

## PETROGRAPHY, GEOCHEMISTRY, AND TECTONIC SIGNIFICANCE OF THE AMPHIBOLITES OF THE ALABAMA PIEDMONT†

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**ABSTRACT.** The Alabama Piedmont contains amphibolites in three structurally distinct tectonic blocks. In the Northern Piedmont, north of the Brevard zone, the Mitchell Dam, Ketchepedrakee, and Beaver Dam Amphibolites occur intercalated with metasedimentary rocks. In the Inner Piedmont block, south of the Brevard zone, the Doss Mountain, Ropes Creek, Waresville, and Zebulon amphibolitic units occur. In the Uchee block of the Southern Piedmont, south of the Towaliga Fault zone, the Hudson Rapids Amphibolite occurs. All amphibolites are interpreted to be of metaigneous origin based upon Niggli trends, presence of relic pyroxene, general geochemical character, and spatial relationship to igneous rocks. The protoliths of the amphibolites were tholeiitic basalts based upon normative mineralogy and chemical distinctions such as alkali-SiO<sub>2</sub>, AFM, and the Y/Nb ratio. REE patterns are flat with slight LREE enrichment. All the amphibolites are geochemically similar except for the Doss Mountain Amphibolite, which has exceptionally low alkali, TiO<sub>2</sub>, REE, and incompatible element contents. Except for the Doss Mountain Amphibolite, the parental basalts represent an oceanic rifting environment; an E-MORB tectonic character is suggested. The Doss Mountain parental basalt, however, represents arc activity.

### INTRODUCTION

The amphibolites of the Alabama Piedmont generally have been presumed to be metaigneous material. With the exception of recent studies of the Mitchell Dam Amphibolite (Bloss, ms) and the Ketchepedrakee Amphibolite (Whittington, ms), however, there are very few geochemical data available to support such a contention. There has previously been little information published on the characteristics and origins of these amphibolites except for a report on the petrography and structure of the Mitchell Dam Amphibolite (Rheams, ms). Thus, our objectives are to summarize the present knowledge of the field relationships and structural settings and to characterize the geochemistry and petrography of the major amphibolites of the Alabama Piedmont. We shall show that they are orthoamphibolites, that they represent tholeiitic basaltic protoliths, and we shall discuss the tectonic environments in which igneous activity occurred.

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## GEOLOGIC SETTING

The Alabama Piedmont can be divided into three lithotectonic provinces (fig. 1) bounded by major fault systems. The Northern Piedmont lies north of the Brevard zone and is bounded on the northwest by the Valley and Ridge province and on the southwest by the Gulf Coastal Plain. South of the Brevard zone are the Inner and Southern Piedmonts, separated by the Towaliga Fault zone and bounded on the south by the Coastal Plain sediments.

The Northern Piedmont is divided by major thrust faults into the Talladega, Coosa, and Tallapoosa blocks. Descriptions are provided by Neathery and Reynolds (1975), Neathery (1975), Tull (1975, 1978), and Tull and Stow (1980). The Talladega block is dominantly metasedimentary rock, but an arc-related metavolcanic sequence, the Hillabee Green-

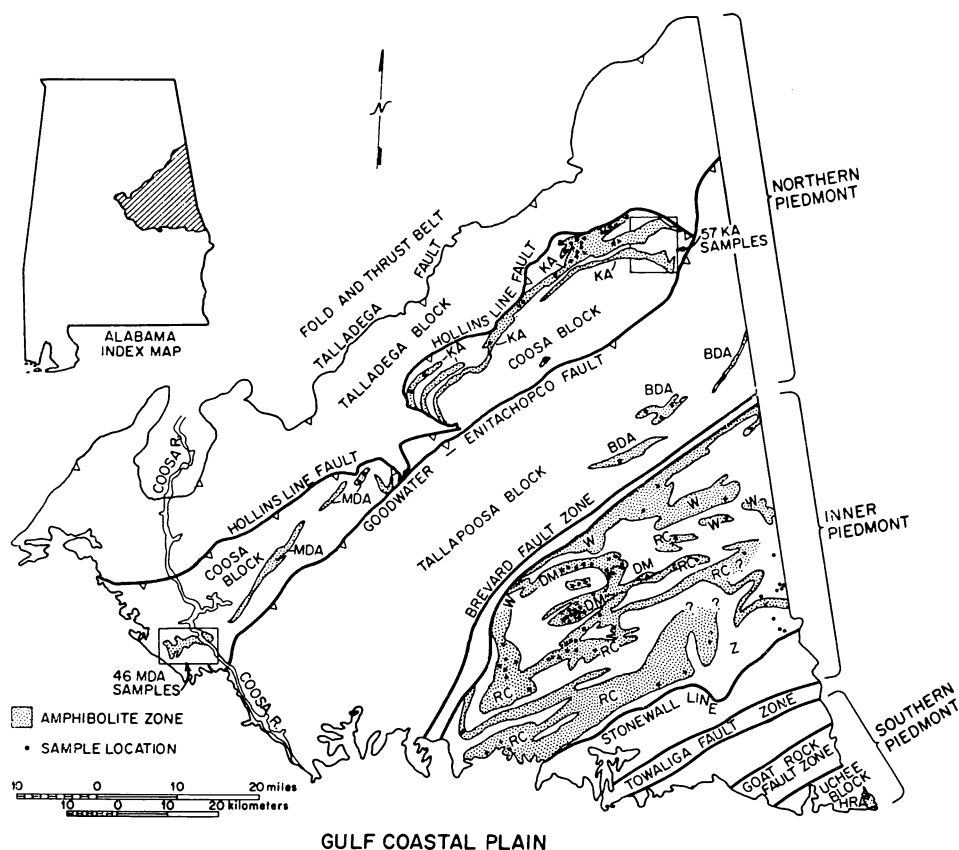


Fig. 1. Map showing generalized distribution of amphibolite rocks in the Alabama Piedmont. Sample locations are shown. In the Northern Piedmont: MDA is the Mitchell Dam Amphibolite; KA, Ketchepedrakee Amphibolite; BDA, Beaver Dam Amphibolite. In the Inner Piedmont: W is the Wareville Formation; RC, Ropes Creek Formation; DM represents the distribution of mafic complexes that include the Doss Mountain Amphibolite; Z, Zebulon Formation. In the Southern Piedmont, HRA is the Hudson Rapids Amphibolite.

stone (Stow, 1982; Tull and Stow, 1980), occurs at the stratigraphic top of the block. Metamorphic grade is lower greenschist. Rocks of the Coosa block are predominantly metasedimentary rocks (graphitic mica schists, garnet mica schists with quartzites) and amphibolites (Mitchell Dam and Ketchepedrakee) of the Ashland Supergroup (Tull, 1978). The Tallapoosa block, bounded by the Goodwater-Enitachopco fault and the Brevard fault zone, is dominantly pelitic metasedimentary rock with a significant amount of granitic rock in the southwestern part. Amphibolites are rare, but the Beaver Dam Amphibolite is found in the southeastern part of the block. There are limited geochronologic data available for the Northern Piedmont. Tull and Stow (1980) interpret the volcanism of the Talladega block to be of Early to Middle Devonian age, whereas Tull (1978) interprets the minimum age of the metasedimentary rocks of the Tallapoosa block to be Middle to Late Cambrian. There are no definitive maximum ages for the rocks of the Coosa block.

Two major lithostratigraphic groups dominate the Inner Piedmont. Between the Brevard zone and the Stonewall Line, amphibolites (Ropes Creek), hornblende schists, and minor pelitic schists and gneisses of the Dadeville Group occur; south of the Stonewall Line is the Opelika Group, consisting of aluminous metapelites, biotite gneisses, mica schists, quartzites, and rare amphibolites (Sears, Cook, and Brown, 1981; Bentley, Neathery, and Scott, in press). Both groups are intruded by granite plutons. In addition, pyroxenite, gabbro, and norite plutons are found within the Dadeville Group. All igneous activity predated the major prograde regional metamorphic event that raised rocks to the Barrovian amphibolite facies (Sears, Cook, and Brown, 1981; Neilson, 1983). There are no definitive ages for rocks of the Inner Piedmont.

The Southern Piedmont consists of the Pine Mountain window and the Uchee block and lies south of the Towaliga fault. The Pine Mountain window consists of a Precambrian basement complex with a cover sequence of quartzite, marble, and schist. The Uchee block consists of coarsely crystalline biotite gneiss with schist and amphibolite.

#### DESCRIPTIONS OF THE AMPHIBOLITES

*General.*—Three major amphibolites from the Northern Piedmont are described in this report: the Mitchell Dam (MDA — 48 samples), the Ketchepedrakee (KA — 86 samples), and the Beaver Dam (BDA — 5 samples). The general distribution of these units, with sample locations, is shown on figure 1. The majority of the MDA samples comes from the vicinity of the Coosa River in Coosa and Chilton Counties (Bloss, ms; Rheams, ms), and the majority of KA specimens comes from the Mica-ville-Turkey Heaven Mountain area of southern Cleburne County (Whittington, ms).

Within the Inner Piedmont extensive geochemical data are available on two amphibolites: the Doss Mountain (DMTA — 35 samples) and the Ropes Creek (RCA — 27 samples). Data are also presented for Inner Piedmont amphibolites from the Waresville Formation (WA — 5 samples) and the Zebulon Formation (ZA — 2 samples). Data for two samples

of the Hudson Rapids Amphibolite (HRA) of the Southern Piedmont are presented. In the following discussion the HRA data are included with those for amphibolites of the Inner Piedmont. The majority of samples of the DMTA and RCA comes from the vicinity of Dadeville in Tallapoosa County.

*Mitchell Dam Amphibolite (MDA).*—The MDA is the most completely studied amphibolite in the Alabama Piedmont. The structural and stratigraphic setting, petrography, geochemistry and tectonic significance of the unit have been discussed by Bloss (ms), Kalk (ms), Rheams (ms), and Schneider (ms). The amphibolite is best exposed along Alabama Highway 22 east of the Coosa River, which is the area from which most of the samples for this investigation came. The MDA is surrounded by and intercalated with metasedimentary rock consisting of garnetiferous schists and gneisses. Contacts between the MDA and the metasedimentary rock are generally sharp, conformable, and non-tectonic; locally faulted contacts and interlayering of the MDA and the schists occur.

Previous investigations have identified four to nine major lithologies and five to six sublithologies of the MDA, including a metagabbroic phase. The most common lithology is a medium-grained, massive to thinly banded and foliated amphibolite composed of greenish to yellowish-brown to black hornblende and plagioclase ( $An_{10-50}$ ) in roughly equal proportions. Relic augite commonly occurs. Plagioclase occurs in laminae or interstitial to the hornblende and is almost always altered to epidote, zoisite, and saussurite. Metamorphic grade is in the staurolite, kyanite, and sillimanite zones of the amphibolite facies. Locally the MDA is retrograded and contains actinolite and sericite.

*Ketchepedrakee Amphibolite (KA).*—The outcrop belt of the KA ranges from less than 100 m to over 1000 m in width. Included within the amphibolite are zones of coarse hornblendite, pyroxenite, felsic dikes and lenses, rare pegmatites, schists, and gneisses. Contacts between the KA and the surrounding metasedimentary rocks are sharp and conformable. Near the southwestern end of the outcrop belt in Clay County the KA is interbedded or infolded with graphite schist and feldspathic biotite gneiss. Locally the amphibolite has been retrograded to a chlorite schist.

The KA varies from massive to moderately foliated and from dark greenish-black to dark bluish-gray. Pods of coarse hornblendite and isolated bodies of pyroxenite occur within the amphibolite. Average modal mineralogy of the KA is hornblende (67 percent), plagioclase (9 percent), and quartz (8 percent); relic clinopyroxene occurs (Whittington, ms). Hornblende grains, generally less than 2 mm long, define the foliation. Plagioclase occurs as untwinned and unzoned grains up to 0.1 mm long and as grains up to 0.7 mm long often with albite twinning or growth zonation (Whittington, ms).

*Beaver Dam Amphibolite (BDA).*—The fabric, texture, and mineralogy of the BDA are highly variable. The unit ranges from highly foliated and schistose to nearly massive; banding of felsic and mafic layers ranges from very thin to thick (several cm), and grain size from very fine to coarse. Mafic segregations occur locally (Neathery and Reynolds, 1975).

The mineralogy of the BDA is dominated by green hornblende and plagioclase. Relic clinopyroxene and enstatite occur. Near major shear zones the amphibolite may have been retrograded and is composed of tremolite, actinolite, oligoclase, epidote, quartz, and chlorite. Neathery and Reynolds (1975) report the grade to be within the kyanite or lower sillimanite zone of the almandine amphibolite facies.

*Ropes Creek Amphibolite (RCA).*—The RCA is the most common rock type found in the Ropes Creek Formation of the Dadeville Group (Sears, Cook, and Brown, 1981). In the Tallassee Synform the Ropes Creek Formation is remarkably free of clastic material (Fleming, Nunan, and Neilson, 1980), but in the Boyds Creek area, thick units of quartzite and sillimanite schist are intercalated with the amphibolites (Sears, Cook, and Brown, 1981). The Ropes Creek Formation structurally overlies the Zebulon Formation, is overlain by the Agricola Formation, and is intruded by both felsic and mafic-ultramafic igneous rocks (Sears, Cook, and Brown, 1981; Neilson, 1983).

The amphibolite is fine-grained (<0.5 mm), equigranular, conspicuously well foliated and lineated, and has compositional banding on a 4 to 8 mm scale. Grain size variations outline a larger scale banding on the scale of 5 to 10 cm (Fleming, Nunan, and Neilson, 1980). In thin section, the most common variety of RCA has a characteristic nematoblastic texture dominated by acicular, yellow-green to olive-green hornblendes which define the foliation and lineation. A subordinate variety has more of a lepidoblastic texture with prismatic hornblendes. All specimens contain quartz and poorly twinned, prismatic, subidioblastic plagioclase (An<sub>33-85</sub>). In some rocks hornblende exhibits ragged grain boundaries, suggesting a second episode of growth. Relic igneous pyroxene has not been identified, but a pale green diopside that coexists with hornblende and plagioclase is occasionally found. Garnet occurs as poikiloblasts, whereas epidote occurs as either subhedral tablets or as xenoblastic aggregates that appear to post-date the major episode of prograde metamorphism. Opaque oxides and sphene are ubiquitous.

*Doss Mountain Amphibolite (DMTA).*—Massive (non-layered) amphibolites associated with mafic-ultramafic plutons in mafic complexes (Bentley and Neathery, 1970) and with the RCA are found throughout the Dadeville Complex (Neilson, 1983). Frequently these amphibolites have outcrop patterns suggestive of elongated, sill-like bodies. In the mafic complexes, the amphibolites form sheaths to partially reconstituted norites and orthopyroxenites and are chemically indistinguishable from the norites (Neilson and Stow, 1980; Stow and others, 1982a). These amphibolites are interpreted as the metamorphosed rims of noritic intrusions, the progenitors of which intruded all members of the Dadeville Group (Neilson, 1983).

In the field, members of the DMTA are recognized by their medium- to coarse-grain size and massive and poorly foliated appearance. The rocks have a dark green to green-black color; many samples are so rich in hornblende that they are called hornblendites. The completely reconstituted DMTA displays a granoblastic-polygonal texture in which the

hornblende and well-twinned plagioclase (An<sub>70-90</sub>) are idioblastic and have straight to gently curving boundaries. Poikiloblasts of garnet occur in Fe + Mg-rich samples, whereas Ca-rich rocks contain a subordinate, pale green diopside. Accessory minerals include sphene, opaque oxides, quartz, and epidote. Relic minerals of igneous origin are common in the less reconstituted members of the DMTA. They include both bronzite and augite as well as "clouded" plagioclase, all of which are found in the Doss Mountain Norite.

*Waresville Amphibolite (WA).*—A suite of delicately interlayered amphibolites, chlorite–actinolite schists, actinolite–feldspathic quartzites, and quartzites, collectively called the Waresville Formation, crops out along the Brevard zone (Bentley and Neathery, 1970). In immediate contact with the Brevard zone, chlorite-rich rocks are the most common, but, away from this zone, amphibole becomes the dominant ferromagnesian mineral. The Waresville Formation is similar to rocks of the Chauga belt as described by Hatcher (1972).

The WA is characterized by a nematoblastic texture in which both plagioclase (well-twinned, but unzoned) and hornblende have smooth grain boundaries. In addition, the amphibolites are fine-grained (<1 mm) and consist of plagioclase, hornblende, quartz, sphene, and opaque oxides with relic augite. Many samples have suffered post-metamorphic alteration in the form of sericitization of plagioclase, the growth of xenoblastic epidote–calcite aggregates, and the extensive development of chlorite. Ultramafic rocks, gabbros, and norites are intimately associated with the WA.

*Zebulon Amphibolite (ZA).*—As mapped by Sears, Cook, and Brown (1981), the Zebulon Formation is the lowest structural unit in the Dadeville Group and represents what is the lower part of the Ropes Creek Formation of Bentley, Neathery, and Scott (in press). Amphibolites (ZA) occur throughout this unit: the lower section is dominated by thin-bedded ocherous amphibolite interlayered with felsic gneiss and purple-weathering schists; the upper portion of the unit is dominated by metasedimentary rocks, including quartzites, felsic gneisses, and purple-weathering schists, in which minor amphibolites occur (Sears, Cook, and Brown, 1981).

*Hudson Rapids Amphibolite (HRA).*—Large amphibolite units are rare in the Southern Piedmont. The largest amphibolite (HRA) occurs in the Uchee Block along the Chattahoochee River just north of Columbus, Ga. (Bentley and Neathery, 1970). The amphibolites are rich in actinolite and orthopyroxene and are frequently cut by discordant feldspathic pegmatites.

#### GEOCHEMISTRY

*Analytical techniques.*—Major element analyses were done in triplicate by atomic absorption spectrophotometry following a LiBO<sub>2</sub> fusion. The elements, Ba, Co, Cr, Cu, Li, Ni, Pb, Sr, V, and Zn, were also determined by atomic absorption spectrophotometry; samples were dissolved in a HNO<sub>3</sub>–HF mixture. Instrumental neutron activation was used for determination of REE, Hf, Ta, Th, and U, and quantitative emission spectrography was used for Ga, Nb, Y, and Zr. Loss on ignition represents a

weight loss following heating to 1000°C of a preweighed sample. Precision for major element analyses is within  $\pm 5$  percent of the amount present ( $\pm 2$  percent for  $\text{SiO}_2$ ); for trace elements precision is generally well within  $\pm 8$  percent except for Ba ( $\pm 20$  percent). Normative analyses were calculated using the assumption that 90 percent of the iron is in the reduced form.

The abundance of data for the WA and BDA (5 samples each) and the HRA and ZA (2 each) does not allow strong conclusions to be drawn concerning these amphibolites. The data are included, however, and discussed where appropriate.

*Determination of orthoamphibolitic nature.*—Most previous references to the amphibolites of the Alabama Piedmont have assumed that the protoliths were igneous (Bentley and Neathery, 1970; Brown and Cook, 1981; Neathery, 1975; Neathery and Reynolds, 1975; Rheams, ms; Sears, Cook, and Brown, 1981; Tull, 1978). These authors have based such a conclusion chiefly upon the intimate association of the amphibolites with gabbros, norites, and pyroxenites, and the presence of relic pyroxenes in the amphibolites. There has been general agreement that the igneous protolith consisted of basaltic flows and tuffs.

Geochemical data supporting the metaigneous nature of the amphibolites are available for only the MDA (Bloss, ms) and the KA (Stow, Neathery, and Tull, 1979; Whittington, ms). Bloss (ms) based her conclusions on the tholeiitic geochemistry of the MDA and the adherence to igneous trends on Niggli diagrams. However, Bloss distinguished one relatively minor sublithology that she interpreted to represent a mixture of mafic igneous and pelitic material based upon geochemistry. The data for the KA (Whittington, ms) represent samples from the vicinity of Turkey Heaven Mountain. Whittington based his conclusions on tholeiitic chemical trends and adherence to Niggli trends and relic pyroxene in the rock.

Amphibolites of the Cartersville, Ga. area, which may be stratigraphically equivalent with the BDA, have also been studied. Kessler and Kessler (1971) argued that they represented metasedimentary material with essentially no basaltic debris; their chemical analyses, however, are very similar to a tholeiitic basalt. Hurst and Jones (1973) and Jones, Hurst, and Walker (1973) reexamined the same amphibolites and concluded that, based upon relic amygdular and porphyritic textures, pillow structures, and Sr isotopes, the protolith was a mantle-derived basalt. Based upon geochemical character and outcrop pattern, the orthoamphibolitic nature of those rocks was later reconfirmed by McConnell (1980).

Figure 2 represents the Niggli c-mg-(al-alk) diagrams for the Alabama amphibolites; the data points fall close to the igneous trend defined by Leake (1964). The data points for the BDA and WA parallel the igneous trend. There is a small number of DMTA samples that lie well off the trend and have low al-alk values. These have extremely low  $\text{Al}_2\text{O}_3$  values (8-11 percent), possibly reflecting a high cumulate pyroxene content; the normative Di + Hy content of these samples is quite high, from 42 to 80 percent. It is also possible that there may have been minor admixture of dolomitic material in these samples. In a further effort to deter-

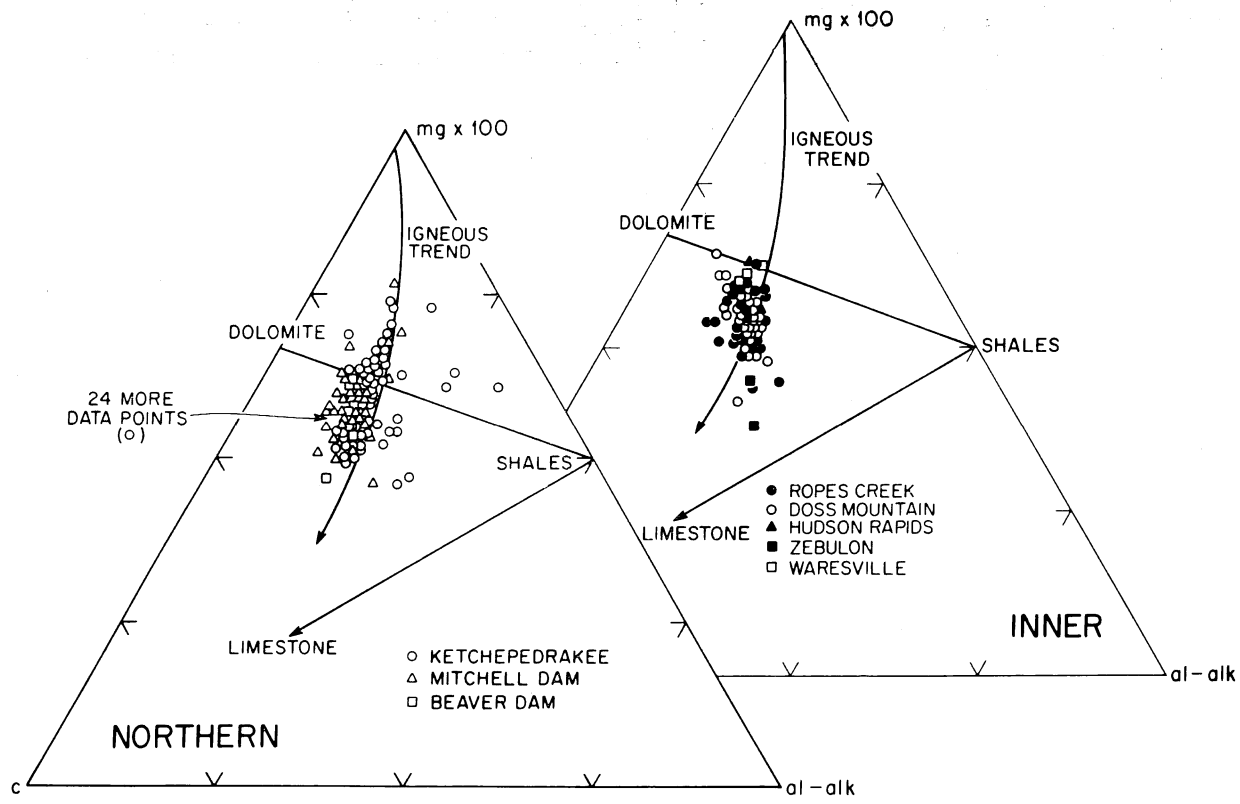


Fig. 2. Niggli c-mg-(al-alk) diagrams (Leake, 1964) for amphibolites from the Northern and Inner Piedmonts.

mine the possible extent of incorporated sediment, the data for the Inner Piedmont were replotted on a Niggli c-(al-alk) diagram (not shown); all samples fall well within the field for igneous rocks. Thus we must conclude that, based upon bulk composition and petrographic data (relic pyroxene), the dominant protolith was igneous for all amphibolites examined.

*General geochemistry and identification of basalt type.*—The question of element mobility must be addressed when attempting to use amphibolite composition to indicate the nature of the igneous protolith. There is general agreement that many constituents (that is, Y, Zr, Nb, Ti, Cr, REE) are relatively immobile during alteration and metamorphism, while others, especially alkali metals, may be highly mobile (Hanson, 1980; Pearce, 1975; Pearce and Cann, 1973; Smith and Smith, 1976). The degree to which element migration has occurred in amphibolites of the Alabama Piedmont cannot be quantitatively judged presently. Based on adherence to igneous trends, our data suggest that significant movement has not occurred, and, for the DMTA, they indicate that migration, even for the alkali metals, is insignificant. Major and trace element concentrations of the DMTA and its parental rock (Doss Mountain Norite) are statistically indistinguishable (Stow and others, 1982a).

The average compositions and standard deviations for the amphibolites are shown in table 1. The compositions of most are similar to those of subalkaline basalts. The ZA is of intermediate to felsic composition based upon the SiO<sub>2</sub> and MgO values but has an exceptionally low alkali content. There are strong similarities in major and trace element abundances among most of the mafic amphibolites, although there are some notable differences. The DMTA has very low concentrations of TiO<sub>2</sub> and Na<sub>2</sub>O and is the most mafic (based upon MgO percent) of any amphibolites. These characteristics are inherited from the parental norite (Stow and others, 1982a). In the Northern Piedmont the KA is enriched in TiO<sub>2</sub> relative to the MDA and BDA. Although the average abundance of FeO\* in the KA is not significantly greater than that of the other amphibolites, in the vicinity of Turkey Heaven Mountain in Cleburne County the KA is very enriched in FeO\* (up to 16.1 percent) and TiO<sub>2</sub> (up to 3.71 percent).

The amphibolites of the Northern Piedmont are similar to each other in their trace element concentrations (table 1), as expected, due to the general similarity in major element abundances. For the Inner Piedmont the most striking differences among amphibolites are for Sr and Cu. Sr is mobile during alteration (Pearce, 1975; Smith and Smith, 1976), and the differences may reflect this mobility.

Based upon the alkali-SiO<sub>2</sub> relationship, the amphibolites of the Alabama Piedmont show subalkaline characteristics (fig. 3). There is no strong alkalic character, although in the Northern Piedmont the KA is consistently more alkalic than is the MDA at an equivalent SiO<sub>2</sub> content. The very low alkali (Na<sub>2</sub>O) content of the DMTA is emphasized in figure 3.

**TABLE 1**  
Average compositions of amphibolites from the Alabama Piedmont,  
standard deviations shown in parentheses when n > 2

	HDA	KA	BDA	DKTA	RCA	WA	ZA	HRA
<u>CHEMICAL COMPOSITION</u>								
SiO <sub>2</sub> ,%	49.70 (3.17)	47.98 (3.80)	48.27 (1.41)	48.00 (2.74)	49.02 (3.13)	48.54 (1.35)	65.95	49.06
Al <sub>2</sub> O <sub>3</sub>	15.26 (1.58)	15.68 (1.59)	14.04 (0.51)	15.80 (2.25)	15.47 (1.60)	14.56 (0.64)	14.42	15.05
TiO <sub>2</sub>	1.15 (0.38)	1.64 (0.65)	1.22 (0.73)	0.45 (0.20)	1.23 (0.31)	1.48 (0.30)	0.41	1.32
FeO <sup>2</sup>	10.37 (1.64)	11.40 (2.07)	11.51 (0.43)	10.49 (2.64)	11.78 (2.00)	12.03 (0.94)	5.59	10.56
MgO	7.60 (2.74)	7.62 (2.62)	7.60 (0.66)	8.35 (1.50)	6.77 (1.03)	7.02 (0.50)	2.58	7.79
CaO	10.99 (2.19)	9.76 (2.72)	12.17 (4.15)	13.25 (1.43)	11.10 (1.84)	11.11 (3.34)	9.80	11.19
Na <sub>2</sub> O	2.80 (0.78)	2.77 (1.05)	2.61 (1.25)	1.11 (0.38)	2.20 (1.14)	2.91 (1.23)	1.20	2.80
K <sub>2</sub> O	0.50 (0.56)	0.33 (0.31)	0.21 (0.11)	0.27 (0.15)	0.38 (0.22)	0.36 (0.48)	0.08	0.82
MnO	0.113 (0.054)	0.184 (0.036)	0.268 (0.160)	0.202 (0.033)	0.218 (0.041)	0.223 (0.086)	0.081	0.194
P <sub>2</sub> O <sub>5</sub>	0.19 (0.05)	--	--	--	--	--	--	--
LOI	1.12 (0.51)	1.89 (1.38)	0.63 (0.32)	0.79 (0.45)	0.84 (0.82)	0.46 (0.20)	0.16	0.38
TOTAL	99.79	99.25	98.53	98.71	99.01	98.69	100.27	99.16
Ba, ppm:	62 (57)	--	--	41 (20)	36 (9.3)	--	--	--
Co	39 (8.3)	40 (5.9)	37 (4.6)	37 (4.9)	39 (4.4)	37 (1.7)	24	38
Cr	283 (167)	338 (214)	301 (126)	223 (192)	248 (178)	248 (100)	132	216
Cu	81 (60)	63 (45)	113 (91)	101 (59)	72 (41)	49 (33)	32	53
Li	19 (9.6)	18 (6.7)	10 (6.3)	16 (12)	15 (9.4)	8.0 (4.2)	10	15
Ni	142 (97)	109 (80)	96 (54)	81 (43)	78 (27)	77 (18)	26	101
Pb	17 (11)	19 (7.5)	--	--	--	--	--	--
Sr	207 (144)	163 (81)	189 (99)	121 (45)	183 (75)	271 (189)	138	295
V	221 (47)	252 (63)	270 (31)	260 (112)	316 (93)	288 (75)	126	262
Zn	86 (24)	88 (30)	114 (39)	77 (21)	99 (22)	83 (19)	42	98
n	48	86	5	35	27	5	2	2
<u>NORMATIVE MINERALOGY</u>								
Q	0.00	0.00	0.00	0.00	0.00	0.00	33.23	0.00
Cr	3.00	2.00	1.26	1.63	2.28	2.16	0.47	4.90
Ab	24.02	24.03	22.51	9.57	18.93	25.01	10.13	23.26
An	27.97	30.12	26.48	38.06	31.74	26.01	33.65	26.35
Ne	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.37
Ol	11.51	12.87	14.59	4.12	4.52	14.96	0.00	16.42
Fo	6.24	6.79	7.45	2.23	2.16	7.28	0.00	8.96
Fa	5.27	6.08	7.14	1.89	2.36	7.68	0.00	7.46
Di	22.44	16.08	28.95	23.81	20.12	24.84	12.44	24.45
Wo	11.40	8.15	14.64	12.09	10.13	12.52	6.21	12.42
En	6.23	4.35	7.62	6.59	4.98	6.26	2.72	6.82
Fs	4.82	3.58	6.70	5.13	5.01	6.06	3.51	5.21
Hy	7.15	9.81	1.95	20.21	18.11	2.19	8.40	0.00
En	4.05	5.41	1.04	11.43	9.08	1.12	3.69	0.00
Fs	3.10	4.40	0.91	8.79	9.03	1.07	4.71	0.00
Mt	1.69	1.89	1.89	1.76	1.93	1.97	0.90	1.71
Il	2.21	3.19	2.36	0.87	2.38	2.86	0.78	2.53

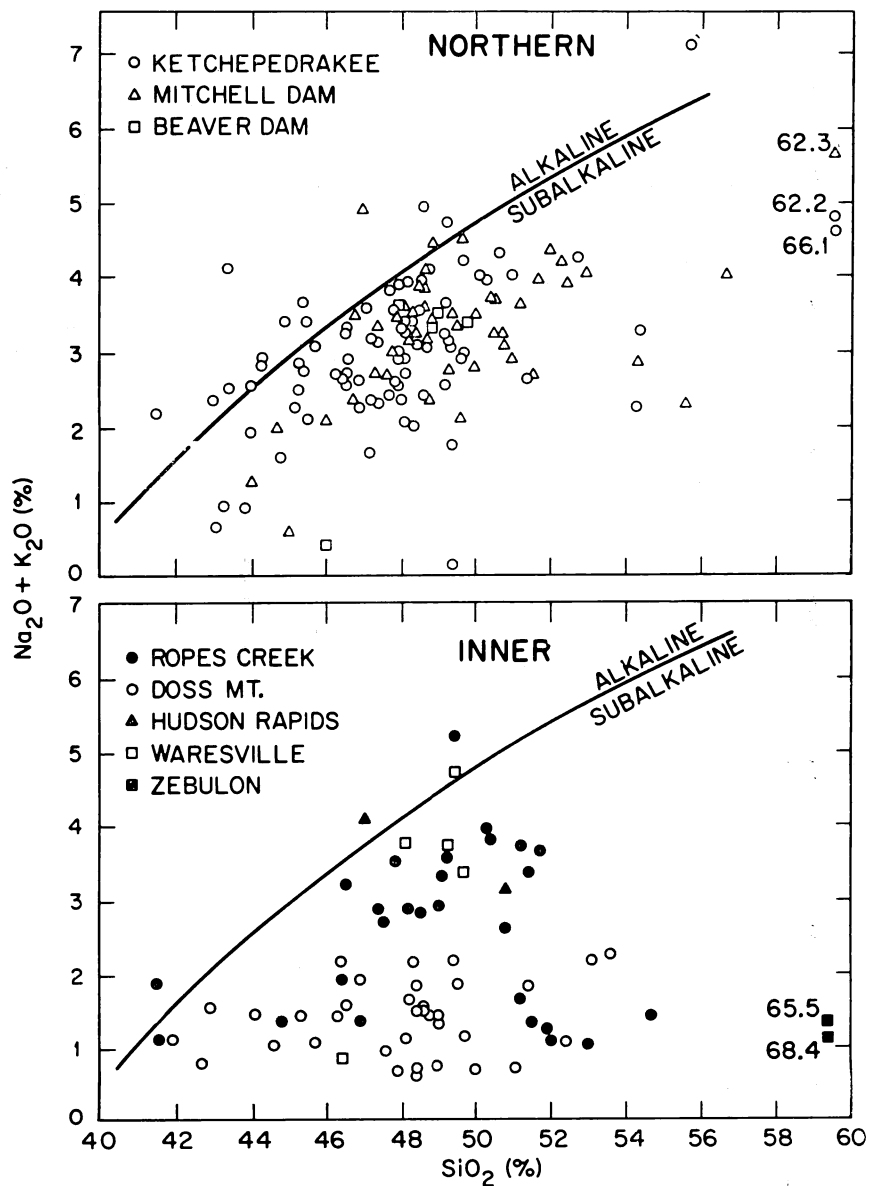


Fig. 3. Alkali- $\text{SiO}_2$  diagrams for amphibolites from the Northern and Inner Piedmonts. Alkaline-subalkaline dividing line is from Irvine and Barager (1971).

The non-alkalic character of the basaltic protoliths is confirmed by the Y/Nb ratios (table 2). Both elements are recognized to be quite immobile during alteration and metamorphism; the Y/Nb ratio is generally less than 1 for alkali basalt and greater than 2 for tholeiitic basalt (1-2 represents transitional; Pearce and Cann, 1973). No ratio is less than 1, and all but one fall in the tholeiitic range.

The AFM relationship allows distinction between tholeiitic and calc-alkaline rocks. In spite of some scatter of points, possibly due to alkali mobility, tholeiitic trends and characters are apparent for the amphibolites (fig. 4). There is a small number of KA and MDA samples that falls in the calc-alkaline field; these represent rocks of intermediate composition ( $\text{SiO}_2 \sim 65$  percent) and one basaltic andesite with a high  $\text{Na}_2\text{O}$  content (6.23 percent). The more highly evolved KA samples represent the rocks from the Turkey Heaven Mountain area. These are geochemically very similar to the ferrobasalts of the Pacific Rise and the Juan de Fuca Ridge with high  $\text{FeO}^*$  and  $\text{TiO}_2$  contents (Bryan and others, 1976). The anomalous BDA sample located on the F-M side represents an amphibolite that contains practically no normative plagioclase ( $\text{Na}_2\text{O} = 0.38$  percent; total alkalis = 0.44 percent); this sample consists of hornblende and relic clinopyroxene. The DMTA samples of the Inner Piedmont define a strong tholeiitic trend with minimal variation of alkalis.

The normative mineralogy of the Northern and Inner Piedmont amphibolites ranges from Ne- to Q-normative basalts. The distribution of data points in the normative Ne-Ol-An-Hy-Q system (not shown) corresponds closely with tholeiites from ocean ridges (Bass, 1971). The MDA, KA, and BDA have similar average normative mineralogies (table 1). Although there is a significant number of Ne-normative samples for the Northern and Inner Piedmonts (especially RCA) the absolute normative Ne contents are generally less than 2 percent and may result either from minor  $\text{Na}_2\text{O}$  metasomatism during alteration or metamorphism or, more likely, from the assumed  $\text{FeO}/\text{Fe}_2\text{O}_3$  ratios used during normative calculations. Thus, we feel that there is no significant alkaline character for the amphibolite protoliths. Indeed, the normative mineralogies for the average composition of most of the amphibolites (table 1) show distinct tholeiitic character.

TABLE 2  
Y/Nb ratios for amphibolites from the Alabama Piedmont

	Range	Average	N
<u>Northern Piedmont</u>			
Mitchell Dam	4.0-9.0	6.4	5
Ketchepedrakee	1.8-8.0	4.5	14
Deaver Dam	5.7-5.8	5.8	2
<u>Inner Piedmont</u>			
Doss Mountain	2.5-3.0	2.8	3
Ropes Creek	2.8-6.9	5.2	4
Wareville	13	13	1
Hudson Rapids	5.8	5.8	1

*Fractionation trends.*—Reference has been made to fractionation trends displayed on the AFM diagrams (fig. 4). Figure 5 presents FeO\*/MgO variation diagrams for Cr, Ni, V, and TiO<sub>2</sub>, constituents whose distributions in tholeiites are strongly controlled by fractionation. Cr and Ni dramatically decrease in abundance during fractionation, with the Cr decrease the more pronounced. V and TiO<sub>2</sub> contents increase with fractionation. The general changes during fractionation are in accord with those described for tholeiitic systems by Miyashiro and Shido (1975) and conform to expectations based upon crystal field stabilization theory (Curtis, 1964). Such observations add credence to our previous conclusion that the amphibolites were derived from igneous protoliths of tholeiitic nature.

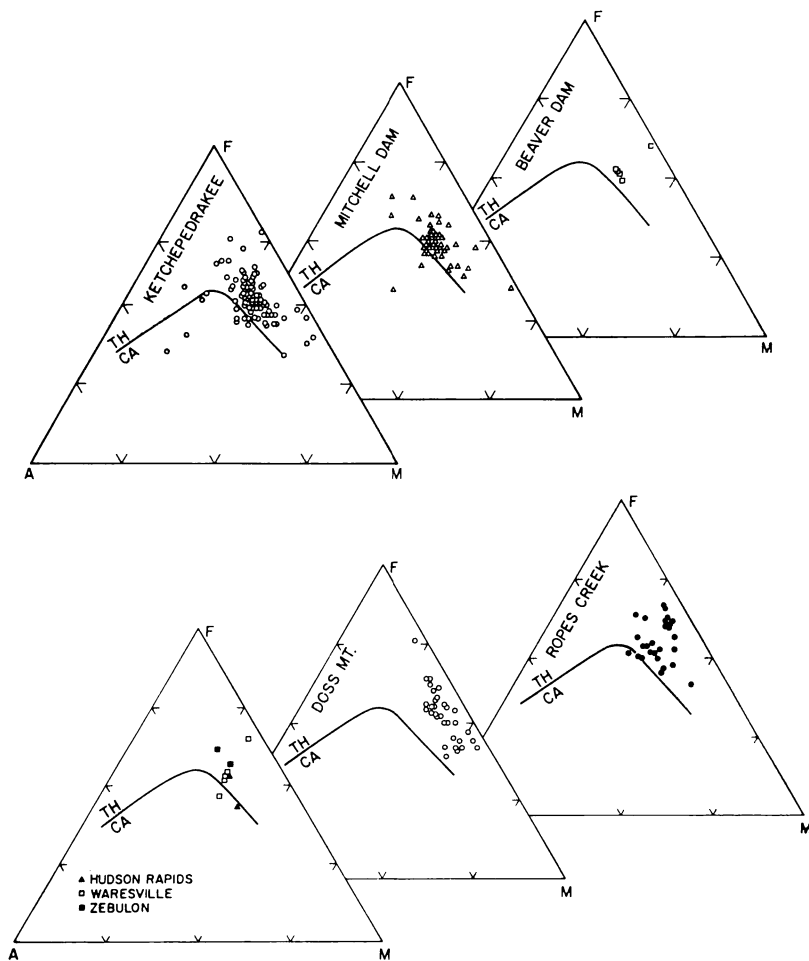


Fig. 4. AFM diagrams for amphibolites from the Northern and Inner Piedmonts. The line marked by TH/CA represents the boundary between tholeiitic and calc-alkaline rocks (from Irvine and Barager, 1971).

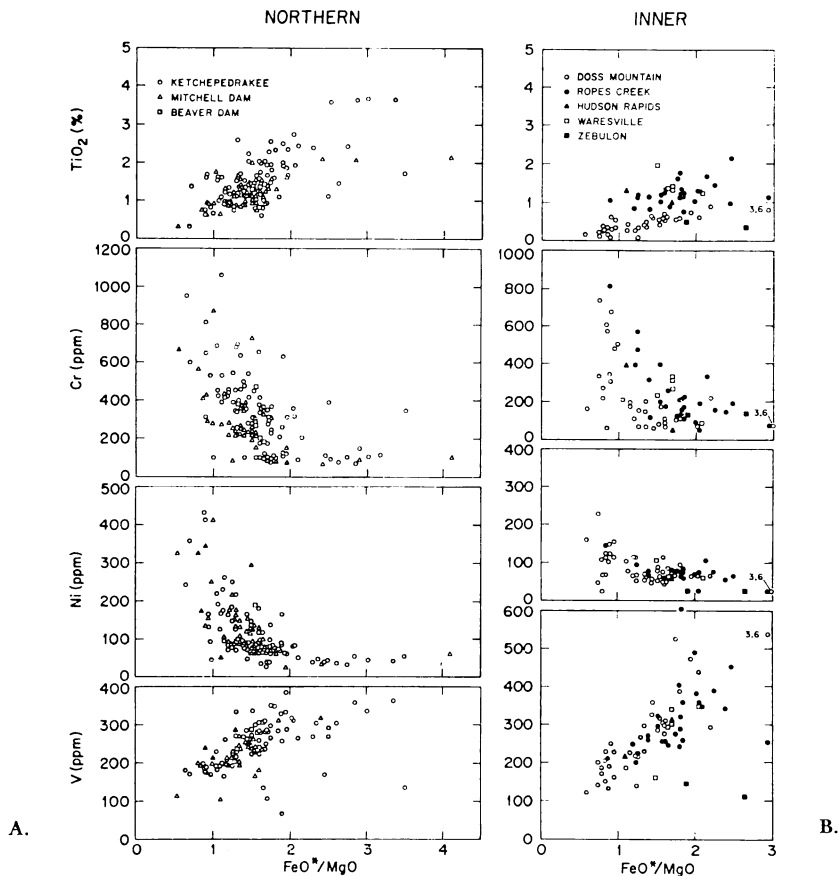


Fig. 5.  $\text{FeO}^*/\text{MgO}$  variation diagrams for rocks from the Northern and Inner Piedmonts.

In the Northern Piedmont (fig. 5) the KA is the most highly fractionated. The samples with high  $\text{FeO}^*/\text{MgO}$  ratios come from the Turkey Heaven Mountain area in Cleburne County, noted previously to be characterized by high  $\text{FeO}^*$  and  $\text{TiO}_2$  contents. At equivalent  $\text{FeO}^*/\text{MgO}$  ratios the KA contains somewhat more Cr and  $\text{TiO}_2$  than does the MDA, although there is no indication of distinctly separate fractionation trends for the two rocks. Aside from this distinction there are no obvious chemical differences among the amphibolites of the Northern Piedmont.

In contrast, the chemistry for amphibolites of the Inner Piedmont (fig. 5) shows a clear and consistent distinction between the DMTA and the other amphibolites. At equivalent  $\text{FeO}^*/\text{MgO}$  ratios the DMTA contains less Cr, Ni, and  $\text{TiO}_2$  than do the RCA, WA, and the HRA. There is little difference in the V contents among the amphibolites. Also, the DMTA is somewhat less evolved, based upon the  $\text{FeO}^*/\text{MgO}$  ratio, than

is the RCA (and WA and HRA). There are a few DMTA samples with  $\text{FeO}^*/\text{MgO}$  ratios less than 1 and with unusually low Cr and Ni values. These samples have relatively low  $\text{FeO}^*$  contents (5.5-7.5 percent) with typical MgO contents; therefore the low  $\text{FeO}^*/\text{MgO}$  ratios. These samples also have high  $\text{CaO}/\text{TiO}_2$  and  $\text{Al}_2\text{O}_3/\text{TiO}_2$  ratios (50-120) suggesting that they may represent cumulate material rich in plagioclase (see the later discussion below on  $\text{CaO}/\text{TiO}_2$  and  $\text{Al}_2\text{O}_3/\text{TiO}_2$  ratios for additional interpretations).

*Rare earth distribution patterns and incompatible element abundances.*—Chondrite-normalized rare earth element (REE) patterns for representative amphibolites are shown in figure 6. The distributions are

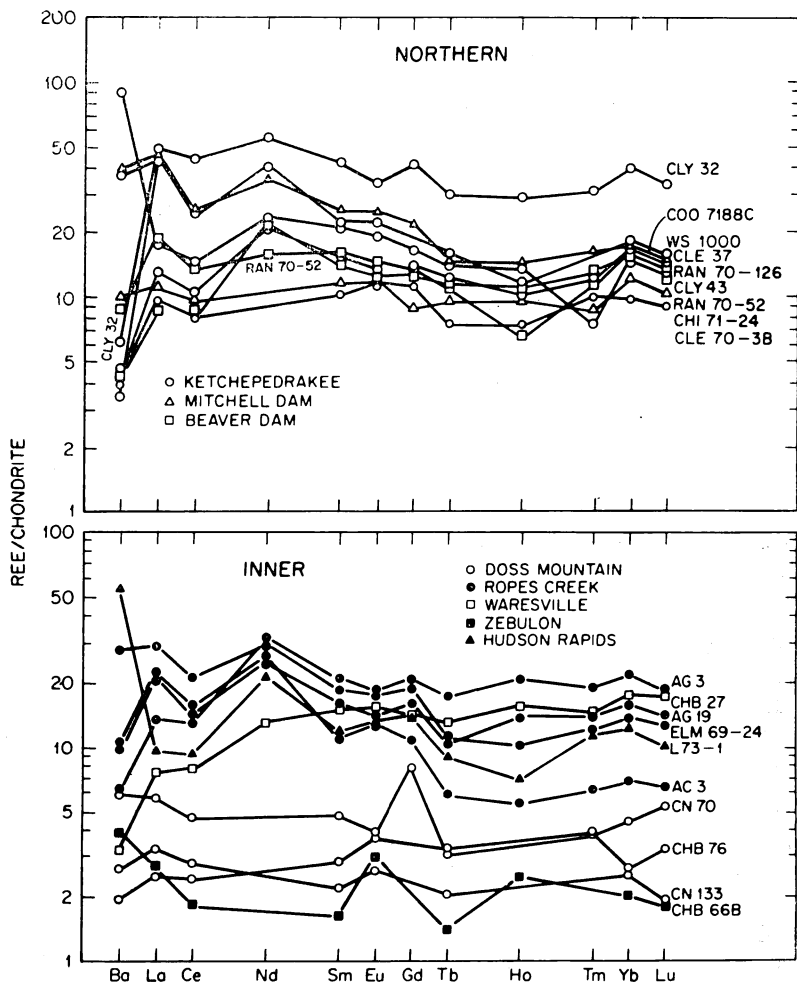


Fig. 6. Chondrite-normalized rare earth element distribution patterns for amphibolitic samples from the Northern and Inner Piedmonts.

generally flat, although there is consistent LREE enrichment for the KA, RCA, and HRA; there is inconsistent LREE enrichment for the MDA and BDA. The DMTA contains very low amounts of REE and exhibits no LREE enrichment. There is a general positive relationship between both the LREE abundance and La/Yb ratios versus FeO\*/MgO ratios. These observations suggest that fractionation (as indicated by the FeO\*/MgO ratios) has influenced the  $\Sigma$ REE levels and the distribution of LREE relative to the HREE. The REE patterns for all the amphibolites, except the DMTA, are similar to those presented by Bryan and others (1976) for type II LIL-enriched tholeiitic ocean ridge basalts and are dissimilar to those of type I LIL-depleted ridge basalts.

Data for incompatible elements (Ba, Ga, Hf, Nb, Pb, Ta, Th, Y, and Zr) other than the REE have been obtained for 19 samples of the amphibolites and are available from the senior author. The data indicate that the DMTA is significantly depleted in most of the elements when compared to the other amphibolites, all of which are rather similar in their incompatible element abundances. The low values for Hf, Ta, Nb, Y, Zr, Pb, (and Ga) in the DMTA are of note. It has previously been pointed out that the DMTA also has very low concentrations of TiO<sub>2</sub> and Na<sub>2</sub>O, which may also be considered incompatible components.

#### TECTONIC SETTINGS

The chemical composition of basaltic rocks from different tectonic settings has been shown to vary significantly. The tectonic settings of some of the Alabama amphibolites have been studied previously based chiefly on geochemical data (Stow and others, 1982b). Bloss (ms) concluded that the MDA protolith was formed in an oceanic rifting environment. A similar conclusion was reached by Stow, Neathery, and Tull (1979) and Whittington (ms) for parts of the KA in Cleburne and Randolph Counties. The Doss Mountain Norite, which we feel represents the parental material for the DMTA, has been shown to be tholeiitic and arc-related (Stow and others, 1982a). Based upon new geochemical data described herein for immobile elements we can confirm and refine the previous conclusions.

Among the major elements, TiO<sub>2</sub> is a reliable discriminator between arc and spreading ridge basalts (Pearce, 1975; Pearce and Cann, 1973) and is relatively immobile during alteration (Pearce, 1975). The average TiO<sub>2</sub> contents of the amphibolites are shown in table 1. The very low TiO<sub>2</sub> contents of the DMTA suggest formation of the protolith in an arc system; in contrast, all other amphibolites, except the ZA, have TiO<sub>2</sub> concentrations similar to those of basalts formed at spreading ridges, with the KA having the highest content.

The following discrimination diagrams are based upon multi-element variations among rocks of different environments. Analytical data for some elements (Zr, Y, Nb, Hf, Ta, Th) are available for a limited number of samples. Only basalts (SiO<sub>2</sub> = 45-52 percent) with CaO + MgO contents between 12 and 20 percent have been plotted. The TiO<sub>2</sub>-Zr relationship (Pearce, 1979; fig. 7) shows a strong correlation for all amphibolites (except DMTA) with ocean floor basalts. However, due to overlap of the

OFB (ocean floor basalt) field with the ARC and WPB (within plate basalt) fields an exclusive correlation can not be made. The DMTA samples plot near the island arc tholeiite field. As previously noted, the Doss Mountain Norite, the parent of the DMTA, is very severely depleted in  $\text{TiO}_2$  (Stow and others, 1982a).

The Cr–Y plot (fig. 8A) of Pearce (1979) and Gale and Pearce (1982) is consistent with the proposed arc heritage of DMTA but does not allow discrimination between WPB and OFB settings for the other amphibolites. Delineation between the WPB and OFB settings can be made with the Zr/Y–Zr diagram (fig. 8B) used by Pearce (1979) and Pearce and Norry (1979). The “within plate” environment can be eliminated, and an oceanic rifting environment indicated for all amphibolites except the DMTA. As above, the DMTA samples fall near the ARC field.

If it is accepted that the RCA, WA, HRA, MDA, KA, and BDA were erupted in an oceanic rifting system, the Hf–Ta–Th plot can be used to determine more specifically the tectonic character of the ridge segment (Wood, Joron, and Trewil, 1979; Wood, 1980). The data points for most amphibolites cluster in the E-MORB (enriched-MORB) field, although some are in the transition zone with the N-MORB (normal-MORB) field (fig. 9). The three DMTA samples are not plotted as their Ta contents are below the lower limit of detection. The moderate levels of relative LREE enrichment seen for the MORB amphibolites (fig. 6) correspond to the REE patterns characteristic of MORB from enriched plume ridge seg-

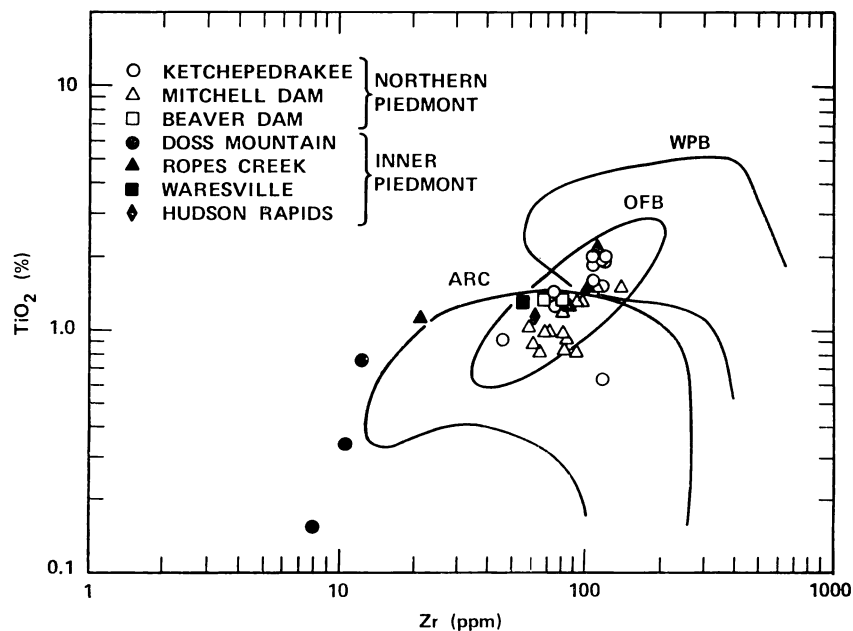
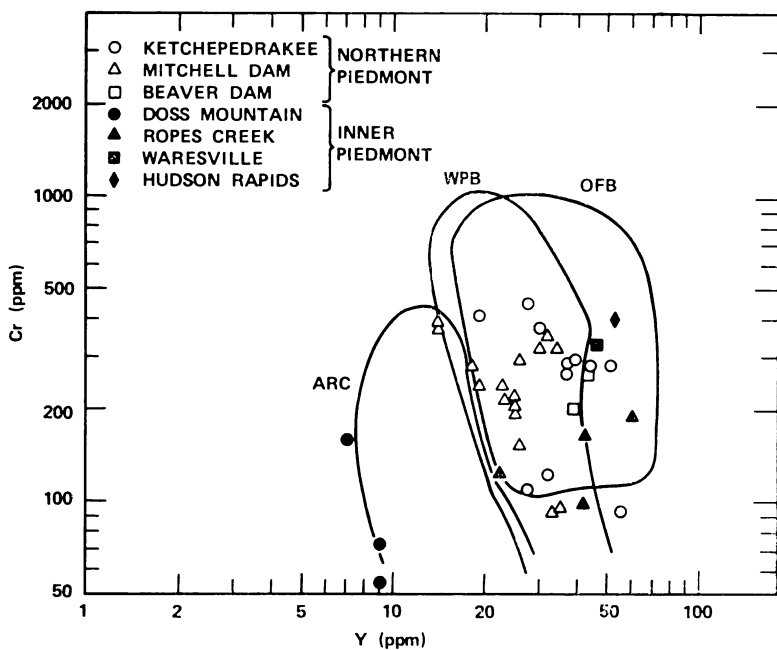
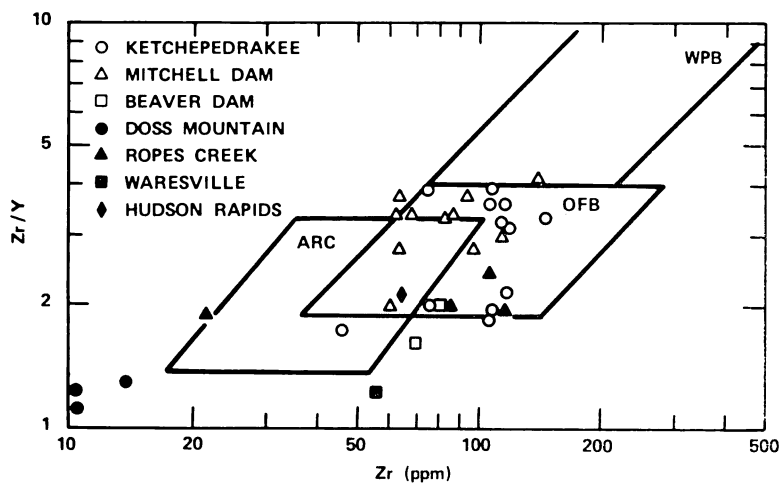


Fig. 7. Distribution of amphibolite data on  $\text{TiO}_2$ (percent)–Zr(ppm) diagram of Pearce (1979). WPB is within-plate basalt; OFB, ocean-floor basalt.



A.



B.

Fig. 8. Distribution of amphibolite data on Cr-Y diagram of Pearce (1979) and Gale and Pearce (1982) (A) and on Zr/Y-Zr diagrams of Pearce (1979) and Pearce and Norry (1979) (B) WPB is within-plate basalt; OFB, ocean-floor basalt.

ments (Sun, Nesbitt, and Sharaskin, 1979), an observation that reinforces the rifting environment conclusion. We interpret the volcanism of the Northern Piedmont to be associated with early rifting stages as proposed by Thomas and others (1980), which occurred no later than Middle to Late Cambrian in what is now the Tallapoosa block. An equivalent time frame may be speculated for the Coosa block.

The spreading rate at divergent plate margins has been related to the  $\text{TiO}_2$  content of basalts (Nisbet and Pearce, 1973). Application of these criteria to the Piedmont amphibolites suggests relatively slow spreading rates, ranging from 1 cm/yr for the MDA, BDA, and RCA to 2 to 3 cm/yr for the KA and WA. Quite high  $\text{TiO}_2$  contents (>2.5 percent) in the KA from the vicinity of Turkey Heaven Mountain suggest that the spreading rate here might have been quite great ( $\sim 10$  cm/yr).

When the amphibolite data for the Inner Piedmont are plotted on the  $\text{Al}_2\text{O}_3/\text{TiO}_2$  versus  $\text{TiO}_2$  percent and  $\text{CaO}/\text{TiO}_2$  versus  $\text{TiO}_2$  percent diagrams (fig. 10) of Sun and Nesbitt (1978), a clear distinction between the DMTA and RCA may be observed. The DMTA correspond tectonically with areas defined by arc and certain ophiolitic samples; the other amphibolites correspond with ocean floor basalts and high- $\text{TiO}_2$  basalts of ophiolite complexes. More importantly, however, the DMTA corresponds to very Ti-depleted magmas, a depletion that may be inherited from the

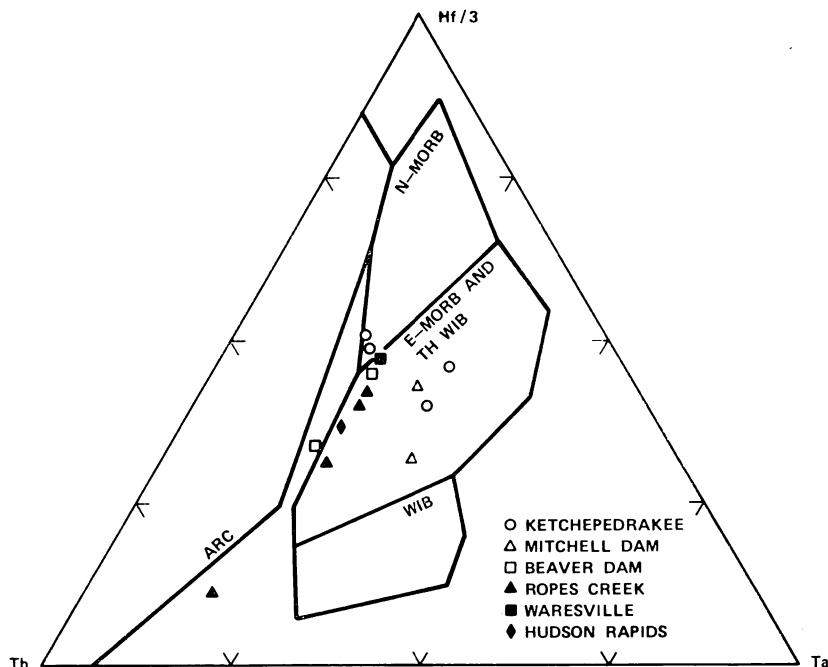


Fig. 9. Distribution of amphibolite data for the Northern (open symbols) and Inner (solid symbols) Piedmonts on HF/3-Th-Ta diagram of Wood (1980). N-MORB and E-MORB represent, respectively, normal and enriched mid-ocean ridge basalts; WIB represents within-plate basalt.

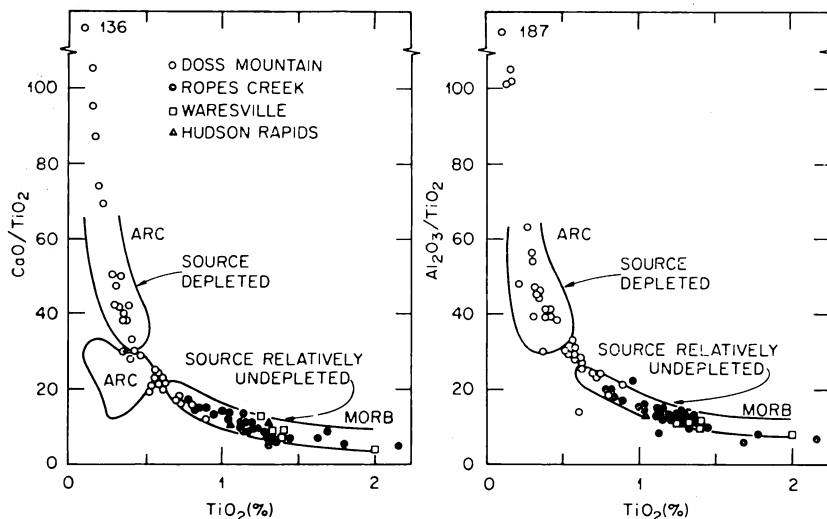


Fig. 10. Distribution of amphibolite data for the Inner Piedmont on CaO/TiO<sub>2</sub>-TiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub>/TiO<sub>2</sub>-TiO<sub>2</sub> diagrams, modified from Sun and Nesbitt (1978).

source rather than by partial melting of undepleted mantle (Sun and Nesbitt, 1978). It has previously been shown that the Doss Mountain Norite also plots in the depleted area on both these diagrams (Stow and others, 1982a).

The recognition of the RCA as an ocean-rifting basalt and the DMTA as typical of arc-related igneous activity allows a statement as to the pre-orogenic history of the Inner Piedmont block to be made. Mapping indicates that the arc-related rocks appear to be intrusive to the ocean-rifting representatives (Neilson, 1983). In addition, the Slaughters Gabbro, also of arc-related parentage, intrudes the RCA (Allison and Neilson, 1981; Stow and others, 1982a). If the interpretation of Sears, Cook, and Brown (1981) that the Stonewall Line is a stratigraphic contact and that the entire sequence within the Inner Piedmont block is the right-side-up is accepted, then the RCA was deposited on continental-type crust. Thus, a preliminary model is proposed in which a back-arc basin developed on continental crust at the leading edge of a plate (generating the RCA and ZA?) which was subsequently invaded by tholeiitic and calc-alkaline magmas due to subduction associated with the first pulse of orogenesis.

The geochemistry of some of the amphibolites of the Northern and Inner Piedmonts may be used to suggest correlations of possibly equivalent units. The compositions of the MDA and KA (table 1), which occur in similar stratigraphic positions in the Coosa block, are similar in most respects. Differences in composition, chiefly for TiO<sub>2</sub>, may result from different spreading rates along the rift. The BDA of the Tallapoosa block is similar compositionally to amphibolites of the Cartersville District, Ga. (McConnell, 1980). The geochemistry of the WA in the Inner Piedmont is similar to that of the RCA suggesting that those two units may be rep-

representative of the same episode of volcanism as proposed by Bentley and Neathery (1970).

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