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Geochemistry of volcanic rocks of the Carolina and Augusta terranes in central South Carolina: An exotic rifted volcanic arc?

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ABSTRACT

This chapter presents new whole-rock, major- and trace-element geochemical data from the Carolina and Augusta terranes in South Carolina. Geochemical data from the Persimmon Fork and Richtex Formations strongly confirm the interpretation of previous workers that the Carolina terrane is a remnant of a subduction-related volcanic arc. These data further suggest that the arc developed either on top of an older arc or on a thinned section of continental crust. Geochronological data from the southern Appalachians indicate that the subduction-related arc in the Carolina terrane developed simultaneously with the initial opening of Iapetus, the "Proto-Atlantic" Ocean. Therefore, the arc could not have formed in the Iapetus Ocean basin, and must be exotic relative to cratonic North America.

INTRODUCTION

The southern Appalachian Piedmont is widely interpreted as a collage of tectonostratigraphic terranes (Fig. 1) accreted to Laurentia (North America) during the Paleozoic (Williams and Hatcher, 1982, 1983; Horton et al., 1989, 1991). The paleogeographic histories of most of the terranes are uncertain because Paleozoic penetrative deformation and regional metamorphism have erased fossils and primary paleomagnetism that might otherwise yield paleogeographic information. However, the Carolina terrane has been interpreted as exotic with respect to Laurentia because it contains an Atlantic Province trilobite fauna of Middle Cambrian age (Secor et al., 1983). This interpretation has recently been questioned by Samson et al. (1990) who noted that the trilobites may have lived in a deep, cold-water environment peripheral to Laurentia, and that, based on paleontologic data alone, displacement of the Carolina terrane relative to Laurentia need not have been great.

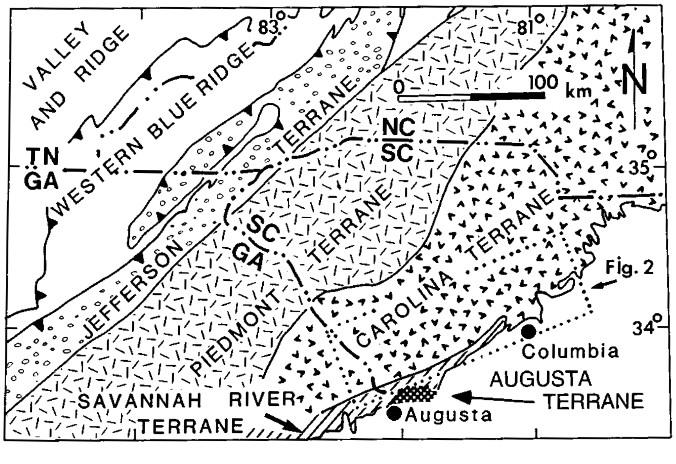

Figure 1. Terrane map of the southern Appalachian orogen (modified from Hatcher et al., 1990, and Horton et al., 1991). Suspect terranes are patterned. Samples 44, 45, 46, 47, 48, 50, and 51 were collected in the Augusta terrane on the east side of the Savannah River, opposite the city of Augusta.

Analysis of the margin of the Laurentian plate, exposed in the Blue Ridge Mountains near the northwestern edge of the Appalachians, indicates the presence of a divergent plate bound-

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ary with associated rift basins and alkalic igneous rocks during the Late Proterozoic (Rankin, 1972, 1975; Goldberg et al., 1986; Rankin et al., 1989). Overlying strata record the development of a passive continental margin and the beginning of carbonate-platform deposition during the early Paleozoic (Rodgers, 1968; Rankin et al., 1989).

Along the southeastern edge of the exposed Appalachians, from southern Virginia to Georgia, sequences of Late Proterozoic and Cambrian metavolcanic rocks and associated epizonal plutonic rocks are widely distributed in the Carolina terrane (Secor et al., 1989; Butler and Secor, 1991; Maher et al., 1991). Interpretation of the paleogeographic history of the Carolina terrane is critically dependent on the plate tectonic setting in which these metaigneous rocks accumulated. If the metavolcanic rocks accumulated at a divergent plate boundary, the Carolina terrane may have developed adjacent to Laurentia during the opening of Iapetus. If the metavolcanic rocks are subduction related, the Carolina terrane must have developed away from Laurentia and outside the Iapetus Ocean basin.

Although Long (1979) interpreted geophysical data to indicate a continental-rift setting for development of the Carolina terrane, all other investigators have concluded from geological and/or geochemical data that the Carolina terrane represents a subduction-related volcanic arc. In east-central Georgia, Whitney et al. (1978) concluded that metavolcanic rocks in the Carolina terrane represent a primitive, ensimatic subduction-related arc. Most other investigators (Butler and Ragland, 1969; Glover and Sinha, 1973; Black, 1980; Feiss, 1982; Rogers, 1982; Harris and Glover, 1988) concluded that the arc developed on at least some sialic crust. Dennis and Shervais (1991) concluded that arc rocks along the northwestern edge of the Carolina terrane in South Carolina experienced a late episode of intra-arc rifting. All of these geological and geochemical studies have been remote from the locality in west-central South Carolina that yielded the Atlantic Province trilobite fauna (Fig. 2). In this chapter, we present new geochemical data from west-central South Carolina that strongly confirm the interpretation of the Carolina terrane as a subduction-related volcanic arc that originated away from the Laurentian margin.

GEOLOGICAL OVERVIEW

In the South Carolina Piedmont (Fig. 1), tectonostratigraphic terranes that include low- to medium-grade metavolcanic and metasedimentary rocks (Carolina, Augusta) are interspersed with terranes that contain predominantly medium- to high-grade gneisses (Savannah River, Piedmont). The analyzed samples that form the basis for this chapter come from the Carolina and Augusta terranes.

Carolina terrane

Previous workers (Secor et al., 1983, 1989; Horton et al., 1991) have defined the Carolina terrane to include a sequence of low-grade metavolcanic and metasedimentary rocks (the Carolina slate belt of Nitze and Hanna, 1896) as well as a sequence of medium- to high-grade gneisses containing abundant igneous and metaigneous intrusions (the Charlotte belt of King, 1955). The Carolina slate belt has been interpreted as a remnant of a volcanic arc, and the Charlotte belt, with its meta-intrusive rocks, has been interpreted as the plutonic infrastructure of the arc (Secor et al., 1982, 1986; Dallmeyer et al., 1986). There is some uncertainty concerning this inferred relationship. Careful modern geochemical comparisons have not been made between the two belts, and our recent unpublished field mapping indicates that their common boundary has been faulted in

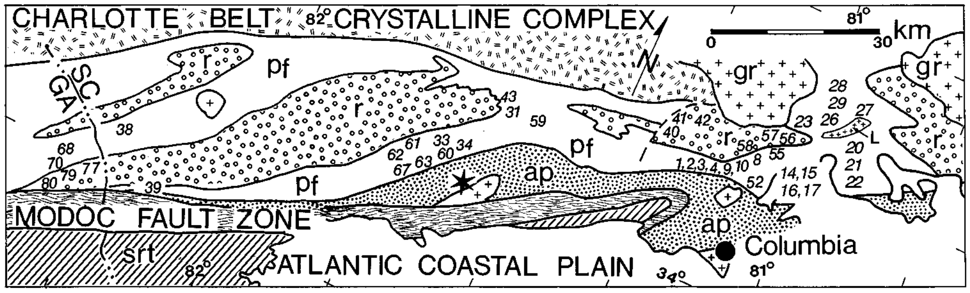


Figure 2. Geologic map showing sample locations and stratigraphic subdivisions of the Carolina terrane in west-central South Carolina (modified from Secor et al., 1986): L = Longtown metagranite, pf = Persimmon Fork Formation, r = Richtex Formation, ap = Asbill Pond formation, gr = granite, srt = Savannah River terrane. Star indicates locality where Middle Cambrian trilobites have been found (Samson et al., 1990). Numbers indicate approximate locations of analyzed samples. Sample numbers separated by commas are too close together to show the relative locations. Precise latitude and longitude of each sample site is shown in Table 1 (see "Geochemistry of Metavolcanic Rocks" section).

many locations in South Carolina. This uncertainty does not affect the present study, because our samples were collected only from the low-grade (Carolina slate belt) part of the Carolina terrane.

In South Carolina, the low-grade part of the Carolina terrane includes three stratigraphic units: the Persimmon Fork Formation, the Richtex Formation, and the Asbill Pond formation (informal usage) (Secor et al., 1986). All of the samples analyzed in the present study are from the Persimmon Fork and Richtex Formations along the southeastern side of the Carolina terrane (Fig. 2).

The Persimmon Fork Formation is an ~3 km thick sequence of mafic to felsic metavolcanic rocks with felsic varieties greatly predominating. Relict primary textures indicate that the felsic and intermediate rocks were deposited as a series of ash-flow tuffs. Relict primary textures include collapsed pumice lapilli, angular lithic lapilli, and flattened shards of altered volcanic glass containing relict primary phases such as plagioclase (Secor et al., 1986). Foliation is developed by flattened pumice shards, which are commonly deflected around relict phenocrysts and lithic fragments. Heterolithic tuff breccias, which contain lithic volcanic clasts as much as 20 cm across in a tuffaceous groundmass, are also common.

Along the Savannah River, the Persimmon Fork Formation contains thick sequences of coarse-grained dacitic lava flows or domes (Lincolnton metadacite; Crawford, 1968; Paris, 1976; Whitney et al., 1978). Carpenter et al. (1982) obtained a late Precambrian (?) age for the Lincolnton metadacite by both Rb-Sr whole-rock (554 ± 20 Ma) and U-Pb zircon (ca. 568 Ma) methods. In many places, the Persimmon Fork Formation is intruded by epizonal plutons of felsite or metagranite such as the Longtown metagranite in central South Carolina (Fig. 2). These plutons may be the intrusive equivalent of eruptive volcanic rocks higher in the stratigraphic section. A U-Pb zircon igneous crystallization age of 549 ± 2 Ma has recently been obtained for the Longtown (J. E. Wright, 1994, personal communication). These isotopic studies are interpreted to indicate a late Precambrian/Early Cambrian (?) age for the Persimmon Fork Formation.

The Richtex Formation is an ~3 km thick sequence of turbiditic metamudstone and metawacke interlayered with mafic metavolcanic rocks that depositionally overlies the Persimmon Fork Formation. Metavolcanic rocks comprise about 10% of the Richtex Formation, most of which are mafic volcanic greenstones. The greenstones are commonly amygdaloidal, suggesting eruption as lava flows into a subaerial or shallow water setting. The age of the Richtex Formation is uncertain, because no geochronological studies have yet been performed on the volcanic rocks that it contains. The Richtex is lithologically similar to the rocks of the Albemarle Group (Milton, 1984) in North Carolina that contain late Precambrian fossils (Gibson et al., 1984).

The Asbill Pond formation also depositionally overlies the Persimmon Fork Formation and is an ~5 km thick sequence of metamudstone and quartzo-feldspathic metasandstone. The metasandstone contains relict sedimentary structures suggestive of very shallow water deposition (Secor and Snoke, 1978; Snoke and Secor, 1979; Secor et al., 1986). The youngest part of the Asbill Pond formation is a mudstone member that has yielded a diverse assemblage of Atlantic Province trilobites that includes seven genera representing at least nine different species (Samson et al., 1990). This assemblage is representative of the *Ptychagnostus atavus* Interval–zone of middle Middle Cambrian age. The relationship between the Richtex Formation and Asbill Pond formation is uncertain. They are spatially separated, but both depositionally overlie the Persimmon Fork Formation (Fig. 2). It is possible that the Richtex is the same age as the lower part of the Asbill Pond but represents a different depositional environment. Alternatively, the Asbill Pond could be entirely younger than the Richtex.

Most of the rocks in the stratigraphic units under discussion contain a pervasive slaty cleavage and have been recrystallized to assemblages characterized by quartz-muscovite-albite-epidote-chlorite ± actinolite, biotite, hematite, paragonite, calcite, zoisite, clinozoisite, chloritoid, microcline, garnet, apatite, zircon, barite. The ^{40}Ar/^{39}Ar whole-rock phyllite age spectra from the interior of the Carolina terrane in South Carolina suggest cooling through white mica argon retention temperatures (~350 °C; Jäger, 1979) during the period 340–320 Ma (Dallmeyer et al., 1986). These data are interpreted to indicate that most of the rocks in the southeastern part of the Carolina terrane were strongly deformed and regionally metamorphosed in the greenschist facies prior to or during the middle Paleozoic. During the late Paleozoic Alleghanian orogeny, the part of the Carolina terrane immediately adjacent to the Modoc fault zone (Fig. 2) was redeformed and reheated above ~350 °C (Dallmeyer et al., 1986). Most of the analyzed samples in this study were collected away from the thermally disturbed rocks associated with the Modoc fault zone.

Augusta terrane

The Augusta terrane comprises rocks traditionally assigned to the Belair belt by Crickmay (1952) in western South Carolina and eastern Georgia (Maher et al., 1994) and contains sequences of low-grade metasedimentary and metavolcanic rocks lithologically similar to those in the Carolina terrane. The metasedimentary rocks were originally wacke and thinbedded siltstone, interbedded with mafic to felsic crystal-lapilli tuff and, less commonly, amygdaloidal basalt. Maher et al. (1981) reported the single occurrence of a lower Paleozoic trilobite thorax from the metasedimentary rocks. All of the rocks in the Augusta terrane contain slaty cleavage and have been recrystallized to mineral assemblages characteristic of the greenschist facies (Maher, 1979). The $^{40}Ar/^{39}Ar$ age spectra of a single whole-rock phyllite sample from the Augusta terrane is interpreted to indicate cooling through the white mica argon retention temperature (~350 °C; Jäger, 1979) at ca. 314 Ma (Maher et al., 1994). The above data are interpreted to indicate that the rocks of the Augusta terrane were deformed and metamorphosed prior to the onset of the Alleghanian orogeny. The Augusta terrane is separated from the Savannah River terrane to the northwest by the Augusta fault. The Augusta fault is interpreted to be a low-angle normal fault that dips to the southeast beneath the Augusta terrane (Maher, 1987). The $^{40}Ar/^{39}Ar$ age spectra from the Augusta fault zone and adjacent terranes are interpreted to indicate a late Alleghanian age (at and after ca. 274 Ma) for the Augusta fault (Maher et al., 1994). All of the analyzed samples from the Augusta terrane were collected more than 3 km southeast of the region of Alleghanian thermal disturbance associated with the Augusta fault.

GEOCHEMISTRY OF METAVOLCANIC ROCKS

Ninety-two samples of metaigneous rock were collected from the Carolina terrane and Augusta terrane in west-central South Carolina (Table 1). From these, 67 of the freshest (least weathered) samples were chosen for whole-rock major- and trace-element analysis, including 42 samples from the Persimmon Fork Formation, 9 samples from the Richtex Formation, 13 from the Augusta terrane, and 3 samples of Longtown granite (Table 2). The samples were analyzed for 10 major elements and 12 trace elements by X-ray fluorescence (XRF) spectrometry at the University of South Carolina using a Philips PW-1400 automated XRF spectrometer and 12 U.S. Geological Survey rock standards. In addition, 19 of these samples, representing the entire range in observed compositions, were analyzed for 26 trace elements, including 8 rare earth elements (REE), by instrumental neutron activation analysis (INAA) at the Oregon State University Radiation Center (Table 3).

Major element chemistry

Metavolcanic rocks from both the Carolina terrane and the Augusta terrane define curvilinear trends on Harker variation diagrams consistent with evolution of similar magma series by crystal fractionation (Fig. 3; all concentrations are normalized volatile free). Amounts of CaO, Fe_2O_3* (total Fe as Fe_2O_3), TiO_2, and MgO all decrease with increasing SiO_2, whereas alkalies increase and alumina shows no change. The amount of MgO decreases exponentially, consistent with crystal fractionation (not mixing) as the dominant process controlling liquid evolution (e.g., Suayah and Rogers, 1991). Trends for both Fe_2O_3* and TiO_2 decrease sharply at SiO_2 = 65 wt%–66 wt%, suggesting magnetite saturation (Fig. 3). TiO_2 is low in all samples: only one sample exceeds 1.5 wt% TiO_2. Most samples with $SiO_2 > 67$ wt% are depleted in Na_2O and enriched in K_2O and Rb relative to less evolved felsic rocks and do not fall on normal fractionation trends (Fig. 3).

Metavolcanic rocks of the Persimmon Fork Formation range from 49 wt% to 75 wt% SiO_2, with no break in continuity. Felsic and intermediate compositions comprise more than 80% of the formation. Three samples are enriched in CaO and depleted in Na_2O, consistent with hydrothermal alteration of the protolith (epidotization). A few samples show major-element enrichments suggestive of crystal accumulation, such as high Al_2O_3 (plagioclase) or MgO (olivine), but most appear to be reasonably close to liquid compositions. Metavolcanic rocks of the Persimmon Fork Formation form a broad trend that straddles the dividing line between tholeiitic and calc-alkaline suites on an alkalies-iron-magnesium (AFM) plot (Fig. 4), but their overall major element characteristics (e.g., decreasing Fe, Ti, and V with increasing Si, low to intermediate K) are low K calc-alkaline (see Gill, 1981). Most (but not all) of the high silica metavolcanics may be classified as high K calc-alkaline (Fig. 3).

Metavolcanic rocks from the Richtex Formation are predominantly mafic, with eight of the nine Richtex samples analyzed having $SiO_2 < 52$ wt%; the other Richtex sample contains 68 wt% SiO_2. Richtex metavolcanic rocks define trends on Harker variation diagrams that parallel those defined by samples of Persimmon Fork Formation, including elevated K_2O and Rb in the only sample with more than 67 wt% SiO_2 (Fig. 3). The distribution of Richtex samples could be considered bimodal, with samples either <52 wt% SiO_2 or >65 wt% SiO_2 (Fig. 3). The scarcity of samples with SiO_2 >52 wt%, however, is in contrast to normal bimodal volcanic provinces, in which felsic rocks generally dominate volumetrically. Metavolcanic rocks of the Richtex Formation are dominantly tholeiitic on an AFM plot (Fig. 4), but other major element characteristics (e.g., decreasing Fe, Ti, and V with increasing Si, low K) are low K calc-alkaline. These characteristics suggest an orogenic magma suite which is transitional from tholeiitic to calc-alkaline.

Four of the Richtex metavolcanic rocks studied here (SAS-57, SAS-58, SAS-77, SAS-79) contain abundant large, euhedral to subhedral phenocrysts of pyroxene (now almost entirely replaced by actinolite). These rocks are identical to mafic flows and dikes described by Dennis and Shervais (this volume) as pyroxene porphyries related to intrusion of zoned mafic-ultramafic complexes in the western Caroline terrane. The occurrence of these rocks in the eastern Carolina terrane suggests a close petrologic association between the eastern and western parts of the Carolina terrane.

Metavolcanic rocks from the Augusta terrane are predominantly mafic to intermediate in composition (11 out of 13 samples <57 wt% SiO_2), in contrast to the intermediate-to-felsic

TABLE 1. SAMPLE LOCATIONS AND DESCRIPTIONS

Sample SAS No.	Quadrangle	Map Unit*	Latitude	Longitude	Field Description
1	Richtex	pf	34.1404	81.2333	Felsic Tuff
2	Richtex	pf	34.1404	81.2333	Felsic Tuff
3	Richtex	pf	34.1437	81.2286	Intermediate Tuff
4	Richtex	pf	34.1437	81.2286	Intermediate Tuff
8	Irmo NE	pf	34.1646	81.1117	Felsic Crystal Tuff
9	Richtex	pf	34.1534	81.1655	Felsic Tuff
10	Richtex	pf	34.1538	81.1661	Mafic Tuff
14	Irmo NE	pf	34.1593	81.0692	Felsic Tuff
15	Irmo NE	pf	34.1615	81.0805	Intermediate Tuff
16	Irmo NE	pf	34.1615	81.0755	Felsic Tuff
17	Irmo NE	pf	34.1609	81.0732	Felsic Epizonal Dike
20	Longtown	pf	34.2998	80.8210	Felsic Tuff
21	Longtown	pf	34.3007	80.8210	Felsic Tuff
22	Longtown	pf	34.3022	80.8196	Mafic Dike
23	Longtown	mg	34.3289	80.8434	Epizonal Granitoid
26	Longtown	mg	34.3405	80.8479	Epizonal Granitoid
27	Longtown	mg	34.3394	80.8476	Epizonal Granitoid
28	Longtown	pf	34.3745	80.8388	Felsic Tuff
29	Longtown	pf	34.3738	80.8383	Mafic and Felsic Tuffs
31	Delmar	pf	34.1010	81.5683	Intermediate Tuff
33	Delmar	pf	34.0271	81.5902	Felsic Tuff
34	Delmar	pf	34.0263	81.5919	Mafic Tuff
38	Parkville	pf	33.8536	82.2264	Felsic Tuff
39	Clarks Hill	pf	33.7459	82.1661	Felsic Tuff
40	Chapin	r	34.1862	81.2968	Mafic Flow
41	Chapin	r	34.1877	81.2903	Mafic Flow
42	Chapin	r	34.1961	81.2593	Mafic Flow
43	Prosperity	pf	34.1348	81.5591	Mafic Tuff
44	North Augusta	A	33.5094	81.9950	Mafic Tuff
45	North Augusta	A	33.5101	81.9946	Mafic Tuff
46	North Augusta	A	33.5113	81.9956	Mafic Tuff
47	North Augusta	A	33.5124	81.9961	Mafic Tuff
48	North Augusta	A	33.5154	81.9976	Mafic Tuff
50	North Augusta	A	33.5162	81.9925	Felsic Tuff
51	North Augusta	A	33.5165	81.9913	Felsic Tuff
52	Blythewood	pf	34.1620	80.9947	Mafic Tuff
55	Irmo NE	pf	34.2133	81.0659	Intermediate Tuff
56	Irmo NE	pf	34.2310	81.0710	Intermediate Tuff
57	Irmo NE	r	34.2398	81.0745	Mafic Flow
58	Irmo NE	r	34.2075	81.1128	Mafic Flow
59	Delmar	pf	34.0762	81.5180	Mafic Tuff
60	Delmar	pf	34.0240	81.5804	Mafic Tuff
61	Saluda South	pf	33.9571	81.7637	Intermediate Tuff
62	Saluda South	pf	33.9513	81.7612	Intermediate Tuff
63	Saluda South	pf	33.9457	81.7531	Felsic Tuff
67	Emory	pf	33.9766	81.6827	Intermediate and Felsic Tuff
68	Plum Branch	pf	33.7635	82.2907	Felsic Tuff
70	Plum Branch	pf	33.7548	82.2915	Felsic Tuff
77	Leah	r	33.7417	82.2831	Mafic Dike
79	Leah	r	33.7081	82.3515	Mafic Dike
80	Leah	r	33.7033	82.3454	Intermediate Tuff

*pf = Persimmon Fork Formation; r = Richtex Formation; mg = Longtown metagranite; A = Augusta terrane.

TABLE 2. MAJOR- AND TRACE-ELEMENT GEOCHEMISTRY OF METAVOLCANIC ROCKS AND METAGRANITES OF THE CAROLINA AND AUGUSTA TERRANES

Sample	SAS-41	SAS-57	SAS-58	SAS-42A	SAS-42B	SAS-40B	SAS-79	SAS-77	SAS-80	SAS-67A	SAS-60	SAS-52C	SAS-22
Unit*	rf	rf	rf	rf	rf	rf	rf	rf	rf	pff	pff	pff	pff
(wt%)													
SiO_2	48.69	47.46	46.42	45.93	45.79	43.97	46.44	48.81	66.90	51.03	50.58	49.23	48.95
TiO_2	1.29	0.67	0.81	1.05	0.86	1.07	0.71	0.75	0.60	1.13	0.70	0.54	1.40
Al_2O_3	15.57	12.30	12.06	17.36	18.36	21.65	12.97	14.53	16.14	17.02	12.83	10.11	13.46
Fe_2O_3	12.54	10.80	11.02	13.21	12.04	11.08	11.78	11.40	3.66	9.57	9.77	8.39	13.70
MnO	0.28	0.16	0.17	0.18	0.17	0.13	0.17	0.18	0.13	0.26	0.16	0.14	0.17
MgO	5.20	13.21	14.33	7.45	5.09	5.56	10.92	8.42	0.65	1.03	11.37	7.30	10.74
CaO	8.87	10.87	11.82	9.39	10.47	10.22	12.40	10.91	2.02	15.67	7.56	15.47	6.40
Na_2O	1.99	1.88	0.99	1.99	2.85	1.43	1.33	1.95	4.95	0.10	2.54	0.58	2.32
K_2O	0.15	0.20	0.03	0.81	1.02	0.04	0.48	0.61	3.95	0.55	1.29	0.01	1.82
P_2O_5	0.03	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.07	0.00	0.00	0.00
LOI	4.72	2.79	3.19	3.42	2.90	3.65	2.40	2.15	1.13	3.27	2.66	8.23	2.78
Total	99.33	100.34	100.84	100.79	99.55	98.83	99.66	99.71	100.13	99.70	99.46	100.00	101.74
(ppm)													
Nb	13	3	13	3	5	1	0	0	7	0	3	5	13
Zr	38	50	76	60	52	44	39	40	133	100	48	34	125
Y	24	15	21	24	20	16	16	14	31	25	16	10	27
Sr	334	579	255	722	669	496	407	502	257	557	191	89	658
Rb	15	10	7	34	36	15	11	25	179	44	26	7	52
Ni	70	189	121	32	23	34	55	41	6	25	113	47	170
Cr	98	714	510	42	44	57	155	99	10	65	327	92	212
V	283	246	198	279	281	255	282	283	27	91	185	192	184
Sc	30	41	42	25	19	34	43	38	7	34	34	34	27
Ba	123	149	54	165	184	92	138	165	842	124	503	34	682
Zn	75	70	83	86	64	86	70	76	128	53	80	74	102
Cu	147	75	77	90	152	93	99	134	11	1	87	17	66
La	24	33	72	28	26	23	28	20	33	27	17	20	39

Persimmon Fork Formation (Fig. 3). Augusta terrane metavolcanic rocks define trends on Harker variation diagrams that parallel those defined by samples of Persimmon Fork and Richtex Formations, with silica contents ranging from 47 wt% to 71 wt% SiO_2 (Fig. 3). Major-element characteristics are transitional from tholeiitic to low K calc-alkaline.

The Longtown metagranite is chemically similar to the silica-rich tuffs of the Persimmon Fork Formation that it intrudes. A distinctive characteristic of these tuffs and the metagranite are their high K_2O and Rb contents, which far exceed concentrations expected to result from simple fractionation of the more primitive metavolcanic samples (Fig. 3).

Trace element chemistry

As expected, the compatible trace elements Cr, Ni, Co, V, and Sc show a negative relationship with SiO_2 in metavolcanic rocks of the Persimmon Fork Formation, Richtex Formation, and Augusta terrane. Incompatible trace elements (Rb, Y, Zr, Hf, Ta, Ba, Th) show a positive correlation with SiO_2 until about 65 wt% SiO_2, after which the concentrations of some trace elements (e.g., Zr, Y) decrease, indicating saturation in late stage accessory phases such as zircon and monazite (Fig. 3). The concentrations of Rb are generally elevated in samples with >67 wt% SiO_2, relative to normal enrichments expected from Rayleigh fractionation. Concentrations of Sr decrease with increasing SiO_2, consistent with plagioclase fractionation (Fig. 3).

Metavolcanic rocks of the Persimmon Fork Formation are enriched in light rare-earth elements (LREE) relative to the heavy rare earth elements (HREE) (Fig. 5). Most samples have low La/Lu ratios (3× to 6× chondrite) and moderate to low La concentrations (15× to 65× chondrite), but two rhyolitic tuffs and one mafic tuff have high La/Lu ratios (11×–13× chondrite), high La concentrations (80×–105× chondrite), and chondrite-normalized REE patterns that cross those of other samples (Fig. 5). These crossing REE patterns show that Persimmon Fork Formation cannot represent a single magma series and must be derived from sources with different compositions and residual mineralogies. The lack of distinct negative Eu anomalies even in the most silicic samples is characteristic of the higher oxygen fugacities in calc-alkaline magma series. Sam-

TABLE 2. MAJOR- AND TRACE-ELEMENT GEOCHEMISTRY OF METAVOLCANIC ROCKS AND METAGRANITES OF THE CAROLINA AND AUGUSTA TERRANES (continued - page 2)

Sample Unit*	SAS-52B pff	SAS-10 pff	SAS-15 pff	SAS-3 pff	SAS-55B pff	SAS-29D pff	SAS-62 pff	SAS-29B pff	SAS-55A pff	SAS-52A pff	SAS-43A pff	SAS-29A pff	SAS-61B pff
(wt%)													
SiO_2	48.65	50.53	62.29	61.57	59.71	60.97	58.41	59.63	57.72	55.81	57.43	58.41	56.58
TiO_2	0.80	1.91	1.15	1.10	0.84	0.62	1.11	0.97	0.93	1.19	1.09	0.67	0.60
Al_2O_3	13.15	13.73	13.35	14.12	15.00	17.45	15.91	16.86	17.01	15.71	12.97	18.86	13.55
Fe_2O_3	10.96	13.07	7.67	7.42	5.93	6.31	8.52	8.15	6.98	10.11	10.80	6.59	8.23
MnO	0.17	0.24	0.20	0.16	0.14	0.18	0.16	0.34	0.11	0.19	0.21	0.19	0.09
MgO	11.70	7.71	3.45	3.58	1.64	1.84	2.62	2.65	1.61	3.79	7.28	2.34	1.22
CaO	8.34	8.60	5.80	5.64	3.94	6.98	7.56	5.15	3.63	6.17	5.13	6.38	14.78
Na_2O	1.04	2.49	2.34	2.38	4.70	3.40	2.35	2.79	5.52	2.70	2.12	3.51	1.77
K_2O	0.01	0.01	0.49	0.72	1.64	0.43	0.09	1.55	1.15	0.14	0.34	1.12	0.04
P_2O_5	0.00	0.00	0.00	0.00	0.00	0.15	0.07	0.06	0.00	0.11	0.00	0.17	0.00
LOI	4.19	3.48	2.33	2.58	4.97	0.54	2.44	0.75	4.18	2.59	2.67	0.80	1.44
Total	99.01	101.77	99.07	99.27	98.51	98.87	99.24	98.90	98.84	98.51	100.04	99.04	98.30
(ppm)													
Nb	4	1	3	3	3	5	3	6	3	1	4	7	1
Zr	51	149	115	111	186	110	118	176	217	111	71	115	40
Y	20	53	42	38	45	22	31	32	46	35	44	19	7
Sr	82	257	392	352	258	451	409	358	283	218	158	481	565
Rb	12	5	20	27	38	22	13	69	33	11	16	50	11
Ni	51	23	11	8	8	14	7	31	8	15	33	12	21
Cr	128	55	17	21	14	24	17	64	11	31	58	19	151
V	243	361	106	136	67	107	116	174	192	202	268	106	141
Sc	39	41	27	26	17	19	23	22	23	39	27	18	29
Ba	60	133	154	199	338	121	76	446	122	117	189	193	20
Zn	79	118	111	117	111	81	108	108	129	109	69	105	37
Cu	111	80	24	28	20	44	18	64	49	17	121	16	13
La	23	15	18	20	26	32	19	35	27	21	32	32	25

ples with high La are also enriched in K_2O, although not all high K_2O samples have high La (Fig. 6). Most samples with high La concentrations also have high La/Lu ratios (Fig. 6).

Mafic and intermediate metavolcanic rocks of the Richtex Formation have REE concentrations that are slightly enriched in LREE (La/Lu ratios 3×–5× chondrite) but with lower La concentrations (25×–32× chondrite) than most samples from the Persimmon Fork Formation (Fig. 5). All samples have low La, low La/Lu ratios, and are low in K_2O (Fig. 6).

Mafic metavolcanic rocks of the Augusta terrane have REE concentrations that are less enriched in LREE than those of the Richtex Formation (La/Lu ratios 3×–5× chondrite; La concentrations 15×–18× chondrite: Fig. 5). One felsic sample (72 wt% SiO_2) has been analyzed: it is richer in REE (La = 65× chondrite) but has the same low La/Lu ratio (2× chondrite) as the mafic metavolcanics. The felsic metavolcanic has a deep negative Eu anomaly, consistent with extensive plagioclase fractionation (Fig. 5). The mafic metavolcanics all have negative Ce anomalies (Fig. 5), suggesting the involvement of clay minerals in their source region. All Augusta terrane samples are low in K_2O and La/Lu (Fig. 6).

Selected trace-element data are summarized in Figure 7 normalized to present-day oceanic crust (Taylor and McLennan, 1985; Sun and McDonough, 1989). Persimmon Fork Formation metavolcanic rocks are depleted in transition metals (Fe, Sc, Co, Ni, Cr) and enriched in large-ion lithophile elements (LILEs) (Ba, Rb, Th, K, Sr, LREE) relative to mid-ocean ridge basalt (MORB). The high field strength elements (Nb, Ta, Zr, Hf, Ti) are depleted relative to the LILEs, forming distinct troughs in the MORB-normalized spider diagram that are characteristic of orogenic magma suites (Thompson et al., 1984; Pearce, 1982).

In contrast, metavolcanic rocks of the Richtex Formation have MORB-like HREE and transition metal concentrations (Co, Ni, Cr) and are less enriched in LILEs than rocks of the Persimmon Fork Formation (Fig. 7). Nb and Ta are depleted relative to the LILEs, but less incompatible high field strength elements (Zr, Hf, Ti) have MORB-like values that are similar to adjacent HREE (Fig. 7). These characteristics are consistent with more primitive oceanic arcs and some back-arc basins (Pearce, 1982).

Mafic metavolcanic rocks from the Augusta terrane have

TABLE 2. MAJOR- AND TRACE-ELEMENT GEOCHEMISTRY OF METAVOLCANIC ROCKS AND METAGRANITES OF THE CAROLINA AND AUGUSTA TERRANES (continued - page 3)

Sample Unit*	SAS-4 pff	SAS-59 pff	SAS-34 pff	SAS-55C pff	SAS-56B pff	SAS-56A pff	SAS-28 pff	SAS-20 pff	SAS-8 pff	SAS-29C pff	SAS-14 pff	SAS-21 pff	SAS-2 pff
(wt%)													
SiO_2	56.29	54.42	53.24	51.89	72.36	58.29	74.48	72.27	71.47	71.20	69.44	69.37	71.12
TiO_2	1.19	0.86	1.42	1.19	0.26	0.62	0.05	0.18	0.54	0.30	0.61	0.40	0.38
Al_2O_3	15.15	15.87	15.18	14.08	13.59	13.97	15.18	14.50	14.14	15.05	14.22	15.09	15.16
Fe_2O_3	10.28	9.14	10.17	12.01	2.29	8.10	0.62	1.99	3.01	1.99	4.71	2.16	2.98
MnO	0.15	0.15	0.20	0.20	0.12	0.14	0.05	0.05	0.09	0.09	0.16	0.08	0.11
MgO	4.83	4.88	6.11	6.62	0.46	3.63	0.08	0.47	1.08	0.51	1.48	0.57	0.96
CaO	4.73	7.03	9.15	5.46	2.03	6.51	0.72	1.28	2.76	1.60	3.08	2.27	3.09
Na_2O	4.53	3.67	2.51	3.99	5.17	2.09	4.89	2.06	3.93	3.87	4.79	4.04	2.61
K_2O	0.09	0.50	0.00	0.32	1.16	1.22	4.61	4.32	1.17	4.50	0.70	3.02	1.47
P_2O_5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.08
LOI	2.41	2.56	2.79	3.76	1.70	4.06	0.38	2.10	1.44	0.50	1.26	2.64	1.32
Total	99.65	99.08	100.77	99.52	99.14	98.63	101.06	99.27	99.63	99.61	100.45	99.64	99.28
(ppm)													
Nb	3	7	3	3	2	4	4	8	1	19	2	5	1
Zr	70	96	96	92	149	90	52	106	154	160	125	129	123
Y	31	10	25	27	37	23	5	8	38	17	43	19	22
Sr	201	568	246	302	101	312	66	183	139	196	324	254	226
Rb	9	29	1	13	49	49	185	129	37	136	23	93	42
Ni	11	24	17	25	10	54	5	9	6	6	8	7	8
Cr	33	25	56	29	12	101	9	7	15	8	15	10	11
V	219	179	224	379	21	168	3	17	41	17	85	17	47
Sc	30	24	38	35	10	27	5	2	9	3	16	9	11
Ba	82	157	69	177	166	150	41	850	245	733	158	572	313
Zn	100	84	98	102	55	83	8	58	81	40	108	74	76
Cu	431	136	25	149	12	20	0	3	6	7	10	11	13
La	11	30	9	21	22	34	19	57	32	52	26	39	22

MORB-normalized trace element patterns similar to rocks of the Richtex Formation, but they are generally less enriched in the LILEs and less depleted in the compatible transition metals than Richtex metavolcanic samples (Fig. 7). The felsic Augusta terrane tuff is strongly depleted in compatible transition metals, Sr, and Eu, and is more enriched in the REE and other LILEs than the mafic volcanics—all suggesting formation by extensive crystal fractionation involving feldspar and mafic silicates (Fig. 7).

When plotted on Pearce and Cann (1973)–type trace-element discrimination diagrams, mafic metavolcanic rocks from the Persimmon Fork Formation, Richtex Formation, and the Augusta terrane have either “arc” or “transitional” geochemical signatures (Fig. 8). On Ti-Zr-Y and Ti-Zr plots, most samples plot in field where “arc” and “MORB” volcanics overlap (Figs. 8a, 8c). On a Ti-Zr-Sr plot, all but two samples plot in “arc volcanic” field (Fig. 8b). On a Ti/V plot (Shervais, 1982), most samples scatter around the “arc”/“MORB” dividing line, except for two andesites from the Persimmon Fork Formation that have low V concentrations (Ti-magnetite fractionation) and one andesite with unusually high Ti (Fig. 8d). Taken together, these diagrams suggest primitive arc tholeiite affinities for the mafic metavolcanic rocks of the Richtex Formation and the Augusta terrane, and more calc-alkaline affinities for mafic metavolcanic rocks of the Persimmon Fork Formation. None of these diagrams supports interpretations of “within plate” type volcanism.

DISCUSSION

Metavolcanic rocks of the Carolina terrane in west-central South Carolina can be classified as metamorphosed basalts, andesites, dacites, and rhyolites on the basis of their major-element geochemistry. Felsic and intermediate samples (andesite, dacite, rhyolite) predominate in the Persimmon Fork Formation, whereas metavolcanic rocks of the Richtex Formation and the Augusta terrane are dominantly basalts or basaltic andesites. Samples from all formations exhibit scatter from normal fractionation trends, which may be attributed in part to element mobility during low-grade metamorphism. Despite this scatter, it is possible to make inferences about the origin of these volcanic suites, their relationships to one another, and their relationships to the tectonic regimes in which they formed.

TABLE 2. MAJOR- AND TRACE-ELEMENT GEOCHEMISTRY OF METAVOLCANIC ROCKS AND METAGRANITES OF THE CAROLINA AND AUGUSTA TERRANES (continued - page 4)

Sample	SAS-70	SAS-1	SAS-33	SAS-68	SAS-31	SAS-38B	SAS-63	SAS-17	SAS-16	SAS-9	SAS-67B	SAS-39A	SAS-23B	SAS-26
Unit*	pff	pff	pff	pff	pff	pff	pff	pff	pff	pff	pff	pff	Lmg	Lmg
(wt%)														
SiO_2	68.51	71.08	67.42	69.16	67.09	70.98	66.32	66.21	65.92	64.20	70.06	68.92	74.33	68.89
TiO_2	0.46	0.38	0.82	0.46	0.68	0.65	0.64	0.86	1.18	0.71	0.97	0.63	0.16	0.25
Al_2O_3	15.25	14.48	14.38	15.58	15.24	14.71	15.66	14.49	14.33	14.02	12.11	15.00	12.99	16.24
Fe_2O_3	2.86	3.27	3.99	2.81	4.41	3.27	4.49	5.79	7.87	5.86	7.15	2.94	1.89	1.65
MnO	0.08	0.11	0.18	0.13	0.15	0.16	0.08	0.16	0.26	0.16	0.09	0.13	0.05	0.09
MgO	0.50	1.10	1.08	0.53	1.89	0.64	1.86	1.59	1.44	2.01	1.28	0.63	0.22	0.62
CaO	1.69	3.22	5.24	1.66	4.04	2.22	2.97	3.82	1.59	4.89	4.20	1.90	1.22	1.22
Na_2O	4.79	2.17	4.80	2.71	2.75	2.62	4.97	4.78	6.18	2.93	1.85	4.69	2.13	5.22
K_2O	4.40	1.45	0.48	4.26	2.53	2.15	0.79	0.75	0.49	1.26	0.08	3.56	4.62	3.60
P_2O_5	0.00	0.07	0.00	0.11	0.00	0.08	0.00	0.00	0.00	0.00	0.21	0.00	0.02	0.00
LOI	0.69	1.96	1.07	0.77	1.73	0.98	1.41	1.36	1.08	1.83	1.14	0.91	0.83	1.14
Total	99.23	99.29	99.46	98.18	100.51	98.46	99.19	99.81	100.34	97.87	99.14	99.31	98.46	98.92
(ppm)														
Nb	7	6	6	11	4	6	5	7	7	3	4	3	10	3
Zr	151	128	140	154	123	135	153	172	188	140	108	122	120	112
Y	40	29	43	31	42	38	34	55	43	46	28	32	12	6
Sr	189	192	228	182	402	330	345	391	304	196	171	306	151	752
Rb	213	41	18	193	63	122	27	25	22	29	16	145	105	117
Ni	12	9	8	8	7	9	12	9	9	9	11	10	6	14
Cr	9	17	13	7	15	5	17	15	14	21	15	11	8	14
V	11	52	16	13	54	6	86	93	102	89	129	26	10	36
Sc	5	10	18	7	17	12	11	17	24	21	16	11	5	4
Ba	897	294	112	907	376	469	303	183	347	225	85	627	776	1,104
Zn	66	70	96	71	113	146	97	101	93	96	79	131	31	65
Cu	12	13	7	12	12	12	19	11	16	15	15	16	5	16
La	39	21	16	43	24	28	28	23	23	29	13	24	44	33

Metavolcanic rocks of the Persimmon Fork Formation appear to represent a cogenetic suite, based on the continuity of SiO_2 distribution, smooth trends on Harker diagrams, characteristic decreases in compatible element concentrations, and increases in incompatible element concentrations with increasing SiO_2. Several lines of evidence, however, show that simple fractionation cannot explain the origin of these rocks. This evidence includes crossing chondrite-normalized REE patterns, elevated K_2O, and Rb concentrations in rocks with high SiO_2, and TiO_2 concentrations that vary by a factor of 2 in primitive samples with <55 wt% SiO_2.

Metavolcanic rocks of the Persimmon Fork Formation have major- and trace-element systematics characteristic of orogenic magma suites. These characteristics include a continuous range in SiO_2 from 46 wt% to 76 wt% with no significant compositional gaps, the depletion of compatible major and trace elements relative to MORB, enrichment in light REE/heavy REE ratios and in LILEs relative to MORB, and the depletion of high field strength elements relative to LILEs. The data presented here are not consistent with the conclusion that the Carolina terrane formed in an intra-continental rift zone, as suggested by Long (1979). Our data show that the Carolina terrane in South Carolina (as represented by the Persimmon Fork Formation) is not typified by bimodal volcanism as suggested by Long (1979)—a complete range in compositions is present from mafic through intermediate to felsic. In addition, all of the mafic metavolcanic rocks have arc-like trace-element concentrations and are not "within-plate basalts."

The preponderance of felsic metavolcanic rocks in the Persimmon Fork Formation also argues against this unit being formed in a primitive, intra-oceanic island arc as suggested by Whitney et al. (1978) for metavolcanic rocks of the Carolina terrane in east-central Georgia. Primitive intra-oceanic arcs are characterized by tholeiitic, dominantly basaltic volcanism with only a small proportion of felsic volcanic rocks (e.g., Baker, 1968; Gill, 1981). Orogenic volcanism along continental margins is generally thought to be dominated by felsic, calc-alkaline volcanic rocks, although continental-margin arcs built upon accreted oceanic terranes are dominantly mafic when averaged over the entire age of the arc (e.g., the Cascades: McBirney, 1984; Andes, southern volcanic zone: Harmon et al., 1984; Hickey et al., 1986).

The transitional nature of Persimmon Fork Formation metavolcanics from tholeiitic to calc-alkaline, the preponderance

TABLE 2. MAJOR- AND TRACE-ELEMENT GEOCHEMISTRY OF METAVOLCANIC ROCKS AND METAGRANITES OF THE CAROLINA AND AUGUSTA TERRANES (continued - page 5)

Sample Unit*	SAS-27 Lmg	SAS-50A Augusta	SAS-51 Augusta	SAS-48D Augusta	SAS-44B Augusta	SAS-48E Augusta	SAS-44A Augusta	SAS-45 Augusta	SAS-48A Augusta	SAS-46A Augusta	SAS-47B Augusta	SAS-47A Augusta	SAS-48C Augusta	SAS-46B Augusta
(wt%)														
SiO_2	70.72	70.43	63.45	54.96	53.40	49.92	50.45	48.33	48.05	47.69	47.66	46.88	53.65	45.46
TiO_2	0.33	0.27	0.84	0.62	1.13	0.67	1.17	1.32	0.98	0.99	0.99	0.87	0.64	0.99
Al_2O_3	14.15	15.46	15.73	14.03	16.62	16.44	16.88	13.23	14.96	13.41	14.40	15.68	18.39	16.69
Fe_2O_3	3.39	3.48	7.13	8.80	11.37	11.37	12.43	14.22	11.96	11.37	11.19	10.52	9.02	11.02
MnO	0.10	0.06	0.24	0.14	0.24	0.16	0.23	0.23	0.16	0.17	0.17	0.18	0.14	0.24
MgO	0.69	0.49	2.33	5.72	5.12	7.35	5.16	7.93	10.14	11.52	11.95	10.65	3.64	10.09
CaO	3.08	0.70	4.76	8.04	7.32	6.29	9.80	8.18	7.87	9.48	8.52	9.49	9.92	9.25
Na_2O	3.23	8.13	2.13	4.28	3.27	4.33	1.91	2.41	2.97	2.12	2.54	1.57	2.33	1.23
K_2O	2.80	0.64	1.49	0.24	0.33	0.33	0.16	0.13	0.43	0.12	0.30	0.25	0.10	0.89
P_2O_5	0.00	0.00	0.08	0.00	0.07	0.00	0.02	0.00	0.00	0.00	0.00	0.04	0.02	0.05
LOI	0.47	0.34	1.85	2.07	2.39	2.73	2.43	2.67	3.22	3.07	3.17	3.39	1.90	3.69
Total	98.96	100.00	100.03	98.90	101.26	99.59	100.64	98.65	100.74	99.94	100.89	99.52	99.75	99.60
(ppm)														
Nb	4	8	7	6	7	1	2	10	0	2	2	4	2	2
Zr	125	226	131	44	50	46	54	63	63	65	79	63	51	64
Y	12	86	46	18	23	28	23	28	25	32	27	21	22	17
Sr	312	54	180	200	180	145	279	269	290	257	286	297	345	197
Rb	101	20	17	12	16	18	15	7	12	10	16	11	13	15
Ni	5	8	17	29	15	28	16	14	59	126	160	180	33	153
Cr	14	7	25	90	42	83	65	41	121	292	296	368	88	350
V	36	0	102	329	370	382	364	378	282	256	245	220	280	262
Sc	13	14	25	31	40	32	45	44	34	33	36	36	28	28
Ba	472	145	189	94	179	166	124	142	168	120	141	161	56	585
Zn	241	56	101	67	86	85	81	88	86	87	79	72	74	88
Cu	12	13	40	88	109	81	71	43	88	72	62	16	29	33
La	22	18	36	18	5	34	16	11	29	18	24	25	19	20

*Carolina terrane includes the Persimmon Fork Formation (pff), Richtex Formation (rf), and Longtown metagranite (Lmg).

LOI = loss on ignition determined by igniting 1 gram of powdered sample at 1,000 °C for 6 hours. Data were renormalized to 100% volatile-free for plotting. All data by XRF spectrometry at the University of South Carolina.

of intermediate to felsic pyroclastic rocks, and their distinctive trace-element characteristics suggest that the Persimmon Fork Formation accumulated in a mature volcanic arc built upon either tectonically thinned continental crust or an older, mature intra-oceanic arc terrane. The occurrence of high K_2O and Rb in rocks with high SiO_2 is also consistent with assimilation of either continental crust or an older, mature arc terrane during fractionation (e.g., Davidson et al., 1988). Evidence for a basement of older orogenic volcanics comes from the central North Carolina area where late Precambrian metavolcanic rocks of the Uwharrie Formation rest unconformably on metavolcanic rocks of the slightly older Virgilina sequence (Harris and Glover, 1988).

Metavolcanic rocks of the Richtex Formation are dominated by mafic flows and tuffs with tholeiitic affinities. Since the Richtex Formation depositionally overlies the dominantly felsic Persimmon Fork Formation, the Richtex Formation may represent an intra-arc rift basin formed within the Persimmon Fork arc, as suggested by Dennis and Shervais (1991). In this model, metasedimentary rocks of the Richtex Formation would be derived from the older Persimmon Fork Formation and deposited within an intra-arc basin, intercalated with mafic volcanics associated with the rifting. Evidence that supports this model includes (1) the stratigraphic dominance of metasediments, which comprise >90% of the Richtex Formation, over metavolcanic rocks, (2) the arc-related geochemical character of mafic metavolcanic rocks of the Richtex Formation, (3) the dominantly mafic character of metavolcanic rocks in the Richtex Formation, and (4) the stratigraphic position of the (dominantly mafic) Richtex Formation overlying the (dominantly felsic) Persimmon Fork Formation. These relationships are the inverse of what we would expect for a normal arc terrane, which would start out dominantly mafic and progress through time toward more felsic compositions (McBirney, 1984; Gill, 1981).

Metavolcanic rocks of the Augusta terrane are geochemically similar to those of the Richtex Formation and may represent a fragment of the Carolina terrane in the hanging wall of

TABLE 3. SELECTED MAJOR ELEMENT AND TRACE ELEMENT DATA USED TO CONSTRUCT FIGURES 4, 5, AND 6*

Sample	XRF FeO (wt%)	XRF K_2O (wt%)	INAA Sc (ppm)	XRF Cr (ppm)	INAA Co (ppm)	XRF Ni (ppm)	INAA Zn (ppm)	XRF Rb (ppm)	XRF Sr (ppm)	XRF Ba (ppm)	INAA La (ppm)	INAA Ca (ppm)
SAS-3/PFF	7.42	0.72	23.7	21	13.2	8	99	27	352	199	11.3	26.0
SAS-10/PFF	13.07	0.01	37.4	55	33.6	23	122	5	257	135	12.4	28.7
SAS-20/PFF	1.99	4.32	2.1	7	2.0	9	26	129	183	850	26.6	41.9
SAS-22/PFF	13.7	1.82	21.8	212	58.2	170	114	52	658	682	25.8	53.7
SAS-28/PFF	0.62	4.61	2.5	9	0.3	5	16	185	66	41	4.6	10.3
SAS-29C/PFF	1.99	4.50	4.0	8	1.8	6	29	136	196	733	32.4	52.7
SAS-34/PFF	10.17	0.10	24.7	56	18.1	17	72	1	246	69	8.6	20.8
SAS-39A/PFF	2.94	3.56	9.6	11	2.6	10	102	145	306	627	19.4	43.5
SAS-52A/PFF	10.11	0.14	25.8	31	25.7	15	125	11	218	117	8.6	18.6
SAS-70/PFF	2.86	4.40	8.2	9	3.0	12	51	213	189	897	30.0	56.3
SAS-40B/RF	11.08	0.04	34.9	57	46.5	34	129	15	496	92	8.7	16.9
SAS-41/RF	12.54	0.15	29.9	98	35.3	70	93	15	334	123	8.3	10.8
SAS-42A/RF*	13.21	0.81	29.0	42	61.7	32	132	34	722	165	9.9	20.4
SAS-56A/RF	8.1	1.22	27.2	101	26.2	54	87	49	312	150	9.5	16.9
SAS-46A/BB	11.37	0.12	35.5	292	43.8	126	111	10	257	120	5.1	9.3
SAS-47A/BB	10.52	0.25	31.8	368	53.2	180	92	11	297	161	5.2	9.4
SAS-48A/BB	11.96	0.43	39.9	121	38.8	59	127	12	290	168	5.2	10.5
SAS-48E/BB	11.37	0.33	27.7	83	36.8	28	127	18	145	166	4.8	6.8
SAS-50A/BB	3.48	0.64	12.9	7	2.2	8	72	20	54	145	20.3	44.0
Ocean Crust	10.5	0.0723	38	270	47	135	85	0.56	90	6.3	2.5	7.5

Sample	INAA Nd (ppm)	INAA Sm (ppm)	INAA Eu (ppm)	INAA Tb (ppm)	INAA Yb (ppm)	INAA Lu (ppm)	XRF Zr (ppm)	INAA Hf (ppm)	INAA Ta (ppm)	INAA Th (ppm)	SRF Nb (ppm)	XRF Ti (ppm)	XRF Y (ppm)
SAS-3/PFF	16.6	4.92	1.53	0.82	2.60	0.40	111	2.7	0.1	1.4	3	6,834	39
SAS-10/PFF	24.9	6.28	1.95	0.99	3.21	0.43	149	3.5	0.3	0.9	1	11,630	54
SAS-20/PFF	11.6	2.12	0.42	0.24	1.34	0.21	106	3.1	0.6	12.0	8	1,139	8
SAS-22/PFF	25.9	5.28	1.52	0.73	1.67	0.25	125	2.8	0.4	3.8	13	8,453	27
SAS-28/PFF	3.9	1.44	0.23	0.22	1.03	0.16	52	3.4	0.9	13.7	4	300	5
SAS-29C/PFF	20.2	4.00	0.86	0.46	2.15	0.32	160	4.4	1.8	19.1	19	1,799	17
SAS-34/PFF	13.6	3.38	1.07	0.54	1.78	0.23	96	1.9	0.1	1.4	3	8,693	26
SAS-39A/PFF	25.1	5.90	1.69	0.78	3.34	0.47	122	3.6	0.4	9.2	3	3,837	33
SAS-52A/PFF	15.3	4.01	1.15	0.53	2.35	0.34	111	2.8	0.2	1.4	1	7,434	36
SAS-70/PFF	26.8	6.06	1.41	0.91	3.89	0.54	151	4.3	0.6	10.7	7	2,818	41
SAS-40B/RF	9.5	2.96	1.03	0.38	1.47	0.19	44	1.0	0.1	3.8	1	6,714	17
SAS-41/RF	11.1	2.69	1.05	0.53	1.46	0.24	38	0.8	0.1	2.9	13	8,153	25
SAS-42A/RF*	12.9	3.03	1.07	0.5	1.82	0.3	86	1.4	0.3	3.3	3	6,475	25
SAS-56A/RF	11.0	3.04	0.99	0.52	2.26	0.34	90	2.2	0.2	2.4	4	3,957	24
SAS-46A/BB	8.4	2.61	1.02	0.51	1.80	0.26	65	1.3	0.1	0.5	2	6,115	33
SAS-47A/BB	9.4	2.74	1.02	0.35	1.76	0.26	63	1.4	0.2	0.3	4	5,455	22
SAS-48A/BB	10.5	2.68	1.00	0.34	1.86	0.28	63	1.7	0.2	0.4	1	5,995	26
SAS-48E/BB	8.0	1.82	0.55	0.29	1.29	0.19	46	1.1	0.1	0.3	1	4,137	29
SAS-50A/BB	27.5	7.40	1.24	1.51	6.79	0.99	226	7.2	0.5	5.5	8	1,619	86
Ocean Crust	7.3	2.63	1.02	0.67	3.05	0.455	74	2.05	0.13	0.12	2.33	7,600	28

*Includes data for REE. Analysis types include XRF and INAA. Oceanic crust from Sun and McDonough, 1990, and Taylor and McLennan, 1985.

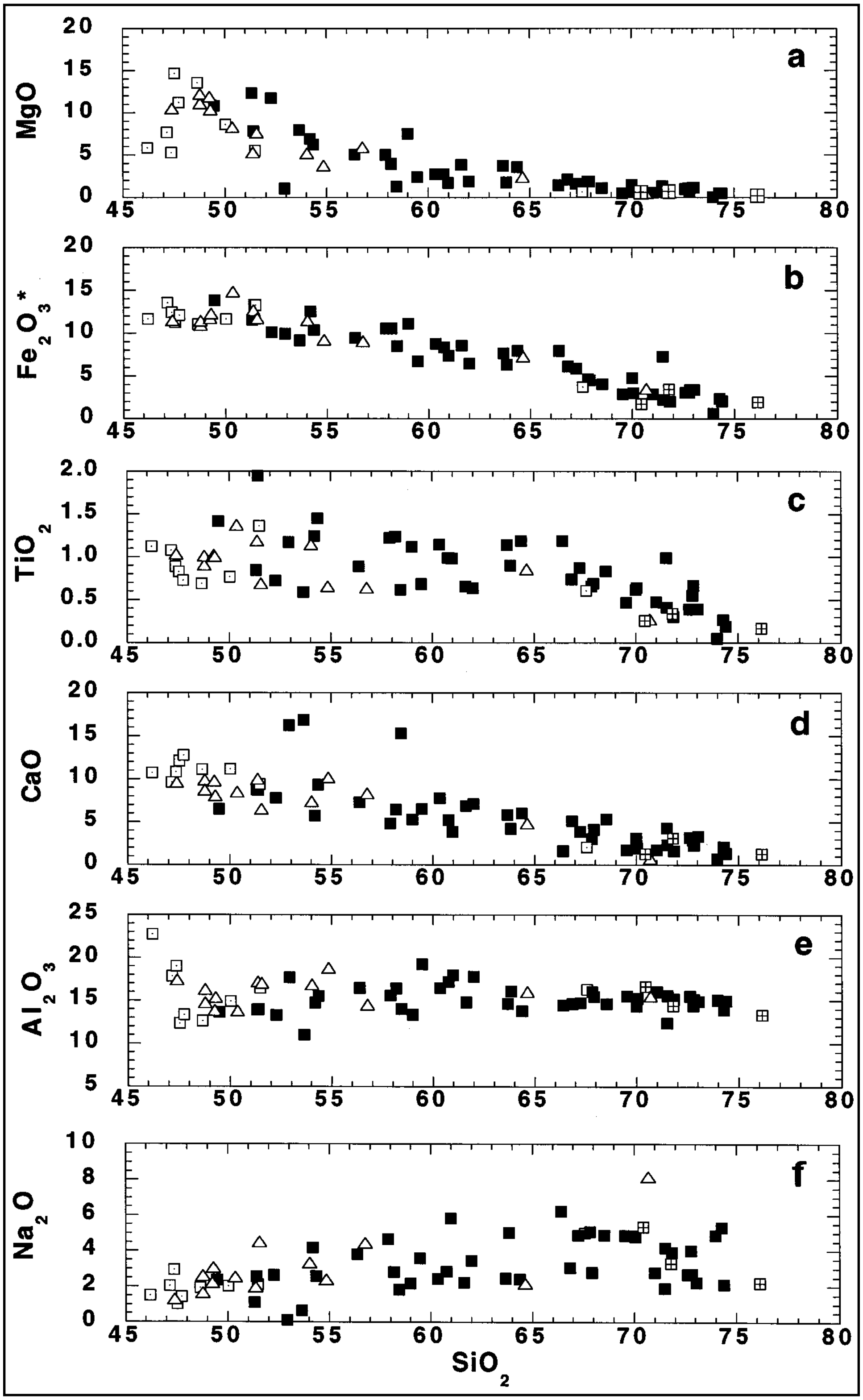
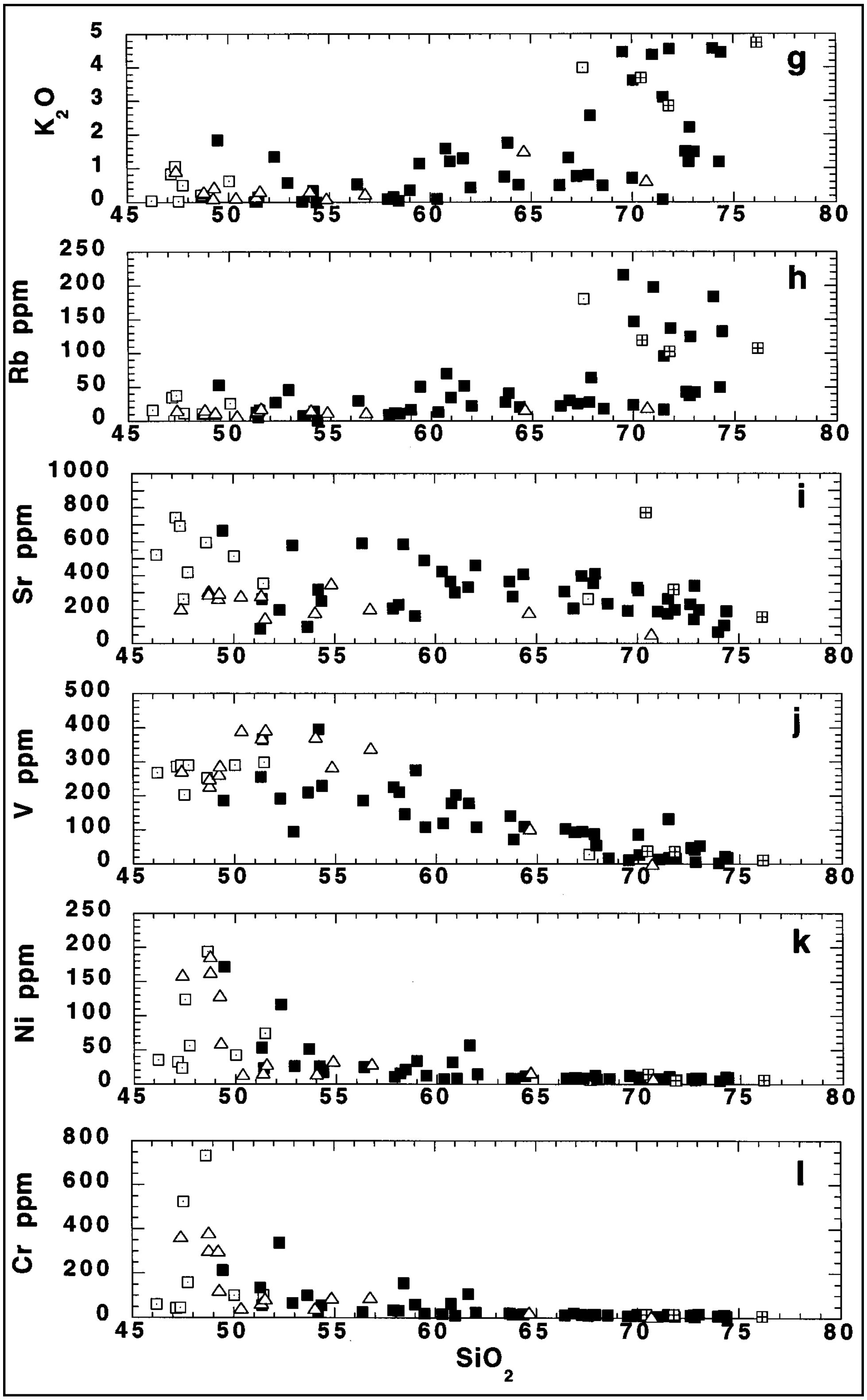


Figure 3 (on this and facing page). Harker variation diagrams for MgO, Fe_2O_3*, TiO_2, CaO, Al_2O_3, Na_2O, K_2O, Rb, Sr, V, Ni, and Cr versus SiO_2. All oxides are shown in wt%. Symbols: filled squares = Persimmon Fork Formation, open squares = Richtex Formation, squares with plus = Longtown metagranite, open triangles = Augusta terrane.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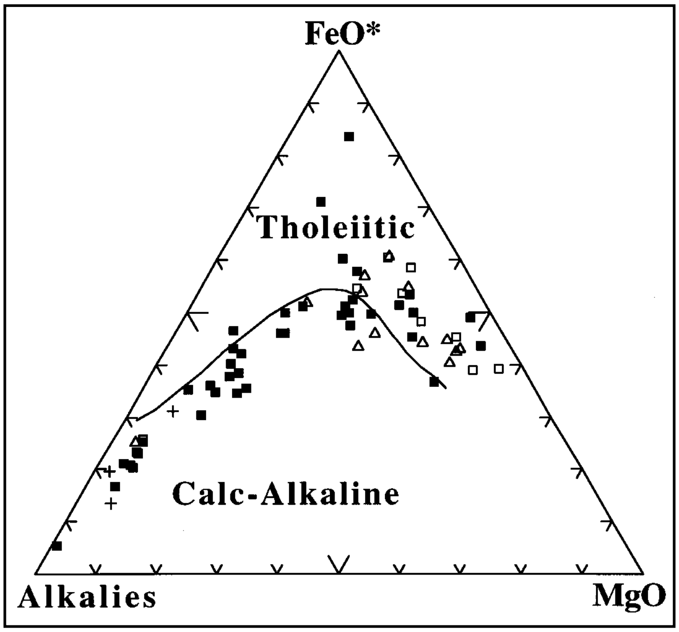

Figure 4. AFM diagram for metavolcanic rocks; symbols as for Figure 3, except Longtown metagranite = plus.

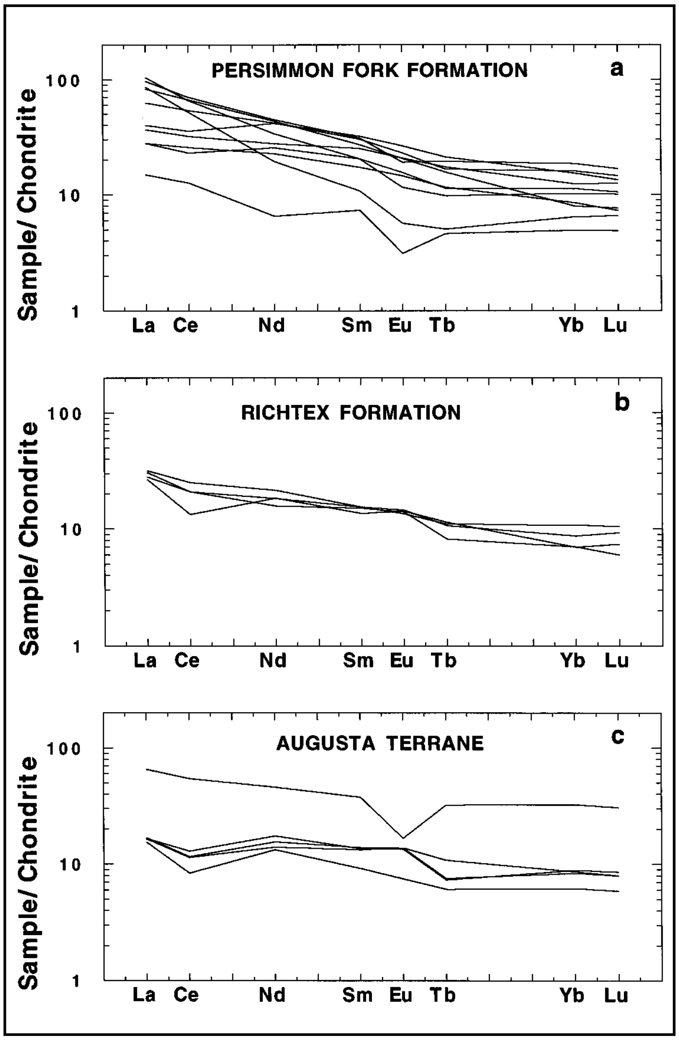

Figure 5. Chondrite-normalized REE concentrations for metavolcanic rocks of the Persimmon Fork Formation, Richtex Formation, and the Augusta terrane. Lack of distinct negative Eu anomalies even in the most silicic samples of the Persimmon Fork Formation is characteristic of the higher oxygen fugacities in calc-alkaline magma series. The single Augusta terrane rhyolite analyzed (SAS-50A) is characterized by a deep negative Eu anomaly, consistent with prolonged plagioclase fractionation and the more tholeiitic nature of the magmas.

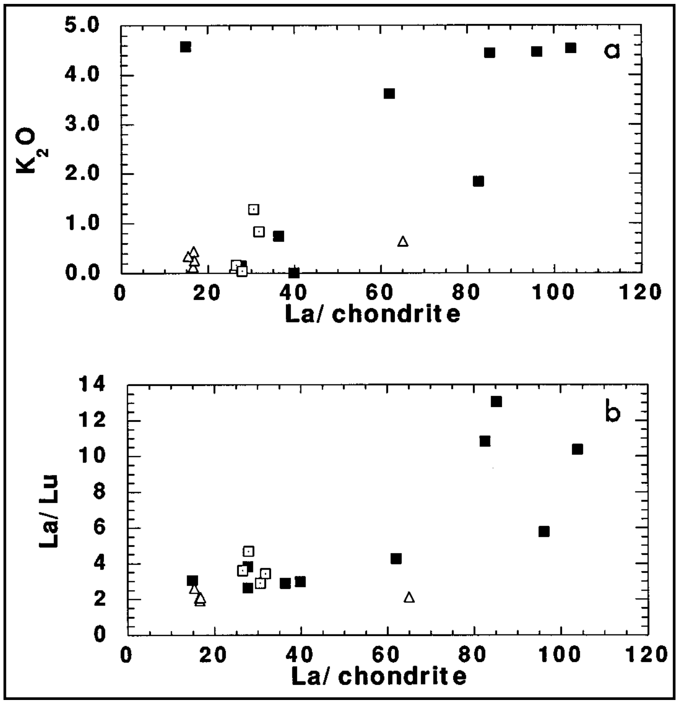

Figure 6. Chondrite-normalized La concentrations versus K_2O concentration and La/Lu ratio. Note that rocks with high La concentrations (>80× chondrite) are also characterized by elevated K_2O concentrations and La/Lu ratios. Some samples with lower La also exhibit abnormally high K_2O. Symbols as for Figure 3.

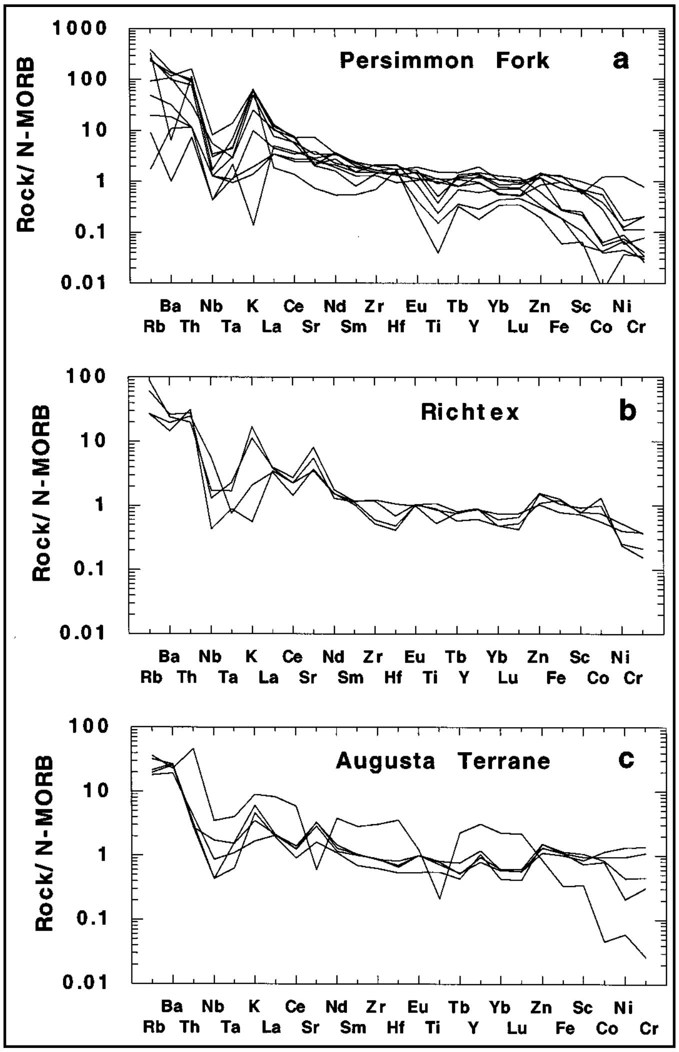

Figure 7. Trace-element concentrations in metavolcanic rocks of the Persimmon Fork Formation, Richtex Formation, and the Augusta terrane normalized to present-day oceanic crust (Taylor and McLennan, 1985; Sun and McDonough, 1989).

the Augusta normal fault, detached during the Alleghanian orogeny, or they may represent an unrelated terrane that formed by the same process as the Richtex Formation. Further correlation of this terrane with the Carolina terrane is impeded by its small size and by the absence of units equivalent to the Persimmon Fork Formation and Asbill Pond formation.

CONCLUSIONS

Geochemical data presented here, along with field and petrographic evidence, suggest that the Carolina terrane in west-central South Carolina formed as a mature volcanic arc built on a substrate of older orogenic volcanic rocks; the basement may have also included tectonically thinned continental crust, but the lack of strong calc-alkaline tendencies in the Carolina terrane metavolcanic rocks argues against this possibility. The presence of intercalated metasediments and mafic metavolcanic rocks overlying felsic pyroclastic rocks of the arc suggests formation of an intra-arc rift basin subsequent to the orogenic volcanism that built the arc. The case for rifting within the arc terrane is supported by data from the northwestern edge of the Carolina terrane, which may represent the axis of the rift basin (Dennis and Shervais, 1991).

The apparent continuation of the Grenville orogenic belt into East Antarctica, India, and Australia (Moores, 1991) has led Dalziel (1991, 1992) and Dalziel et al. (1994) to suggest that in the late Precambrian the southeastern Laurentian margin was located within a huge supercontinent adjacent to the southern parts of South America and South Africa (Fig. 9). Although the initial rifting of the southeastern Laurentian margin may have begun as early as ca. 735 Ma (Goldberg et al., 1986), the Iapetus Ocean did not open until 625–555 Ma (Bond et al., 1984). In contrast, geochemical data presented here, as well as the geochemical and geochronological data of previous investigators (Glover et al., 1971; Glover and Sinha, 1973; Wright and Seiders, 1980; Carpenter et al., 1982; Dallmeyer et al., 1986), indicate that rocks of the Carolina terrane record convergent tectonism and the subduction of oceanic crust during the period 620–530 Ma. Thus, the subduction-related volcanic arc of the Carolina terrane was active during the initial opening of the Iapetus Ocean, and the Carolina terrane could not therefore have formed in the Iapetus Ocean basin. In the late Precambrian, the nearest open ocean to the southeastern Laurentian margin was an embayment of the Pacific Ocean adjacent to East Gondwana (location A, Fig. 9). The Carolina terrane may have originated as a subduction-related volcanic arc within or adjacent to this part of the Pacific Ocean. Alternatively, the trilobite assemblage from the Carolina terrane has greatest affinities with assemblages now found in Bohemia (Samson et al., 1990). This has led Nance and Murphy (1994) to suggest that in the late Precambrian the Carolina terrane was located in proximity to Spain and Morocco, on the other side of Gondwana from Laurentia (location B, Fig. 9), thousands of kilometers from the southeastern Laurentian margin. By either of the above alternatives, the Carolina terrane is exotic relative to the southeastern Laurentian margin.

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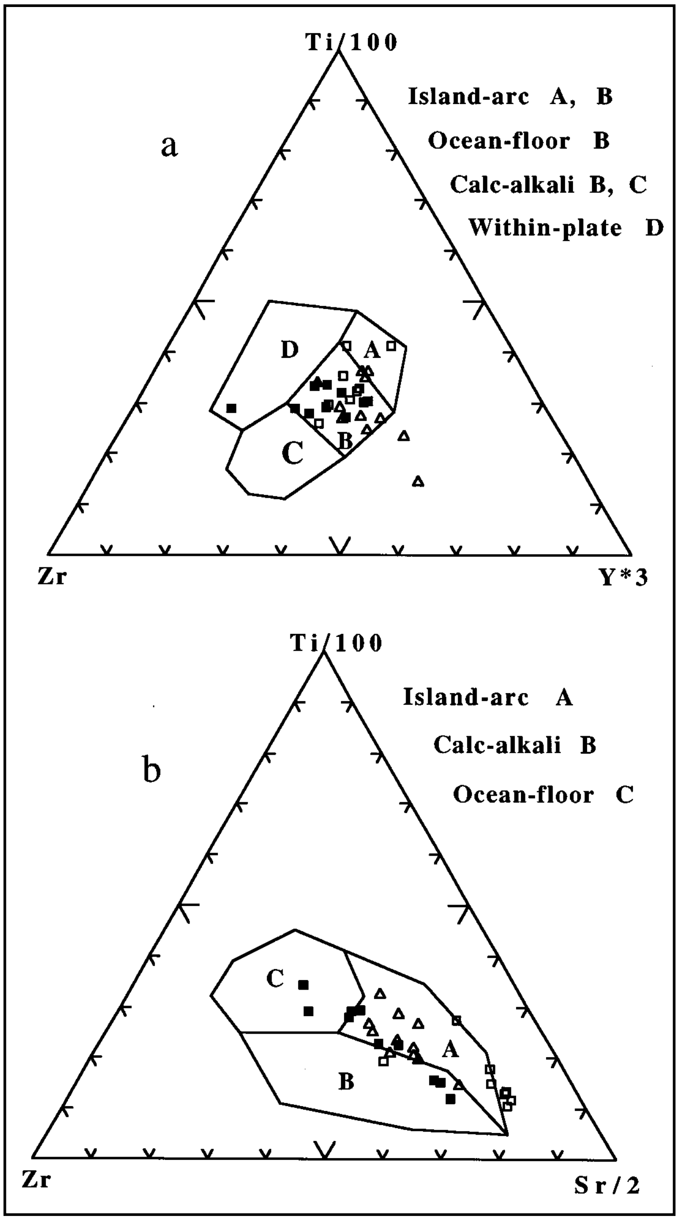


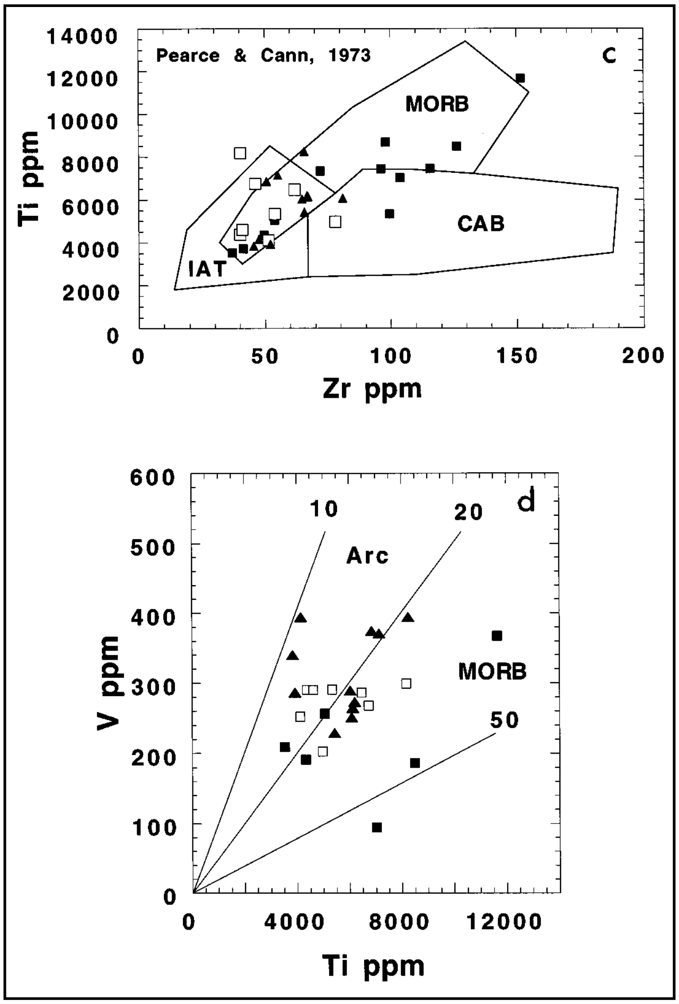
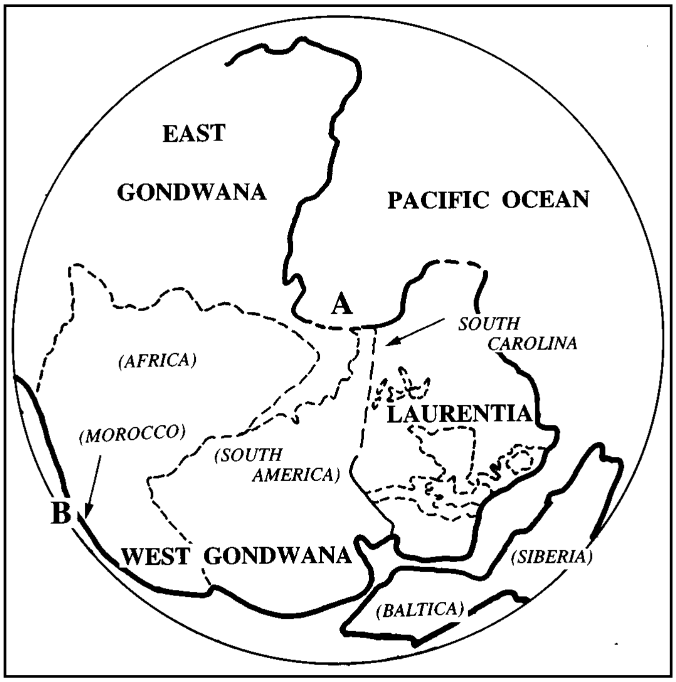


Figure 8. Tectonic discrimination diagrams for mafic metavolcanic rocks of the Persimmon Fork Formation, Richtex Formation, and the Augusta terrane, after Pearce and Cann (1973) and Shervais (1982); symbols as for Figure 3, except Augusta terrane = filled triangles in 8c and 8d. IAT = island arc tholeiite; CAB = calc-alkaline basalt; MORB = mid-ocean ridge basalt; Arc = island arc tholeiite, calc-alkaline basalt, and arc shoshonites.

Figure 9. Map showing the inferred position of the southeastern Laurentian margin at ca. 570 Ma (modified from Dalziel et al., 1994). Letters A and B mark possible locations for the Carolina terrane. Present outlines of Africa, South America, the Great Lakes, Hudson Bay, and some of the Canadian Arctic islands are shown for orientation. The late Precambrian locations of the Gondwanan part of Morocco and the Laurentian part of South Carolina are also shown. The Iapetus Ocean formed subsequent to 570 Ma in the space provided by the separation of Laurentia and Gondwana.



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