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# THE PERSIMMON CREEK GNEISS, EASTERN BLUE RIDGE, NORTH CAROLINA-GEORGIA: EVIDENCE FOR THE MISSING TACONIC ARC?

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## ABSTRACT

**The Persimmon Creek Gneiss (PCG) is a metamorphosed pluton in the Eastern Blue Ridge that ranges widely in composition, from gabbro to granodiorite, with tonalite dominating. Plagioclase (both magmatic and recrystallized) is by far the most abundant mineral. Quartz, biotite, and epidote are also ubiquitous, whereas potassium feldspar is sparse or absent and hornblende is present only in the most mafic rocks. The abundant sub- to euhedral epidote has euhedral zoning and is probably magmatic. Zircon ion probe U-Pb data indicate that the PCG crystallized 468 Ma and carried abundant inherited zircons, mostly of Grenville age.**

**In keeping with its obvious lithologic variability, the PCG ranges widely in major element composition (52-70 wt% $SiO_2$, ~1-3 wt% $K_2O$). It is depleted in high field strength elements and displays moderate LREE enrichment (~50-150 x chondrite), flat HREE at ~10 x chondrite, negative Eu anomalies, and moderate Sr concentrations (300-400 ppm). In all of these respects except HFSE depletion, it is unique among Ordovician plutons of the northern Georgia - South Carolina - North Carolina Blue Ridge and Inner Piedmont. Its Nd-Sr-O isotopic composition falls between those of mafic-ultramafic rocks and metasedimentary and basement rocks of the Blue Ridge and Inner Piedmont.**

**The geochemistry, mineral assemblages and textures, and field relations of the PCG suggest that it represents a deep-seated pluton that crystallized from a wet, oxidized magma. We propose that it formed as a result of subduction preceding Taconic collision of the Piedmont Terrane with Laurentia. It may be a rare remnant of a weakly developed, short-lived arc.**

## INTRODUCTION

The Eastern Blue Ridge and Inner Piedmont together comprise the Piedmont Terrane (Williams and Hatcher, 1983) or Piedmont Zone (Hibbard and Samson, 1995), which constitutes the core of the southern Appalachians. This region, located between undisputed Laurentian

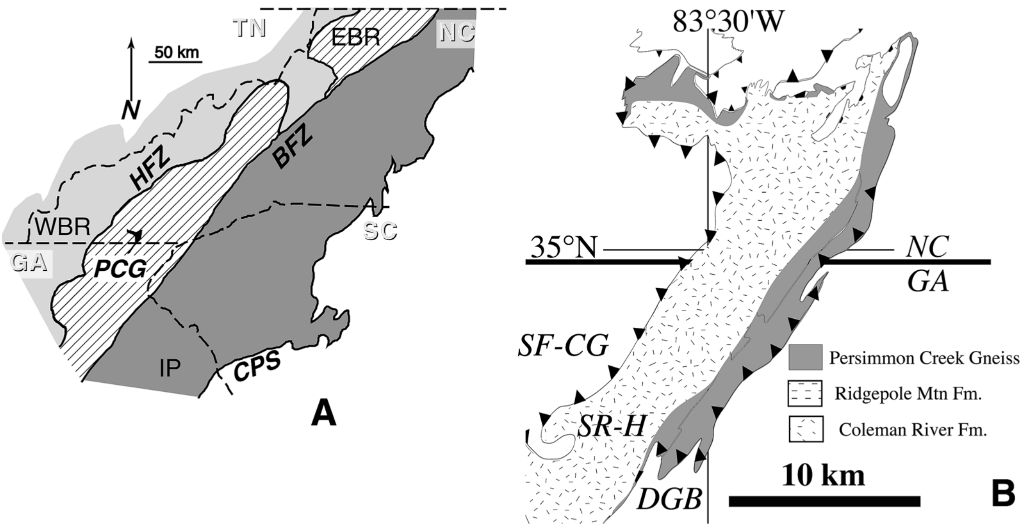



**Figure 1. (a) Location of the Persimmon Creek Gneiss (PCG) with respect to major tectonic features (HFZ: Hayesville fault zone; BFZ: Brevard fault zone; CPS: Carolina-Piedmont suture; IP: Inner Piedmont; EBR: Eastern Blue Ridge; WBR: Western Blue Ridge. (IP + EBR = Piedmont Terrane) (b) Persimmon Creek Gneiss and its immediate surroundings, modified from Hatcher (1999). DGB: Dahlonega Gold Belt; SR-H: Soque River-Hayesville thrust sheet; SF-CG: Shope Fork-Chunky Gal thrust sheet.**

crust and the exotic Carolina Terrane, remains an enigmatic aspect of Southern Appalachian crustal evolution. In the simplest models, it represents (a) the easternmost edge of Laurentia's passive margin; (b) an exotic terrane that was accreted to Laurentia via subduction during the Ordovician Taconic Orogeny (Williams and Hatcher, 1983; Shaw and Wasserburg, 1984; Horton and others, 1989); or (c) an original part of Laurentia that rifted away in Late Precambrian time but was subsequently reaccreted during the Taconic Orogeny (Hatcher, 1978; Hatcher, 1989; Hatcher and Goldberg, 1991). Based on the presence of both eclogite and metabasalts with oceanic affinity, especially near the western margin of the terrane, researchers generally infer that its history involved subduction (i.e., model b or c) (e.g., Willard and Adams, 1994; Stewart and others, 1997; Thomas, 2001).

If subduction did in fact occur, then by analogy with modern and paleosubduction zones the Piedmont Terrane should contain an assemblage of plutonic rocks with a wide range in composition, including abundant intermediate lithologies. Yet though the southern Appalachian orogen of western North Carolina and northern Georgia does contain common felsic intrusive rocks, intermediate plutonism appears to be rare (cf. Miller and others, 1997; Vinson and others, 1999). To our knowledge the only example of intermediate plutonism in this region is the Persimmon Creek Gneiss (PCG), a metamorphosed pluton in the Eastern Blue Ridge Belt of the Piedmont Terrane (Hatcher, 1979). Its composition thus suggests that it may reflect subduction-related magmatism. The goal of this study is to describe the PCG, suggest a possible environment of formation, and consider its implications for the history of the Southern Appalachian orogen as a whole.

## GEOLOGIC SETTING

The PCG straddles the North Carolina-Georgia border in the Eastern Blue Ridge portion of the Piedmont Terrane (Figure 1). It intrudes the Coleman River and the Ridgepole Mountain formations, metasedimentary units of the Coweeta Group that are exposed in the Soque River/Hayesville thrust sheet. Prime exposures of the approximately 130 $km^2$ pluton are found at Pickens Nose, Bearpen Creek, and Bearpen Mountain in southern Macon County, North Carolina, and along Persimmon Creek in northwestern Rabun County, Georgia (Meschter, 2001; Hatcher, 1979).

## METHODS

Fresh samples were collected from roadcuts and outcrops for thin sections, chemical analyses, and zircon separation. Standard mineral separation techniques were used to extract individual zircon grains from two of the samples, CPCMUL and PCHC. Zircons were handpicked and mounted in epoxy with standard AS57. Internal zoning of individual zircons was imaged by cathodoluminescence on an SEM at Stanford University; zoning images were then used as a guide for selection of analytical spots (cf. Miller and others, 2000). U-Pb analyses were performed at the University of California-Los Angeles using the Cameca IMS 1270 high-resolution ion microprobe. Both zircon rims and cores were analyzed with the primary beam focused to a ~20 micron spot. Analyses were corrected for common Pb using a $^{204}Pb$ correction, assuming common Pb ratios of $^{206}Pb/^{204}Pb = 17.98$, $^{207}Pb/^{204}Pb = 15.59$, and $^{208}Pb/^{204}Pb = 37.1$. All reported uncertainties in text and figures are $\pm 2\sigma$.

Minerals and textures were identified and described by standard optical microscopy. Zoning of epidote was visible in transmitted light and was further characterized using backscattered electron imaging (Hitachi S-4200 scanning electron microscope at Vanderbilt University).

Whole rock powders of fresh samples were used for major and trace element and O, Nd, and Sr isotopic analysis. Major and trace elements were analyzed by Activation Laboratories, Inc., using X-ray fluorescence, inductively coupled plasma mass spectrometry (ICP-MS), instrumental neuron activation analysis (INAA) and direct coupled plasma spectrometry. Silicate O isotope analyses were performed at Geochron Laboratories. Nd and Sr isotopic analyses were performed at the University of North Carolina-Chapel Hill on a multi-collector VG sector 54 mass spectrometer.

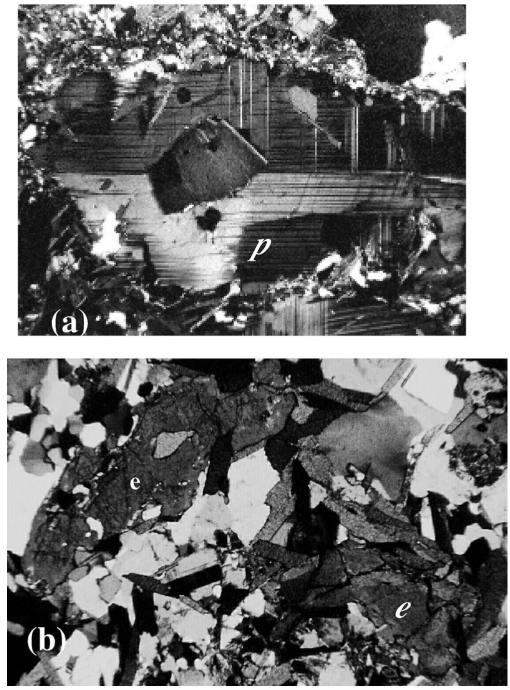



**Figure 2. Photomicrographs of characteristic petrographic features of Persimmon Creek Gneiss. (a) Relict coarse, magmatic plagioclase [p] with modified grain boundary, surrounded by fine-grained, dynamically recrystallized quartz and feldspar. (b) Coarse, subhedral, zoned epidote [e].**

## FIELD AND PETROGRAPHIC CHARACTERISTICS

The PCG ranges in texture from weakly foliated and medium-coarse grained to finer grained and well foliated. The most prominent lithology is poorly foliated and characterized by abundant large, equant plagioclase grains set in a finer grained matrix, mostly of biotite and quartz. In the field and in thin section (Figure 2a) the plagioclase appears to be magmatic but recrystallized at its margins. Better foliated samples retain vestiges of magmatic texture in thin section but plagioclase and other minerals show strong evidence of recrystallization. There appears to be a continuum from magmatic to thoroughly recrystallized texture, which is supported by reconnaissance cathodoluminescence investigation of plagioclase. Multiple lu-

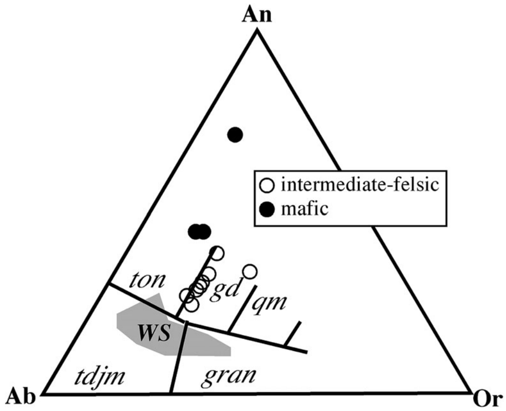



**Figure 3. Normative feldspar compositions of Persimmon Creek Gneiss with classification scheme of Barker (1979). Abundant biotite in samples is reflected in relatively high normative Or (granodiorites in the norm-based scheme are modal tonalites). Samples characterized as mafic are a gabbro and two diorites with <10% normative quartz. *ton:* tonalite*; gd:* granodiorite*; qm:* quartz monzonite*; tdjm:* trondhjemite*; gran:* granite.**

minescent populations correspond to textural variants and suggest multiple episodes of plagioclase formation in response to magmatic, metamorphic/deformational, and hydrothermal events.

Typical samples of PCG contain approximately 60-65% plagioclase, 20% quartz, 10-15% biotite, and minimal potassium feldspar and are thus modally tonalites. In terms of their norms, these samples lie on the boundary between granodiorite and tonalite (Figure 3), with the shift toward normative Or resulting from the fact that most of K and therefore most Or component is in biotite. A few samples are more mafic, with less quartz and abundant hornblende, and are classified as diorites and hornblende gabbros. Epidote is present in most samples; muscovite occurs in the more felsic rocks; and hornblende is restricted to mafic rocks. Garnet is present locally (see below). Allanite, apatite, sphene, and zircon are common accessory minerals. Epidote is relatively abundant (up to 5%), commonly occurring as subhedral prisms (Figure 2b). or as rims around euhedral to subhedral allanite. Subhedral morphology, euhedral zoning marked by variations in birefringence, and the presence of allanite cores suggests that at

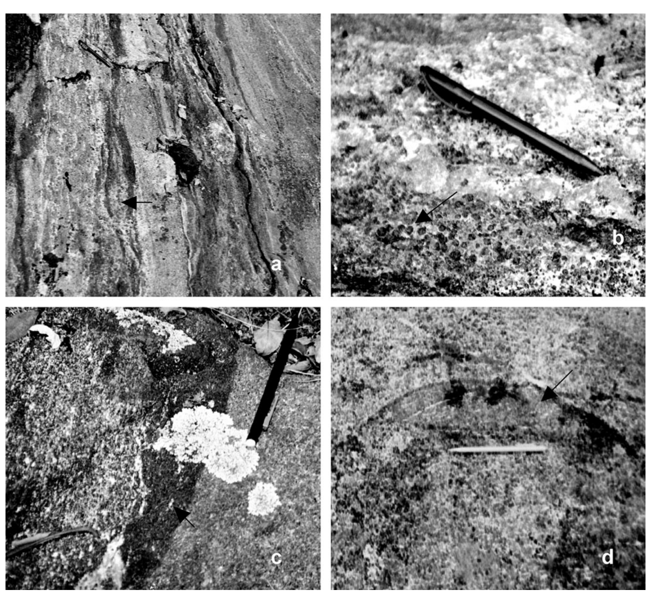



**Figure 4. Exposures of Persimmon Creek Gneiss; pencil for scale. (a) Septum of garnet-rich metasedimentary rock enclosed and injected by Persimmon Creek Gneiss; arrow points to coarse garnet-rich zone. (b) Close-up of garnet-rich zone in (a). (c) Mafic sheet (arrow) separating coarser and finer variants of Persimmon Creek Gneiss. (d) Enclave of dioritic material in Persimmon Creek Gneiss.**

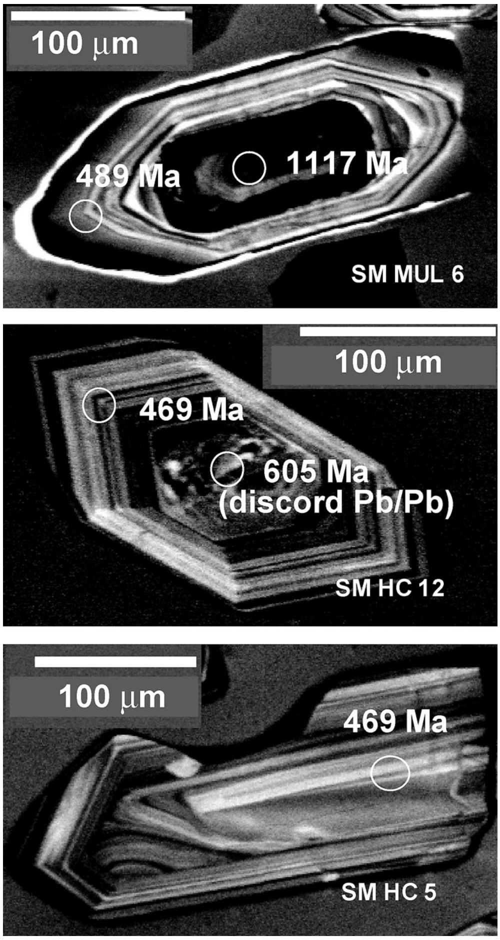



**Figure 5. Cathodoluminescence images of zircons separated from Persimmon Creek Gneiss showing typical zoning. Ages are $^{206}Pb/^{238}U$, except for $^{207}Pb/^{206}Pb$ age of one highly discordant core (probably actually Grenville age).**

least in part the epidote crystallized from magma rather than as a metamorphic mineral (Zen and Hammarstrom, 1984; Keane and Morrison, 1997).

Although most exposures of PCG are relatively homogeneous, some are heterogeneous and preserve evidence for interactions between contrasting lithologies. Screens and xenoliths of metasedimentary Coleman River Formation appear to have disaggregated and partially dissolved into the PCG, contaminating the host as indicated by locally abundant garnet and more siliceous and peraluminous compositions (Figure 4a,b). Hornblende-rich mafic enclaves are common in some areas and are especially abundant where dioritic to gabbroic magmas appear to have mingled with the main PCG magma as extensive sheets and larger enclaves (Figure 4c,d). Hornblende is present only in these areas and may reflect hydridization.

## AGE AND ZIRCON INHERITANCE

Zircons extracted from two samples of the PCG for this study, like those from the previously studied sample P22 (Miller and others, 2000), are typically euhedral and moderately elongate and are marked by strong, oscillatory zoning that strongly indicate magmatic growth (Figure 5). Grains from P22 and new sample CPCMUL contain almost ubiquitous, well-defined cores with magmatic overgrowths. Though fairly common, cores are much less abundant in zircons from sample PCHC than in the other two samples.

Thirty five apparent ages of analyzed spots from what appear to be magmatic zones (concentric, euhedral, oscillatory) range from 414 to 510 Ma, with 2σ between ~±7 and 23 Ma (Table 1; Figure 6). In each sample, these ages can be divided into three groups: 489-510 Ma (4 total analyses); 455 and 477 Ma (21, the majority); and younger "ages" of 414-454 Ma (10 analyses). The younger ages almost certainly indicate partial Pb loss or local recrystallization, and the older ages may represent an inherited component derived from rocks formed during a slightly older magmatic episode. We interpret the bulk of the ages to indicate the true crystallization age.

The twenty-one ages between 455 and 477 Ma, when pooled, yield an age of 468 ± 3 Ma (MSWD 1.8). Individual samples differ marginally if their ages are taken alone [P22 (9 analyses) 468 ± 3 Ma (MSWD 3.0), CPCMUL (5 analyses) 464 ± 6 Ma (MSWD 1.0), and PCHC (7 analyses) 468 ± 6 Ma (MSWD 0.8)], and the populations differ slightly in a probability plot (Fig. 6c). Nonetheless, ages of all three samples are clearly very similar, and ages within error and relatively low MSWD for the pooled analyses suggest that all reflect the same crystalliza-

**Table 1. U-Pb zircon data for Persimmon Creek Gneiss samples.**

| | Age (Ma) | Age (1 s.e.) | Age (Ma) | Age (1 s.e.) | Age (Ma) | Age (1 s.e.) | | 1 s.e. | | 1 s.e. | | 1 s.e. | Radiogenic |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| analysis | $^{206}$Pb/$^{238}$U | $^{206}$Pb/$^{238}$U | $^{207}$Pb/$^{235}$U | $^{207}$Pb/$^{235}$U | $^{207}$Pb/$^{206}$Pb | $^{207}$Pb/$^{206}$Pb | $^{206}$Pb/$^{238}$U | $^{206}$Pb/$^{238}$U | $^{207}$Pb/$^{235}$U | $^{207}$Pb/$^{235}$U | $^{207}$Pb/$^{206}$Pb | $^{207}$Pb/$^{206}$Pb | $^{206}$Pb (%) |
| **sample PCMUL:** | | | | | | | | | | | | | |
| MUL_1_sp1 | 708 | 10 | 794 | 10 | 1042 | 14 | 0.11610 | 0.00177 | 1.1850 | 0.02132 | 0.07404 | 0.00051 | 99.86 |
| MUL_2_sp1 | 476 | 9 | 471 | 9 | 444 | 36 | 0.07662 | 0.00146 | 0.5894 | 0.01391 | 0.05579 | 0.00090 | 99.93 |
| MUL_3_sp1 | 1440 | 22 | 1451 | 14 | 1467 | 15 | 0.25020 | 0.00434 | 3.1730 | 0.05765 | 0.09197 | 0.00074 | 99.88 |
| MUL_4_sp1 | 462 | 6 | 473 | 7 | 524 | 25 | 0.07436 | 0.00095 | 0.5930 | 0.01070 | 0.05784 | 0.00067 | 100.00 |
| MUL_3_sp2 | 414 | 12 | 422 | 10 | 463 | 18 | 0.06636 | 0.00194 | 0.5148 | 0.01545 | 0.05627 | 0.00045 | 99.87 |
| MUL_5_sp1 | 948 | 10 | 960 | 8 | 986 | 9 | 0.15840 | 0.00173 | 1.5730 | 0.01915 | 0.07201 | 0.00032 | 99.99 |
| MUL_5_sp2 | 451 | 7 | 450 | 11 | 450 | 54 | 0.07238 | 0.00125 | 0.5581 | 0.01734 | 0.05593 | 0.00135 | 99.56 |
| MUL_6_sp1 | 1074 | 16 | 1089 | 12 | 1117 | 12 | 0.18130 | 0.00301 | 1.9210 | 0.03334 | 0.07685 | 0.00044 | 99.70 |
| MUL_6_sp2 | 489 | 7 | 487 | 7 | 477 | 23 | 0.07882 | 0.00109 | 0.6155 | 0.01127 | 0.05664 | 0.00058 | 99.99 |
| MUL_7_sp1 | 903 | 7 | 986 | 11 | 1176 | 25 | 0.15040 | 0.00127 | 1.6420 | 0.02731 | 0.07914 | 0.00100 | 98.05 |
| MUL_8_sp1 | 471 | 7 | 466 | 6 | 445 | 27 | 0.07571 | 0.00111 | 0.5826 | 0.01009 | 0.05581 | 0.00069 | 99.96 |
| MUL_9_sp1 | 1088 | 32 | 1117 | 21 | 1173 | 38 | 0.18380 | 0.00590 | 2.0030 | 0.06292 | 0.07905 | 0.00153 | 99.91 |
| MUL_10_sp1 | 1125 | 32 | 1151 | 21 | 1202 | 25 | 0.19060 | 0.00590 | 2.1080 | 0.06433 | 0.08019 | 0.00103 | 99.90 |
| MUL_11_sp1 | 458 | 6 | 463 | 7 | 487 | 26 | 0.07362 | 0.00097 | 0.5774 | 0.01015 | 0.05688 | 0.00068 | 99.98 |
| MUL_12_sp1 | 958 | 8 | 982 | 7 | 1035 | 8 | 0.16020 | 0.00140 | 1.6290 | 0.01682 | 0.07377 | 0.00030 | 99.98 |
| MUL_12_sp1 @1 | 1100 | 24 | 1114 | 19 | 1143 | 23 | 0.18600 | 0.00445 | 1.9970 | 0.05596 | 0.07784 | 0.00092 | 99.79 |
| MUL_14_sp1 | 1393 | 20 | 1421 | 12 | 1463 | 9 | 0.24130 | 0.00383 | 3.0530 | 0.04657 | 0.09177 | 0.00044 | 99.93 |
| MUL_15_sp1 | 449 | 9 | 449 | 8 | 449 | 30 | 0.07206 | 0.00145 | 0.5556 | 0.01287 | 0.05592 | 0.00077 | 99.89 |
| MUL_16_sp1 | 460 | 9 | 458 | 10 | 449 | 31 | 0.07399 | 0.00152 | 0.5703 | 0.01509 | 0.05590 | 0.00079 | 99.91 |
| MUL_17_sp1 | 446 | 5 | 444 | 4 | 431 | 18 | 0.07171 | 0.00077 | 0.5483 | 0.00679 | 0.05546 | 0.00044 | 99.94 |
| MUL_18_sp1 | 1097 | 51 | 1104 | 42 | 1119 | 64 | 0.18550 | 0.00936 | 1.9670 | 0.12240 | 0.07692 | 0.00247 | 99.77 |
| MUL_19_sp1 | 434 | 9 | 438 | 8 | 458 | 22 | 0.06965 | 0.00155 | 0.5391 | 0.01223 | 0.05614 | 0.00055 | 100.00 |
| MUL_20_sp1 | 1093 | 10 | 1143 | 7 | 1240 | 7 | 0.18470 | 0.00176 | 2.0830 | 0.02014 | 0.08179 | 0.00028 | 99.97 |
| MUL_21_sp1 | 1085 | 18 | 1143 | 14 | 1255 | 16 | 0.18330 | 0.00334 | 2.0820 | 0.04314 | 0.08242 | 0.00067 | 99.94 |
| MUL_22_sp1 | 1158 | 17 | 1159 | 14 | 1162 | 16 | 0.19670 | 0.00312 | 2.1320 | 0.04212 | 0.07860 | 0.00064 | 99.94 |
| MUL_23_sp1 | 929 | 18 | 949 | 14 | 996 | 15 | 0.15500 | 0.00329 | 1.5460 | 0.03373 | 0.07234 | 0.00054 | 99.62 |
| **sample PCHC:** | | | | | | | | | | | | | |
| HC_1_sp1 | 936 | 9 | 975 | 8 | 1063 | 13 | 0.15620 | 0.00168 | 1.6110 | 0.02010 | 0.07481 | 0.00047 | 99.94 |
| HC_2_sp1 | 475 | 7 | 470 | 8 | 446 | 42 | 0.07653 | 0.00110 | 0.5892 | 0.01190 | 0.05583 | 0.00106 | 99.90 |
| HC_2_sp2 | 477 | 8 | 476 | 8 | 469 | 24 | 0.07677 | 0.00130 | 0.5974 | 0.01330 | 0.05643 | 0.00060 | 99.94 |
| HC_3_sp1 | 453 | 7 | 459 | 6 | 490 | 25 | 0.07274 | 0.00113 | 0.5713 | 0.00928 | 0.05697 | 0.00065 | 99.95 |
| HC_4_sp1 | 454 | 5 | 456 | 8 | 462 | 41 | 0.07302 | 0.00080 | 0.5661 | 0.01270 | 0.05623 | 0.00105 | 99.91 |
| HC_5_sp1 | 469 | 9 | 460 | 11 | 418 | 44 | 0.07541 | 0.00143 | 0.5734 | 0.01670 | 0.05514 | 0.00110 | 99.79 |
| HC_6_sp1 | 455 | 4 | 452 | 6 | 436 | 26 | 0.07306 | 0.00070 | 0.5600 | 0.00862 | 0.05559 | 0.00064 | 99.96 |
| HC_7_sp1 | 451 | 7 | 466 | 9 | 539 | 46 | 0.07254 | 0.00115 | 0.5826 | 0.01390 | 0.05826 | 0.00122 | 99.96 |
| HC_8_sp1 | 495 | 5 | 489 | 4 | 463 | 9 | 0.07981 | 0.00080 | 0.6191 | 0.00598 | 0.05627 | 0.00024 | 99.87 |
| HC_8_sp2 | 511 | 6 | 494 | 9 | 419 | 40 | 0.08240 | 0.00093 | 0.6267 | 0.01410 | 0.05516 | 0.00098 | 99.23 |
| HC_9_sp1 | 1128 | 23 | 1132 | 19 | 1138 | 28 | 0.19120 | 0.00416 | 2.0480 | 0.05550 | 0.07767 | 0.00108 | 99.87 |
| HC_10_sp1 | 466 | 7 | 463 | 8 | 451 | 36 | 0.07491 | 0.00119 | 0.5780 | 0.01270 | 0.05596 | 0.00090 | 99.92 |
| HC_11_sp1 | 458 | 7 | 450 | 10 | 407 | 52 | 0.07363 | 0.00120 | 0.5570 | 0.01580 | 0.05486 | 0.00128 | 99.76 |
| HC_12_sp1 | 605 | 25 | 648 | 31 | 799 | 64 | 0.09846 | 0.00425 | 0.8926 | 0.05800 | 0.06575 | 0.00201 | 99.98 |
| HC_12_sp2 | 469 | 9 | 463 | 9 | 436 | 40 | 0.07547 | 0.00142 | 0.5783 | 0.01460 | 0.05558 | 0.00100 | 99.84 |
| HC_13_sp1 | 433 | 8 | 454 | 10 | 564 | 54 | 0.06940 | 0.00140 | 0.5636 | 0.01570 | 0.05891 | 0.00145 | 99.98 |
| HC_14_sp1 | 466 | 6 | 467 | 8 | 474 | 29 | 0.07497 | 0.00103 | 0.5846 | 0.01200 | 0.05656 | 0.00073 | 100.00 |

$^{204}$Pb correction for common Pb analysis labels (e.g. **MUL_1_sp1**) refer to sample, zircon grain, and point on zircon; "**@1**" indicates repeat analysis at same spot

tion age.

Ages of inherited cores are also similar among the three samples (Figure 6a,b; Miller and others, 2000). Five variably discordant cores from P22 had $^{207}$Pb/$^{206}$Pb ages of 1.0-1.4 Ga. In sample CPCMUL, 9 of the 15 analyzed cores are concordant at 1.09-1.15 Ga, two are concordant at ~ 1.4 Ga, and four are discordant but yield $^{207}$Pb/$^{206}$Pb ages of 1.0-1.2 Ga. Among the sparse cores in PCHC zircons, one is concordant at 1.13 Ga and two are discordant with $^{207}$Pb/$^{206}$Pb ages of 0.8 and 1.1 Ga.

## GEOCHEMISTRY

The eleven analyzed samples analyzed range in $SiO_2$ content from 53 to 73 wt% (Table 2; Fig. 7). The more felsic samples (>58 wt%

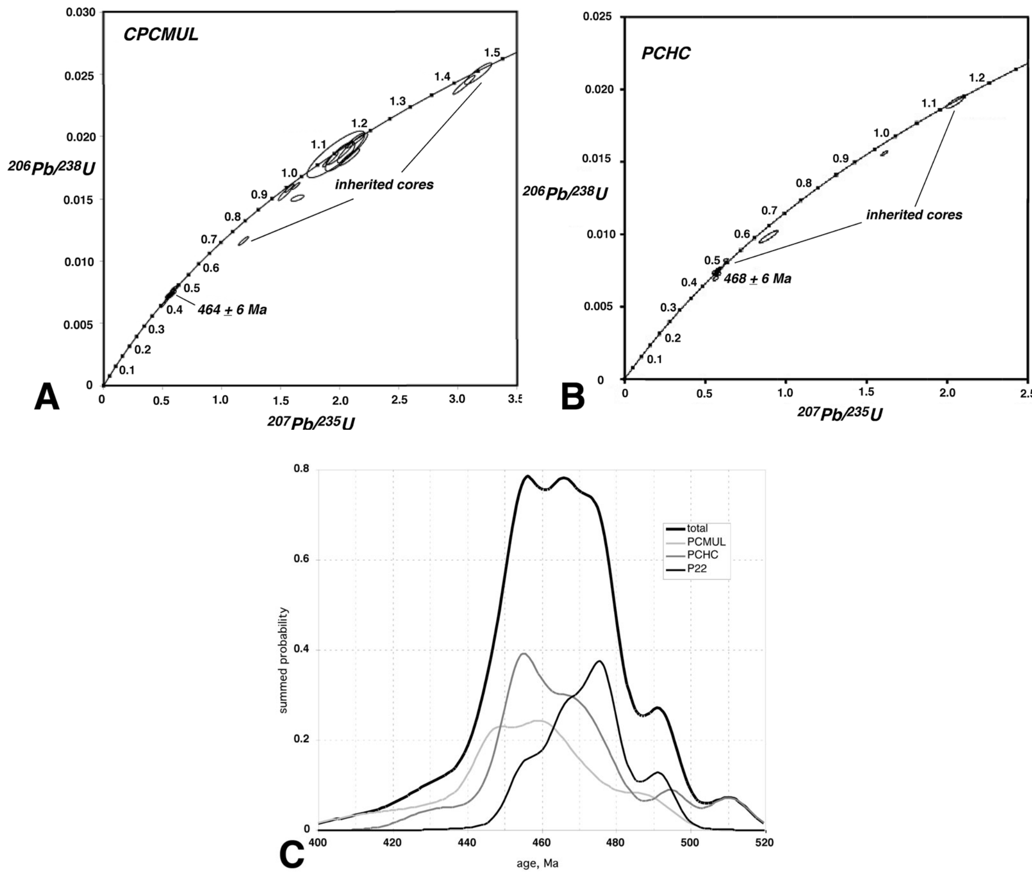



**Figure 6. U-Pb data. (a) Concordia plot, sample CPCMUL. (b) Concordia plot, sample PCHC. (c) Summed Gaussian probability distributions (Deino and Potts, 1992) for all analyses of each sample, including P22 (Miller and others, 2000), and all samples combined.**

$SiO_2$) are peraluminous, whereas the more mafic samples are metaluminous. Sample PCBC2, from a screen heavily contaminated by metasedimentary material, is geochemically distinct from the other samples, with the highest $SiO_2$ (the only sample with >70% $SiO_2$) and Zr and lowest $K_2O$, $Na_2O$, CaO, Sr, and $Al_2O_3$ concentrations of any sample, along with unusually low Rb and high Fe for so silicic a rock. The most mafic sample, hornblende gabbro PC-GAB, is also distinctive, with very high CaO and MgO and very low $Na_2O$ and $K_2O$, as well as generally low incompatible element concentrations. The other samples possess moderate concentrations of $K_2O$ (1.5-3.3 wt%) and Sr (320-540 ppm), moderate but variable light rare earth element (LREE) enrichment (~50-150 x chondrite), a flat heavy rare earth (HREE) pattern at ~10 x chondrite, and modest but distinct negative Eu anomalies (Figure 8a). All samples also exhibit depletion in high field strength elements (HFSE) including Ta, Nb, P, and Ti (Figure 8b) and plot in the volcanic arc granite field on tectonic discrimination diagrams (e.g. Figure 9).

Initial $\varepsilon_{Nd}$ values of the three samples analyzed range from –4.1 to –4.9, and initial $^{87}Sr/^{86}Sr$ ratios from 0.7081 to 0.7091 (Table 2). The compositions cluster near the primitive end (high $\varepsilon_{Nd}$, low $^{87}Sr/^{86}Sr$) of the fields for basement gneisses and metasedimentary rocks of the Piedmont Terrane, displaced slightly toward the field of mafic rocks of the Eastern Blue Ridge (B. Bream and P. Fullagar, unpub. data; Thomas, 2001)(Figure 10).

Two typical samples of the PCG have $\delta^{18}O$

**Table 2. Elemental and isotopic compositions of Persimmon Creek Gneiss samples.**

| | P22A | PCLU1 | CPCU1 | CPCMUL | PCBC2 | PCHC | CPC6 | PC-GAB | PCQ2 | PC22B | PCPN |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$, wt% | 57.9 | 65.59 | 62.53 | 64.89 | 72.86 | 59.19 | 57.78 | 52.81 | 56.71 | 54.66 | 69.90 |
| $TiO_2$ | 0.82 | 0.52 | 0.593 | 0.471 | 0.892 | 0.734 | 1.2 | 0.836 | 0.571 | 1.201 | 0.268 |
| $Al_2O_3$ | 18.1 | 16.99 | 17.77 | 16.45 | 12.11 | 19.54 | 17.36 | 11.62 | 16.76 | 19.34 | 16.00 |
| $Fe_2O_3$(total) | 6.36 | 4.29 | 3.92 | 4.27 | 4.62 | 4.83 | 7.59 | 7.81 | 7.11 | 6.76 | 2.44 |
| MnO | 0.07 | 0.073 | 0.092 | 0.074 | 0.112 | 0.082 | 0.111 | 0.136 | 0.119 | 0.087 | 0.040 |
| MgO | 3.19 | 2.14 | 2.47 | 2.24 | 1.26 | 3.05 | 4.36 | 11.24 | 5.82 | 3.64 | 0.99 |
| CaO | 5.94 | 3.73 | 4.01 | 4.23 | 2.56 | 4.82 | 4.55 | 12.22 | 7.43 | 7.91 | 3.35 |
| $Na_2O$ | 3.32 | 3.73 | 3.82 | 3.89 | 2.81 | 3.64 | 2.5 | 0.89 | 2.93 | 3.56 | 3.96 |
| $K_2O$ | 2.52 | 2.23 | 2.3 | 2.45 | 1.42 | 2.57 | 3.33 | 0.54 | 1.54 | 1.54 | 2.38 |
| $P_2O_5$ | 0.23 | 0.15 | 0.15 | 0.16 | 0.11 | 0.21 | 0.25 | 0.09 | 0.13 | 0.19 | 0.14 |
| LOI | 0.5 | 0.99 | 1.07 | 0.97 | 1.73 | 1.1 | 1.43 | 1.78 | 1.20 | 1.14 | |
| Total | 99.2 | 100.44 | 98.73 | 100.1 | 100.5 | 99.77 | 100.46 | 99.98 | 100.32 | 100.02 | 99.47 |
| Rb, ppm | 83 | 85 | 77 | 72 | 40 | 80 | 107 | 5 | 54 | 51 | 65 |
| Sr | 441 | 382 | 440 | 415 | 289 | 504 | 324 | 342 | 387 | 536 | 361 |
| Ba | 570 | 472 | 624 | 563 | 455 | 662 | 476 | 87 | 322 | 399 | 900 |
| Y | 24 | 11 | 16 | 23 | 28 | 21 | 27 | 27 | 25 | 33 | 12 |
| Zr | 240 | 200 | 183 | 185 | 338 | 239 | 150 | 95 | 173 | 210 | 121 |
| Hf | 7.7 | 5.2 | 4.8 | 4.9 | 7.3 | 5.3 | 3.5 | 3.4 | 5.2 | 6.3 | 5 |
| Nb | 7 | 9.6 | 6.1 | 7.9 | 10.3 | 7.4 | 8.6 | 6.1 | 8.3 | 9.7 | 7 |
| Ta | 0.5 | 0.9 | 0.62 | 0.64 | 0.65 | 0.68 | 0.79 | 0.48 | 0.49 | 0.67 | 0.7 |
| V | 91 | 66 | 73 | 61 | 77 | 84 | 149 | 228 | 128 | 192 | 34 |
| Ni | 21 | 17 | 21 | 15 | 17 | 24 | 23 | 93 | 45 | <1 | 7 |
| Cr | 40 | 34.2 | 42 | 40.5 | 41 | 50 | 39.3 | 739 | 285 | -0.5 | 16 |
| La | 44.6 | 29.4 | 53.9 | 31.8 | 25.2 | 19.6 | 29.8 | 21.8 | 17.2 | 16.1 | 17.1 |
| Ce | 90.4 | 58.9 | 110 | 65.3 | 55.4 | 43.1 | 53.4 | 42.8 | 39.6 | 38.8 | 35.1 |
| Pr | 11 | 6.64 | 12.4 | 7.38 | 6.39 | 5.14 | 6.96 | 7.13 | 5.02 | 5.42 | 4 |
| Nd | 38 | 25.3 | 46.4 | 28.8 | 28.5 | 24.4 | 30.2 | 34.6 | 22.1 | 27 | 18.5 |
| Sm | 7.1 | 3.99 | 7.64 | 5.26 | 5.33 | 5.12 | 5.58 | 7.78 | 5.27 | 7.19 | 3.6 |
| Eu | 1.57 | 1.00 | 1.38 | 1.07 | 1.22 | 1.21 | 1.42 | 1.83 | 1.27 | 1.77 | 0.96 |
| Gd | 6.6 | 3.32 | 5.87 | 4.53 | 5.06 | 4.47 | 5.17 | 6.73 | 5.01 | 6.73 | 3.3 |
| Tb | 0.9 | 0.48 | 0.72 | 0.66 | 0.73 | 0.64 | 0.79 | 0.99 | 0.84 | 1.2 | 0.4 |
| Dy | 4.8 | 2.94 | 3.33 | 3.58 | 4.18 | 3.05 | 4.33 | 5.26 | 5.04 | 7.34 | 2.6 |
| Ho | 1 | 0.49 | 0.58 | 0.74 | 0.86 | 0.51 | 0.82 | 0.95 | 0.99 | 1.44 | 0.4 |
| Er | 2.5 | 1.29 | 1.42 | 2.1 | 2.6 | 1.29 | 2.26 | 2.68 | 2.95 | 4.11 | 1.3 |
| Tm | 0.4 | 0.204 | 0.205 | 0.332 | 0.4 | 0.169 | 0.331 | 0.37 | 0.443 | 0.595 | 0.1 |
| Yb | 2.3 | 1.18 | 1.18 | 2.14 | 2.58 | 0.99 | 2.06 | 2.25 | 2.82 | 3.77 | 1.1 |
| Lu | 0.36 | 0.187 | 0.154 | 0.306 | 0.409 | 0.138 | 0.304 | 0.32 | 0.422 | 0.545 | 0.14 |
| Th | 6.9 | 7.05 | 11.7 | 10.8 | 7.38 | 3.59 | 5.2 | 4.88 | 2.33 | 1.49 | 3.8 |
| U | 1.1 | 0.89 | 0.89 | 1.43 | 1.01 | 0.73 | 1.3 | 1.9 | 0.96 | 0.49 | 2.6 |
| $^{87}Rb/^{86}Sr$ | - | - | - | 0.467 | - | 0.468 | - | - | - | 0.230 | - |
| $^{87}Sr/^{86}Sr_{(0)}$ | - | - | - | 0.7113 | - | 0.7122 | - | - | - | 0.7096 | - |
| $^{87}Sr/^{86}Sr_{(t)}$ | - | - | - | 0.7082 | - | 0.7091 | - | - | - | 0.7081 | - |
| $^{147}Sm/^{144}Nd$ | - | - | - | 0.1115 | - | 0.1373 | - | - | - | 0.1635 | - |
| $^{143}Nd/^{144}Nd_{(0)}$ | - | - | - | 0.51216 | - | 0.5122O | - | - | - | 0.51233 | - |
| $^{143}Nd/^{144}Nd_{(t)}$ | - | - | - | 0.51182 | - | 0.51178 | - | - | - | 0.51182 | - |
| $\varepsilon_{Nd(0)}$ | - | - | - | -9.32 | - | -8.49 | - | - | - | -6.07 | - |
| $\varepsilon_{Nd(t)}$ | - | - | - | -4.21 | - | -4.92 | - | - | - | -4.08 | - |
| $\delta^{18}O$, ‰ | - | - | - | 7.6 | 11.2 | 8.2 | - | - | - | | - |

(o): present day; (t): initial

values of 7.6 and 8.2 ‰, fairly characteristic for intermediate to felsic rocks. A third sample, PCBC2, which appears in the field to be severely contaminated by metasediment, has a much higher $\delta^{18}O$ value of 11.2 ‰.

## COMPARISONS WITH OTHER ORDOVICIAN AGE PLUTONS IN THE PIEDMONT TERRANE

Other Ordovician plutons of the Piedmont Terrane of NC-SC-GA (the Whiteside pluton of the Eastern Blue Ridge Belt [Miller et. al, 1997]

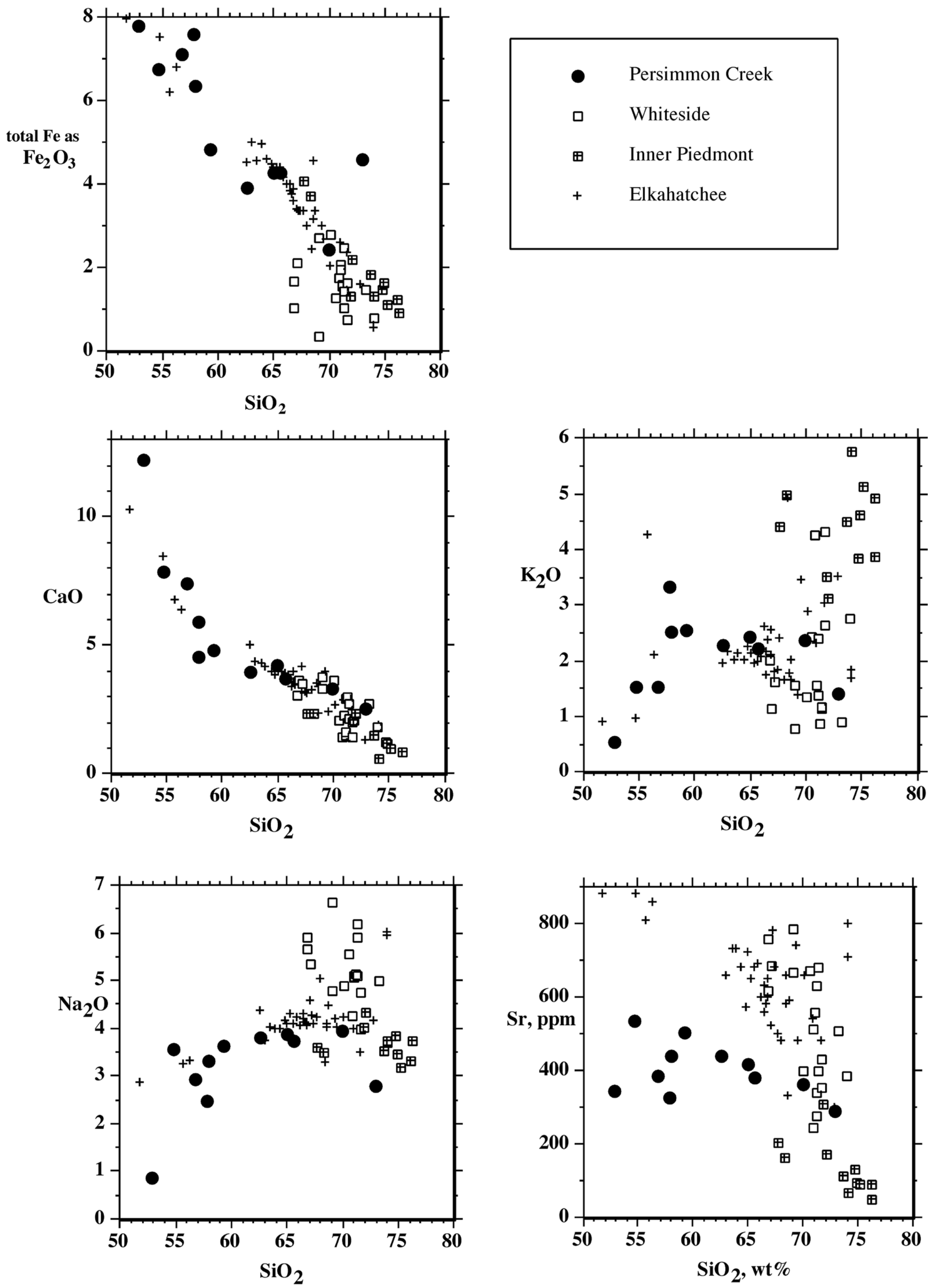
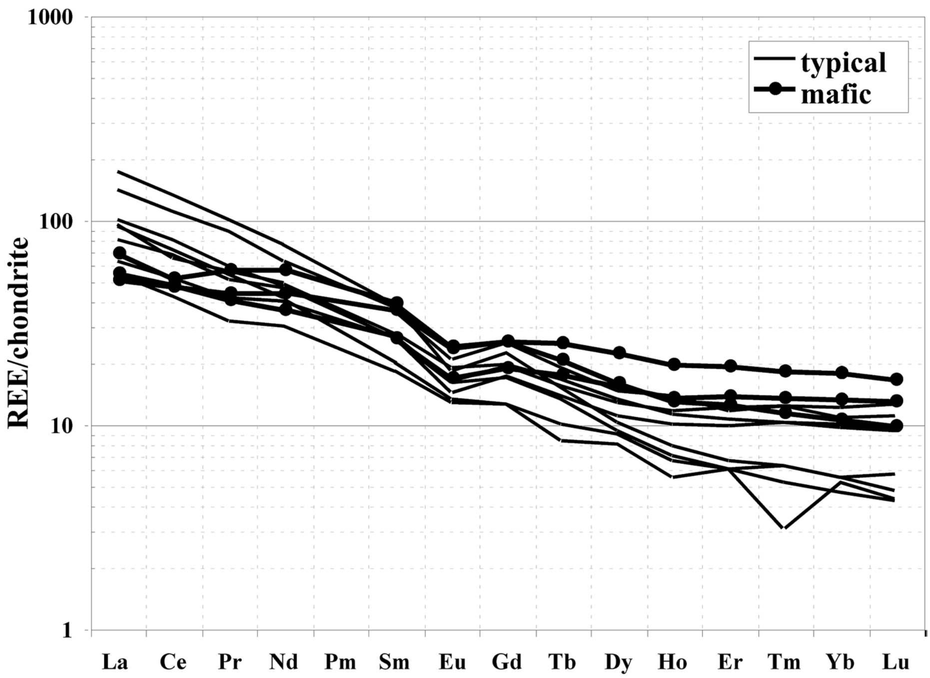



**Figure 7. Harker plots comparing elemental compositions of Persimmon Creek Gneiss with those of other Ordovician plutons from the Piedmont Terrane (Whiteside pluton, Eastern Blue Ridge Belt, NC [Miller and others, 1997, and unpub. data]; Elkahatchee quartz diorite, Eastern Blue Ridge Belt, AL [Drummond and others, 1994]; Inner Piedmont plutons, NC-SC [Vinson, 1999]).**



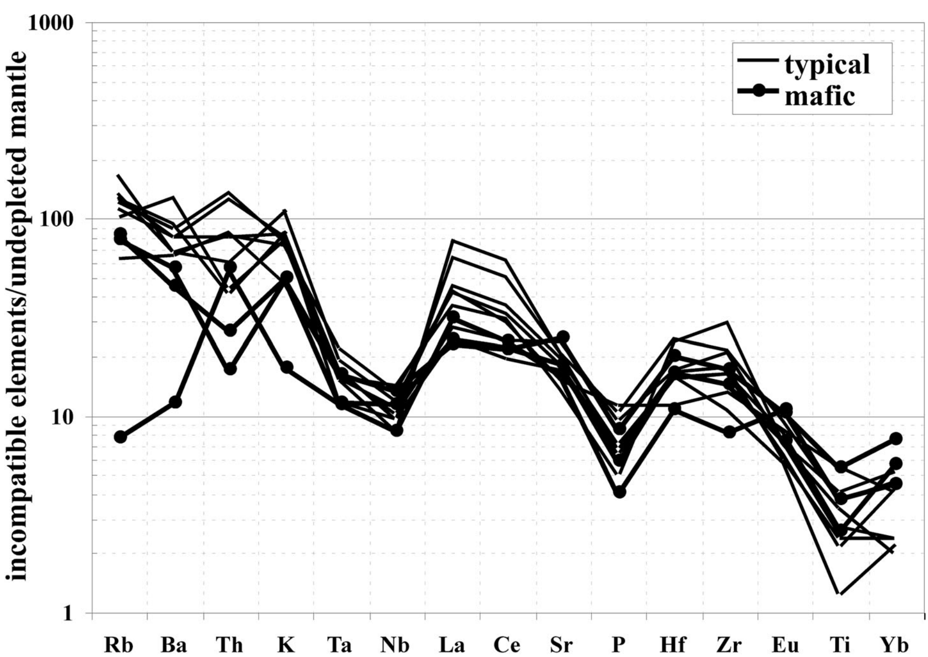




**Figure 8. (a) Chondrite-normalized rare earth element plots for Persimmon Creek Gneiss samples. (b) Undepleted mantle-normalized (Sun and McDonough, 1989) spider plots for Persimmon Creek Gneiss samples.**

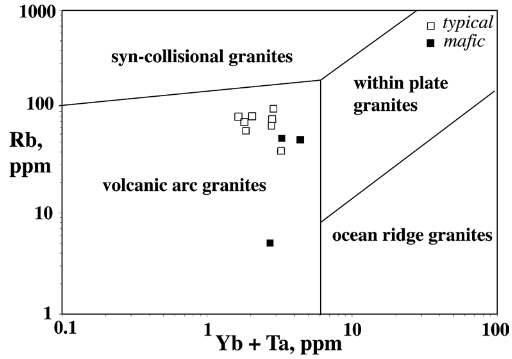



**Figure 9. Persimmon Creek Gneiss samples plotted on Rb vs. Yb + Ta tectonic discrimination diagram of Pearce and others (1984).**

and plutons in the Inner Piedmont Belt [Vinson, 1999; Vinson and others, 1999]) are distinct from the PCG in several respects:

(1) Both Whiteside and the Inner Piedmont plutons are more felsic and have a narrower range of $SiO_2$ concentration, from 66-75 wt% (Figure 7).

(2) The Whiteside pluton has much lower HREE concentrations than the PCG (Figure 11) and many samples have positive rather than negative Eu anomalies (Miller and others, 1997). Inner Piedmont plutons have higher LREE and HREE and larger negative Eu anomalies (Vinson and others, 1999; Vinson, 1999). Whiteside tends to have lower incompatible element concentrations and the Inner Piedmont plutons higher incompatible element concentrations than PCG.

(3) Despite being more mafic, the PCG is more isotopically evolved than either the Whiteside or Inner Piedmont plutons (lower $\varepsilon_{Nd}$, generally higher initial $^{87}Sr/^{86}Sr$) (Fig. 10).

(4) Also despite being more mafic, the PCG has markedly lower Sr concentrations than the Whiteside pluton. Inner Piedmont plutons, on the other hand, are much poorer in Sr (Figure 11).

(5) Most Harker diagrams do not indicate any coherent patterns, and by implication petrogenetic relationships, that include both the PCG and either of the other data sets (Figure 7).

## INTERPRETATION

### General Tectonic Environment of Formation

The petrologic characteristics of the PCG are

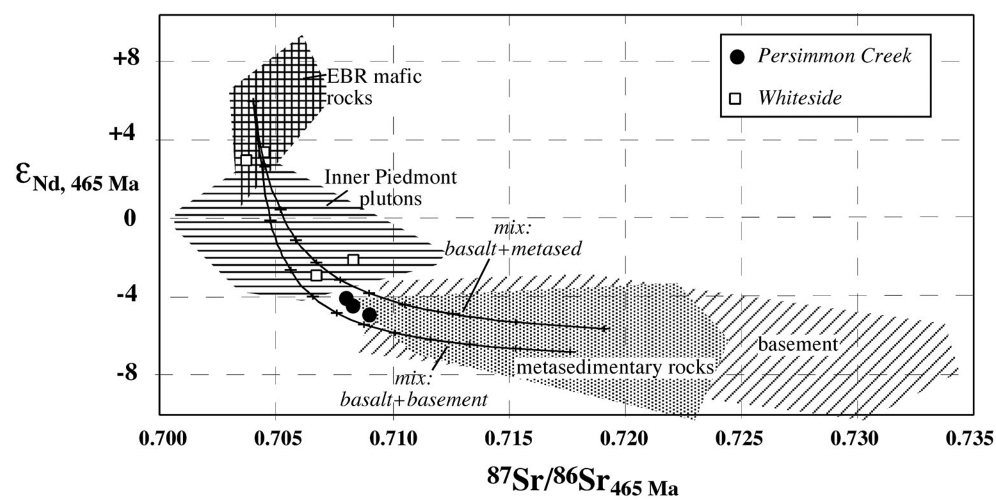



**Figure 10. Initial Sr and Nd isotopic ratios of Persimmon Creek Gneiss and Whiteside pluton samples compared to major lithologies of the Piedmont Terrane at 465 Ma (Fullagar, Bream, Carrigan, Vinson, and Thomas, unpub. data). Mixing models involving island arc basalt + average Piedmont Terrane metasediment and IAB + average basement shown for comparison. Arc basalt has isotopic composition of typical Eastern Blue Ridge mafic rocks ($\varepsilon_{Nd}$ +6, $^{87}Sr/^{86}Sr$ 0.704; 10 ppm Nd, 500 ppm Sr); metasediment: -5.6, 0.719; 36 ppm, 164 ppm; basement: -6.8, 0.7175; 82 ppm, 268 ppm. Tick marks on mixing curves represent 10% increments of end members.**

generally consistent with formation in a subduction zone environment. It exhibits compositions ranging from mafic to felsic and comprises especially abundant intermediate rocks, as is typical for rocks generated in this setting. It also has the subduction zone elemental signature of HFSE depletion. The abundance of apparently primary hydrous mafic silicates (biotite, epidote, local hornblende) and absence of anhydrous mafic minerals is also consistent with a subduction zone setting.

Other attributes of the PCG are distinctive for a subduction-related pluton. The extreme abundance of inherited zircon contrasts sharply with most plutons that form as a direct consequence of subduction processes. Furthermore, the isotopic composition of the PCG is highly evolved for an Ordovician pluton of intermediate composition, demonstrating that it has a major mature crustal component and that it was not formed in a primitive arc.

### Petrogenesis

The following model for PCG petrogenesis appears to be consistent with the data and observations presented above. (1) Magma generated in the mantle wedge of a subduction zone intruded into tectonically emplaced, metasedimentary and basement rock in the deep crust. (2) Partially melted country rock then mixed with the crystallizing mafic material to produce a crystal-rich hybrid mush with an intermediate composition. (3) Further influxes of mafic magma were incorporated as enclaves or dike-like sheets. The magma, cooled by the hybridization process, did not remain hot enough to completely dissolve the zircon already present in the crustal contaminant, so new zircon nucleated around the older grains during crystallization. The hydrous, epidote-bearing assemblage supports emplacement as a relatively cool, wet, oxidized magma in the deep middle crust (>~6 kbar?) (Schmidt and Thompson, 1996).

Such a model can be tested using the Sr and Nd isotopic compositions of the PCG and pre-Ordovician rocks of the Piedmont Terrane (Bream and others, 2001a,b; Carrigan, 2000; Fullagar, Bream, and Carrigan, unpub. data). Figure 10 demonstrates that simple mixtures of a mafic component with regional basement and metasedimentary rocks of the Eastern Blue Ridge Belt can provide reasonable matches for isotopic compositions and trend of the PCG samples. These models suggest that PCG contains roughly 50% of the primitive (~subduction zone) component.

### Constraints on Paleozoic Tectonics

The age of the PCG constrains the time at which the Piedmont Terrane accreted to Laurentia. If the pluton was emplaced during subduction that preceded accretion, then accretion must have occurred later than ~468 Ma. Alternatively, it may have been emplaced during final closure of the ocean basin that presumably separated some or all of the Piedmont Terrane from autochthonous Laurentia. In this case, the age of the pluton approximates the initiation of accretion.

It is noteworthy that volcanic sequences of identical age are abundant immediately to the southwest in Georgia and Alabama in the structurally underlying Dahlonega Gold Belt and its possible equivalents (Thomas and others, 2001; McLellan and Miller, 2000). These volcanic sequences are thought to mark subduction related arcs.

## Implications of Intermediate Plutonism for Southern Appalachian Tectonics

The PCG appears to be the only pluton with intermediate composition or direct evidence for involvement of mafic magma in the Piedmont Terrane of North Carolina, South Carolina, and Georgia. Other plutons in this region are more felsic and geochemical data suggest a very different petrogenetic history from the PCG. For example, although the Whiteside pluton is isotopically primitive, it is far more felsic and its high Sr and low HREE suggest an entirely crustal derivation from a deep (garnet-bearing, feldspar-poor) mafic source (Miller and others, 1997), (Figure 7, 11). The Inner Piedmont plutons are also much more felsic and appear to lack entirely a mafic component.

Farther southwest, in Alabama, the Elka-

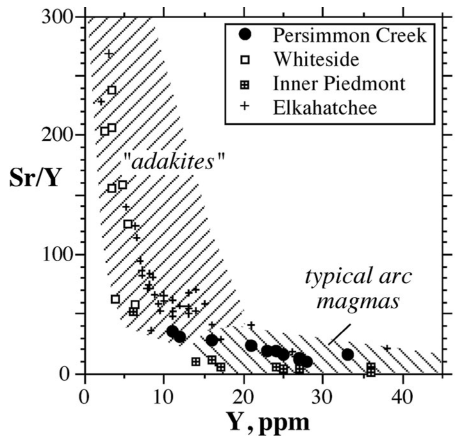



**Figure 11. Sr/Yb vs. Yb discrimination diagram, comparing Piedmont Terrane Ordovician plutonic rocks to "adakites" (equilibrated at deep levels with garnet-rich, feldspar-poor residues) and modern arc and granitic rocks (Drummond and Defant 1990; Defant and Drummond 1990; Defant and others 1991; Yogodzinski and others 1995).**

hatchee "Quartz Diorite," like the PCG, includes mafic to felsic rocks and is dominantly tonalitic (Figure 7; Drummond et al, 1994, 1997)(though it shares the Whiteside high Sr, low HREE - Figure 11). The Elkahatchee is the largest intrusive complex exposed in the eastern Blue Ridge (880 km$^2$) and is interpreted to be subduction-related.

That intermediate plutonism appears to be rare in Georgia, North Carolina, and South Carolina, but perhaps more substantial farther southwest, might be explained by a variation on model (c), described in the introduction: perhaps the small ocean basin created when the Piedmont terrane rifted from Laurentia narrowed from the southwest to the northeast (analogous to the modern Red Sea or Gulf of California) (cf. Thomas and others, 2001). When spreading ceased and convergence commenced, more oceanic crust would have been available for subduction in the southwest than in the northeast, and thus more voluminous plutonism ensued in those areas.

## CONCLUSIONS

Mineralogy, field relationships, and geochemistry are consistent with the hypothesis that the Persimmon Creek Gneiss was generated in a subduction zone and emplaced at depth. Significant amounts of inherited zircon and the evolved isotopic compositions of the rocks are somewhat anomalous for this setting but do not necessarily contradict the hypothesis. Rather, the data simply indicate extensive interaction between mafic magma and evolved, deep middle crust. If the Persimmon Creek Gneiss is, in fact, subduction related, then its age of 468 Ma marks the earliest possible time of accretion of the Piedmont Terrane to Laurentia. Finally, the scarcity of intermediate plutonism in the Piedmont Terrane of North Carolina, South Carolina, and Georgia, and the more voluminous intermediate plutonism in the corresponding regions of the southwesternmost Appalachians, may constrain the geometric and tectonic character of the subduction zone and the ocean basin that it consumed.

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