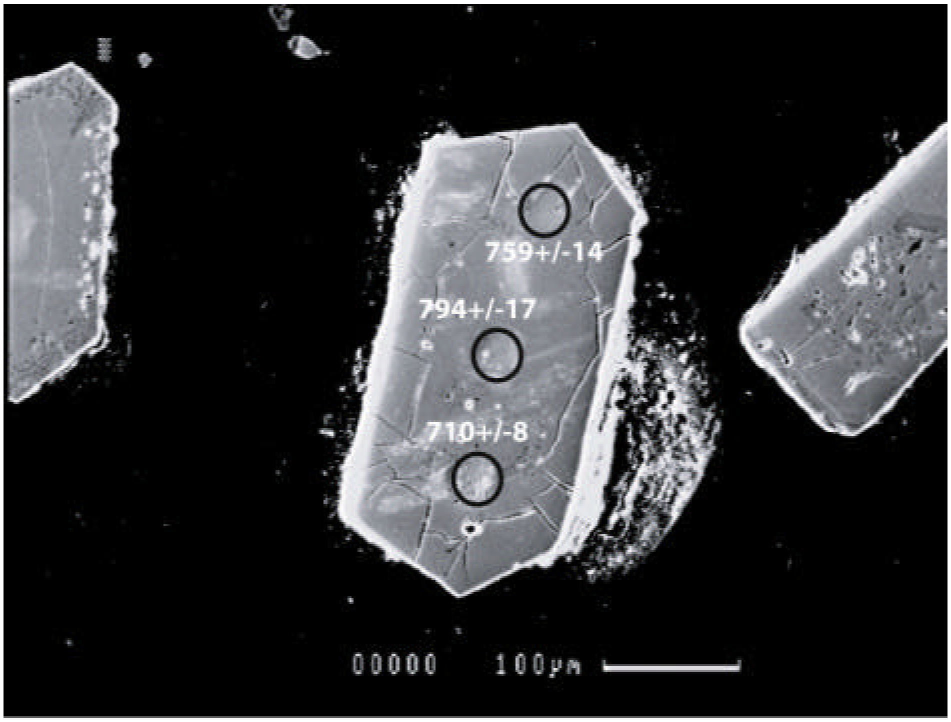
Appendix B: SEM images after ion probe work

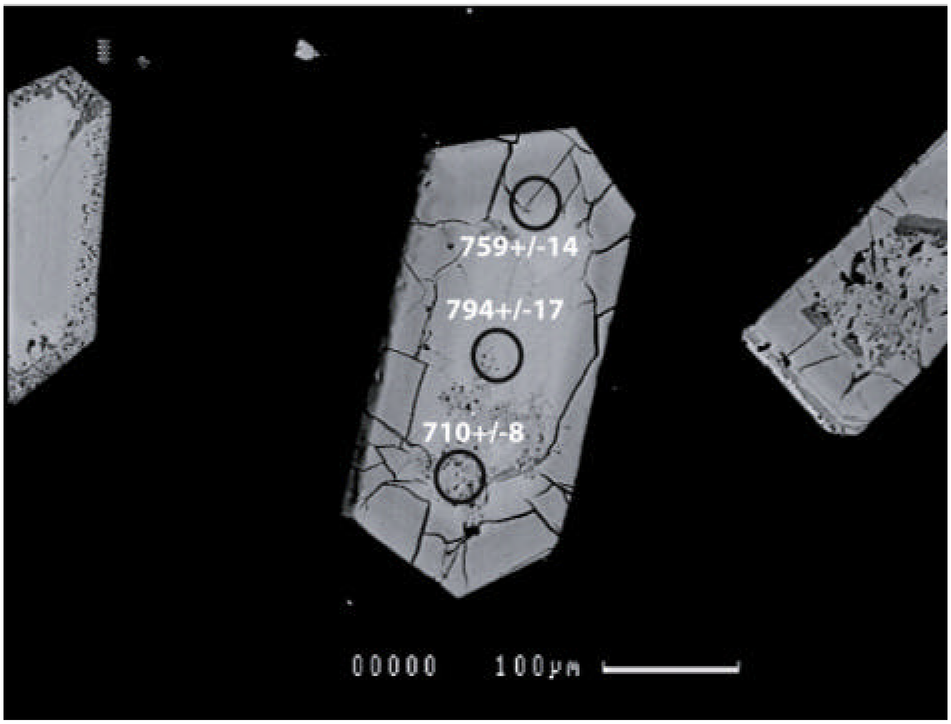
Images of zircons from plutons of the Late Cryogenian Magmatic Province. Black circles represent locations of spot analysis with the calculated 206Pb/238U age in Ma. The upper image is taken using secondary electron imaging while the lower is taken using backsatter electron imaging.

White Oak Creek pluton (WOC c1r4g1)

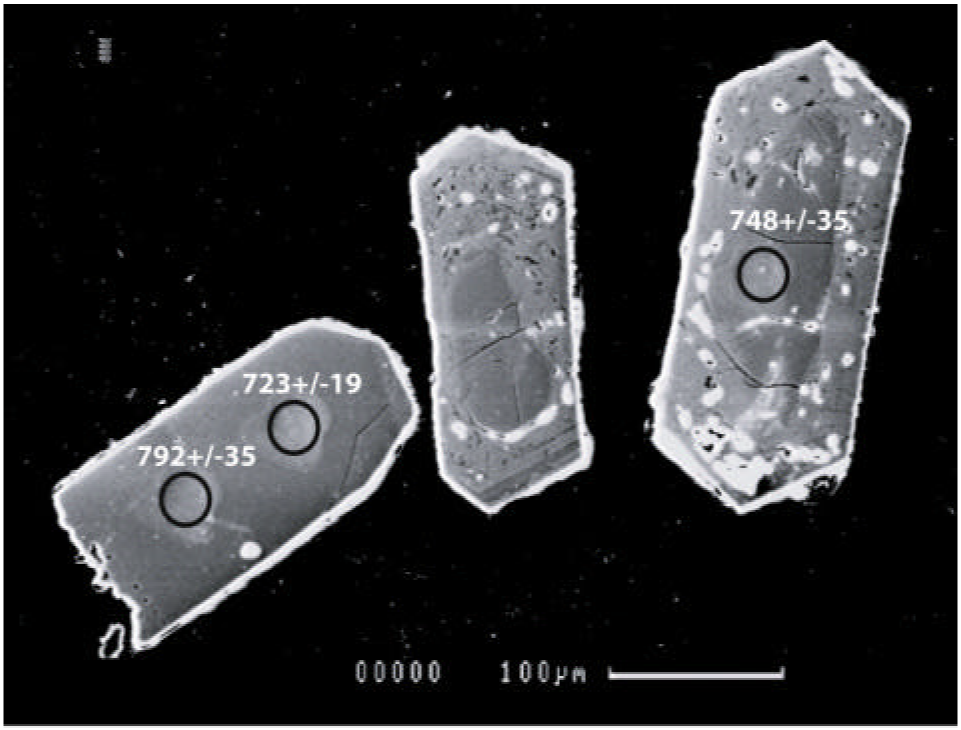


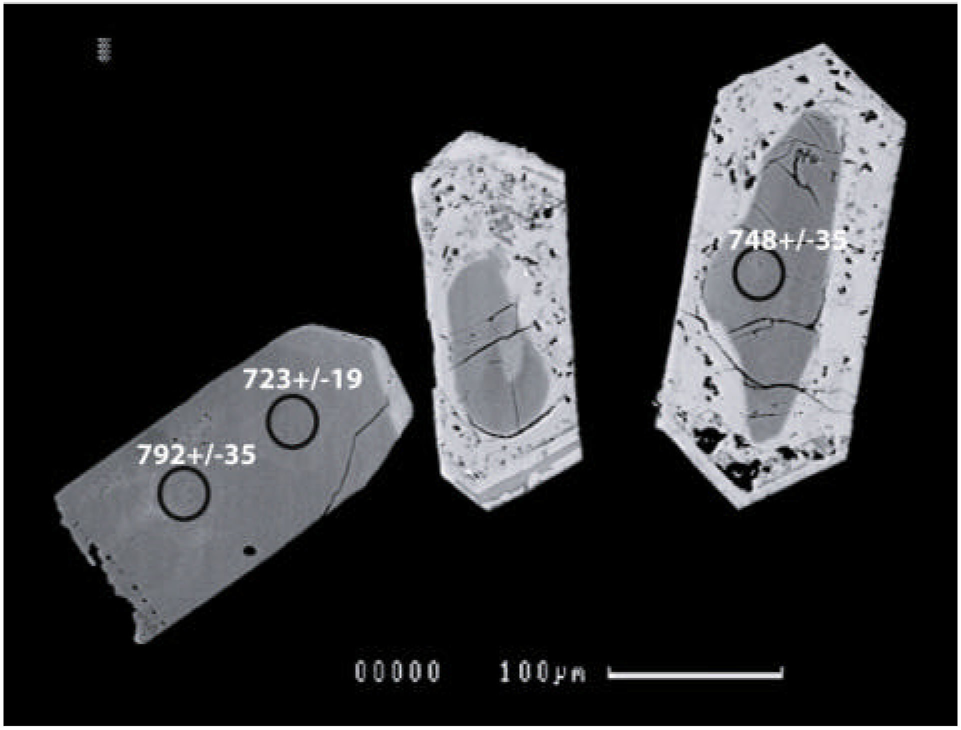
White Oak Creek pluton (WOCc1r4g4)



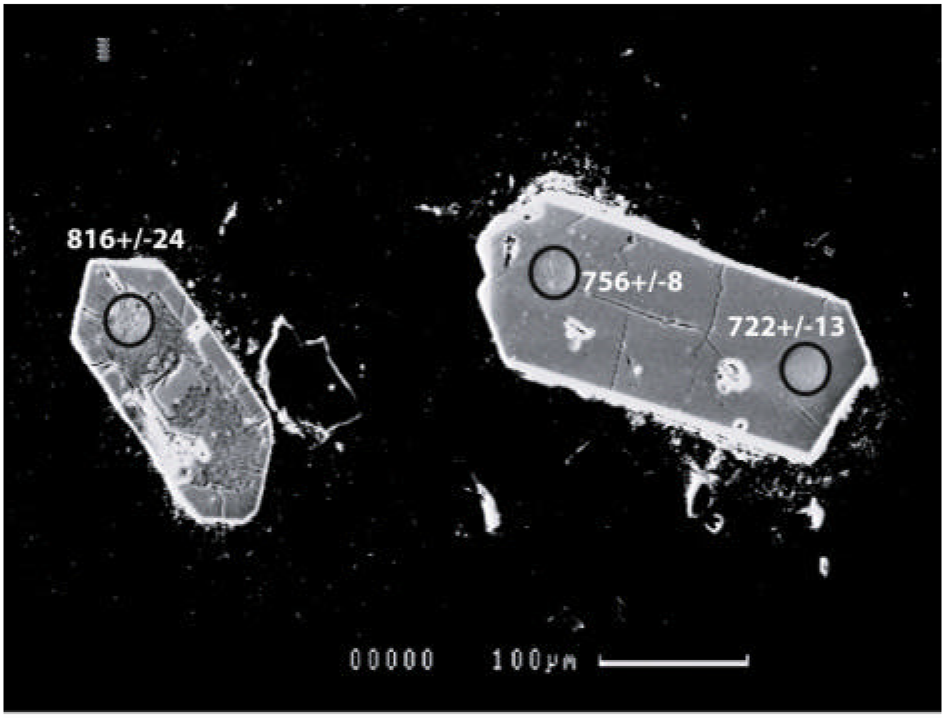


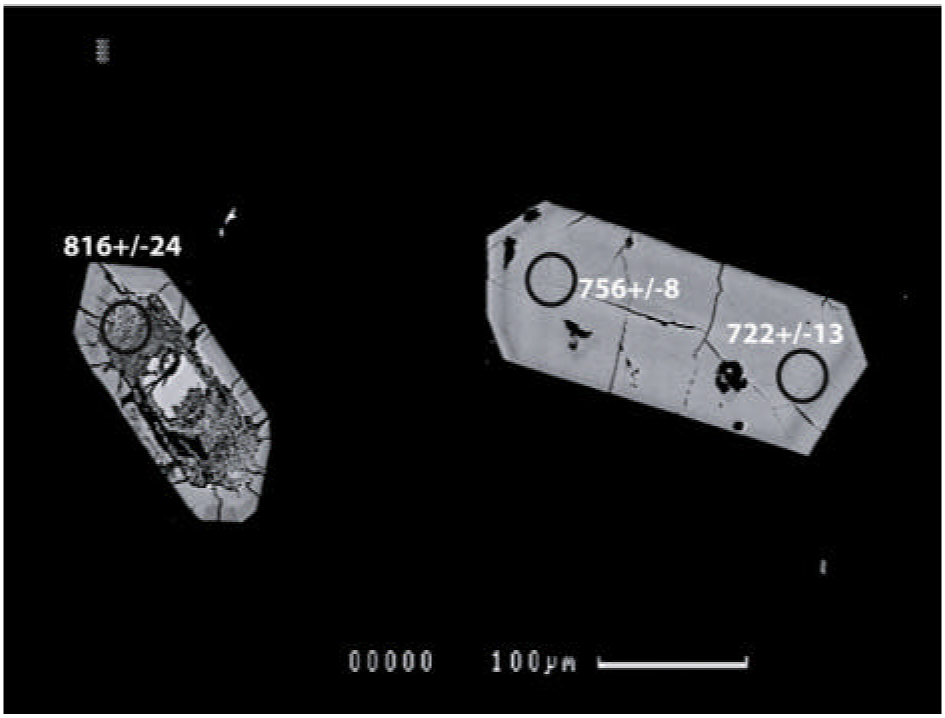
Suck Mountain pluton (Smc1r6g1)



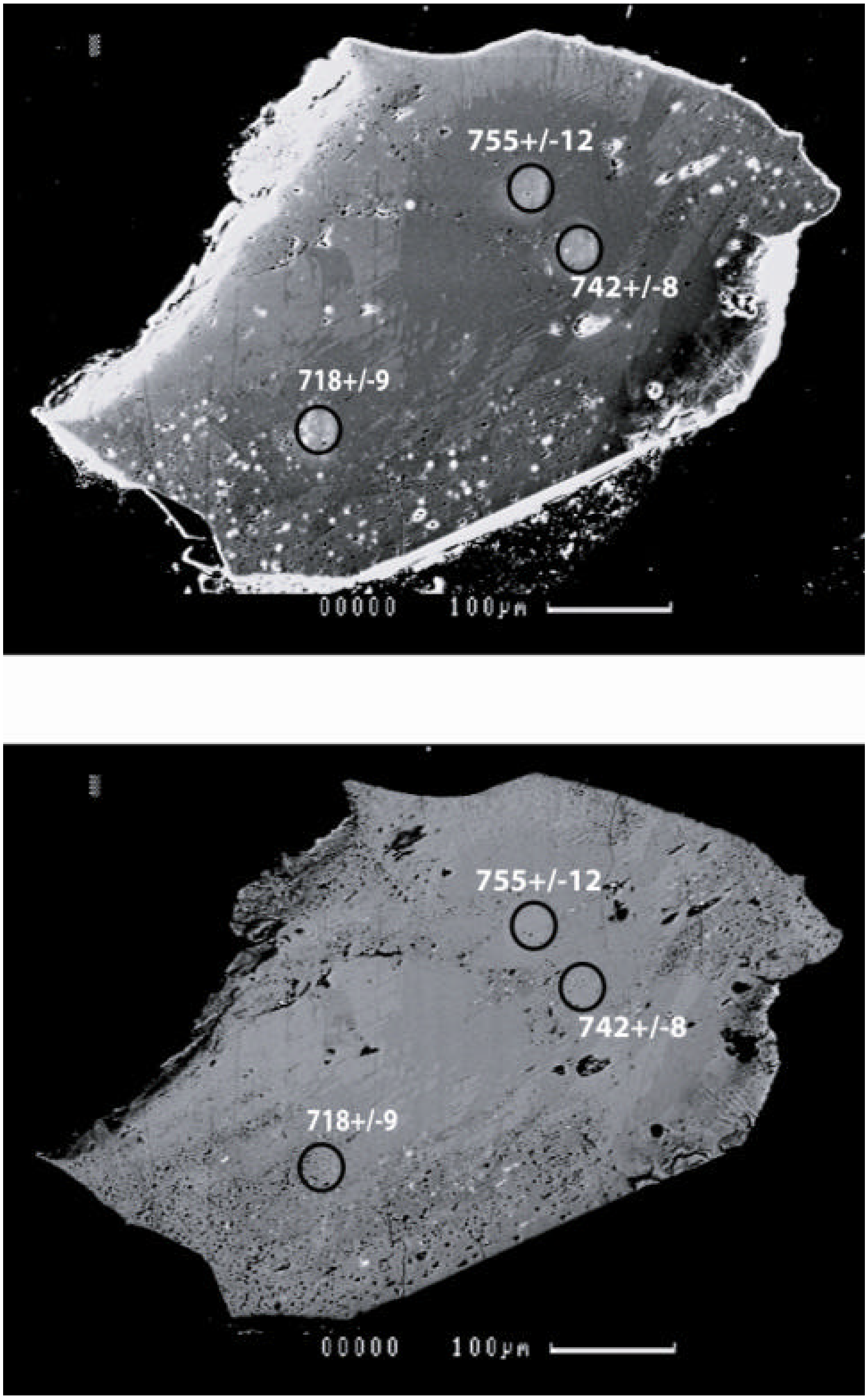


Suck Mountain pluton (Smc1r7g4&5)

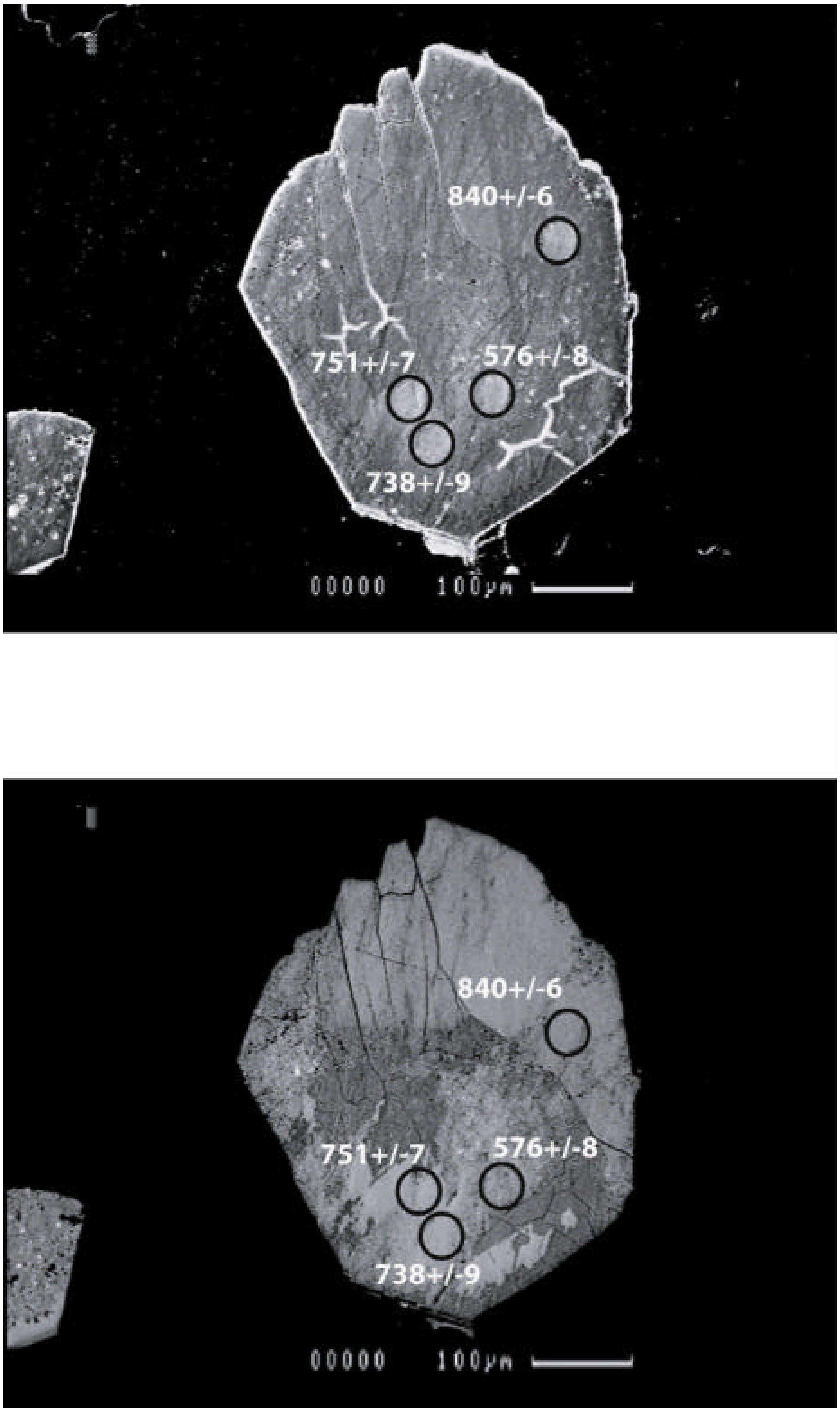




Amissville pluton (AMc1r9g2)

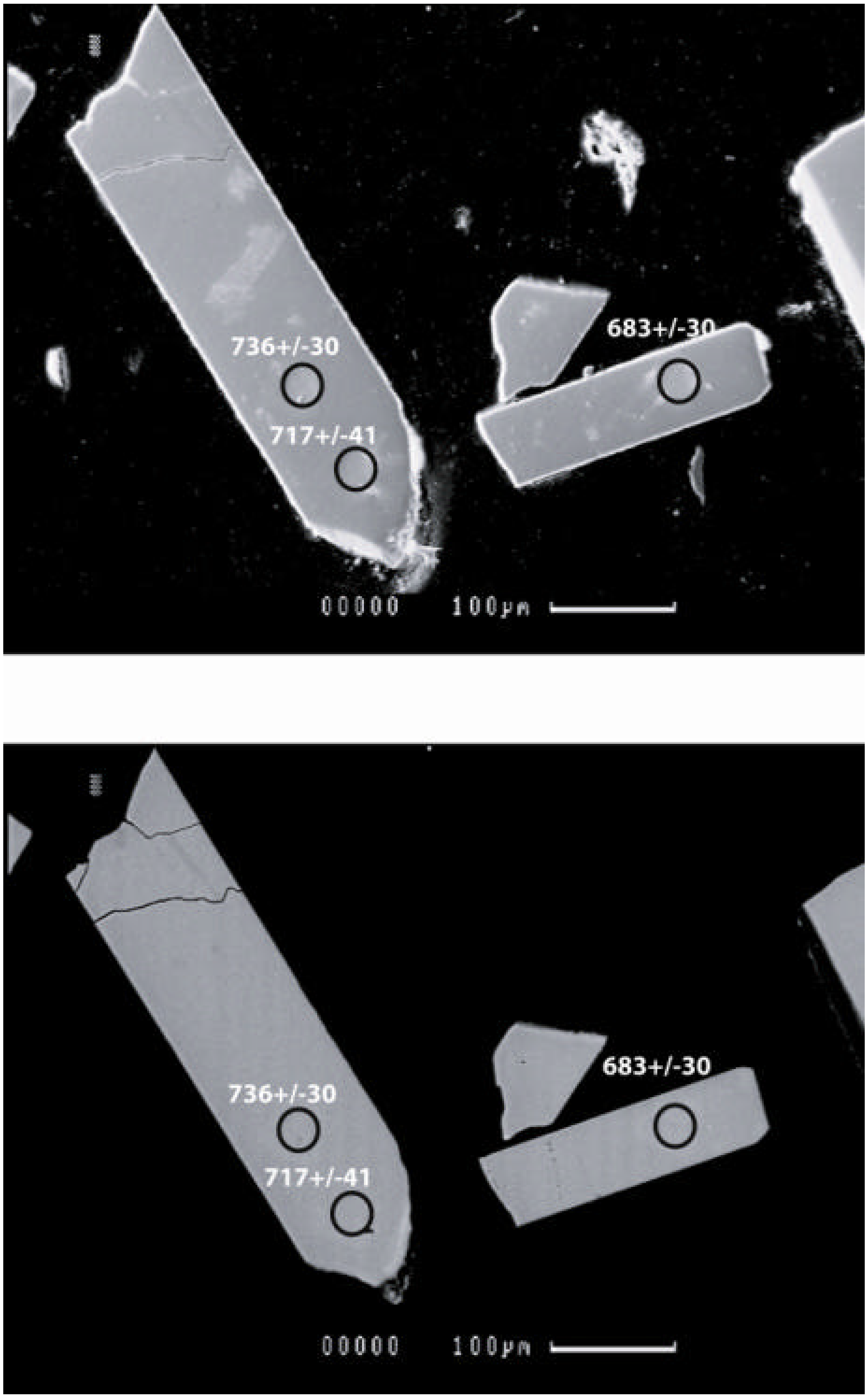


Amissville pluton (Amc1r9g6)

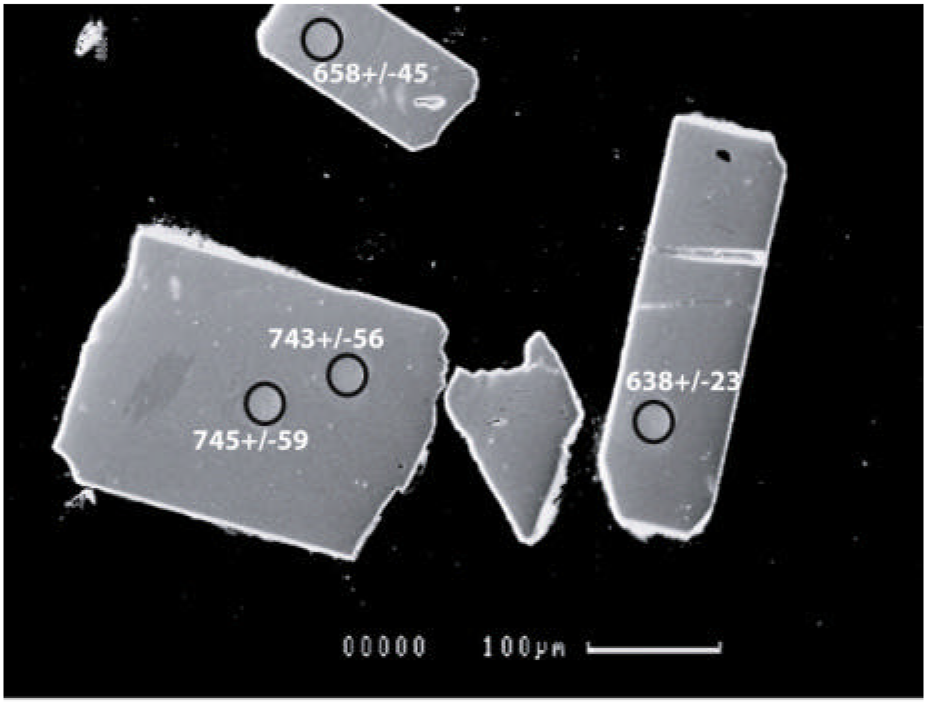


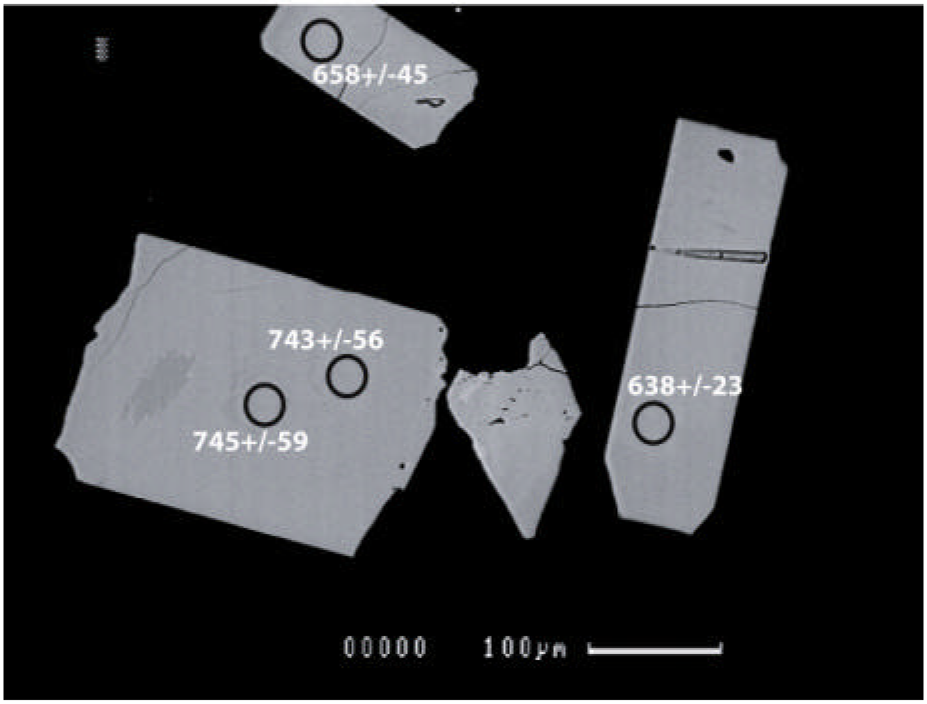
Images of zircons from plutons of the Early Cryogenian Suite. Black circles designate spot analysis locations with calculated $^{206}Pb/^{238}U$ ages in Ma. The upper images are secondary electron images while the lower images are backscatter electron images.

Dillons Mill pluton (Dmc1r2g4&5)

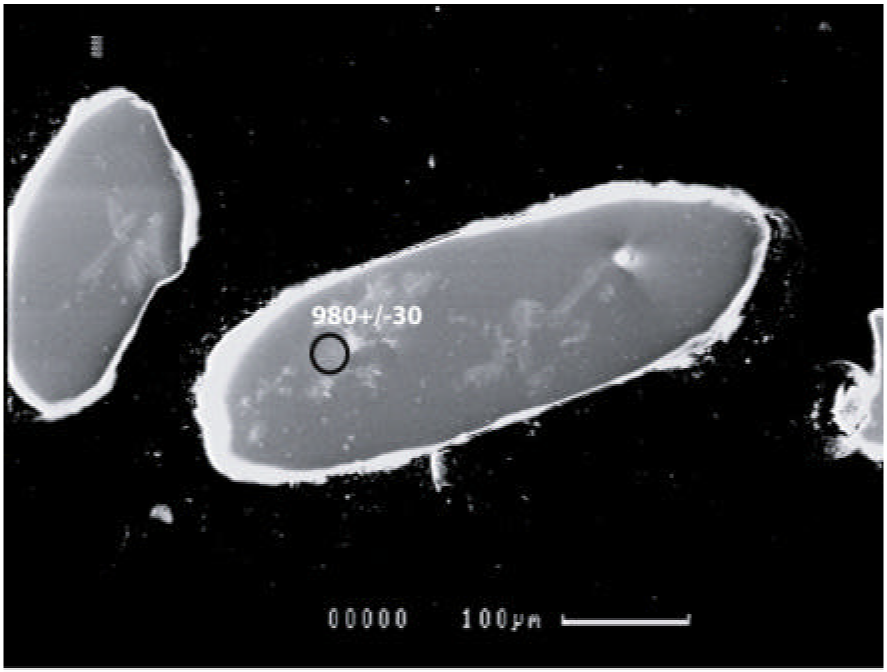


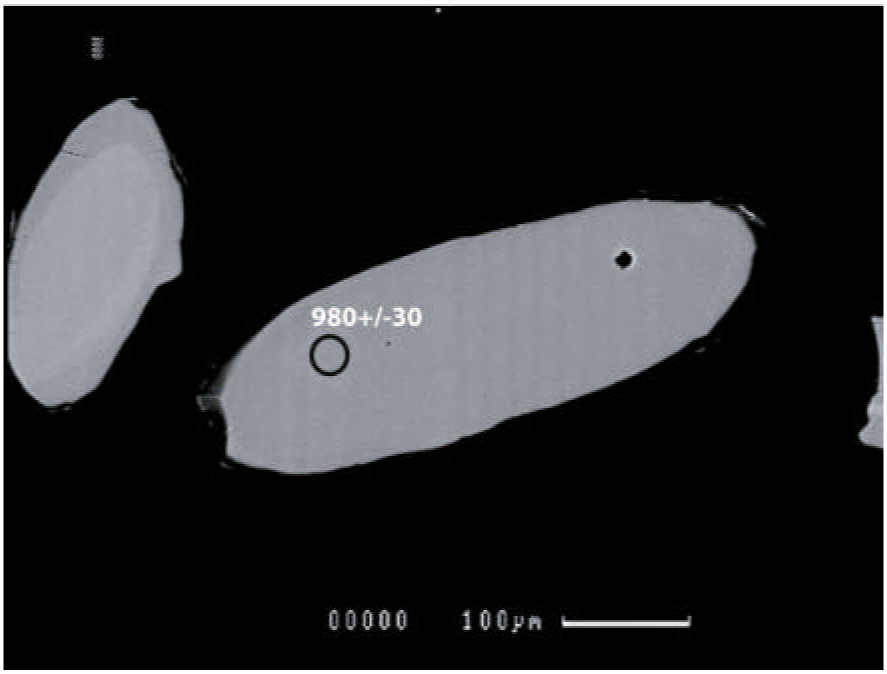
Dillons Mill pluton (Dmc1r2g6,7&9)



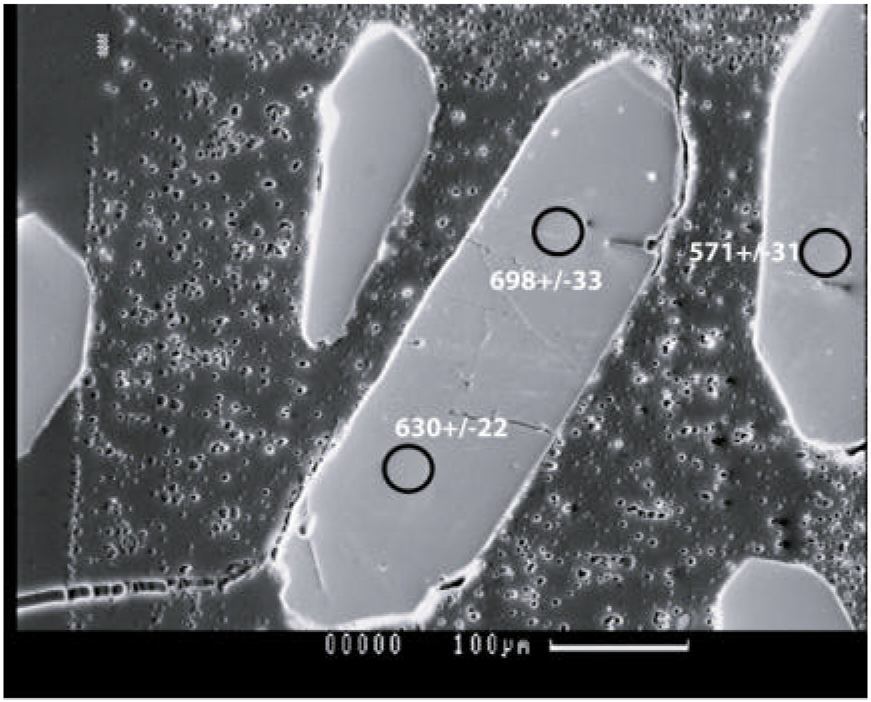


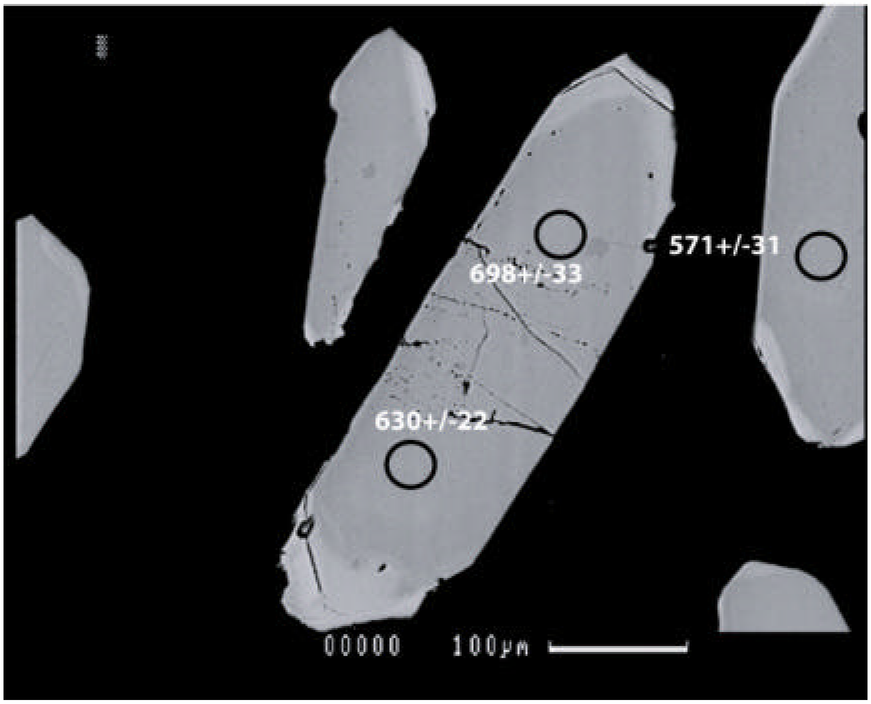
Dillons Mill pluton (Dmc1r3g1)



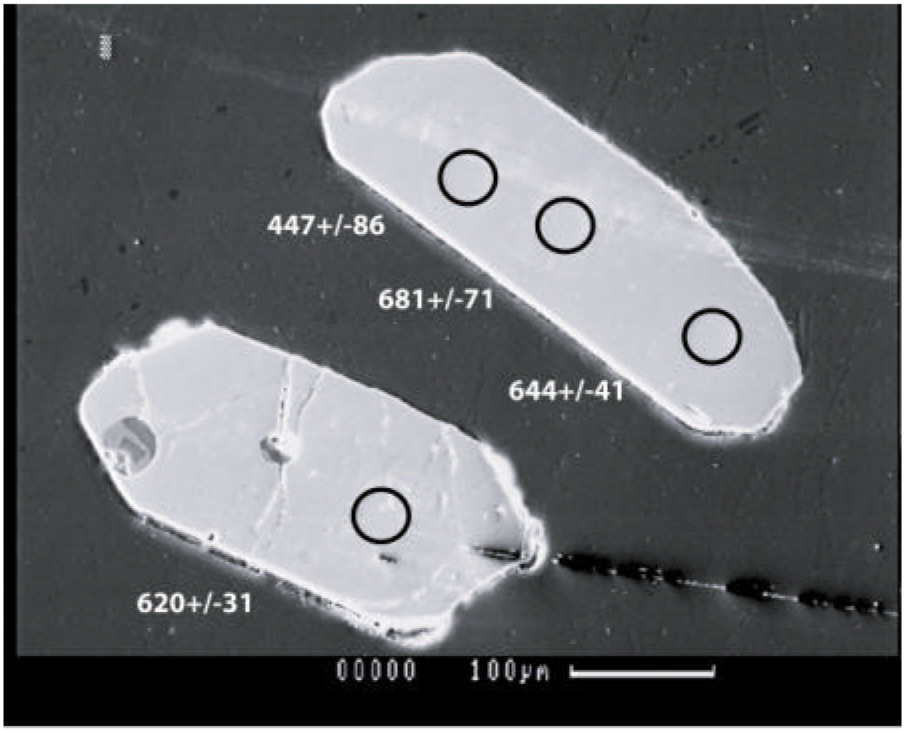


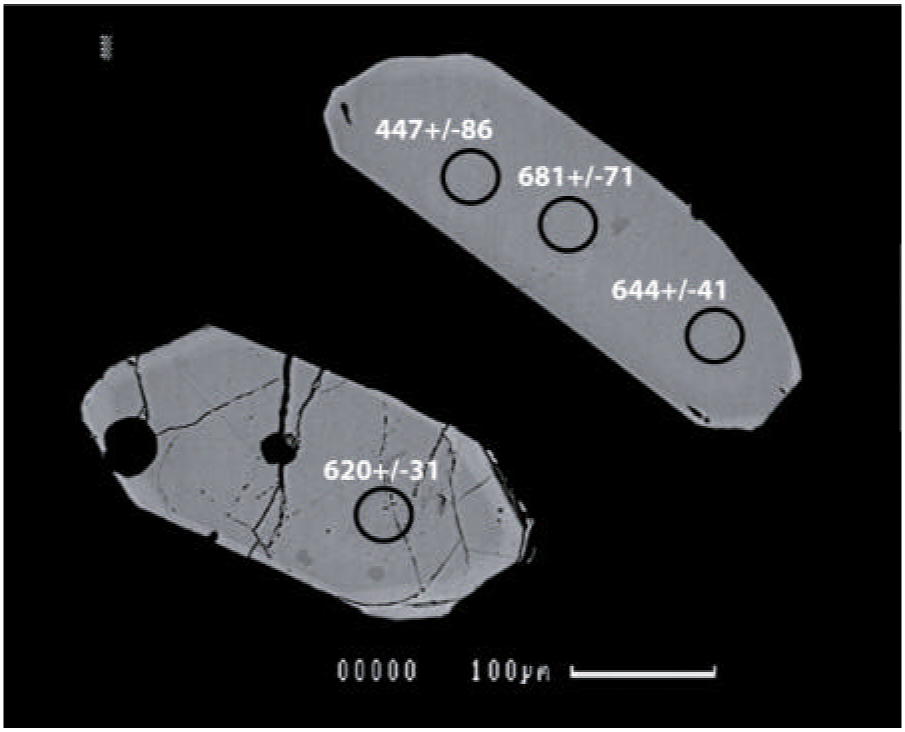
Mobley Mountain pluton (MMc2r6g6&g6a&g7)



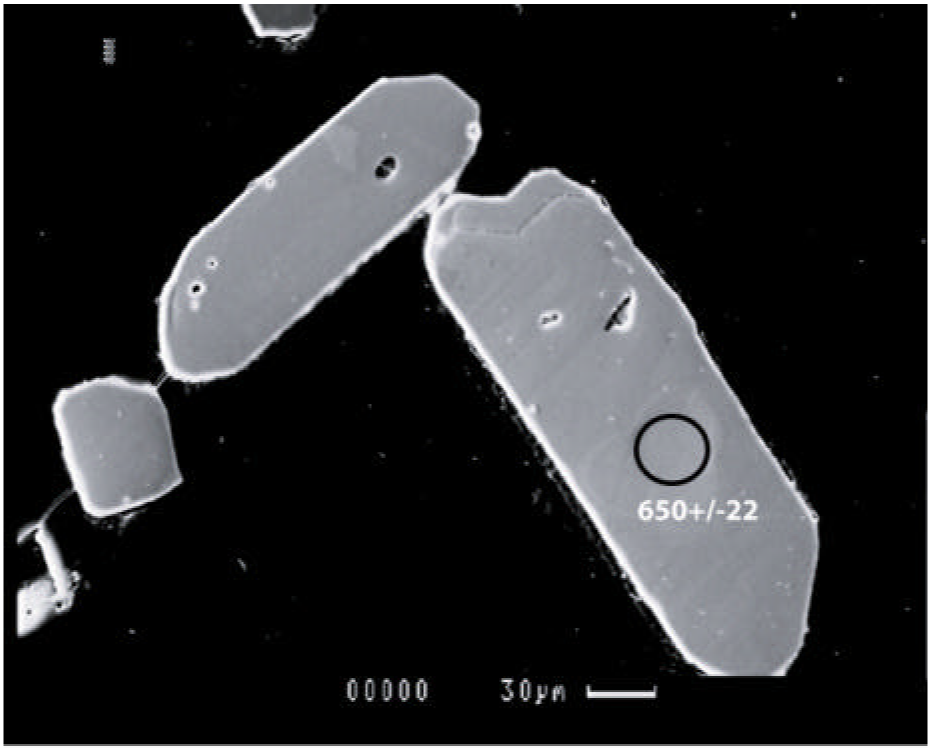


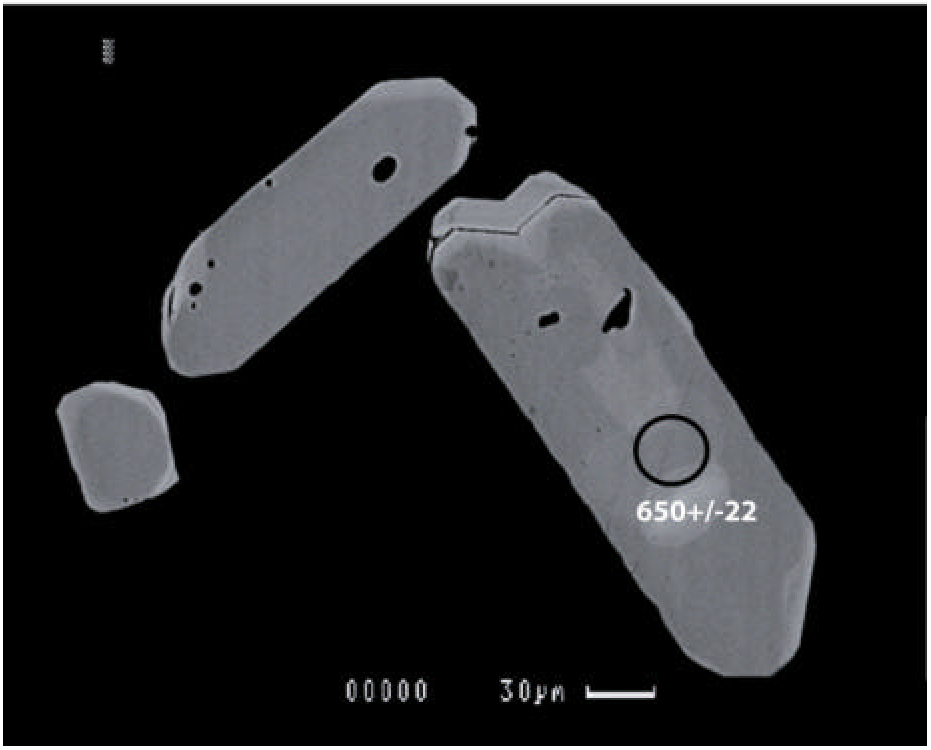
Mobley Mountain pluton (MMc2r6g2&g2a&g2b&g3)



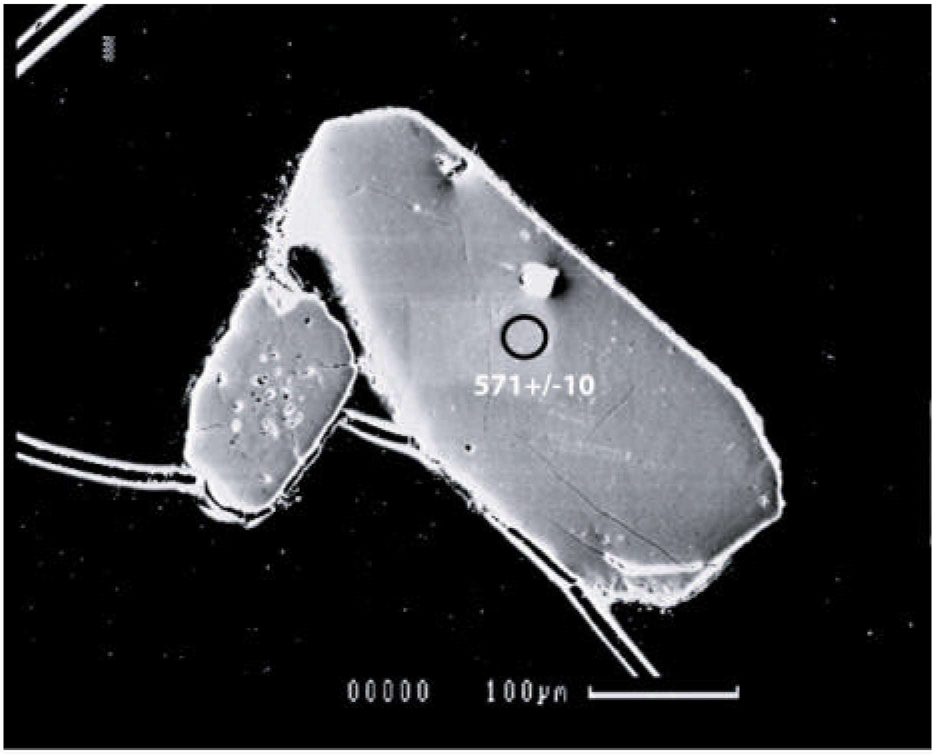


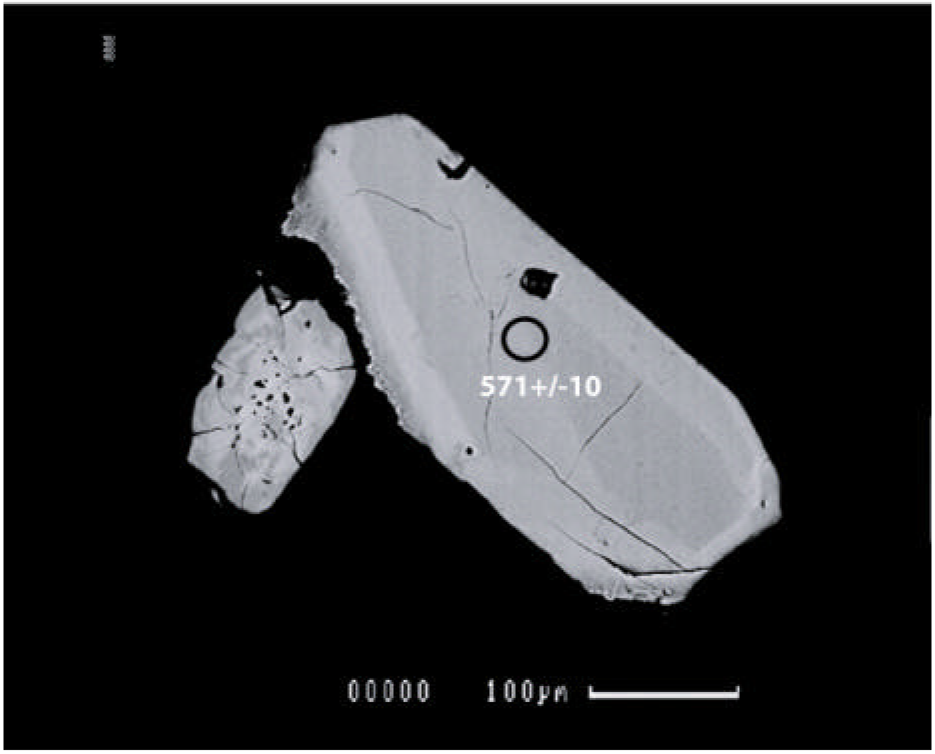
Mobley Mountain pluton (MMc2r6g1)



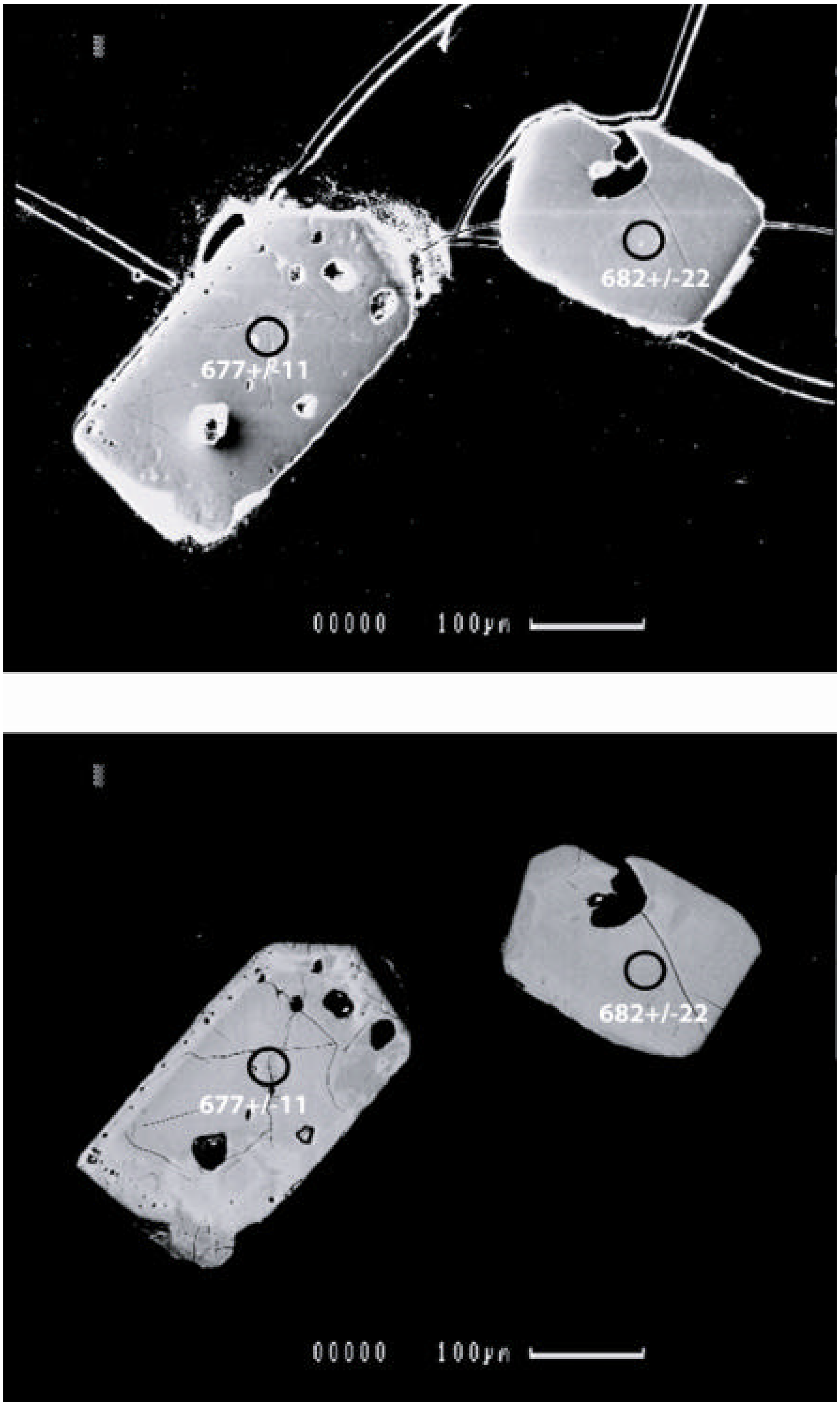


Rockfish River pluton (RRc3r9g1)

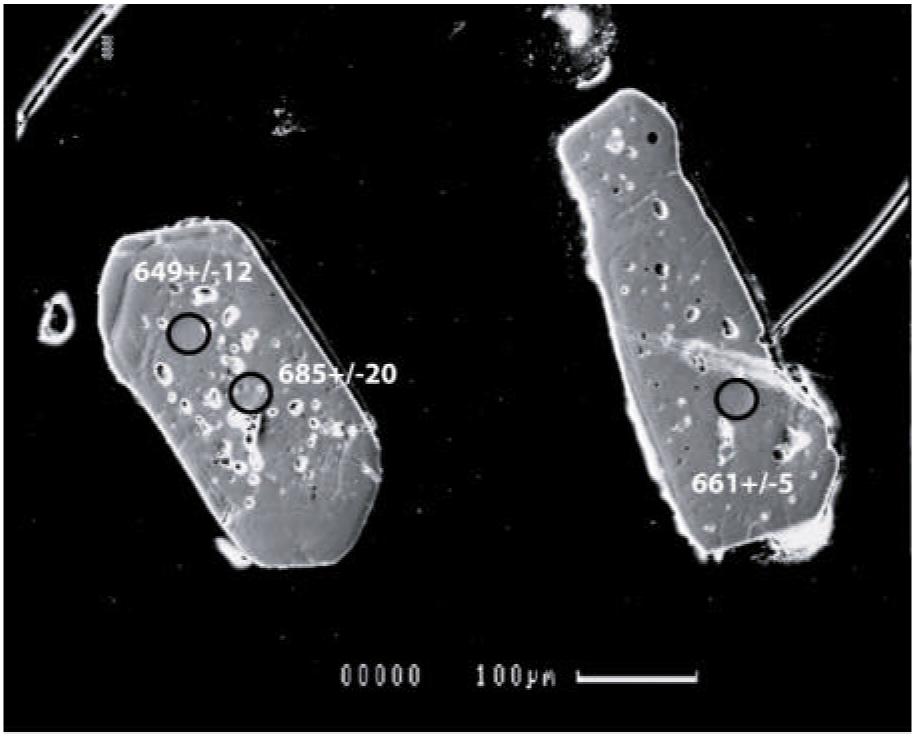


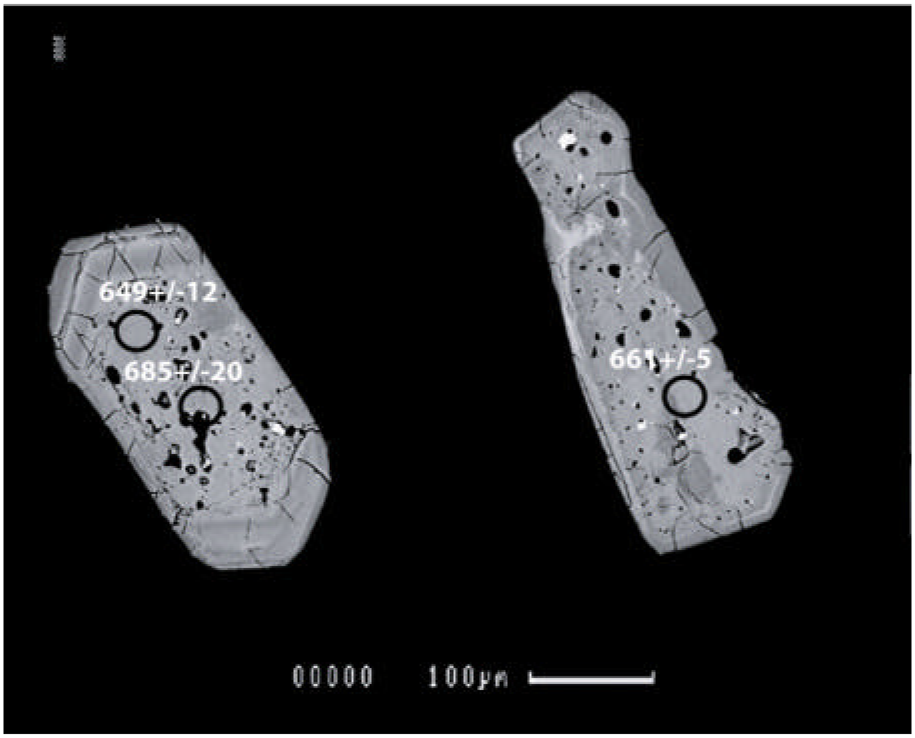


Rockfish River pluton (RRc3r9g4&g5)

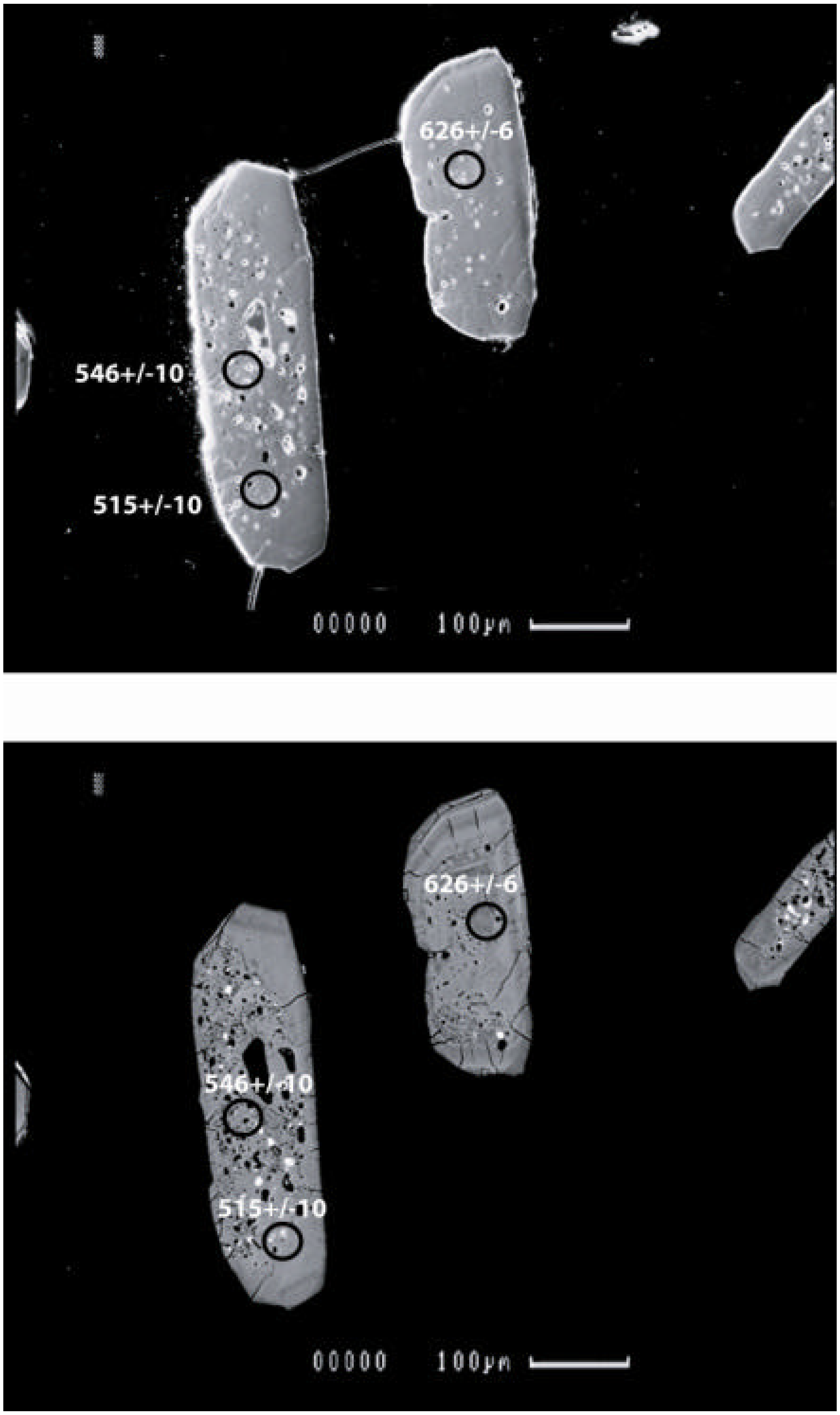


Fine Creek Mills (FCc3r3g1&g1s2@1&g2)

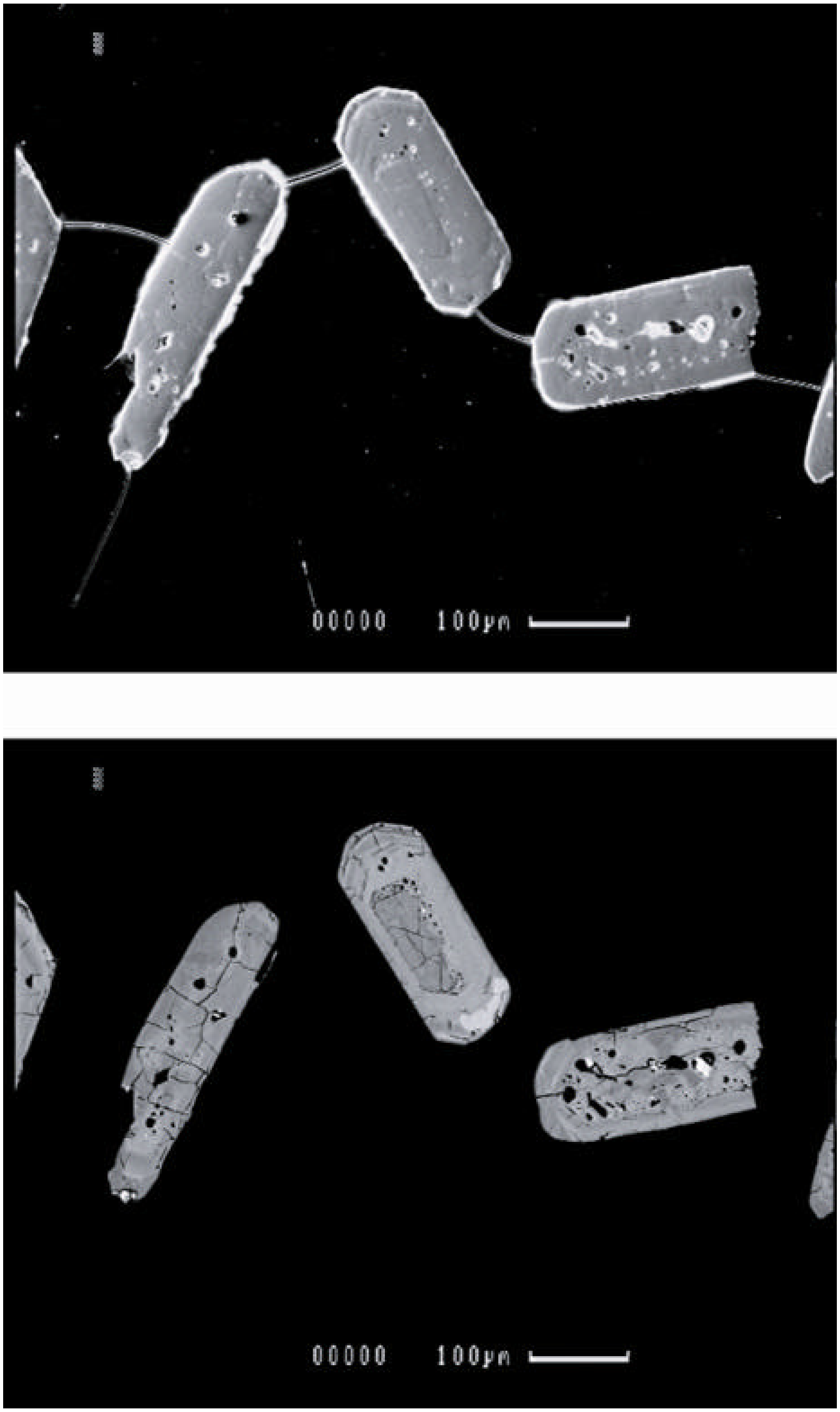




Fine Creek Mills pluton (FCc3r3g5s1&g5s2@1)



Fine Creek Mills pluton



Vita

Maria was born on January 3, 1980 in the outskirts of Moscow, Russia. She moved to Cedarhurst, New York State (USA) with her family in 1991 where she completed her high school degree with the class of 1997. She graduated with honors from Binghamton University in 2001 and pursued graduate studies at Virginia Tech from 2001 to 2003. Upon completion of her Maters of Science in Geology Maria will be starting a job with Advanced Resources International in Arlington, Virginia