

The Carolina terrane in northwestern South Carolina: Insights into the development of an evolving island arc

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ABSTRACT

We present petrologic and whole rock geochemical data from metagneous rocks in the northwestern Carolina terrane in South Carolina. Metaplutonic rocks form zoned intrusive complexes ~10 km in diameter that range from dioritic rims to clinopyroxenite-hornblendite-serpentinite cores. The complexes intrude metavolcanic rocks that include ankaramites and pyroxene porphyries as well as more common laminated amphibolites and greenstones. This rock association is not restricted to this area, but is also recognized in other parts of the western Carolina terrane including central Georgia, along the Georgia–South Carolina border, in north-central South Carolina, and central North Carolina. Whole rock data indicate a wide range in SiO₂ content, fractionation trends that are transitional between tholeiitic and calc-alkaline, enrichments in large ion lithophile elements (LILE) and depletions in high field strength elements (HFSE), and Ti/V ratios between 10–20. Regional metamorphism and deformation accompanied arc magmatism ca. 570–535 Ma. We interpret the association to indicate rifting of a pre-existing volcanic arc. Deep seated fracturing accompanying arc-rifting is interpreted to be the mechanism by which highly magnesian magmas ascend to high crustal levels without appreciable fractionation. The mafic-ultramafic zoned intrusive complexes and associated volcanic rocks formed at the same time or slightly after the Persimmon Fork Formation in the well-characterized eastern portions of the Carolina terrane. Strong lithologic and temporal similarities between the Cadomian orogeny (Brittany, France) and the Carolina terrane suggest that Cadomia may be a better candidate for comparison with Carolina than the Avalon terrane of New England or Maritime Canada.

INTRODUCTION

The Carolina terrane is one of several exotic terranes recognized in the southern Appalachian hinterland (Fig. 1; Williams and Hatcher, 1982; Horton et al., 1989, 1991). The Carolina terrane is a late Precambrian through Middle Cambrian composite volcanic island arc that formed in a position exotic to North America (Secor et al., 1983). Paleomagnetic evidence suggests that the arc was accreted to Laurentia in the Middle Ordovician (Vick et al., 1987; Noel et al., 1987), and rocks of the terrane have been overprinted by middle and late Paleozoic

intrusive, metamorphic, and/or deformational events (e.g., Secor et al., 1986; Horton et al., 1987).

The purpose of this chapter is to evaluate the evolution of the arc prior to its accretion to Laurentia. The terrane is best known through the study of rocks in the eastern Piedmont (Carolina slate belt) where low metamorphic grade volcanoclastic and epiclastic rocks comprise a well-characterized stratigraphy (e.g., Milton, 1984; Secor et al., 1986; Harris and Glover, 1988). The central and western portions (Charlotte belt) of the terrane in South Carolina, near the terrane's contact with the Inner Piedmont, have been less well studied. Here the meta-

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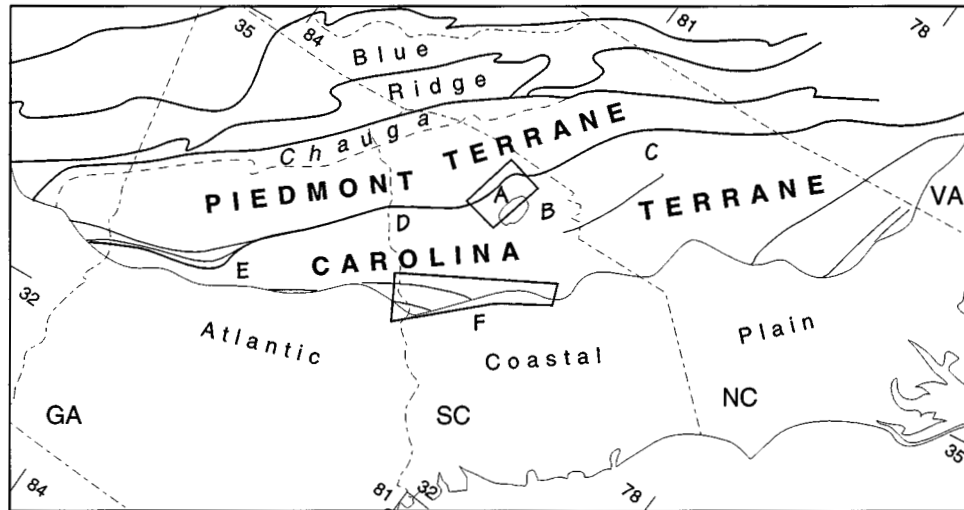


Figure 1. A terrane map of the southern Appalachian orogen (adapted from Dennis, 1991). A: area of Figure 2 (Oval is the outline of the Bald Rock pluton); B: York-Chester complex; C: Davie County (Mocksville) complex; D: Latimer complex; E: Berner mafic complex; F: Location of study of Shervais et al. (this volume); GA—Georgia; SC—South Carolina; NC—North Carolina; VA—Virginia.

morphic grade increases to amphibolite facies; there are abundant epizonal plutons and multiple intrusive events; and the rocks are more highly strained than the time-equivalent strata in the east. In this chapter, we present a history for these rocks based on detailed field mapping, petrography, and whole rock geochemistry of representative metavolcanic and metaplutonic rock types. This study combined with recent and ongoing U-Pb mineral age studies in the central Piedmont (e.g., Dennis and Wright, 1993; Dennis et al., 1993) reveals the diachronous and semicontinuous nature of magmatism and deformation of an evolving island arc terrane.

GEOLOGICAL OVERVIEW

Carolina terrane

The Carolina terrane in the Carolinas is conventionally divided into belts of alternating lower (greenschist) and higher (amphibolite facies) metamorphic grade: Carolina slate, Charlotte, Kings Mountain. The juxtaposition of these alternating high- and low-grade belts is thought to be a middle to late Paleozoic feature, dominantly controlled by faulting. Locally, however, belt boundaries are not coincident with faults, and gradual metamorphic grade changes may be mapped across the boundaries (e.g., Halik, 1983). Despite faulting internal to the Carolina terrane that makes it difficult to trace map units across belt boundaries, systematic variations in trace element chemistry (e.g., Sharp, 1985) and isotope systematics (e.g., LeHuray, 1986) confirm lithologic inferences that these belts are parts of a single lithotectonic unit. Rocks of the Carolina terrane are separated from those of the Inner Piedmont by the central Piedmont suture. Over much of its length the central Piedmont suture has been reactivated one or more times, the most recent

ductile motion occurring as retrograde, dextral strike-slip motion during Alleghanian time (Dennis and Shervais, 1992).

Eastern Carolina terrane. The eastern Carolina terrane in South Carolina comprises three formations: The Persimmon Fork Formation is conformably overlain to the northwest by the Richtex Formation, and conformably overlain to the southeast by the (informally named) Asbill Pond formation. The Persimmon Fork Formation is an andesitic volcanic unit with hypabyssal intrusives (Little Mountain, Lincolnton, and Longtown) that yield U-Pb zircon ages ca. 550 Ma (Whitney et al., 1978; Carpenter et al., 1982; Dallmeyer et al., 1986; Barker et al., 1993). The Richtex Formation consists of turbiditic wackes intercalated with greenstones. At least locally the contact between the Persimmon Fork Formation and Richtex Formation has been reactivated as a fault. The Asbill Pond formation includes a lower and an upper mudstone separated by coarser-grained siliciclastic shelf rocks. The upper mudstone contains the exotic Batesburg fauna of Middle Cambrian age (Samson et al., 1990) and is believed to be the youngest exposed sedimentary unit in the Piedmont of the Carolinas and Georgia.

Western Carolina terrane. In South Carolina and adjacent Georgia, the western portions of the Carolina terrane are dominated by upper greenschist to lower amphibolite facies mafic and ultramafic rocks that include volcanic and plutonic protoliths. Where these rocks have been mapped in detail they are recognized as zoned mafic-ultramafic plutonic complexes intrusive into a sequence of intercalated mafic to intermediate metavolcanic rocks.

Two and possibly three zoned intrusive complexes have been recognized west of the Bald Rock granite in northwestern South Carolina: the Wildcat Branch complex of Horkowitz (1984) and the Mean Crossroads complex of Dennis (1988); the

Hammett Grove Metaigneous Suite of Mittwede (1989) may represent portions of a zoned complex disrupted and emplaced by late Paleozoic transpressive motion. The Wildcat Branch and Mean Crossroads complexes are crudely zoned from mafic-rich cores to more felsic, dioritic rims. These complexes are dominated (60%–70%) by coarse-grained (~1 cm) metadiorite gneisses and quartz diorites that form the outermost zone and are ~10 km in diameter. The metadiorites surround foliated metamorphosed gabbro and hornblende gabbro. Metagabbros may compose up to 10%–15% of a complex by area. Grain size in these gabbros is typically 1–2 cm. Pyroxene, hornblende, and plagioclase are recognized as cumulate phases in the gabbros, but mappable layering is not observed. The cores of the zoned complexes are made up of coarse-grained (1–3 cm) metaclinopyroxenites and hornblendites and locally serpentinite. These meta-ultramafic cores are typically <2 km in diameter and may form up to ~15%–20% of the zoned intrusive complex by area.

The zoned complexes intrude fine-grained greenstones and amphibolites that are interpreted to be volcanic rocks. Metamorphosed basalts and basaltic andesites are recognized in the field as actinolitic amphibolites, feldspar- and pyroxene-phyric amphibolites, and amygdaloidal greenstones. The volcanic origin of these rocks is clear from their fine grain size, epidote-plagioclase-quartz-filled amygdules, pumiceous lapilli, and occurrence of plagioclase phenocrysts 1–2 mm in length. Fine-grained laminated amphibolites are interpreted as mafic to intermediate tuffs. Poorly laminated, more massive actinolitic amphibolites are interpreted to represent massive basaltic or basaltic andesite flows. Mafic metavolcanic rocks are finely foliated on the mesoscopic scale, but the presence of fine-grained polygonal quartz and feldspar and relatively coarse, idioblastic amphibole implies recrystallization under static conditions. Intermediate to felsic lapilli tuffs are also recognized but are much less common. The felsic and mafic rocks are intercalated on a 1–10 m scale, and map boundaries between the units are gradational.

Locally these volcanic rocks are as much as 40% modally composed of clinopyroxene phenocrysts 0.5–1.5 cm across that have been replaced by actinolitic amphibole. Field observations indicate these to be present as flows, dikes, and possibly as crystal-rich tuffs. Metamorphosed dikes with ankaramitic (olivine + pyroxene phenocrysts) or picritic (olivine phenocrysts) compositions cut through both plutonic rocks and volcanic country rocks and are interpreted to represent the parent liquids from which both the zoned complexes and the lavas crystallized.

The mafic metavolcanic rocks are cut by narrow (<150 m) corridors of quartz-sericite schist that may be traced several kilometers along strike. These zones are a historical locus of gold prospecting and mining. The zones appear to be spatially related to hypabyssal metagabbros and are interpreted to represent hydrothermal alteration contemporary with volcanism. It is not clear whether faulting was important in the genesis of these zones. It is possible to trace metamorphosed andesitic

pyroclastic rocks into sillimanite-sulfide-magnetite-quartz schists, with abundant 2–3 cm sillimanite-after-kyanite prisms. These rocks are interpreted to indicate extensive hydrothermal alteration of an intermediate volcanic protolith.

Metamorphosed mafic and ultramafic dikes crosscut the quartz-sericite zones. This important observation shows that formation of the quartz-sericite zones was contemporaneous with mafic and ultramafic volcanism. The quartz-sericite zones thus developed in late Precambrian–Early Cambrian time prior to middle or late Paleozoic events affecting the accreted arc.

The late Precambrian to earliest Paleozoic rocks of the western Carolina terrane are intruded by middle to late Paleozoic intrusives. In particular, we note the presence of the unmetamorphosed and undeformed 383 ± 5 Ma (Rb-Sr whole-rock; Mittwede and Fullagar, 1987) Pacolet granite and the ca. 400 Ma Buffalo gabbro and the ca. 323 Ma (U-Pb zircon; Dennis and Wright, 1993) Bald Rock granite in the map area under consideration. These younger intrusives are part of larger igneous suites unrelated to late Precambrian–Early Cambrian development of the Carolina arc and are discussed elsewhere by other authors (e.g., Butler and Fullagar, 1978; Fullagar and Butler, 1979; McSween et al., 1984; Speer et al., 1986; Horton et al., 1987).

PETROLOGY AND GEOCHEMISTRY OF THE METAIGNEOUS ROCKS

Samples for this study were collected from four U.S. Geological Survey 7.5' quadrangles (Philson Crossroads, Cross Anchor, Glenn Springs, and Jonesville) in northwestern South Carolina that had been mapped in detail at a scale of 1:24,000 (Fig. 2; Horkowitz, 1984; Willis, 1984; and Dennis, 1988, respectively). These quadrangles contain the terrane boundary between the Carolina terrane and the Inner Piedmont, and they contain critical exposures of the zoned intrusive complexes and their associated volcanic pile described here and in Dennis and Shervais (1991, 1992).

Forty samples of upper greenschist to lower amphibolite facies metaplutonic rocks (representing pyroxenites, hornblendites, gabbros, and diorites) and 39 samples of metavolcanic rocks (representing basalts, andesites, dacites, and tholeiitic ankaramites) were analyzed by X-ray fluorescence (XRF) spectrometry for 9 major elements and 12 trace elements at the University of South Carolina. The samples were analyzed using a Philips PW1400 automated XRF spectrometer and 12 U.S. Geological Survey rock standards. These data are presented in Table 1 (plutonic rocks of the zoned intrusive complexes) and Table 2 (metavolcanic rocks and dikes). In addition, 20 of these samples 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. These samples were selected to display a range of REE compositions by choosing them based on a wide range of Zr contents (20–200 ppm). The INAA data are presented in Table 3. Sample locations are listed in Appendix I.

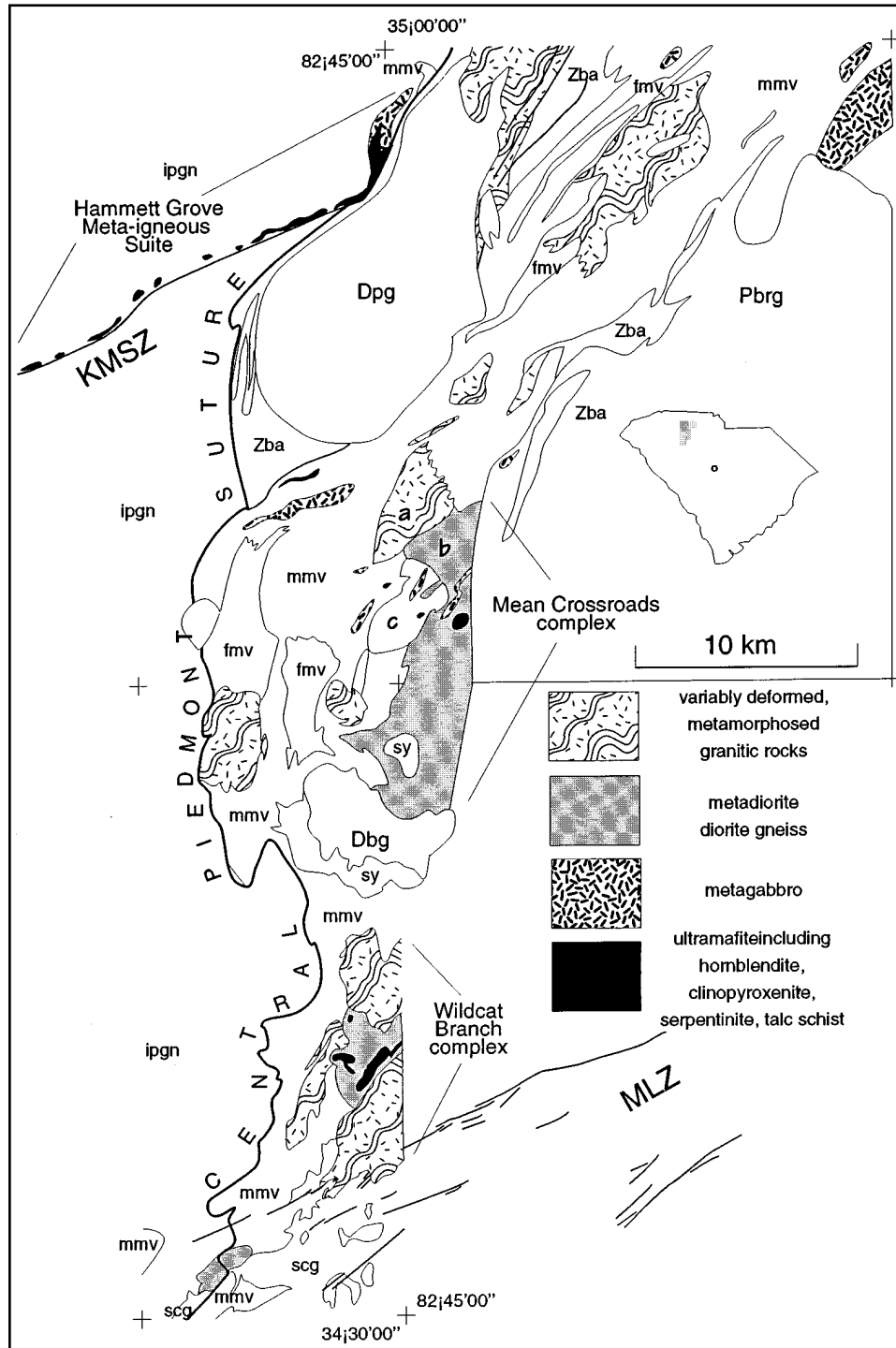


Figure 2. Geologic map of the Carolina terrane in northwestern South Carolina (modified from Dennis and Shervais, 1991): fmv—felsic metavolcanic; ipgn—undifferentiated inner piedmont gneisses; mmv—mafic metavolcanic; scg—Sand Creek granite; sy—syenite; Dbg—Devonian Buffalo gabbro; Dpg—Devonian Pacolet granite; KMSZ—Kings Mountain shear zone; MLZ—Middleton Lowndesville zone; Pbrg—Pennsylvanian Bald Rock granite; Zba—Late Precambrian Battleground Formation. Localities mentioned in text: a—metamorphosed biotite porphyry granodiorite; b—Mean Crossroads metadiorite gneiss; c—unfoliated, unmetamorphosed diorite pluton.

TABLE 1. MAJOR- AND TRACE-ELEMENT ANALYSES OF ZONED INTRUSIVE COMPLEX ROCKS BY XRF SPECTROMETRY*

Sample	1346a	2425-13	2425-11-2	2425-11	2425-12	2425-14	2425-4	2425-2	2425	2425-1	2425-6-2	2425-15	2425-8
Rock type	Ol Pxite	Ol Pxite	Ol Pxite	Ol Pxite	Ol Pxite	Ol Pxite	Pxite	Pxite	Pxite	Pxite	Pxite	Pxite	Pxite
(wt%)													
SiO ₂	47.48	52.59	52.10	52.12	51.86	51.99	54.87	54.78	55.15	54.79	54.83	54.97	55.98
TiO ₂	0.48	0.38	0.37	0.37	0.48	0.38	0.57	0.57	0.53	0.46	0.53	0.56	0.77
Al ₂ O ₃	7.63	4.54	5.22	5.31	5.31	5.28	6.13	6.25	6.87	7.66	7.07	6.82	6.97
FeO*	10.87	7.50	8.16	7.99	7.98	7.55	8.27	8.60	8.21	8.37	7.72	8.07	8.76
MnO	0.25	0.20	0.21	0.22	0.23	0.22	0.21	0.28	0.21	0.20	0.19	0.20	0.19
MgO	22.12	15.91	16.78	16.73	16.63	15.73	14.67	14.65	13.89	13.41	13.17	13.00	12.96
CaO	10.07	14.56	15.72	15.87	16.10	17.39	13.49	13.15	13.07	13.18	14.40	14.62	12.45
Na ₂ O	0.55	0.62	0.76	0.71	0.69	0.77	0.92	0.94	1.06	1.14	1.19	1.06	0.93
K ₂ O	0.09	0.23	0.30	0.31	0.32	0.31	0.50	0.39	0.65	0.43	0.66	0.37	0.64
(ppm)													
Nb	0	0	2	1	0	1	5	6	5	8	3	3	7
Zr	31	26	36	32	35	33	34	56	74	61	68	69	137
Y	13	13	14	16	16	14	15	22	23	20	24	23	34
Sr	22	44	48	48	43	52	77	73	81	111	79	75	71
Rb	5	7	9	8	9	8	15	9	15	10	17	13	15
Ni	180	124	127	126	131	115	109	106	86	99	83	75	71
Cr	586	1275	964	992	1142	1296	703	675	690	654	703	487	349
V	189	161	168	168	200	182	201	200	180	193	184	202	255
Sc	52	69	67	72	72	68	64	68	68	64	67	72	63
Ba	190	60	74	88	145	118	222	305	177	110	169	138	141
Zh	77	70	78	76	76	75	73	73	77	69	70	71	66
Cu	20	1	3	2	4	3	9	11	5	20	5	5	4
Mg#	78.40	80.14	78.56	78.88	78.78	78.78	75.97	75.23	75.10	74.07	75.12	74.18	72.52

TABLE 1. MAJOR- AND TRACE-ELEMENT ANALYSES OF ZONED INTRUSIVE COMPLEX ROCKS BY XRF SPECTROMETRY* (continued - page 2)

Sample	2425-6	2425-5	2425-9	2425-3	2425-7	1550	2425-10	1516	2426	2425-8-2	1577	2292	2428	2468	2420
Rock type	Pxite	Pxite	Pxite	Pxite	Pxite	Hbite	Plag Pxite	Ol Gabbro	Ol Gabbro	Ol Gabbro	Ol Gabbro	Ol Gabbro	Gabbro	Gabbro	Gabbro
(wt%)															
SiO ₂	54.67	52.98	55.55	57.30	58.85	48.97	53.73	48.23	51.21	51.12	48.80	49.28	53.25	52.18	50.43
TiO ₂	0.58	0.73	0.53	0.55	0.65	1.23	0.69	0.64	0.71	0.70	0.60	1.11	0.47	0.52	1.41
Al ₂ O ₃	9.36	8.60	8.12	6.88	6.77	13.96	10.15	11.71	11.87	11.93	15.88	16.45	14.54	15.02	16.54
FeO*	8.41	9.37	7.74	6.91	7.42	13.62	8.99	10.03	10.98	11.08	10.26	9.36	5.35	8.52	10.40
MnO	0.26	0.21	0.25	0.19	0.22	0.23	0.23	0.24	0.23	0.24	0.17	0.14	0.24	0.16	0.16
MgO	12.66	12.31	12.12	11.84	11.30	9.61	11.36	11.77	11.32	11.23	9.42	8.27	9.75	8.62	7.79
CaO	11.65	13.70	13.62	14.07	12.73	9.61	12.56	16.06	11.02	11.07	12.81	12.43	15.13	11.19	9.99
Na ₂ O	1.70	1.13	1.32	1.11	0.96	2.04	1.36	0.70	1.57	1.58	1.24	2.28	0.96	2.65	2.65
K ₂ O	0.38	0.60	0.42	0.87	0.80	0.09	0.60	0.25	0.60	0.59	0.40	0.24	0.18	0.71	0.14
(ppm)															
Nb	6	4	5	5	7	8	6	8	3	4	6	4	2	3	0
Zr	143	49	70	96	133	70	65	101	40	43	24	71	51	62	111
Y	41	18	29	24	54	33	29	34	18	16	13	18	18	13	36
Sr	235	125	113	66	67	142	137	391	119	118	161	321	372	975	381
Rb	11	16	15	23	25	7	13	4	11	9	12	9	6	19	3
Ni	96	69	75	81	76	11	58	17	59	60	70	83	19	85	107
Cr	287	346	604	486	446	44	265	39	583	572	253	514	24	272	189
V	141	276	177	176	134	547	231	164	331	333	410	251	64	192	268
Sc	64	56	63	67	62	45	61	29	48	52	43	52	29	29	34
Ba	114	137	228	253	257	109	131	68	143	137	100	129	110	165	144
Zn	108	83	77	49	85	90	81	80	79	77	83	92	157	92	98
Cu	1	27	4	1	3	179	17	10	30	22	42	93	4	28	36
Mg#	72.85	70.08	73.64	75.32	73.09	55.70	69.26	67.67	64.75	64.38	62.08	61.17	76.49	64.33	57.18

TABLE 1. MAJOR- AND TRACE-ELEMENT ANALYSES OF ZONED INTRUSIVE COMPLEX ROCKS BY XRF SPECTROMETRY* (continued - page 3)

Sample Rock Type	2246A Gabbro	1885 Gabbro	2018 Gabbro	1829 Hb Gabbro	1992 Hb Gabbro	2466 Hb Diorite	1565 Bf Diorite	2246b Diorite	2432 Diorite	1806 Diorite
(wt%)										
SiO ₂	49.01	51.10	50.67	50.81	49.26	53.84	55.02	57.02	61.98	65.77
TiO ₂	0.74	0.88	0.83	0.89	1.16	2.74	0.58	1.01	0.72	0.73
Al ₂ O ₃	14.37	16.12	17.30	15.73	15.76	14.02	17.09	15.43	15.18	13.09
FeO*	9.06	11.53	10.79	11.44	13.92	11.57	8.65	7.15	6.83	6.90
MnO	0.27	0.16	0.16	0.17	0.19	0.16	0.15	0.17	0.13	0.15
MgO	6.91	6.54	5.52	6.83	5.71	4.97	6.13	4.98	3.73	3.94
CaO	17.77	10.55	11.71	11.26	10.11	7.81	8.60	12.54	6.86	8.13
Na ₂ O	0.75	2.39	2.08	2.10	2.75	4.14	3.32	1.05	2.59	1.00
K ₂ O	0.76	0.20	0.43	0.24	0.41	0.16	0.10	0.35	1.68	0.05
(ppm)										
Nb	4	3	6	3	4	10	10	2	8	3
Zr	47	61	52	60	80	188	62	51	147	184
Y	17	22	16	22	28	45	13	18	19	72
Sr	351	388	644	321	523	382	328	413	225	188
Rb	24	9	10	8	10	5	5	13	60	3
Ni	19	29	31	30	21	14	44	19	22	12
Cr	82	59	65	67	57	49	106	121	53	30
V	279	294	348	375	619	290	196	381	175	111
Sc	39	44	36	43	40	29	31	52	22	19
Ba	143	75	99	135	141	189	74	107	421	91
Zn	76	70	58	72	66	109	88	73	83	46
Cu	49	156	82	122	178	62	23	43	53	6
Mg#	57.64	50.28	47.70	51.56	42.24	43.36	55.84	55.41	49.32	50.45

*Samples normalized to 100% volatile free.

TABLE 2. MAJOR- AND TRACE-ELEMENT GEOCHEMISTRY OF METAVOLCANIC ROCKS BY XRF SPECTROMETRY*

Sample	1584	2004	1512	1417	1419	2473b	1535	1510	1730	2473a	2462a	1831	1506
Rock Type	Ankaramite	Ankaramite	Ankaramite	Ankaramite	Ankaramite	Augite	Augite	Augite	Hi-Mg	HB Porph	Basalt	Basalt	Basalt
	Dike	Tuff	Tuff	Tuff	Tuff	Porph.	Porph Tuff	Porph Tuff	Basalt Tuff				
(wt%)													
SiO ₂	47.73	55.08	48.60	49.43	50.51	47.32	51.07	49.04	50.78	43.95	49.87	50.12	50.49
TiO ₂	0.50	0.42	0.45	1.00	0.77	0.79	0.55	0.58	0.63	1.10	0.89	1.68	0.71
Al ₂ O ₃	8.09	7.94	7.01	15.48	13.89	12.81	12.12	12.59	12.06	14.29	16.34	14.75	15.11
FeO*	9.62	10.38	10.44	10.49	9.15	8.05	8.59	9.22	8.43	13.68	10.83	13.77	7.86
MnO	0.15	0.22	0.27	0.17	0.21	0.18	0.26	0.19	0.22	0.26	0.21	0.23	0.19
MgO	21.68	14.84	21.40	10.53	10.94	13.08	11.97	11.37	10.70	11.66	5.98	7.44	8.77
CaO	10.97	9.31	10.64	9.03	12.99	15.94	13.18	15.70	15.23	11.70	11.52	10.34	15.76
Na ₂ O	0.62	1.11	0.60	3.28	1.02	1.04	1.42	0.79	1.49	1.35	3.00	0.92	0.73
K ₂ O	0.12	0.26	0.11	0.11	0.14	0.50	0.53	0.16	0.17	1.38	0.87	0.03	0.12
(ppm)													
Nb	3	5	7	8	4	0	6	3	5	2	10	7	0
Zr	31	51	32	53	40	51	134	71	64	61	49	96	64
Y	25	23	15	20	19	25	23	30	23	33	21	28	25
Sr	21	76	20	370	377	419	344	380	398	151	263	638	263
Pb	5	11	12	6	5	2	9	2	8	28	11	6	3
Ni	347	265	164	120	131	4	15	18	14	16	18	21	67
Cr	1444	549	608	310	336	48	28	34	35	50	93	75	49
V	210	171	190	289	244	250	113	197	177	424	332	705	171
Sc	56	43	65	36	37	29	25	37	25	33	37	46	34
Ba	106	50	213	92	99	207	94	355	87	375	199	180	58
Zn	61	80	72	74	98	93	100	89	91	103	94	84	97
Cu	36	47	20	77	10	26	3	36	7	15	89	448	10
Mg#	80.07	71.82	78.52	64.16	68.06	74.33	71.30	68.73	69.35	60.30	49.58	49.06	66.55

TABLE 2. MAJOR- AND TRACE-ELEMENT GEOCHEMISTRY OF METAVOLCANIC ROCKS BY XRF SPECTROMETRY* (continued - page 2)

Sample Rock Type	2472 Basalt	2464c Basalt	1306 Basalt	2467b Basalt	2467a Basalt	2464b Basalt	2464a Basalt	2467c Basalt	2478 Basalt	2462b Basalt	1908 Bas And	2474b Bas And	2474a Bas And
(wt %)													
SiO ₂	51.05	51.07	51.17	51.21	51.38	51.47	51.51	51.82	51.87	52.42	53.75	54.18	54.21
TiO ₂	1.43	1.65	1.60	0.96	0.93	1.65	1.62	0.93	0.80	0.83	0.76	0.73	0.74
Al ₂ O ₃	14.36	14.71	14.40	15.98	16.15	14.52	14.50	16.42	14.59	16.53	14.71	14.72	14.32
FeO*	10.15	12.58	10.79	10.95	10.81	12.44	12.38	10.77	10.81	10.40	10.78	11.01	11.16
MnO	0.17	0.17	0.17	0.18	0.16	0.17	0.17	0.17	0.25	0.16	0.17	0.20	0.20
MgO	5.61	6.55	7.55	5.51	5.47	6.58	6.53	5.13	8.06	4.71	6.22	5.03	5.06
CaO	15.87	9.32	10.31	10.86	10.69	9.16	9.32	10.47	11.92	9.94	11.47	12.17	12.64
Na ₂ O	0.77	3.03	3.23	2.74	2.92	3.07	2.99	2.73	0.94	3.45	1.15	1.34	1.04
K ₂ O	0.08	0.30	0.27	1.08	0.97	0.31	0.35	1.05	0.32	1.09	0.56	0.14	0.15
(ppm)													
Nb	0	7	6	5	7	6	12	5	3	9	8	4	4
Zr	114	98	133	55	38	85	92	50	41	51	78	45	45
Y	48	31	45	16	18	29	30	26	27	20	24	15	37
Sr	1104	814	350	498	488	569	605	500	213	205	283	372	434
Pb	4	14	9	13	8	11	5	17	8	24	10	9	1
Ni	35	26	49	27	23	30	24	27	18	22	10	18	19
Cr	82	65	183	64	66	81	66	62	41	91	38	35	36
V	282	513	314	338	331	522	510	332	390	360	369	304	317
Sc	37	45	39	33	33	44	42	33	38	36	33	37	32
Ba	67	143	145	160	140	111	136	169	92	154	92	53	58
Zn	85	81	86	91	85	79	81	88	77	80	47	79	80
Cu	4	118	34	126	160	144	148	161	16	77	11	233	190
Mg#	49.64	48.14	55.49	47.26	47.42	48.54	48.46	45.90	57.09	44.68	50.68	44.87	44.70

TABLE 2. MAJOR- AND TRACE-ELEMENT GEOCHEMISTRY OF METAVOLCANIC ROCKS BY XRF SPECTROMETRY* (continued - page 3)

Sample Rock Type	1906b Andesite	2037 Andesite	McClure Andesite	2470a Andesite	2470b Andesite	2470c Andesite	1906a Andesite	1889 Andesite	1927 Dacite	1484a Dacite Tuff	1484d Dacite Tuff	1484f Dacite Tuff	2274 Rhyolite
(wt%)													
SiO ₂	56.13	56.24	56.42	56.76	57.28	58.17	58.39	58.68	61.71	61.74	64.00	65.18	69.19
TiO ₂	0.72	0.79	0.73	0.43	0.70	0.62	0.79	0.76	0.66	0.64	0.88	0.71	0.54
Al ₂ O ₃	14.58	15.39	16.71	14.25	15.66	17.29	15.54	15.53	13.61	17.01	16.19	16.07	16.46
FeO*	12.11	9.19	7.65	4.12	8.49	6.99	10.13	7.71	6.28	5.45	4.87	4.24	3.74
MnO	0.23	0.15	0.17	0.22	0.14	0.14	0.19	0.32	0.34	0.11	0.10	0.09	0.05
MgO	4.33	5.65	4.66	8.89	4.69	3.86	3.22	4.48	4.12	3.51	2.38	2.13	0.43
CaO	9.83	8.64	9.64	13.72	11.07	11.50	9.78	11.19	12.00	4.71	4.69	4.02	0.92
Na ₂ O	1.28	2.39	3.25	0.80	1.01	0.82	1.33	0.86	0.87	4.65	4.45	5.24	6.40
K ₂ O	0.26	1.17	0.44	0.62	0.59	0.32	0.21	0.36	0.19	1.90	2.20	2.08	1.98
(ppm)													
Nb	3	12	20	5	9	2	2	3	3	9	6	60	6
Zr	66	97	80	220	89	52	81	93	81	133	200	191	142
Y	51	19	17	50	20	19	47	37	37	15	32	23	24
Sr	234	221	441	291	567	575	323	178	374	515	177	234	284
Pb	3	47	9	11	9	7	7	3	5	49	61	69	77
Ni	20	33	19	25	21	16	12	17	13	15	12	13	7
Cr	37	62	26	33	54	51	34	39	26	36	17	30	14
V	324	252	222	44	255	182	274	143	95	180	107	97	19
Sc	35	29	22	23	33	29	32	33	21	11	9	12	10
Ba	129	263	120	865	134	157	73	31	69	275	297	349	964
Zn	45	85	114	127	69	41	54	111	101	94	79	88	106
Cu	258	69	38	0	9	5	23	14	6	69	55	47	13
Mg#	38.92	52.28	52.04	79.36	49.61	49.61	36.19	50.89	53.95	53.49	46.54	47.25	17.12

*Samples normalized to 100% volatile free.

TABLE 3. MAJOR- AND TRACE-ELEMENT ANALYSES BY INSTRUMENTAL NEUTRON ACTIVATION ANALYSIS*

Sample	1417	1419	1484a	1484d	1484f	1550	1584	1730	1806	1831	1889
(wt%)											
FeO	8.99	8.73	5.11	4.94	3.93	12.92	10.45	8.34	6.92	13.29	7.42
Na ₂ O	3.89	1.20	4.89	4.13	5.35	2.20	0.68	1.53	1.19	0.84	0.87
(ppm)											
Sc	38.8	33.7	13.6	14.0	12.5	52.4	58.1	27.7	18.0	46.8	24.9
Cr	343	386	19	9	11	11	1544	11	8	37	10
Co	42.3	41.7	17.3	11.8	10.6	42.2	82.9	21.0	15.5	42.5	13.8
Zn	159	132	60	54	50	230	295	112	74	235	121
Rb	<2.7E+01	<3.3E+01	70	65	73	<5.7E+01	34	<3.0E+01	<1.9E+01	<3.6E+01	<3.0E+01
Cs	0.35	<1.0E+00	1.7	1.5	2.2	<9.3E-01	0.49	0.38	<5.1E-01	0.36	<8.1E-01
Sr	320	432	374	162	182	<3.9E+02	<3.0E+02	410	227	516	315
Ba	233	220	306	334	438	<6.3E+02	201	221	135	218	190
La	8.2	9.4	12.8	18.2	17.8	8.7	6.7	9.9	10.0	18.5	14.9
Ca	<3.3E+01	22.1	27.5	40.9	39.5	22.3	14.4	22.2	26.2	44.1	34.6
Nd	12.5	12.1	14.0	22.2	19.9	17.0	8.2	14.6	20.5	26.1	21.4
Sm	3.16	3.11	3.16	5.24	4.46	5.47	2.34	4.15	6.75	6.57	5.27
Eu	1.21	1.05	0.85	1.32	1.02	1.75	0.73	1.13	1.68	1.89	1.82
Tb	0.52	0.42	0.50	0.89	0.67	1.05	0.35	0.76	1.67	1.00	1.06
Yb	1.87	1.50	1.82	3.14	2.50	3.51	1.18	2.61	6.33	2.64	2.97
Lu	0.26	0.22	0.25	0.45	0.37	0.50	0.14	0.40	0.93	0.38	0.42
Zr	58	<4.2E+02	123	219	203	<4.2E+02	<3.9E+02	56	133	80	195
Hf	1.2	1.4	3.5	5.8	6.2	2.0	0.8	2.5	5.9	2.7	3.0
Ta	0.15	<3.3E-01	0.25	0.52	0.47	0.20	0.18	0.18	0.15	0.20	0.17
Th	1.0	1.2	2.8	4.8	5.2	0.6	0.9	1.1	0.9	2.0	2.1
Sample	1906a	1906b	1908	2428	2462b	2464c	2468	2470	2472	2478	Percent
(wt%)											
FeO	11.44	9.78	11.06	5.02	8.98	13.52	7.90	7.87	9.43	10.88	5
Na ₂ O	1.10	1.67	1.07	0.89	3.52	3.35	3.02	0.96	0.57	0.91	3
(ppm)											
Sc	31.6	31.3	35.1	16.6	41.5	49.4	33.2	29.1	34.8	33.3	3
Cr	13	12	15	13	78	47	284	33	51	18	10
Co	22.5	21.1	29.2	8.6	28.1	40.2	33.8	24.5	27.5	20.7	5
Zn	127	130	134	81	152	198	119	120	137	125	15
Rb	<2.8E+01	<3.3E+01	<3.6E+01	<1.9E+01	<4.2E+01	<4.2E+01	32	12	17	<4.2E+01	10
Cs	<7.8E-01	<9.0E-01	<8.4E-01	0.11	<1.1E+00	0.50	0.49	0.87	<7.8E-01	0.47	5
Sr	383	336	348	331	321	538	800	372	767	242	12
Ba	192	220	145	150	<4.2E+02	<4.8E+02	259	199	186	<4.2E+02	10
La	12.5	18.0	9.1	7.1	7.5	7.6	6.4	9.8	5.1	5.1	3
Ca	29.5	40.1	21.4	15.5	13.4	<1.6E+01	15.0	22.7	17.1	<1.8E+01	7
Nd	19.1	26.8	14.6	<2.4E+01	8.6	<7.2E+01	<5.1E+01	13.0	<4.8E+01	8.3	12
Sm	4.38	6.45	3.53	2.52	23.7	3.82	2.08	2.73	5.11	2.39	5
Eu	1.42	2.39	1.14	0.97	0.87	1.35	0.89	0.89	1.93	0.92	5
Tb	0.91	1.27	0.72	0.46	0.45	0.80	0.46	0.52	1.55	0.44	5
Yb	3.00	3.10	2.66	2.01	1.40	2.41	1.63	1.85	5.33	1.96	5
Lu	0.44	0.40	0.38	0.32	0.22	0.36	0.23	0.27	0.82	0.33	5
Zr	105	80	<4.3E+02	116	<3.9E+02	<4.8E+02	81	<3.3E+02	53	77	15
Hf	2.1	2.3	2.0	1.5	1.3	3.1	1.1	2.6	4.0	1.6	5
Ta	0.12	0.13	0.13	0.07	0.11	0.14	<3.0E-01	0.25	0.16	<3.0E-01	5
Th	1.5	2.3	1.6	1.4	0.8	1.0	0.3	2.3	0.4	0.9	5

*Relative uncertainty in percent.

E \equiv $\times 10^{\text{exp}}$, where exp is the whole number following E.

Plutonic rocks

Plutonic rocks of the zoned intrusive complexes include hornblende, feldspathic pyroxenite (\pm olivine), gabbro (\pm olivine, \pm hornblende), and diorite. These rocks have all been metamorphosed to upper greenschist or lowermost amphibolite facies assemblages, such that pyroxene is commonly replaced by fibrous actinolite \pm chlorite, olivine by talc or serpentine, and plagioclase by epidote + quartz. Relict igneous plagioclase is commonly preserved; relict diopsidic pyroxene is less common, but is observed locally (e.g., Horkowitz, 1984). Relict igneous textures are recognized in many of the samples, and pseudomorphs of pyroxene or igneous hornblende are common. The pyroxenites and hornblendites are consistently coarse grained (1–3 cm) and exhibit relict decussate textures. The gabbros and diorites are generally finer grained (\leq 1 cm) with more equigranular textures. In general, these rocks show little or no metamorphic fabric despite their thorough metamorphic recrystallization. Nonetheless, in some highly strained gneisses (e.g., 1806), the plutonic protolith is apparent only through the consistent variations in major- and trace-element chemistry.

The major- and trace-element chemistry of the hornblendites, pyroxenites, and gabbros is consistent with their origin as cumulates from primitive basaltic magmas. The ultramafic cumulates are high in MgO (12%–22%), CaO (10%–18%), and Cr (300–1,400 ppm), and low in Al₂O₃ (4%–10%), TiO₂ (0.4%–0.6%), Sr (22–235 ppm), and alkalis (Fig. 3). The mafic cumulates (olivine gabbro, gabbro) are lower in MgO (5%–11%) and Cr (<600 ppm) and higher in Al₂O₃ (12%–18%), Sr (120–975 ppm), and alkalis than the ultramafic cumulates, consistent with the high cumulus plagioclase content of the gabbros. In general, the ultramafic cumulates are high in compatible trace metals (Cr, Ni, Sc) and low in incompatible trace elements (Sr, Rb, Nb, Y). Gabbros are generally low in all of these elements except the plagiophile element Sr. Vanadium is highest in hornblende-rich cumulates (550–620 ppm; hornblende, hornblende gabbro).

The diorites have major- and trace-element compositions that approximate a liquid line of descent from “andesite” (54 wt% SiO₂) to “dacite” (66 wt% SiO₂). With increasing silica, MgO, FeO*, and CaO all decrease, while Al₂O₃ and TiO₂ are relatively constant (Fig. 3). The alkalis scatter and show no consistent correlations with silica, indicating that these elements were relatively mobile during low to intermediate temperature regional metamorphism. The diorites are much lower in Cr, Ni, and Sc than the cumulates, and higher in Rb (as much as 60 ppm) and Y (as much as 70 ppm). Overall, the diorites are chemically similar to the intermediate and felsic volcanic rocks discussed in the following section, and may represent intrusive equivalents of these lavas.

Four samples of plutonic rock from the zoned intrusive complexes have been analyzed for REE concentrations (Fig. 4a). Two gabbros are enriched in LREE, with small positive Eu anomalies, consistent with plagioclase accumulation. A

hornblende-rich cumulate is also LREE rich, with La = 28 \times chondrite and no Eu anomaly. The diorite 1806 has a nearly flat chondrite-normalized REE pattern, with La = 33 \times chondrite and a deep negative Eu anomaly—consistent with an origin by plagioclase-dominated fractional crystallization.

Volcanic rocks

Volcanic rocks associated with the zoned intrusive complexes are dominantly basalt or basaltic andesite, with less common andesite, dacite, and rhyodacite. In general, the relative abundance of each rock type decreases with increasing silica content of the rock. Like the plutonic rocks, the volcanic rocks have been metamorphosed to upper greenschist or lowermost amphibolite facies assemblages comprising actinolite, chlorite, albite, quartz, epidote, and (in the more felsic rocks) biotite. Tuffaceous rocks are generally fine grained and finely laminated (mm scale) with alternating mafic and felsic rich laminae. Flows and dikes are more massive (poorly laminated) but also fine grained, except for pseudomorphs of fibrous actinolite after pyroxene (as much as 1.5 cm across) or epidote + quartz after feldspar (as much as several mm across).

For purposes of discussion and plotting, we recognize four broad groups of metavolcanic rock: (1) tholeiitic ankaramites, (2) high-Mg basalts and basaltic porphyries, (3) normal low-Mg basalts and basaltic andesites, and (4) intermediate to felsic volcanic rocks (andesite, dacite, rhyodacite). The geochemical characteristics exhibited by these rocks suggest that their parent lavas were also parental to the zoned intrusive complexes, as we discuss further in a following discussion.

Tholeiitic ankaramites are pyroxene and olivine megacrystic lavas that may contain as much as 40% phenocrysts modally (Fig. 5). Mapped occurrences include flows, dikes, and crystal-rich tuffs. These rocks are characterized chemically by high concentrations of MgO (10%–22%), Cr (300–1,440 ppm), and Ni (120–350 ppm), and lower than normal Al₂O₃ (7%–15%), TiO₂ (0.4%–1.0%), and Sr (20–80 ppm). The most mafic samples do not represent magmatic compositions, but are crystal cumulates similar to olivine pyroxenites of the zoned intrusive complexes in composition. Nonetheless, the origin of these samples as lava flows or dikes is confirmed by their field relations and by their porphyritic textures, which are distinct from the decussate textures of the intrusive cumulates (Fig. 5). The less mafic samples (1417 and 1419) have been highly strained; thus relict phenocrysts are not observed, but their chemical compositions closely approximate those expected for primitive, unfractionated magmas.

The high-Mg basalts include augite and hornblende porphyries, as well as basalts with no relict phenocrysts. These lavas are characterized by high MgO (11%–13%) but with low Cr (30–50 ppm) and Ni (<30 ppm) concentrations relative to the tholeiitic ankaramites. Compared to the normal, low-Mg basalts (next paragraph), these lavas are lower in TiO₂ (0.55%–0.8%), Al₂O₃ (12%–13%), and FeO* (8%–9%), and

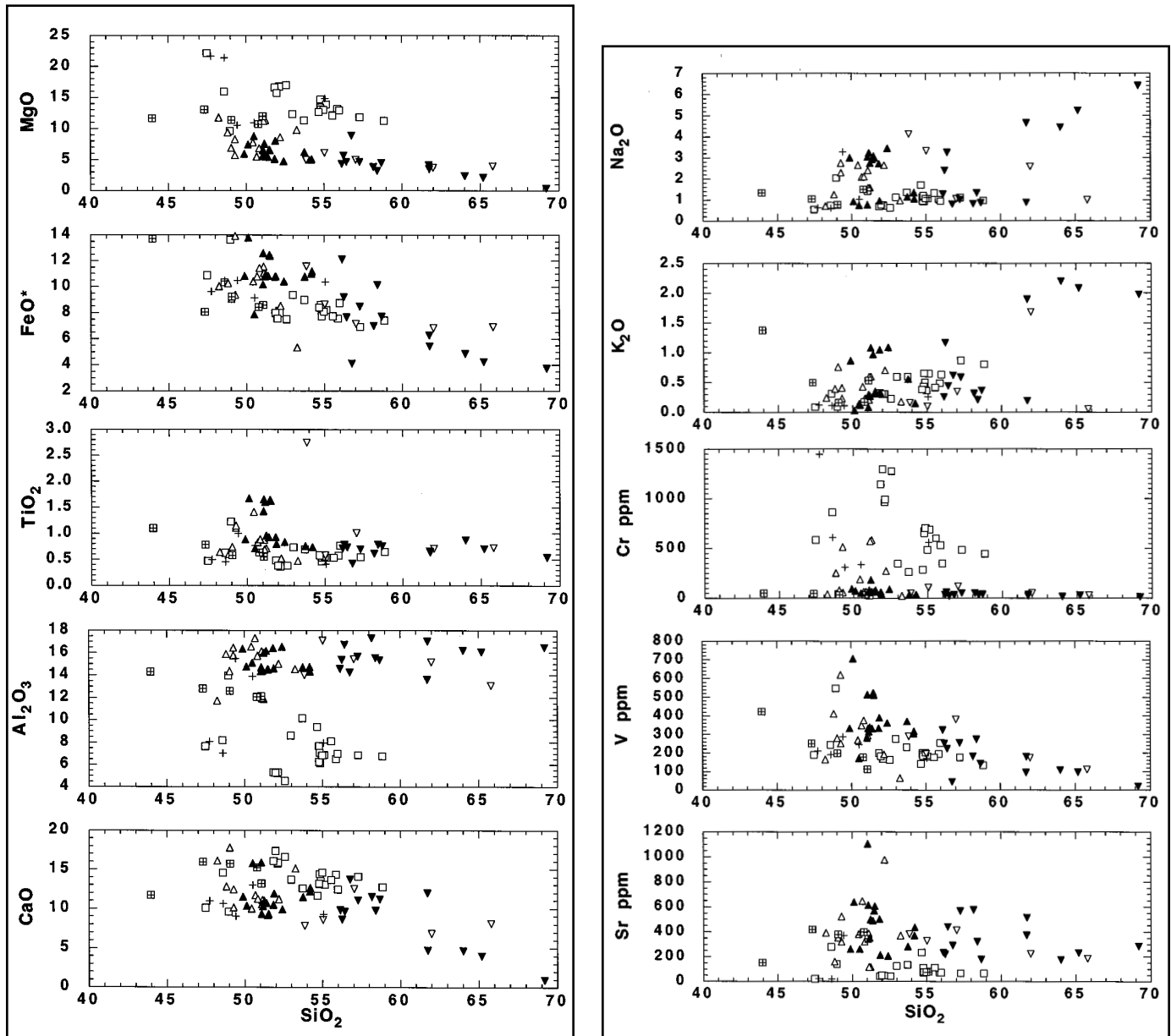


Figure 3. Harker variation diagrams for MgO, FeO*, TiO₂, Al₂O₃, CaO, Na₂O, K₂O, Cr, V, and Sr versus SiO₂. Filled symbols: metavolcanic rocks (crossed square = ankaramites, plus sign = high-Mg basalts; triangles pointed up = low-Mg basalts and basaltic andesites; inverted triangles = andesites and dacites). Open symbols: zoned intrusive complexes (squares = pyroxenite or hornblende, triangles pointed up = gabbros, inverted triangles = diorites).

higher in CaO (13%–16%). An exception to this general trend is hornblende porphyry sample 2473a, which is somewhat higher in TiO₂, FeO*, and V, and lower in CaO (Table 2). The chemical composition of the high-Mg lavas appears to be controlled by the accumulation of mafic phenocrysts, similar to the more mafic tholeiitic ankaramites. The primary difference between the augite porphyries of this group and the tholeiitic ankaramites described above seems to be the lack of primary olivine in the augite porphyries, and the composition of the

pyroxenes, which were more Fe rich and Cr poor in the augite porphyries than in the ankaramites.

Low-Mg basalts and basaltic andesites are the most common metavolcanic rock types in the areas mapped. These rocks have chemical compositions typical of normal, arc-related basalts, with 5%–9% MgO, 0.7–1.7% TiO₂, 14.3–16.5% Al₂O₃, and 9.3–15.9% CaO (Table 2). Cr, Ni, Sc, Rb, and Nb are all low, whereas Sr (200–600 ppm) and V (170–700 ppm) exhibit wide ranges in concentration. Overall, these elements display

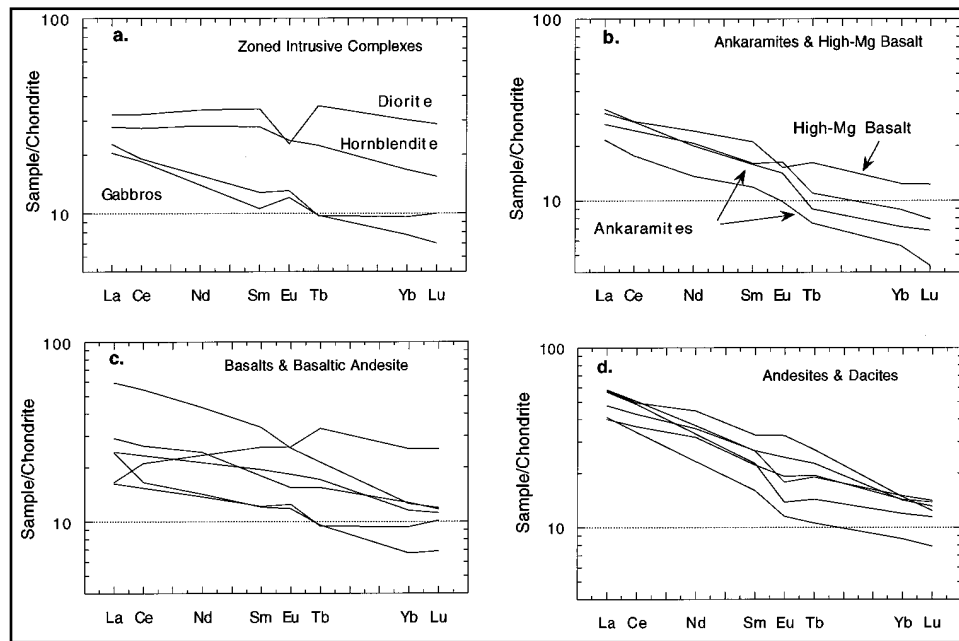


Figure 4. Chondrite-normalized REE concentrations for (a) plutonic rocks of the zoned intrusive complexes, (b) ankaramites and high-Mg basalts, (c) low-Mg basalts and basaltic andesites, and (d) andesites and dacites.

fractionation trends that are intermediate between tholeiitic and calc-alkaline magma series; for example, TiO_2 is generally low but relatively constant in concentration (Fig. 3). These lavas probably approximate a liquid line of descent, but minor variations in their major- and trace-element systematics show that several magma series must be involved.

Intermediate to felsic volcanic rocks include andesite, dacite, and rhyodacite, which occur most commonly as tuffs and tuff breccias. These rocks are characterized by low compatible element concentrations, and high concentrations of incompatible elements such as Rb and Y (as much as 80 ppm each). They are similar chemically to the intrusive diorites, and appear to define a liquid line of descent from the more primitive basaltic magmas. However, the scatter in chemical variation trends caused by element mobility during metamorphism makes it impossible to test quantitative fractionation models.

Sixteen samples of metavolcanic rock have been analyzed for REE concentrations (Fig. 4). Three ankaramites are LREE enriched with $\text{La} = 20\text{--}30\times$ chondrite, $\text{La/Lu} = 1.8\text{--}4.3\times$ chondrite, and very small positive Eu anomalies (Fig. 4b). These anomalies may result from clinopyroxene accumulation and not from plagioclase. A high-Mg basalt is also LREE rich with $\text{La} = 30\times$ chondrite, $\text{La/Lu} = 2.2\times$ chondrite, and a very small negative Eu anomaly (Fig. 4b). The low-Mg basalts and basaltic andesites have more variable patterns (Fig. 4c). Most samples are LREE rich with $\text{La} = 17\text{--}30\times$ chondrite, $\text{La/Lu} = 1.6\text{--}3.7\times$ chondrite, and in some samples, very small \pm Eu anomalies (Fig. 5b). One sample (1831) is strongly enriched in LREE, with $\text{La} = 70\times$ chondrite and $\text{La/Lu} = 5\times$ chondrite.

Another sample (2472) is LREE depleted, with $\text{La} = 18\times$ chondrite, and $\text{La/Lu} = 0.65\times$ chondrite (Fig. 5c). Intermediate to felsic samples are LREE rich, with $\text{La} = 40\text{--}60\times$ chondrite, $\text{La/Lu} = 2.9\text{--}5.2\times$ chondrite, and small negative Eu anomalies (Fig. 4d).

DISCUSSION

Origin of the volcanic rock series

Metavolcanic rocks in the western portion of the Carolina terrane in north-central South Carolina include tholeiitic ankaramites, pyroxene and hornblende porphyries, high-Mg basalts, low-Mg basalts and basaltic andesites, andesites, dacites, and (rare) rhyodacites. The rocks of the western Carolina terrane are distinguished from metavolcanic assemblages in the eastern portion of the Carolina terrane (e.g., Shervais et al., this volume) by the predominance of mafic lavas and by the occurrence of pyroxene megaphyric ankaramites and pyroxene porphyries. In the eastern Carolina terrane, metavolcanic rocks of the Persimmon Fork Formation are dominantly intermediate to felsic in composition. Metavolcanic rocks of the Richtex Formation are dominantly mafic (with some high-Mg basalts), but pyroxene megaphyric lavas are not observed. In addition, metavolcanic rocks form a relatively small proportion of the Richtex Formation, which consists largely of metamorphosed mudstones and wackes (Secor et al., 1986; Shervais et al., this volume). In contrast, metasedimentary rocks are rarely recognized in the western part of the Carolina terrane, which consists

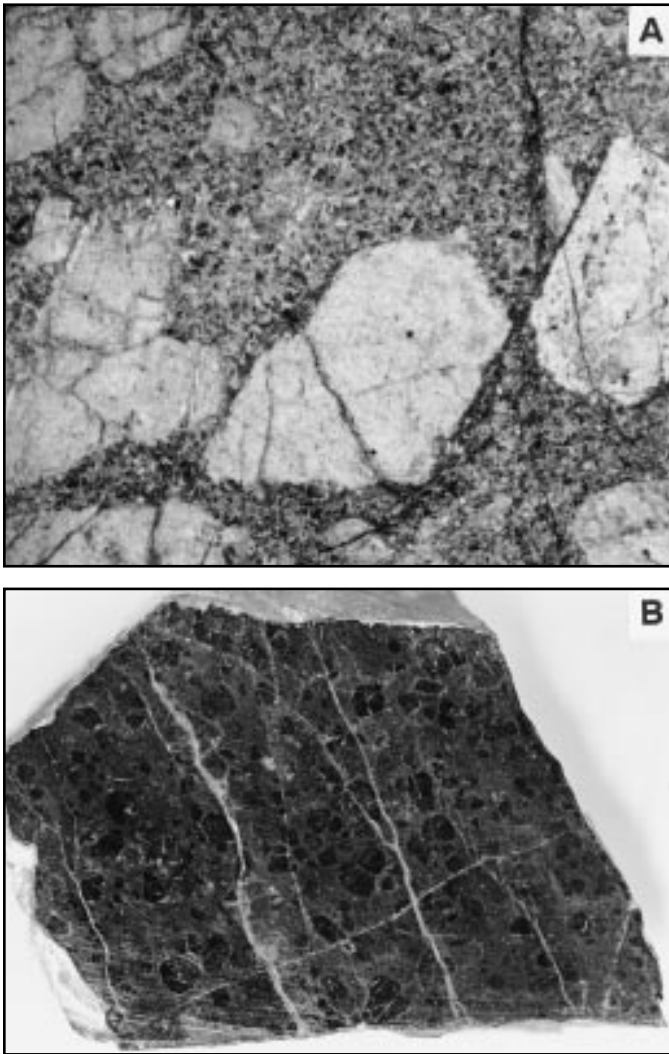


Figure 5. Photomicrograph (A) and hand specimen (B) of Sample 1512: metamorphosed ankaramite tuff. Clinopyroxene phenocrysts replaced by actinolite. Field of view in (A) is 25 mm. Slab (B) is 10 cm across.

almost entirely of metavolcanic assemblages and the associated zoned intrusive complexes (Dennis and Shervais, 1991).

Chondrite-normalized REE ratios indicate that almost all of the metavolcanic rocks are enriched in LREE ($La = 17\times\text{--}70\times$ chondrite, $La/Lu = 2\times\text{--}5\times$ chondrite), even those with $>20\%$ MgO, which indicates that these rocks were derived from primary magmas with similar enriched REE concentrations. The metavolcanic rocks are also enriched in LILE (e.g., Rb, Ba, Th, K, La, Ce) relative to normal-mid-ocean ridge basalt (N-MORB) and depleted in high field strength elements (e.g., Ta, Nb, Zr, Ti) relative to the LILE on N-MORB normalized “spider” diagrams (Fig. 6). Ankaramites are enriched in the compatible transition metals (Sc, Co, Ni, Cr), but all of the other metavolcanic samples are depleted in these elements relative to N-MORB.

All of these geochemical characteristics suggest formation

of the western Carolina terrane volcanic assemblages at a convergent plate boundary, above a subduction zone. The origin of these magmas in a supra-subduction zone setting is confirmed by other trace-element systematics, such as a Ti-V plot (Fig. 7). This plot shows that all but two of the mafic metavolcanic rocks analyzed here have Ti/V ratios of 10–20, consistent with an island arc origin for these lavas (Shervais, 1982). Thus, these magmas cannot represent a rifted margin magmatic suite like the Crossnore igneous complex (Rankin, 1972, 1975; Goldberg et al., 1986) or oceanic rocks associated with spreading center volcanism or plume volcanism.

A predominance of basaltic lavas is generally associated with juvenile or immature island arc volcanism. In the southwest Pacific, however, pyroxene megaphyric lavas (tholeiitic ankaramites; augite porphyries) are most commonly found in island arcs that have undergone rifting or uplift as a result of collision with subducting fracture zones or spreading centers. The classic examples of this are New Georgia in the Solomon Islands (Stanton and Bell, 1969; Ramsay et al., 1984) and several islands in the Vanuatu chain (e.g., Barsdell and Berry, 1990). A similar origin is likely for the western Carolina terrane, as we discuss in more detail in the next section.

Origin and significance of the zoned plutonic complexes

Butler (1989, 1991) recognized at least three centers of mafic-ultramafic zoned complexes and associated volcanic rocks in the Carolinas: the Davie County or Mocksville (North Carolina) complex (Taylor, 1982), the York-Chester (South Carolina) complex (Wagener, 1974; Butler, 1988; Dennis and Shervais, 1991), and the Latimer (Georgia–South Carolina) complex (Griffin, 1979). The Berner mafic complex (Georgia; Hooper and Hatcher, 1989) may also belong to this group. All of these complexes are characterized by the association of ultramafic cumulates (pyroxenites and hornblendites) with more common gabbro and/or diorite and by the intrusion of these rocks into nearly coeval metavolcanic assemblages. In some areas, pyroxene megaphyric lavas provide a link between the intrusive complexes and the associated volcanic sequence.

Similar relations were reported by Snoko et al. (1982) in the Sierra Foothills and Klamath Mountains of the western Cordillera. They inferred that these complexes require the ascent of highly magnesian parent magmas to shallow crustal levels without appreciable fractionation and that this is most likely to occur during rifting of an active subduction-related arc. They compared their observations to arc terranes in the southwestern Pacific (e.g., Vanuatu, New Georgia).

Dennis and Shervais (1991, 1992) applied this hypothesis to the metamorphosed zoned complexes and metamafic and ultramafic rocks of the Carolina terrane in northwestern South Carolina. The association of highly mafic lavas with zoned mafic-ultramafic intrusive complexes, Mg- and Ca-rich major-element chemistry, and crystallization sequence (olivine-pyroxene-plagioclase) are interpreted to record a

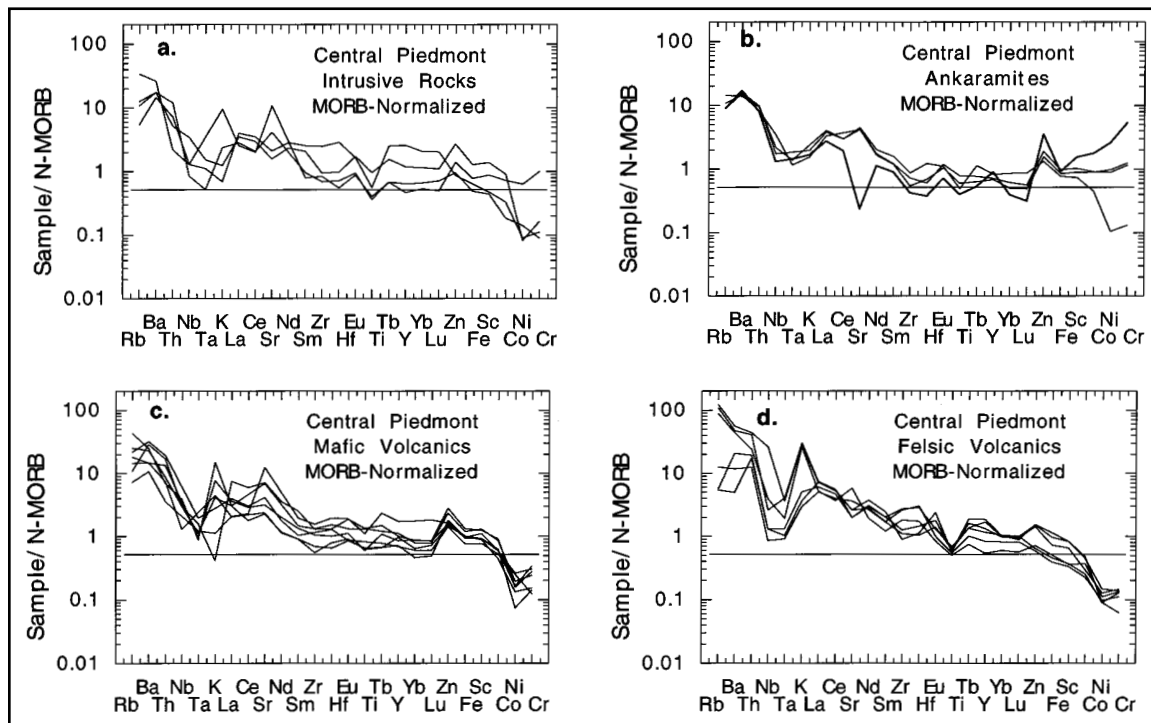


Figure 6. Trace-element concentrations in metavolcanic and metaplutonic rocks of the western Carolina terrane normalized to present day oceanic crust (Taylor and McLennan, 1985; Sun and McDonough, 1989): (a) plutonic rocks of the zoned intrusive complexes, (b) ankaramites and high-Mg basalts, (c) low-Mg basalts and basaltic andesites, and (d) andesites and dacites. Note enrichments in LREE, K, Rb, Th, and Ba, and negative anomalies in the HFSE (Nb, Ta, Ti) relative to the LILE, which are characteristic of arc volcanic series (Pearce, 1982). Basalts, andesites, and dacites are generally depleted in compatible transition metals (Sc, Co, Ni, Cr), but ankaramites are enriched in these elements and may represent primary magmas.

magmatic event in which the lithospheric thinning that accompanied arc rifting allowed highly mafic lavas to ascend without appreciable fractionation and erupt at the surface.

Timing of the intrusive events and orogeny in the Carolina terrane

Recent geochronologic data in the Glenn Springs and Jonesville 7.5' quadrangles (Dennis and Wright, 1993) place arc rifting in the context of diachronous-semicontinuous penetrative deformation and intrusion in an evolving subduction-related arc and extend a late Precambrian–Early Cambrian regional penetrative deformation across the width of the Carolina terrane (Dennis et al., 1993). A biotite porphyry granodiorite pluton intruding amphibolites (Fig. 2, “a”) appears to contain all the fabric elements in those amphibolites and yields a U-Pb zircon crystallization age of ca. 570 Ma. Heterogeneously deformed Mean Crossroads complex metadiorite gneiss yields a U-Pb zircon crystallization age of 540 Ma (Fig. 2, “b”). From this we estimate that the age of the Mean Crossroads and Wildcat Branch zoned plutonic complexes is ca. 540 Ma. The

contact between metadiorite and metabasalt is intruded by an undeformed, unmetamorphosed diorite (Fig. 2, “c”). This pluton was dated by the U-Pb zircon method and yielded a crystallization age ca. 535 Ma. Thus arc rifting in the western portions of the Carolina terrane in South Carolina was accompanied by penetrative deformation in the period 570–535 Ma.

The ca. 570 Ma strongly foliated biotite porphyry granodiorite intruding mafic metavolcanic rocks is significant in that it demonstrates that not all the mafic volcanic rocks are the same age as the zoned complex plutonic rocks. Because the Mean Crossroads complex yields a crystallization age ca. 540 Ma, some mafic metavolcanic rocks, at least the ones intruded by the biotite porphyry granodiorite, predate the zoned complexes by about 30 Ma. Secondly, although the granodiorite gneiss appears to contain all the fabric elements that are preserved in the mafic metavolcanic rocks, it may be the case that the mafic metavolcanic rocks were already well foliated at the time of intrusion. The results of Dennis and Wright (1993) demonstrate that regional metamorphism and fabric development in this area are late Precambrian to Cambrian in age. If the granodiorite does not contain all fabric elements recognized in the rocks it intrudes, then the initiation of metamorphic fabric development

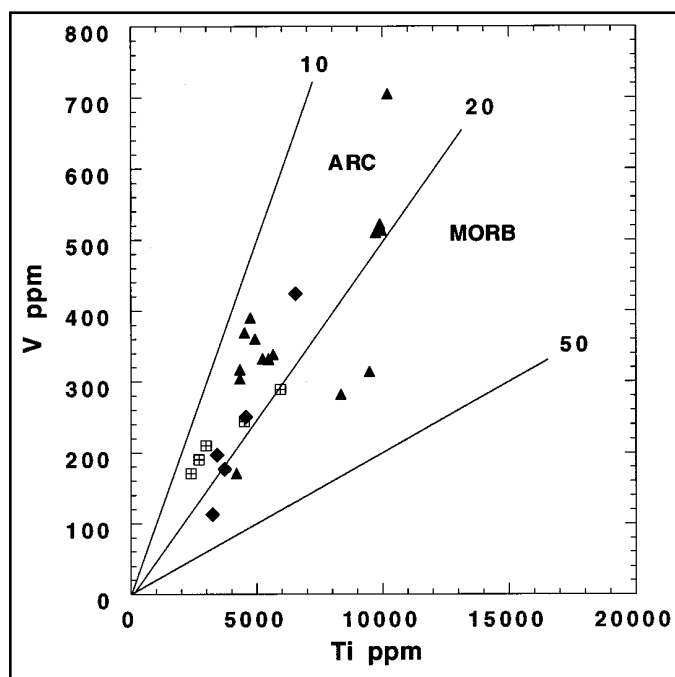


Figure 7. Ti-V plot for basic metavolcanic rocks of the western Carolina terrane (<55% SiO₂). Almost all samples have Ti/V = 10–20, characteristic of arc volcanic series (Shervais, 1982). Two samples with higher Ti/V ratios (~30) are mylonites with quartz veins, which may have been affected by more intense element mobility than the other samples. See Figure 3 for an explanation of symbols.

in the western Carolina terrane is even older than 570 Ma. This reflects the ongoing penetrative regional deformation at relatively shallow crustal levels (<garnet isograd, ca. 425 °C) contemporary with active volcanism.

A remarkable aspect of the deformation in this area is its extreme heterogeneity in rocks of the same protolith, the same metamorphic grade, and the same age. For example, Sample 1512 is interpreted to be an ankaramitic tuff (Fig. 5), and clinopyroxene phenocrysts are pseudomorphed by actinolitic amphibole. Good volcanic textures are still preserved. Samples 1417 and 1419 are also interpreted to be ankaramitic tuffs on the basis of major- and trace-element whole rock chemistry, yet there is no meso- or microscopic textural evidence for a volcanic origin. These rocks are mapped as actinolitic hornblende schists in a sequence of meta-andesites. Wildly varying strain gradients may also be a characteristic of active volcanic arcs. We stress that the accumulation of volcanic material, deformation and metamorphism are within limits of error contemporaneous with each other.

This area is unusual in that a large segment (50 km) of the terrane-bounding fault that separates the Carolina terrane from the Inner Piedmont has not been reactivated by late Paleozoic transcurrent and transpressive motion. As a result, it is possible to infer relative timing of pre-Alleghanian, ductile motion on the central Piedmont suture. Dennis (1991, his Fig. 2b) shows

that the central Piedmont suture crosscuts this regional foliation between Spartanburg and Laurens, and the fault where mapped here must postdate the regional metamorphic fabric. Ductile motion on the central Piedmont suture must have ceased prior to ca. 400 Ma, because syenite dikes radiating out from a ring syenite surrounding the Buffalo gabbro and intruding mafic metavolcanic amphibolites are undeformed, and the ca. 383 Ma Pacolet granite does not contain solid-state deformation fabrics that are unrelated to the Carboniferous Kings Mountain shear zone. Thus we can bracket ductile deformation on the central Piedmont suture between 535 Ma and 400 Ma.

As noted earlier the age of volcanism in the eastern Carolina terrane is indicated by the ages of hypabyssal intrusives to be ca. 550 Ma, the same age as that in the western Carolina terrane. Yet in the well-preserved volcanic, volcanoclastic, and epiclastic stratigraphy of the eastern Piedmont, there is little indication of the ongoing deformation and metamorphism that accompanied accumulation of the volcanic pile. The hypothesis of Dennis and Shervais (1991) may be correct: the Richtex Formation represents the remains of an intra-arc rift basin with turbiditic wackes shed from the eroding arc intercalated with basalts erupted far from the axis of active arc rifting. It is also possible, however, that at the same time the Persimmon Fork Formation was being erupted in the east, the zoned intrusive complexes and related extrusive rocks were forming in the west, and the Richtex Formation largely postdates them both.

Dennis et al. (1993) suggest that late Precambrian to Early Cambrian regional metamorphism and fabric development may extend across the Carolina terrane. The ca. 550 Ma hypabyssal Longtown metagranite is weakly deformed to massive and intrudes strongly deformed Persimmon Fork Formation. This may be a reflection of the effect of grain size on deformation, but it may also be a consequence of intrusion of the Longtown relatively late in the kinematic history. Dennis et al. (1993) also cite a possible angular unconformity beneath the trilobite-bearing upper mudstone of the Asbill Pond formation. This contact is apparent on plate I of Secor et al. (1986). Dennis et al. (1993) interpreted the poorly cleaved Middle Cambrian upper mudstone of the Asbill Pond to post-date regional deformation in the eastern Piedmont. Thus, the late Precambrian to Early Cambrian ongoing, semicontinuous orogenic development clearly documented in the Carolina terrane in northwestern South Carolina may also be observed across the width of the terrane in the eastern Piedmont.

Cadomia connection?

The age and lithology of rocks of the Cadomian orogeny (D'Lemos et al., 1990) suggest a strong link with the rocks described here. Compilation of Nd isotopic systematics of igneous rocks in the Carolina-Avalon terranes by Nance and Murphy (1994) resulted in a comparative study of the basement character on which each fragment accumulated. The resulting

reconstruction (their fig. 4) places Carolina between Cadomia and Spain, adjacent to Morocco, with Bohemia filling in the puzzle between Carolina, Cadomia and the Trans-Amazonian–Eburian and Central Amazonian–Liberian craton. The position of Cadomia next to the Proterozoic craton is controlled by the mostly negative ϵ_{Nd} data of Cadomia interpreted by D’Lemos and Brown (1993) and Nance and Murphy (1994) to indicate the ca. 600 Ma mixing of mantle material with Icartian (i.e., 2 Ga)–like basement. Eastern Avalonia (southern England and Wales) shows a range of ϵ_{Nd} values similar to those of Cadomia, whereas West Avalonia (New England and Maritime Canada) and Carolina are all reported by Nance and Murphy (1994) to yield strongly positive ϵ_{Nd} values, indicating relatively recent mantle extraction and relatively little crustal involvement. The position of Bohemia is controlled by reported similarities in its faunal assemblage with that of Batesburg (Carolina) (Samson et al., 1990). While this location of Carolina is not particularly well constrained, and a comparison between the geology of northwestern France and that of the Carolina terrane is beyond the scope of this chapter, in light of the temporal and lithologic similarities between the geology described here and that of portions of Cadomia, a few observations are in order.

The Cadomian orogeny records the accumulation of a subduction-related volcanic arc on Proterozoic basement over the period 700–425 Ma and the sinistral transcurrent assembly of portions of that arc system in late Precambrian time (ca. 540 Ma) (Brown et al., 1990; the source of the following descriptions). From northwest to southeast in Brittany, the terranes that make up the North Armorican composite terrane are the St. Brieuc, St. Malo, and Mancellian. The northwesternmost Guernsey–La Hague structural block of the St. Brieuc terrane comprises foliated plutonic complexes of volcanic arc granites. Post-tectonic intrusives are ca. 500 Ma. The Jersey structural block is interpreted to represent higher structural levels and a greater distance from the trench. The St. Malo terrane is interpreted to be an inverted back-arc or intra-arc basin made up of migmatite. The Mancellian terrane is made up of low-grade supracrustal Brioverian sediments into which the Mancellian Batholith (ca. 530 Ma) is emplaced. This arrangement is crudely like that of the Carolina terrane in the Carolinas: the lower metamorphic grade, mafic western Carolina terrane to the northwest; the high-grade core of the Charlotte belt, and the low-grade Carolina slate belt to the southeast. How it is strikingly different is in the documentation of sinistral transpression broadly contemporaneous with magmatism. It is possible that faults roughly corresponding to belt boundaries in the Carolina terrane originated along a late Precambrian transpressive plate boundary, but subsequent mid- to late Paleozoic tectonism overprinted and obscured the original nature of these contacts. Although the Late Proterozoic kinematics of Brittany may not be shared with Carolina, future mapping and re-evaluation of published maps should consider this possibility. Our observations and Nance and Murphy’s (1994) reconstruction suggest that in the late Pre-

cambrian, Carolina may have more in common with Cadomia than the Avalon terrane of New England and Maritime Canada.

CONCLUSIONS

(1) The Carolina terrane is an exotic volcanic arc terrane in the hinterland of the southern Appalachian Piedmont. The eastern portions of the terrane comprise a well-studied, low-grade felsic to intermediate volcanic and epiclastic stratigraphy. In the western portions of the terrane, the metamorphic grade is generally higher (although no higher than middle amphibolite facies), and the rocks are more highly strained and have a variety of mafic and ultramafic protoliths.

(2) Metaplutonic rocks intrude greenstones and amphibolites interpreted to represent their extrusive equivalents in the northwestern portions of the Carolina terrane in South Carolina. The metaplutonic rocks form zoned intrusive complexes that range from dioritic rims to clinopyroxenite-hornblende-serpentinite cores. Metavolcanic rocks include megaphyric ankaramites and pyroxene porphyries as well as more common laminated amphibolites. The ultramafic volcanic rocks occur as dikes cutting intrusive and extrusive rocks and flows within the extrusive section.

(3) This rock association is not unique to northwestern South Carolina; it is also observed on the western edge of the Carolina terrane in the central Georgia Piedmont, at the Georgia–South Carolina line, north and east of the Bald Rock pluton in north-central South Carolina, and in central North Carolina.

(4) Whole rock geochemical data from metaigneous rocks in the Wildcat Branch and Mean Crossroads complexes are consistent with their origin above a subduction zone. Salient features of the data are the wide range in SiO_2 content, transitional tholeiitic–calc-alkaline fractionation trends, enrichments in LILE, and concomitant depletions in HFSE, and Ti/V ratios of 10–20.

(5) Geochronologic data support field observations that indicate regional metamorphism and heterogeneous penetrative deformation accompanied arc magmatism between 570 Ma and 535 Ma. Field observations include metamorphosed mafic dikes crosscutting quartz-sericite schist zones well known from gold exploration. Transposition of rock units is highly variable.

(6) The preceding points are consistent with an origin for the intrusive-extrusive association through rifting of an active subduction-related arc, following analogs in the Mesozoic Klamath Mountains and western Sierra Foothills, California, and modern rifted arc terranes of the southwestern Pacific.

(7) Intrusion of the zoned complexes is approximately the same age or slightly younger (ca. 10 Ma) than the Persimmon Fork Formation, a felsic to intermediate composition volcanic unit in the Carolina slate belt. Effects of the regional metamorphic and deformation event may extend across the Carolina into

the eastern Piedmont. We believe that deposition of the Middle Cambrian upper mudstone of the Asbill Pond formation post-dates this event.

(8) There are reasonable lithologic and temporal similarities between the Carolina terrane and the Cadomian orogeny of Brittany, France. Future tectonic studies may extend this comparison. Cadomia may represent a better candidate for comparison with Carolina than the Avalon terrane of New England or Maritime Canada.

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APPENDIX 1. LATITUDE AND LONGITUDE OF ANALYZED SAMPLES

Sample	Latitude °N	Longitude °W	Sample	Latitude °N	Longitude °W
METAPLUTONIC ROCKS					
1346	34°49'57"	81°47'12"	2246	34°45'31"	81°51'13"
1516	34°47'29"	81°46'21"	2246	34°45'31"	81°51'14"
1550	34°49'27"	81°46'40"	2292	34°47'41"	81°44'15"
1565	34°46'13"	81°46'07"	2420	34°46'18"	81°42'47"
1577	34°46'44"	81°45'55"	2425	34°46'27"	81°43'12"
1806	34°50'46"	81°44'26"	2426	34°46'32"	81°43'17"
1829	34°47'12"	81°50'27"	2428	34°46'41"	81°43'31"
1885	34°47'38"	81°48'28"	2432	34°46'35"	81°43'39"
1992	34°48'25"	81°48'27"	2466	34°34'06"	81°47'37"
2018	34°47'21"	81°47'25"	2468	34°35'39"	81°46'50"
METAVOLCANIC ROCKS					
1306	34°48'38"	81°49'09"	1927	34°50'07"	81°47'34"
1417	34°45'43"	81°47'29"	2004	34°46'16"	81°50'26"
1419	34°45'50"	81°47'13"	2037	34°45'40"	81°46'04"
1484	34°45'17"	81°47'39"	2274	34°45'25"	81°46'44"
1506	34°46'21"	81°48'37"	2462	34°31'50"	81°47'53"
1510	34°48'04"	81°46'44"	2464	34°32'25"	81°47'52"
1512	34°47'35"	81°46'08"	2464	34°32'25"	81°47'50"
1535	34°48'48"	81°45'33"	2467	34°35'36"	81°46'53"
1584	34°46'36"	81°44'19"	2470	34°34'48"	81°46'54"
1730	34°51'47"	81°41'57"	2472	34°42'20"	81°48'49"
1831	34°47'39"	81°50'29"	2473	34°42'16"	81°48'37"
1889	34°51'43"	81°40'23"	2474	34°42'21"	81°48'36"
1906	34°51'03"	81°40'54"	2478	34°43'14"	81°46'18"
1908	34°51'58"	81°40'57"	McClure	34°48'00"	81°45'45"

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