

THE GABBRO-METAGABBRO ASSOCIATION OF THE SOUTHERN APPALACHIAN PIEDMONT

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ABSTRACT. Large, composite gabbro-metagabbro complexes occur in an arcuate chain within the Charlotte belt of the Carolina Piedmont. Preliminary age dating suggests that metagabbros are 500 to 600 my old. Conditions of metamorphism for metagabbros were approx 500° to 550°C and 5 kb, appropriate to depths of 17 to 18 km. Observed variations in metamorphic intensity probably reflect local accessibility of fluids. Crystallization ages for most gabbros determined by the Sm/Nd mineral isochron method are 399 to 407 my, though one petrologically distinctive pluton is older (~ 479 my). Gabbroic bodies are thick cylindrical or lopolithic intrusions emplaced at depths of 13 to 17 km. Crystallization sequences for their tholeiitic parental magmas were dominated by fractionation of olivine (or orthopyroxene), plagioclase, and clinopyroxene to produce ortho- and mesocumulates. Syenites are the end fractionation products associated with several gabbros. Fe-enrichment trends in minerals are limited, and the presence of abundant hydrous phases suggests crystallization at high PH_2O . Irregular distributions of gabbroic rock types and general absence of layering within these plutons may reflect either emplacement as crystal mushes, convective stirring, or multiple intrusive pulses. The close field association of gabbro and metagabbro suggest tectonic control of the sites of magma generation and/or ascent. The tectonic setting cannot be precisely specified, but the features of these complexes are consistent with their formation at a compressional plate margin.

INTRODUCTION

Intrusive complexes of gabbro and metagabbro occur in many orogenic belts, but the origin of such mafic associations is a perplexing problem. A chain of these complexes intrudes rocks of the Charlotte belt in the southern Appalachian Piedmont, a part of which is illustrated in figure 1. Additional gabbro and/or metagabbro plutons extend along strike south into Georgia and eastward of this line within the Carolina slate belt.

Some previous studies of individual gabbro-metagabbro complexes (for example, Hermes, 1968) concluded that they formed when gabbro fortuitously intruded earlier, regionally metamorphosed gabbroic plutons.

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However, the repeated field association of gabbro and metagabbro in numerous complexes located along an arcuate trend (fig. 1), understandably not recognized in work on individual complexes, suggests that the juxtaposition of these rock types is neither fortuitous nor random. Similar complexes in the Alabama Inner Piedmont are apparently large, incompletely metamorphosed intrusions within which some of the gabbroic protolith remained unaltered (for example, Neilson and Stow, 1980). Although some parts of metagabbro units in the Charlotte belt are nearly unaltered, field relationships indicate that these complexes are composite intrusions. What then is the origin of this association?

In this paper we will summarize the petrologic and chemical characteristics of the Farmington, Barber, Concord, Mecklenburg, and Ogden complexes (fig. 1) as representatives of this gabbro-metagabbro association in the southern Appalachians. The age and depth of emplacement of gabbro plutons and the conditions of metamorphism will be discussed. Finally, we will attempt to constrain the parental magma types, the origin of this association, and the tectonic environment in which these complexes formed.

ANALYTICAL METHODS

Modal analyses for rocks of the Mecklenburg complex, the Ogden gabbro, and the Concord gabbro have been published by Hermes (1968), McSween (1981a), and Olsen, McSween, and Sando (1983), respectively. Additional modal data for the other complexes were determined utilizing procedures outlined in theses by Clark (ms) and Olsen (ms). Averaged data for each intrusion are shown in table 1; individual modal determinations are listed in the above references.

Microprobe analyses of major mineral phases in the Mecklenburg, Ogden, and Concord gabbros were reported by Hermes (1970), McSween (1981a), and Olsen, McSween, and Sando (1983). Other data were obtained with a MAC Model 400S electron microprobe at the University of Tennessee, using operating conditions and correction procedures described by Olsen, McSween, and Sando (1983). These previously unpublished data are presented here only in diagrammatic form but are tabulated in the theses listed above.

Bulk XRF chemical analyses of rocks of the Mecklenburg and Concord complexes were obtained by Hermes (1968) and Cabaup (ms), respectively, and bulk AA analyses of rocks of the Barber pluton were reported by Strange (ms). Analytical methods and assessment of data quality are discussed in these references. These analyses reported only total Fe; for normative calculations, we assumed $\text{Fe}_2\text{O}_3/\text{FeO} + \text{Fe}_2\text{O}_3$ ratios for average gabbro (0.24, Nockolds, 1964). Butler and Ragland (1969) reported additional analyses, and trace element concentrations were determined by Price (ms) and Strange (ms). Average chemical analyses for each pluton are presented in table 1. We think these average values may be a valid way to compare plutons, though samples may not represent the correct volumetric distributions within the plutons.

Gabbro-Metagabbro Association

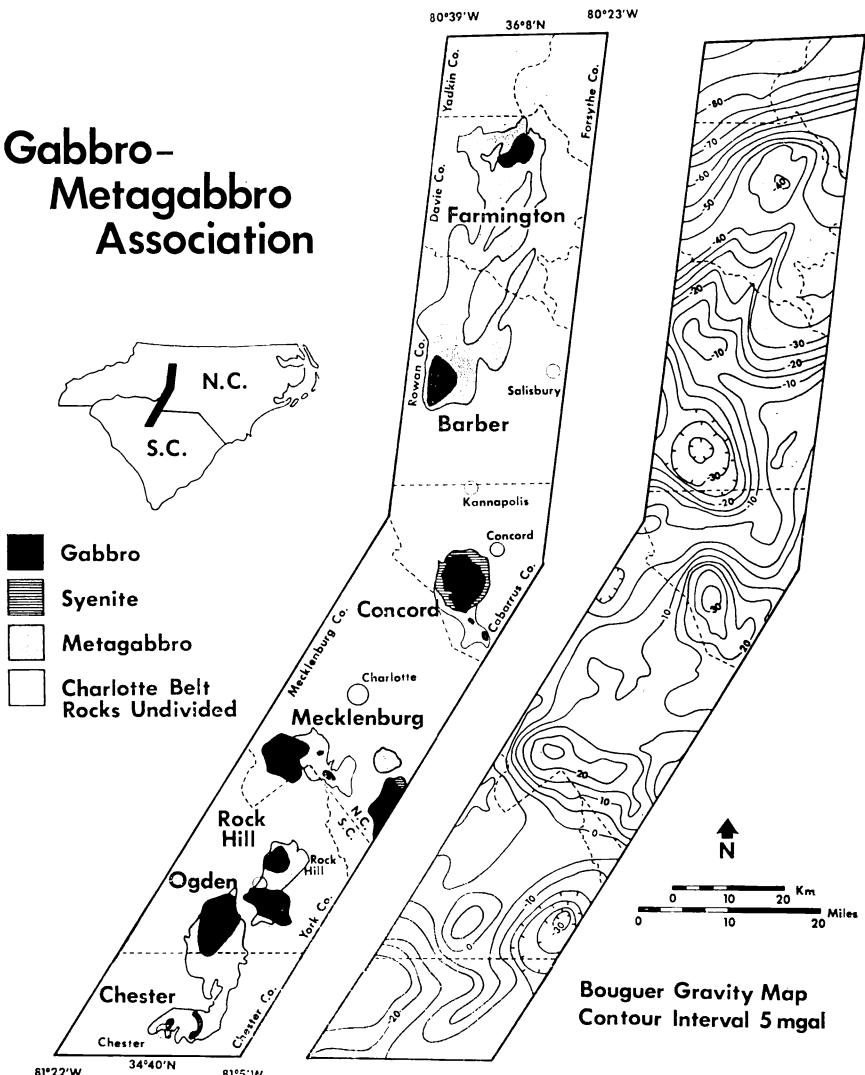


Fig. 1. Location of gabbro-metagabbro complexes in the North and South Carolina Piedmont. The country rocks are mostly undifferentiated rocks of the Charlotte belt, except for Milton belt rocks north of the Farmington complex. The map is modified from Butler (1966), Hermes (1968), Clark (ms), Deetz (ms), McSween (1981a), Wilson (1981), Olsen (ms), and unpublished work by Harden and McSween. The simple Bouguer gravity map is modified from Talwani, Long, and Bridges (1975), Wilson and Daniels (1980), and unpublished data from the National Geophysics and Solar Terrestrial Data Center.

TABLE I
Average modal and chemical analyses of gabbro and metagabbro
(standard deviations⁺ in parentheses)

	Modal compositions (volume percent)						
	Mecklenburg Gabbro	Ogden Gabbro	Concord Gabbro	Farmington Gabbro	Barber Gabbro	Mecklenburg Metagabbro	Barber Metagabbro
plagioclase	54.6(77)	61.8(88)	57.4(71)	62.0(69)	56.5(47)	53.0(83)	32.4(220)
olivine	8.2(71)	6.6(62)	3.7(45)	7.2(49)	—	—	1.0(10)
clinopyroxene	14.9(72)	13.1(80)	6.9(60)	8.0(63)	4.8(24)	13.9(54)	1.0(8)
orthopyroxene	4.1(33)	7.9(28)	10.3(30)	10.9(35)	14.3(58)	1.3(23)	3.9(24)
amphibole	12.3(72)	5.7(54)	16.0(108)	9.4(70)	6.3(55)	19.3(113)	48.5(300)
biotite	2.2(26)	1.3(14)	1.0(13)	0.9(12)	5.7(44)	5.8(51)	1.0(5)
opacites	3.5(19)	3.5(20)	3.8(17)	1.6(10)	3.4(20)	5.5(28)	2.5(18)
apatite	0.2(2)	0.1(1)	0.2(2)	0.1(1)	0.1(1)	0.6(5)	0.1(1)
quartz	—	—	—	—	8.8(54)	—	—
[No. analyses]	31[*]	24[**]	33[***]	21[†]	21[††]	25[*]	30[††] ^x
	Chemical compositions (weight percent, trace elements in ppm)						
SiO ₂	47.8(12)	49.0	49.6(11)	48.4	56.1(17)	49.3(11)	46.8(26)
TiO ₂	1.12(3)	0.93	1.20(37)	0.39	0.69(10)	1.80(56)	0.83(31)
Al ₂ O ₃	17.1(26)	17.7	17.6(15)	17.1	16.2(6)	16.1(14)	17.4(27)
MgO	10.0(26)	8.84	9.59(202)	10.6	4.66(54)	6.13(81)	8.45(344)
FeO [■]	10.0(22)	9.04	9.73(131)	7.77	9.67(72)	11.4(27)	12.2(28)
MnO	0.15(2)	0.14	0.14(2)	0.13	0.15(2)	0.17(4)	0.18(5)
CaO	9.91(121)	9.64	10.5(9)	11.8	8.15(91)	9.68(116)	11.8(24)
Na ₂ O	1.99(39)	2.77	2.51(40)	2.12	2.90(28)	2.40(43)	1.82(78)
K ₂ O	0.37(18)	0.27	0.31(15)	0.15	0.69(11)	0.98(47)	0.24(10)
Total	98.44	98.33	101.18	98.46	99.21	97.96	99.72
[No. analyses]	31[*]	8[\$]	46[\$]	5[\$]	19[†††]	17[*]	29[†††]
V	148	172	116	103	244	101	293
Cr	139	202	166	187	43	72	134
Ni	506	369	745	391	43	106	69
[No. analyses]	4[§§]	8[§§]	6[§§]	5[§§]	19[†††]	3[§§]	29[†††]

[*] Hermes, 1968; [**] McSween, 1981a; [***] Olsen, 1982; [†] Harden, unpublished; [††] Clark, 1980; [†††] Strange, 1983; [\$] Butler and Ragland, 1969; [§§] Price, 1969; ⁺ In terms of least unit cited; ^x Also includes 7.6 percent epidote + chlorite; [■] Total Fe as FeO.

We selected one fresh, unaltered sample each of the Farmington, Barber, and Ogden gabbros for age dating by the Sm-Nd mineral isochron method and obtained 40 to 400 mg mineral separates of plagioclase and pyroxene for each sample following procedures described by Olsen, McSween, and Sando (1983). Following a 30-min wash in 2.5 N HCl, the separates were dissolved in ultrapure HF-HNO₃-HClO₄. Approximately 100 mg of powdered whole-rock from each sample were also dissolved. Separation of Nd and Sm followed the University of Paris two-column cation-exchange technique, described by Zindler and others (1979). All isotopic measurements were made on the nine-inch automated mass spectrometer (Nima-B) at M.I.T.; Nd isotopic compositions were determined on unspiked aliquots of the dissolved samples, except for the Farmington sample, where spiked samples were analyzed, and a correction for the spike contribution to ¹⁴³Nd/¹⁴⁴Nd was applied to the measured values. Sm and Nd concentrations were determined by standard isotope dilution techniques using mixed spikes enriched in ¹⁴⁹Sm and ¹⁴⁸Nd or ¹⁵⁰Nd. We judge analytical precisions to be 0.003 to 0.004 percent for ¹⁴³Nd/¹⁴⁴Nd and 0.5 percent for ¹⁴⁷Sm/¹⁴⁴Nd (2σ errors) based on replicate analyses of standards. ¹⁴³Nd/¹⁴⁴Nd values reported here are relative to 0.512630 for U.S.G.S. standard rock BCR-1. The same whole-rock powders of Ogden, Barber, and Farmington gabbros used for Sm-Nd dating were analyzed for Sr isotopic composition and Rb and Sr concentrations using standard isotope dilution techniques (Hart and Brooks, 1977). Sr isotopic measurements were normalized to a value of 0.7080 for the Eimer and Amend SrCO₃ standard. The measured Rb/Sr ratios and the Sm-Nd ages were used to calculate the initial ⁸⁷Sr/⁸⁶Sr ratios in table 2.

FIELD RELATIONSHIPS

The host rocks of the Charlotte belt into which the gabbro-metagabbro complexes were emplaced consist predominantly of granitic gneisses, mica schists, and amphibolites. Metamorphic assemblages in these rocks generally record staurolite or kyanite grade (amphibolite facies) conditions, though sillimanite occurs locally around some intrusions (Overstreet, 1970). These meta-igneous and meta-sedimentary rocks were intruded by granitoid plutons during three intervals at 595 to 520, 415 to 385, and 325 to 265 my ago (Fullagar, 1971; Fullagar and Butler, 1979). The latter group of intrusions is post-metamorphic, as the thermal peak of the major metamorphic event (Taconic) in the Charlotte belt probably occurred 460 ± 20 my ago (Hatcher and others, 1980; Butler and Fullagar, 1982). However, some of the granitoid plutons of the 415 to 385 my group are apparently syn-metamorphic, suggesting that metamorphism in parts of the Charlotte belt may have been later than in other areas of the Piedmont (Tull, 1980). The only evidence of Acadian (380 ± 20 my) metamorphism in the Charlotte belt is localized within the Gold Hill-Silver Hill shear zone that marks the belt's eastern boundary in the northern part of figure 1 (Butler and Fullagar, 1978).

These Charlotte belt rocks have also been intruded by mafic complexes, consisting predominantly of gabbro and metagabbro. Small bodies

TABLE 2
Results of new isotopic analyses

Sample	($^{143}\text{Nd}/^{144}\text{Nd}$) measured	$^{147}\text{Sm}/^{144}\text{Nd}$	($^{143}\text{Nd}/^{144}\text{Nd}$) initial	($^{87}\text{Sr}/^{86}\text{Sr}$) measured	$^{87}\text{Rb}/^{86}\text{Sr}$	($^{87}\text{Sr}/^{86}\text{Sr}$) initial	$\epsilon\text{Nd}^{(t)*}$	$\epsilon\text{Sr}^{(t)*}$
OGDEN			0.512283 \pm 30			0.70371 \pm 5	+3.6 \pm 0.5	- 6.7 \pm 1
0-58 plag	0.512439 \pm 20	0.0606						
0-58 WR	0.512631 \pm 18	0.1270		0.70375 \pm 5	0.00752			
0-58 opx	0.512714 \pm 17	0.1592						
0-58 cpx	0.512727 \pm 18	0.1720						
BARBER			0.512195 \pm 25			0.70325 \pm 5	+3.7 \pm 0.4	-11.9 \pm 1
BP-45 plag 1	0.512429 \pm 17	0.0711						
BP-45 plag 2	0.512379 \pm 20	0.0632						
BP-45 WR	0.512826 \pm 17	0.2029		0.70409 \pm 5	0.1231			
BP-45 cpx	0.512650 \pm 17	0.1432						
FARMINGTON			0.512280 \pm 25			0.70363 \pm 5	+3.4 \pm 0.4	- 7.7 \pm 1
S-10-68 plag	0.512454 \pm 20	0.0654						
S-10-68 WR	0.512699 \pm 18	0.1649		0.70365 \pm 5	0.00393			
S-10-68 cpx	0.512832 \pm 17	0.2085						

$$*\epsilon\text{Nd}^{(t)} = \left[\frac{(^{143}\text{Nd}/^{144}\text{Nd})_{\text{sample, } t}}{(^{143}\text{Nd}/^{144}\text{Nd})_{\text{CHUR, } t}} - 1 \right] \times 10^4$$

t = Emplacement Age

$\epsilon\text{Sr}^{(t)}$ Calculated analogously

Parameters used for calculating CHUR evolution:

$$^{147}\text{Sm}/^{144}\text{Nd} = 0.1967$$

$$(^{143}\text{Nd}/^{144}\text{Nd})_{\text{today}} = 0.512622$$

$$^{87}\text{Rb}/^{86}\text{Sr} = 0.0896$$

$$(^{87}\text{Sr}/^{86}\text{Sr})_{\text{today}} = 0.7047$$

of syenite associated with gabbro (fig. 1) apparently formed by differentiation of the parental gabbroic magmas at depth prior to emplacement (Olsen, McSween, and Sando, 1983). Contacts between mafic complexes and other Charlotte belt rocks are normally sharp and discordant, and xenoliths of granitic gneisses occur within metagabbros. In some complexes metagabbro abuts metamorphosed ultramafic rocks (hornblendites) or metamorphosed basaltic flows (amphibolites) that are difficult to distinguish from metagabbros in the field.

Outcrops within the mafic complexes are limited by deep weathering, and gabbro and metagabbro cannot be distinguished in saprolite except where abundant rock float occurs. Because of this difficulty, the boundaries between gabbro and metagabbro shown in figure 1 have been determined only approximately in most cases. Intrusive relationships between metagabbro and gabbro plutons are inferred from the absence of gradational contacts between adjacent outcrops of the two lithologies, from the truncation of veins within metagabbro against gabbro in isolated samples of rock float, and from the presence of large inclusions or roof pendants of metagabbro within three of the large gabbroic plutons (not illustrated at the scale of fig. 1; for locations of large xenolithic blocks see Hermes, 1968; McSween, 1981a). These observations suggest a protracted history of multiple intrusion for all these complexes.

The gabbroic plutons vary in modal mineralogical composition but generally show no systematic patterns in the internal areal distributions of lithologic types. An exception is the concentrically zoned Barber pluton. (The gabbroic intrusion within the Barber complex was originally called the Bear Poplar pluton (Clark, ms) but is here referred to as part of the Barber gabbro-metagabbro complex to conform with other nomenclature.) Mesoscopic layering has been reported in only one pluton (South Rock Hill—Chalcraft, 1970). The irregular rock distribution patterns and lack of pronounced layering phenomena may reflect emplacement of these bodies as crystal mushes or stirring by repeated injections of magma or by convection.

Each complex is clearly delineated by positive Bouguer gravity anomalies (fig. 1). Generally the gravity anomalies are significantly more intense over areas mapped as gabbro, suggesting that the gabbro intrusions extend to greater depths than the associated metagabbros. Geophysical studies suggest that individual gabbro bodies are cylindrical (Hermes, 1968; Chalcraft, 1970; Olsen, McSween, and Sando, 1983) or lopolithic (Wilson, 1981; Taylor and Butler, 1982) and extend to depths of 2 to 6 km.

MINERALOGY AND PETROGRAPHY

Gabbros.—Rocks of the Farmington, Concord, Mecklenburg, and Ogden plutons are composed of variable amounts of plagioclase, orthopyroxene, clinopyroxene, olivine, hornblende, and biotite, with accessory apatite, magnetite, ilmenite, hematite, hercynitic spinel, pyrite, and pyrrhotite (table 1). Figure 2 shows modal variations of major minerals for samples from various plutons.

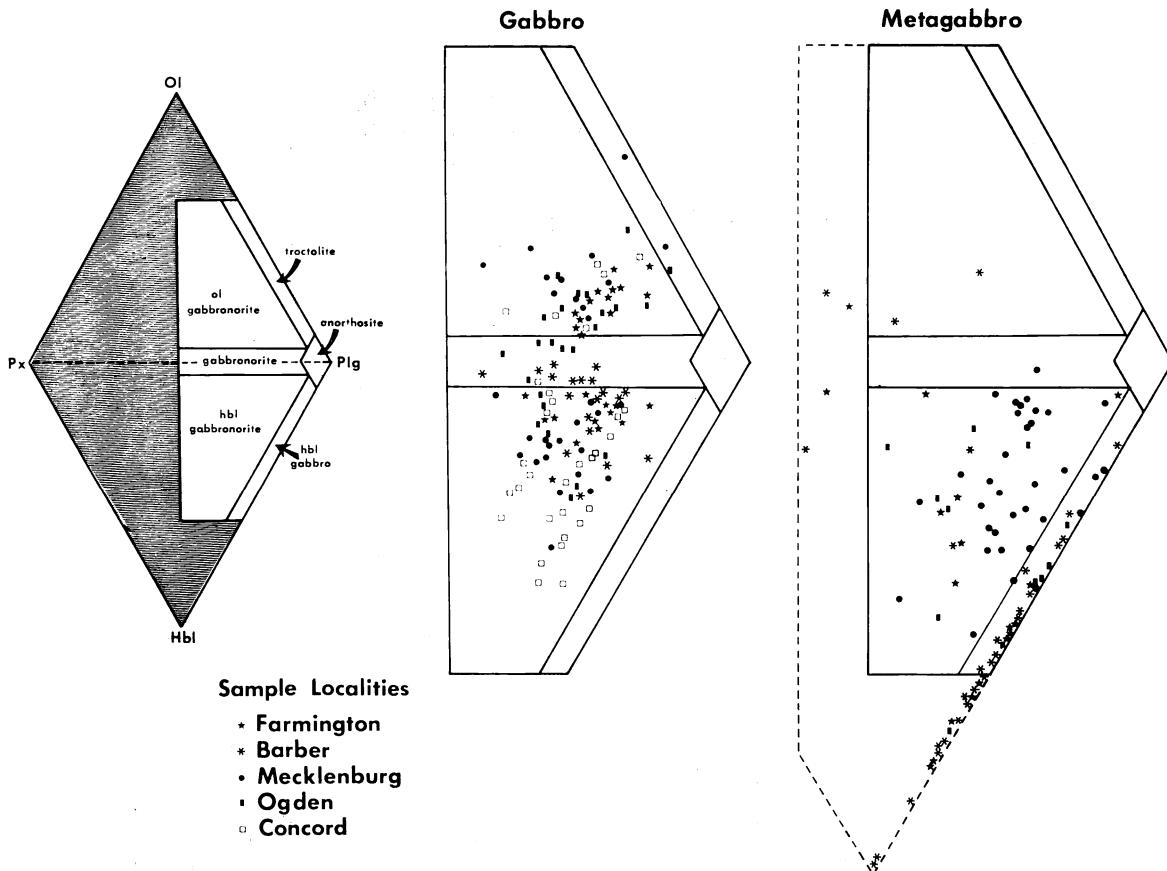


Fig. 2. Modal data for gabbros and metagabbros. Samples are plotted either in the olivine–pyroxene–plagioclase (upper) triangle or the hornblende–pyroxene–plagioclase (lower) triangle, depending on whether olivine or hornblende predominates, even though both minerals may be present. Classification system within the unshaded inset is that of Streckeisen (1973).

Crystallization sequences for these plutons were dominated by early olivine and plagioclase, joined later by clinopyroxene. These three minerals occur as cumulus phases, although not all three necessarily occur in every specimen. (The term *cumulus* is used here only as a textural description for discrete grains, as applied by Irvine, 1982.) Accumulation of plagioclase and olivine produced troctolites in some cases, but most rocks are gabbronorites. The gabbronorites are ortho- or mesocumulate rocks composed of cumulus plagioclase and olivine with postcumulus (poikilitic) clinopyroxene and orthopyroxene, or cumulus plagioclase and clinopyroxene with postcumulus (poikilitic) hornblende and orthopyroxene. Less commonly, all three cumulus phases coexist in the same rock. Plagioclase grains show preferred orientations in some samples. Grain sizes vary considerably (0.5-7mm), and most coarse-grained rocks contain large proportions of postcumulus minerals.

The Barber gabbro is distinct from the other plutons in that it contains cumulus orthopyroxene, clinopyroxene, and plagioclase, without olivine, enclosed by postcumulus hornblende. Rocks of this pluton also contain significant quantities of interstitial quartz (16 percent) and biotite (up to 13 percent) as well as accessory magnetite, ilmenite, hematite, pyrite, and pyrrhotite (table 1). All samples are noritic with orthopyroxene greatly predominating over clinopyroxene. In contrast to the other plutons, the Barber gabbro is concentrically zoned; the interior contains more quartz, and the exterior more hornblende and biotite.

Compositions of the major minerals in these plutons are summarized in figure 3. The analyzed samples were selected to span the range of petrologic properties and rock types contained within each pluton. Co-existing phases in figure 3 are joined by tie-lines. Except for plagioclase, all minerals are compositionally homogeneous, and all grains of a given mineral in any one sample have the same compositions. Clinopyroxenes are augites typically composed of 80 to 83 mol percent Di-Hd, 3 to 6 mol percent CaTs, and 2 to 3 mol percent Jd components. Orthopyroxenes are hypersthenes containing 4 to 5 mol percent MgTs and up to 2 mol percent Di-Hd. Hornblende compositions are plotted in figure 3 in terms of Ca, Mg, and Fe; these amphiboles are pargasites and magnesio-hastingsites in the terminology of Leake (1978). Variations in molar Mg/Fe + Mg among olivines and biotites are also illustrated; biotites contain appreciable TiO_2 (≥ 5 wt percent). Plagioclases are normally zoned with bytownite cores and labradorite or andesine rims.

Many primary minerals in these gabbros display evidence of complex late-magmatic and subsolidus reactions. Olivine in direct contact with late-magmatic hornblende has formed symplectic intergrowths of orthopyroxene and magnetite, and biotite commonly forms rims around opaque oxide minerals. Pyroxenes contain crystallographically oriented plates and rodlets of ilmenite and magnetite formed by subsolidus oxidation. Many composite magnetite-ilmenite grains are separated internally by thin selvages of green hercynitic spinel. Ilmenite grains commonly contain lamellae of hematite.

An important feature of each of these plutons is the very limited Fe-enrichment trends in mafic minerals developed during crystallization (fig. 3). This is consistent with limited differentiation in place because the bodies may have been emplaced as crystal mushes. This feature may also have resulted from crystallization at relatively high f_{O_2} and is consistent with the presence of abundant amphibole, mica, and magnetite. A third possibility is that repeated intrusions of primitive magma buffered major element chemistry (O'Hara, 1977). The range of mineral compositions for each individual intrusion is slightly different, although all plutons appear to show parallel crystallization trends. Mafic silicates are more magnesian,

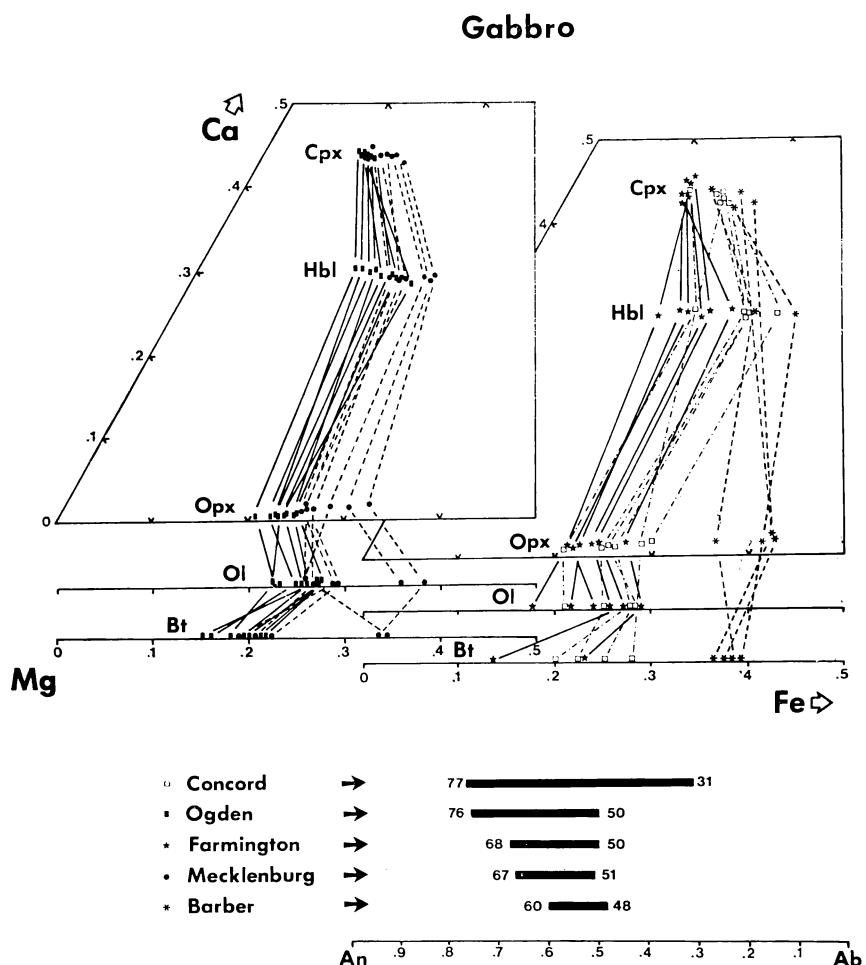


Fig. 3. Microprobe analyses (mol percent) of minerals in individual gabbro plutons. The compositions of clinopyroxene (Cpx), hornblende (Hbl), orthopyroxene (Opx), olivine (Ol) and biotite (Bt) coexisting in the same samples are joined by tie-lines. Plagioclase grains are zoned, and the horizontal bars indicate the ranges of compositions determined for all rocks within each pluton.

and plagioclase core compositions generally more calcic, in the Farmington and Ogden gabbros than in the Concord and Mecklenburg gabbros. It is interesting to note that syenite has been found only in these latter two complexes (Wilson, 1981; Olsen, McSween, and Sando, 1983). The most Fe-rich mafic minerals and sodic plagioclase cores occur in the Barber gabbro.

Metagabbros.—Most metagabbro bodies are only partly recrystallized and retain some relict igneous textural and mineralogical features. In a thorough description of the Mecklenburg metagabbro, Hermes (1968) grouped rocks into three types based primarily upon degree of recrystallization: type 1 metagabbros have relict igneous textures; type 2 samples are recrystallized to form granoblastic textures; and type 3 rocks display faint to distinct banding. Hermes' classification applies to metagabbroic rocks of the other complexes as well, although an additional type (here called type 0) is added to delineate samples found in several complexes of essentially unmetamorphosed gabbroic protolith that retained their original mineralogy as well as texture. The various types of metagabbro have no systematic distribution within each complex but appear to be intermingled in random fashion.

Many type 0 rocks are similar in mineralogy and texture to the gabbros already described. Prominent minerals include orthopyroxene, clinopyroxene, plagioclase, olivine, and hornblende. However, plagioclase in these is clouded by small calcite and epidote inclusions, and in some specimens coronas have formed between plagioclase and olivine grains. These coronas consist of two parts: the rim in contact with plagioclase is amphibole intergrown with vermicular spinel, and the rim in contact with olivine is composed of orthopyroxene.

In type 1 metagabbros igneous textures are preserved; however, mafic silicates are selectively replaced by aggregates of amphibole, leaving plagioclase intact except for minor epidote and sericite alteration. Coronas produced by reaction between olivine and plagioclase can be observed in some type 1 rocks, even though olivine is no longer present. On this basis the Barber metagabbro is inferred to have formed from an olivine-bearing protolith, in contrast to the quartz norites of the associated gabbroic pluton. Igneous textures are obliterated in granoblastic type 2 and banded type 3 rocks.

Most metagabbro samples are of type 1; type 2 rocks are less abundant; and type 3 rocks are uncommon. All these types (1-3) consist primarily of plagioclase and hornblende (fig. 2). Lesser amounts of clinopyroxene appear to be in textural equilibrium with plagioclase and hornblende in most samples. Some relict orthopyroxene commonly occurs in type 1 and 2 samples, although most grains are pseudomorphed by chlorite or fibrous actinolitic amphibole. Olivine is absent, having been converted to pyroxene or amphibole at an early stage (Hermes, 1968). Epidote and clinozoisite replace plagioclase where it is in contact with oxide minerals and occur as stringers crosscutting some samples. Biotite, chlorite, quartz, apatite, titanite, magnetite, sericite, serpentine, magnetite, ilmenite, calcite, and pyrite are accessory minerals (table 1).

Compositions of major minerals in metagabbros are summarized in figure 4. The diagram to the left shows the compositions of relict igneous minerals in type 0 and some type 1 metagabbros. Although compositions of most minerals are similar to those in gabbros, plagioclase core compositions in metagabbros are commonly more calcic. In the ACF diagram to the right of figure 4 are projected compositions of coexisting phases in texturally recrystallized type 2 and 3 metagabbros. It is possible that these do not represent equilibrium compositions, as many contain additional relict phases. The compositions of plagioclase rims become progressively more sodic proceeding from type 0 to type 3 metagabbros. Most plagioclase grains retain some zoning, even in recrystallized types (fig. 4). Hornblende compositions change progressively from tschermakitic hornblende to magnesio hornblende (terminology of Leake, 1978) as metamorphic intensity increases.

COMPOSITION AND DIFFERENTIATION OF PARENTAL MAGMAS

Average chemical compositions for all analyzed samples of each gabbro pluton and of several metagabbros are presented in table 1. In cases with large numbers of analyses, these values may represent the average compositions of the plutons if the vertical distributions of rocks are not too different from the horizontal outcrop patterns; in these cases standard deviations are also reported (table 1). All gabbros except Barber are similar; relative to the other plutons Barber rocks are higher in SiO_2 and K_2O and lower in MgO . Variations in alkalis, FeO^* , and MgO of analyzed samples of the Mecklenburg (Hermes, 1968), Concord (Cabaup, ms), and Barber (Strange, ms) gabbros, the only plutons for which abundant chemical data have been collected, are illustrated in figure 5A. Normative compositions for these rocks are summarized in figure 5B. Gabbroic samples are tholeiites, but the compositional relationship of these rocks to their parental magmas is not clear. Most samples do not plot near the compositional fields of typical tholeiitic lavas (fig. 5B), presumably because of fractionation effects. The addition of cumulus olivine, clinopyroxene, and plagioclase (all observed in Mecklenburg and Concord) would translate individual gabbro compositions in figure 5B toward the Ol-Di join; cumulus orthopyroxene and clinopyroxene in Barber samples would push them toward the Di-Hy join. Consequently, parental magma compositions for all these gabbros were probably tholeiitic.

The limited compositional variations observed in individual gabbros suggest that differentiation of these magmas after emplacement was limited to local variations in the proportions of cumulus phases and intercumulus liquid, and evolved residual melts were not segregated. The contemporaneous syenitic magmas of the Concord and Mecklenburg complexes likely formed at depth prior to emplacement, because no intermediate rock types have been found (Olsen, McSween, and Sando, 1983).

Butler and Ragland (1969) assumed that the gabbroic rocks of the Piedmont were genetically related to the associated late-Paleozoic granitoid plutons and thus defined the mafic end of a calc-alkaline trend.

Metagabbro

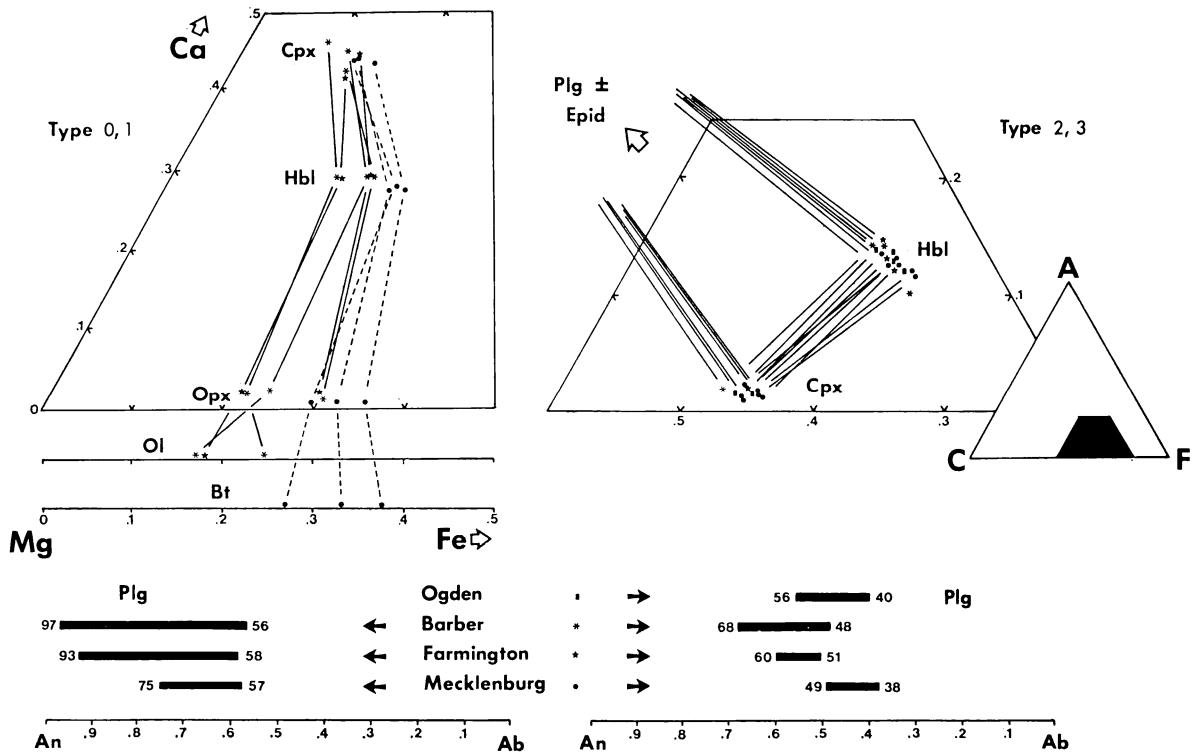


Fig. 4. Microprobe analyses (mol percent) of minerals in individual metagabbro bodies. On the left are compositions of relict igneous phases in type 0 and 1 metagabbros, and on the right are metamorphic minerals in type 2 and 3 metagabbros. Plagioclases are zoned, and the horizontal bars indicate ranges of compositions determined for all rocks of that type within each pluton.

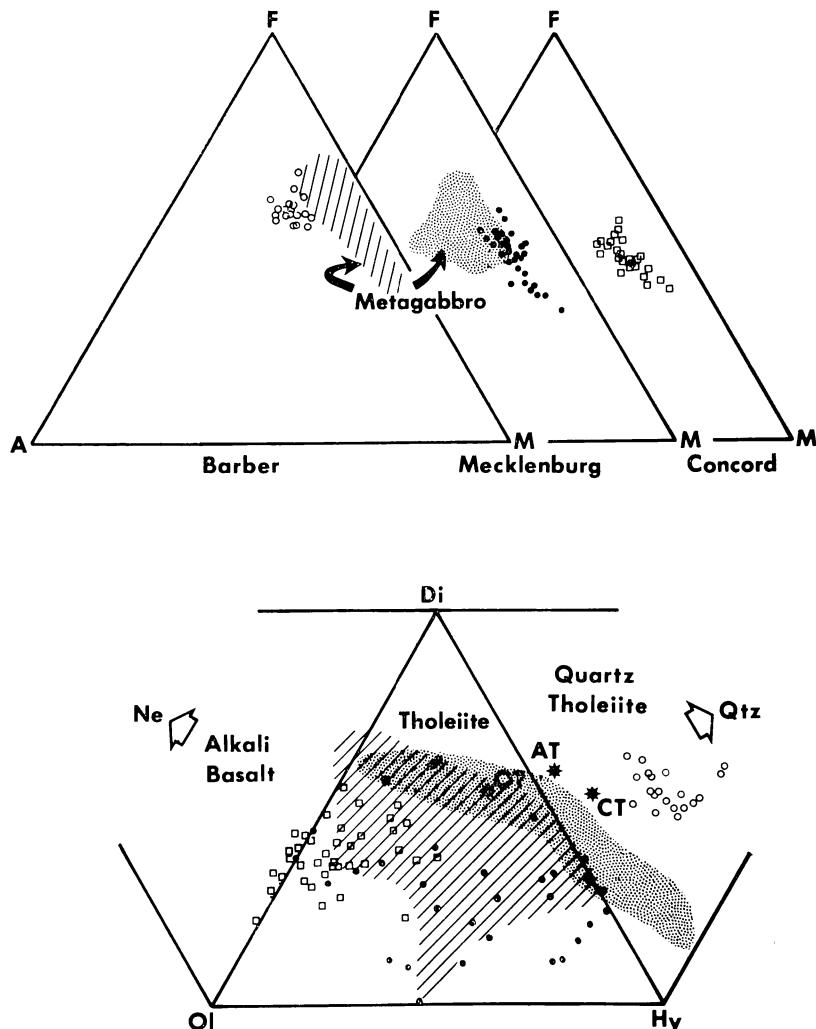


Fig. 5. Chemical variations in gabbros and metagabbros of the Barber, Mecklenburg, and Concord complexes, from Hermes (1968), Cabaup (1969), and Strange (ms). (A) A(alkalis)-F(FeO*)-M(MgO) diagram (wt percent); (B) Normative compositions. Representative tholeiitic magma compositions are as follows: OT (oceanic tholeiite) is the average mid-ocean ridge basalt of Engel, Engel, and Havens (1965); CT (continental tholeiite) is the average of Yakima and Picture Gorge basalts from the Columbia River plateau of Waters (1961); and AT (arc tholeiite) is the representative island-arc tholeiite of Jakes and White (1971).

Unfortunately the distinction between tholeiitic and calc-alkaline trends cannot be evaluated from bulk analyses because of the limited compositional ranges of gabbroic rocks (fig. 5A). These trends are blurred in rocks with less than ~ 54 wt percent silica (Miyashiro, 1974; Kay, Kay, and Citron, 1982), and most gabbroic samples have silica contents of 45 to 50 percent. Analyses of Cr, V, and Ti (table 1) overlap both the calc-alkaline and tholeiitic fields (Miyashiro and Shido, 1975). Contents of Ni (table 1) are anomalously high for either trend (Ishikawa, 1968) and presumably reflect olivine accumulation. It is more probable that the granitoid plutons were not produced by calc-alkaline differentiation of gabbroic magmas but formed by anatexis of lower crust (Wenner, 1981). This is consistent with the crustal signature found in Nd isotopes in Charlotte belt granites by Sando and Hart (1982); however, their results leave open the possibility of a juvenile, mantle-derived (gabbroic) contribution to the granitic magmas.

The average analyses of Mecklenburg and Barber type 1 and 2 metagabbros are presented in table 1. Hermes (1968) concluded that metamorphism was isochemical, based on the compositional similarities of the various metagabbro types. Compositions of Mecklenburg metagabbros are different from most gabbros but are similar to analyses of the Barber gabbro (fig. 5). The Mecklenburg metagabbro and Barber gabbro have lower MgO and higher K₂O abundances, as well as lower contents of Cr and Ni (table 1), which may indicate these were more highly fractionated magmas. However, Barber metagabbros are similar in composition to other gabbros.

CONDITIONS OF METAGABBRO METAMORPHISM AND GABBRO EMPLACEMENT

Conditions of metamorphism are difficult to quantify because metagabbro assemblages are commonly in disequilibrium. The wide variations in metamorphic intensity experienced by metagabbros probably reflect local availability of water, as suggested by Hermes (1968). Titanium contents of amphiboles are sensitive to metamorphic grade (Raase, 1974), and comparison of Ti contents of type 2 and 3 amphiboles (commonly 0.1-0.3 atoms per 23 oxygens) with Raase's data suggest amphibolite facies conditions. Calculations employing the plagioclase-hornblende geothermometer of Spear (1980) using typical type 2 and 3 metagabbro hornblende compositions (Hermes, 1970; Clark, ms) and coexisting plagioclase rim compositions (An₃₈₋₄₀) give equilibration temperatures in the range 500° to 550°C (appropriate to amphibolite facies conditions). The presence of minor chlorite in many metagabbros is consistent with metamorphic temperatures less than 550°C, as Liou and others (1974) observed the growth of chlorite from experimental hornblende-plagioclase-quartz assemblages below that temperature. These metamorphic temperatures are lower than that required to synthesize clinopyroxene from basaltic compositions (Spear, 1981), suggesting that all observed clinopyroxenes may be relict. Reaction coronas formed at olivine-plagioclase grain boundaries in some metagabbros suggest pressures of 5 to 7 kb (Gardner and Robins, 1974). The occurrence of amphibole in these coronas indicates the presence of a

fluid phase that might lower the pressure at which such a reaction would occur (Walawender, 1976); however, the lower end of this pressure range is appropriate for the temperature interval suggested above under conditions of a normal geothermal gradient.

Estimates of conditions of emplacement of gabbro plutons are derived from several lines of evidence. The compositions of coexisting clinopyroxene and orthopyroxene in equilibrium with olivine and calcic plagioclase can be used to constrain pressure using the petrogenetic grid of Herzberg (1978). Compositions of typical pyroxene pairs in olivine gabbro-norites from the Concord, Farmington, Ogden, and Mecklenburg samples (fig. 3) give pressure estimates in the range of 3.5 to 5.0 kb, in agreement with results obtained by Garrison and Taylor (1981) for the Chester pluton. This method cannot be used for Barber samples because olivine is absent. Emplacement of the Concord gabbro was accompanied by an approximately contemporaneous syenite ring dike (Olsen, McSween, and Sando, 1983). Discrete grains of microcline and albite in this syenite suggest pressures of at least 5 kb, if P_{H_2O} is assumed to equal lithostatic pressure. A comparison of these methods therefore gives an overlapping pressure estimate of ~ 5 kb.

The pressure and temperature conditions of metamorphism are appropriate to depths of approx 17 to 18 km, assuming a normal geothermal gradient. Of course, it is not certain that the geothermal gradient was normal, but no petrologic indicators for an abnormal gradient have been noted in other Charlotte belt rocks that experienced Taconic metamorphism. The gabbro plutons were apparently emplaced at similar or slightly less depths (14-17 km) than those estimated for metamorphism of the earlier metagabbros.

AGES OF GABBRO AND METAGABBRO

Figure 6 shows the results of Sm-Nd dating of four of the unmetamorphosed gabbros of this study, including previously published results for the Concord gabbro (Olsen, McSween, and Sando, 1983). Ages indicated for the Ogden, Farmington, and Concord gabbros are within error of each other (399-407 my) and are consistent with synchronous emplacement of all three plutons. These values agree well with a biotite K-Ar age of 391 ± 8 my obtained by Stephen A. Kish (personal commun., 1982) for a sample of Concord gabbro. The age for the Barber gabbro (479 ± 24 my) is well outside analytical error of the other three. This result has been checked by replicate analysis of both clinopyroxene and plagioclase, including independent preparation of a second plagioclase separate.

Although these are mineral isochrons, we interpret the recorded ages to be emplacement (crystallization) ages. All the minerals analyzed were fresh, unaltered igneous phases. In contrast to the case of the Rb-Sr system in this rock type, pyroxene appears to be the major host for both parent Sm and daughter Nd and thus probably controls diffusive exchange between minerals. Exchange involving pyroxene is unlikely below magmatic temperatures, as calculated closure temperatures for Sm in diopside are above 850°C even for improbably slow cooling rates (Sneer-

inger, ms). The ages recorded by this method should therefore not be affected by slow cooling from metamorphic temperatures, as is the case for many K-Ar and Rb-Sr mineral ages from the Piedmont.

The time interval between emplacement of gabbros and metagabbros is not known. In other parts of the Charlotte belt, metagabbroic rocks are occasionally cut by early granitic bodies, suggesting metagabbro intruded before ~ 520 my ago (Butler and McSween, 1983). In the neighboring Carolina slate belt, metagabbro sills and lopoliths (Butler, 1979) intrude volcanic rocks dated at 580 my (Wright and Seiders, 1977). We have obtained a preliminary plagioclase-whole rock two-point Sm-Nd isochron age of $567 \pm \sim 50$ my for a sample of type 0 Barber metagabbro, which is consistent with the above field observations.

Other constraints on the time of intrusion of metagabbros in the complexes studied here are that they are intruded by ~ 400 my old plutons (contact relations between the older Barber gabbro and metagabbro are obscure) and are metamorphosed. The inferred thermal peak of the Taconic metamorphic event was at 460 ± 20 my (Hatcher and others, 1980), presumably a minimum age for metagabbro emplacement. Hornblende $^{40}\text{Ar}/^{39}\text{Ar}$ ages for southern Appalachian rocks commonly range from 470 (Taconic) to 350 my (Sutter, 1982). Although a few of the

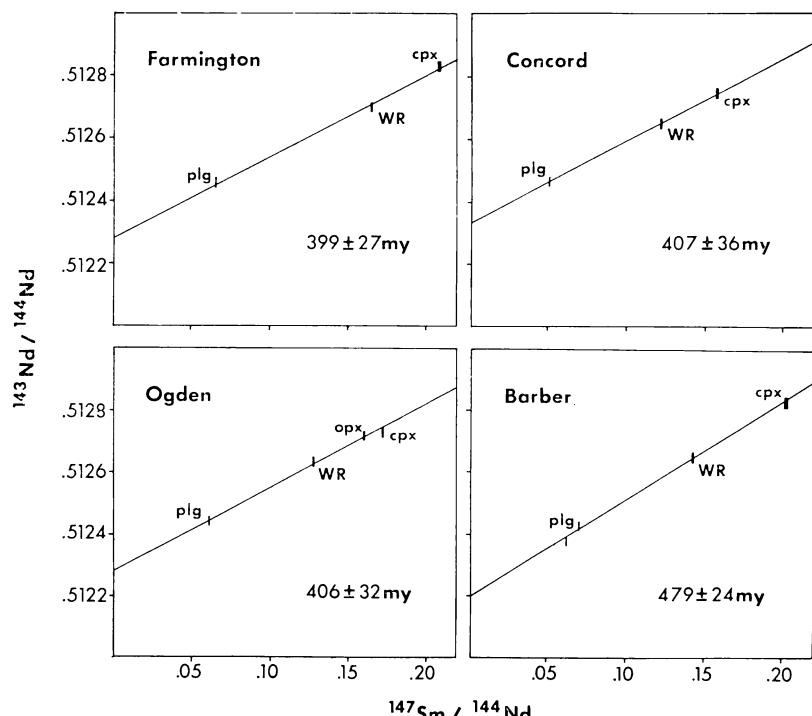


Fig. 6. Sm-Nd mineral isochrons for gabbro samples, defined by plagioclase and clinopyroxene separates and whole rock (WR) samples.

younger ages may represent Acadian metamorphism, this later event was apparently very localized in the Piedmont (Butler and Fullagar, 1982). Hornblende begins to retain quantitatively its radiogenic ^{40}Ar at 500°C (Sutter, 1982), so these cooling ages approximate the times at which metamorphism under the conditions determined for metagabbros could occur. Thus metamorphism of metagabbros may not provide a very firm constraint on their time of emplacement.

The 479 my intrusion age of the unmetamorphosed Barber gabbro is surprising in view of the metamorphic ages in this part of the Piedmont. Emplacement of this metagabbro and gabbro as discrete pulses is supported by our dating results as well as compositional differences, although contact relations are obscure. The most likely explanation for the absence of metamorphism in the Barber gabbro is that it was intruded after the metamorphic peak; this is permissible when the errors on the ages of gabbro and metamorphism are considered. An alternative would be for emplacement to precede or coincide with peak metamorphism but with local availability of fluids insufficient for subsequent metamorphism, as invoked for type 0 metagabbros.

ORIGIN OF THE GABBRO-METAGABBRO ASSOCIATION

Calculations of the mechanics of magma ascent have been performed by Marsh (1976; 1978). Reasonable parameters for these calculations indicate that the first few bodies of rising magma will crystallize at depth because their velocities are slowed as they rise into cold lithosphere with high viscosity. Only with repeated intrusions through the same channelways can lithosphere become hot enough to insulate successive batches of magma and permit them to rise to higher levels before they crystallize. McSween (1981b) suggested that these gabbro-metagabbro complexes might represent such chimneys of reintrusion. However, this explanation may be feasible only if the time spans between emplacement of metagabbro and gabbro are limited.

If gabbro-metagabbro complexes required long time intervals for assembly, as now seems likely, there must have been persistent structural or tectonic control of the sites of magma generation and/or emplacement. This idea is supported by the arcuate pattern in which complexes are located at roughly regular intervals (fig. 1). Regeneration of magmas along the same trend obviously occurred, but this seems unlikely to be the controlling factor in the origin of this association, because gabbros and metagabbros are localized at certain positions along the axis of the trend. It appears more likely that ascending magmas repeatedly utilized the same pathways, possibly because of structural weaknesses induced by early metagabbro ascent.

POSSIBLE TECTONIC SETTINGS

If metagabbros in these complexes were emplaced between 520 to 580 my ago, they may represent plutonic equivalents of the Cambrian volcanic arc sequence developed in the Carolina slate belt (for example, Feiss, 1982). Igneous activity during this period was clearly associated

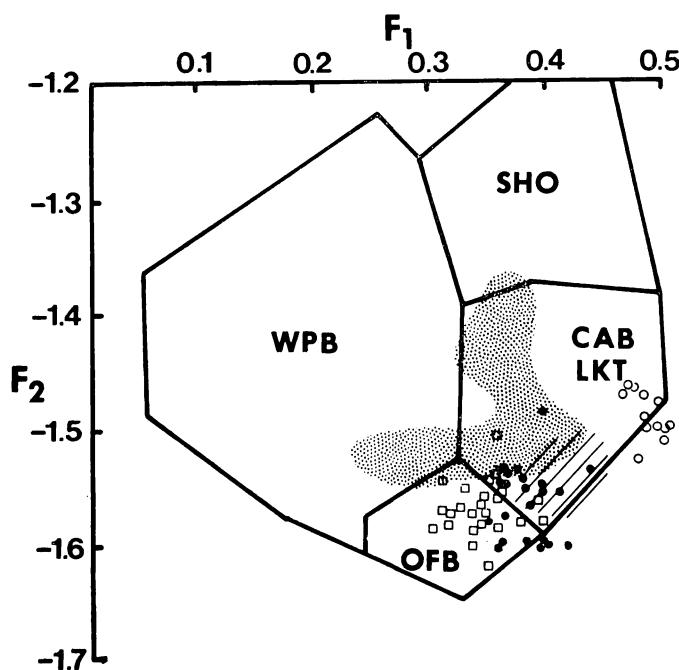
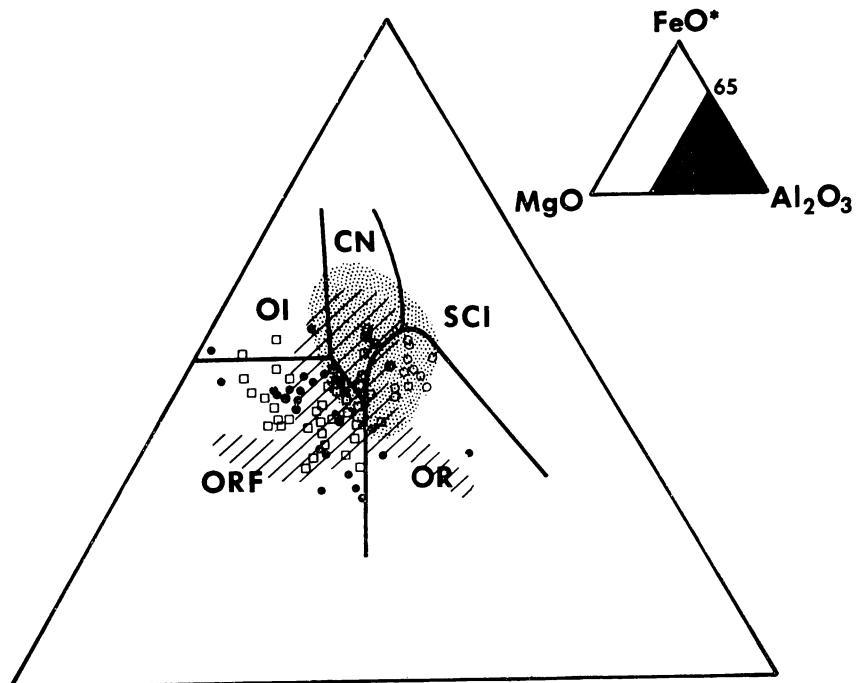
with a subduction zone (Hatcher, 1978), though no consensus has been reached about its nature.

The tectonic setting of the Piedmont in middle Ordovician time, appropriate for emplacement of the Barber pluton, was also characterized by subduction (Hatcher, 1978). Petrologic and geochemical similarities between the Barber gabbro and the Mecklenburg metagabbro argue for similar, if not the same, tectonic environments.

The tectonic setting during Siluro-Devonian time, corresponding to most gabbro crystallization ages, is not well constrained. Butler and Fullagar (1982) suggested that the 415 to 385 my intrusive episode could not be related to compressional tectonics because of the absence of associated metamorphism; however, during this time the Charlotte and Carolina slate belts (Avalon terrane) were presumably joined to the North American continent along the central Piedmont suture to the west of the Charlotte belt (Williams and Hatcher, 1982). Thrusting of western terranes under the Avalon plate probably resulted in crustal thickening, melting, and mantle upwarp (Sinha and Zeitz, 1982). The petrographic and chemical characteristics of these gabbroic bodies are very similar to those of gabbroic plutons in the Peninsular Ranges of California (Walawender and Smith, 1980) and the Cordillera of Peru (Mullan and Bussell, 1977), for which compressional margin settings have been proposed. However, the common occurrence of rocks with compositions intermediate between gabbro and granite, as noted in these and in other dissected orogenic zones (Erikson, 1977; Ishizaka and Yanagi, 1977; Price and Sinton, 1978; de Albuquerque, 1979), constitutes a difference between these areas and the southern Appalachian Piedmont. Nevertheless, examples of bimodal suites in compressional environments have been reported (for example, Strong, 1979).

Petrologic similarities can also be found with plutonic suites of rifted continental areas, for example, the aligned mafic intrusives of the Inner Hebrides, Scotland (Stewart, 1965). Such extensional suites are characterized by bimodal distributions of rock compositions, as in the southern Appalachians, but they commonly include peralkaline rocks as well (Petro, Vogel, and Wilband, 1979).

Major-element discriminant diagrams have been developed for the recognition of basaltic rocks from various tectonic settings. Although strictly applicable only to volcanic rocks, such methods can provide constraints for plutonic rocks if the direction of chemical change as a result of fractionation is known. Two different approaches to this technique are illustrated in figure 7. Figure 7A was formulated by Pearce, Gorman, and Birkett (1977) using volcanic rocks slightly more siliceous (51-56 percent SiO_2 calculated anhydrous) than most of the gabbroic samples studied here. Mecklenburg metagabbros and Barber gabbros plot in the fields of continental (CN) and orogenic (OR) basalts, whereas Mecklenburg and Concord gabbroic samples and some Barber metagabbros generally plot in the field of ocean ridge and floor (ORF) basalts. This latter assignment is probably incorrect and reflects olivine, clin-



pyroxene, and plagioclase accumulation which shifted these analyses toward the MgO apex or the $\text{MgO}-\text{Al}_2\text{O}_3$ join in this diagram. Figure 7B (Pearce, 1976) is a plot of two discriminant functions calculated from complete major element analyses. All plotted values meet the required screen ($\text{CaO} + \text{MgO} = 12.20$ percent) used to define basalts, although some additional gabbro samples did not. Mecklenburg and Barber metagabbros and Barber gabbros fall within the field of calc-alkaline basalts (CAB) and low-K tholeiites (LKT), suggesting an orogenic character. Most Mecklenburg and Concord gabbroic samples again plot within the ocean floor basalt (OFB) field. The latter could be cumulates derived from parental magmas in the calc-alkaline and low-K tholeiite fields (CAB + LKT). Function F_2 is dominated by MgO (and K_2O), and increasingly negative values for gabbroic rocks reflect olivine and pyroxene accumulation. Function F_1 is controlled by TiO_2 and SiO_2 , and derivation from parental magmas in the within plate basalt (WPB) field would require removal of a Ti-bearing phase or addition of a high silica phase, neither of which was noted.

Recent efforts by isotope geochemists have established the Sr and Nd characteristics of a broad spectrum of modern igneous rocks types, which is of potential use in discriminating the possible tectonic environments of older rocks of obscure origin. We have used this information to interpret the results of our isotopic analyses of the gabbros, plotting our samples in terms of initial epsilon parameter (parts in 10^4 deviation from bulk earth isotopic composition 400 my ago) in figure 8. All four gabbros fall in the depleted mantle quadrant on the so-called mantle array (O'Nions, Hamilton, and Evenson, 1977). None show any isotopic evidence for a seawater-altered oceanic crustal component for Sr, as has been proposed for some magmas from modern subduction zone settings plotting to the right of the mantle array (Hawkesworth, O'Nions, and Arculus, 1979). The position of our samples is similar to that of some rocks from known subduction zone environments (Hawkesworth and others, 1979b) and thus is consistent with the model we favor. However, the isotopic data are certainly not conclusive in this respect, since both ocean-island basalts and the least contaminated lavas from some flood basalt provinces (for example, Columbia River) are known to overlap with our rocks as well (Carlson, Lugmair, and Macdougall, 1981).

In summary, metagabbro parental magmas were apparently associated with a Cambrian subduction zone. Gabbros were post-orogenic intrusions temporally associated with accretion of the Avalon terrane. The features of these plutons are similar to those of other compressional boundaries.

Fig. 7. Major element discriminant diagrams for basaltic rocks from various tectonic settings. Symbols for Barber, Concord, and Mecklenburg gabbros and metagabbros as in figure 5. (A) A portion of the $\text{FeO}^*-\text{MgO}-\text{Al}_2\text{O}_3$ diagram (wt percent) of Pearce, Gorman, and Birkett (1977) showing the compositional fields of volcanic rocks from oceanic islands (OI), ocean ridge and floor (ORF), continents (CN), spreading center islands (SCI), and orogenic zones (OR). (B) Plot of discriminant functions F_1 and F_2 (Pearce, 1976), showing the fields of ocean floor basalts (OFB), calc-alkaline basalts and low-K tholeiites (CAB + LKT), within-plate basalts (WPB), and shoshonites (SHO).

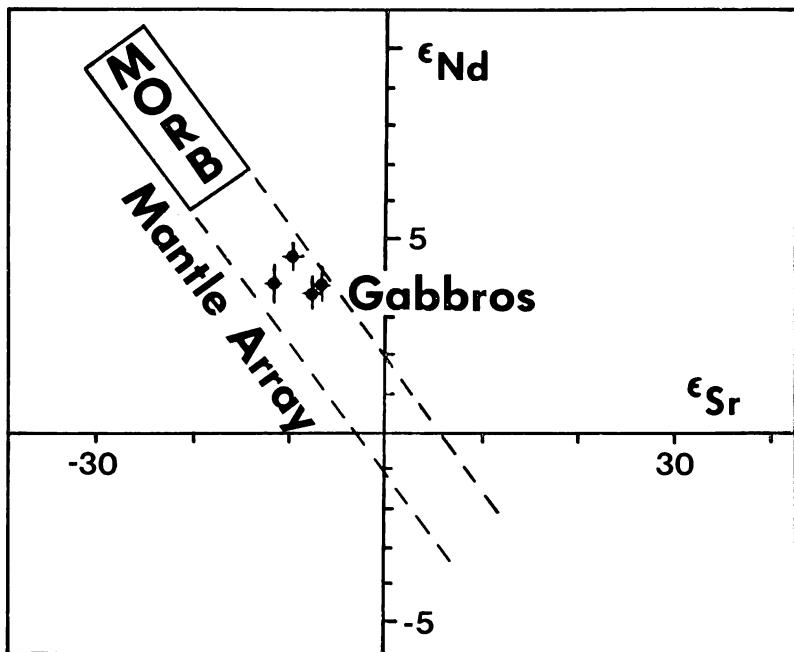


Fig. 8. "Paleo" $\epsilon_{\text{Nd}}-\epsilon_{\text{Sr}}$ diagram at $t = 400$ my, with data and error bars for initial ratio determinations for the four gabbros in this study. Upper boundary on the mantle array was calculated from the present-day limit of MORB isotopic composition by assuming a two-stage evolutionary history for its source. This source composition was assumed to be chondritic until 2 by ago, and the parent-daughter ratios required to generate the modern isotopic composition from that time were used to correct the diagram to the age of the gabbros. This evolutionary model is not unique, but others such as those assuming continuous differentiation do not produce significant differences.

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