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Paleomagnetic results from seven Middle Paleozoic plutons in the Appalachian Piedmont of North and South Carolina

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ABSTRACT

Seven isotopically dated plutons of similar middle Paleozoic age (approx. 400 Ma) were sampled for paleomagnetic study. The results from 12 sites (152 samples) within these plutons show two types of remanence behavior that appear fairly consistent with rock composition. The more leucocratic rocks (9 sites) tend to yield single-component magnetizations, of generally lower coercivities and blocking temperatures relative to the other units, that are considered to represent a recent viscous overprint. The mesocratic to melanocratic rocks show both single- and multicomponent magnetizations, the latter giving characteristic directions isolated through remagnetization-plane analysis. Three sites are considered reliable and yield paleomagnetic poles, of inferred Early Devonian age, that may reflect a 30° southward displacement from stable North America. One large site (25 samples) gives a remagnetized pole position of inferred Carboniferous age consistent with poles from North America, perhaps indicating that the Piedmont may have become part of the North American plate by this time.

1. INTRODUCTION

The southern Appalachian orogen comprises a thick sequence of extensively deformed rocks that reflect a prolonged history of tectonic activity. Recent models developed to describe this activity are necessarily complex, being based in part on the premise that portions of the orogen originated elsewhere (1-3). Paleomagnetic data from eastern New England and the coastal Maritime Provinces and cratonic North America imply sinistral strike-slip movement between the two regions during the time period from Middle Devonian to Late Carboniferous (4-6). This has led to speculation on whether the southern Appalachian Piedmont was involved in this or a similar displacement (7,8).

Paleomagnetic studies in the southern Appalachian Piedmont either have been directed toward a single rock unit (9,10) or have encompassed a number of units varying widely in rock type, location, and assigned age (11-13). The paleomagnetic poles calculated for units dated as Carboniferous (14,15) generally correspond with poles of a similar age from the North American craton (9,11,12), whereas the paleomagnetic results from older rocks for the most part have proved difficult to interpret (11-13). Rao and Van der Voo (10), however, isolated an inferred Late Ordovician magnetization from a single pluton in the Appalachian Piedmont of Delaware, using remagnetization circle analysis, suggesting that the Piedmont was far south of North America at that time.

This study was undertaken to provide paleomagnetic results that could contribute to the understanding of the early to middle Paleozoic tectonic development of the southern Appalachians. With reliable paleomagnetic data, the allochthonous portions of the southern Appalachian orogen could be distinguished and some limits placed as to their points of origin. To avoid potential problems due to remagnetization or post-emplacement tilting, difficult to assess from the paleomagnetic results of a single pluton, seven plutons of approximately Late Silurian to Early Devonian age (16) were sampled from the Piedmont of North and South Carolina. Although some of these units have been included in other paleomagnetic studies of broader scope (12,13), the paleomagnetic results were inconclusive. Difficulties were encountered in this study as well, due mostly to secondary magnetic overprinting, but those few results considered reliable support an allochthonous origin for the southern Appalachian Piedmont.

2. GEOLOGY AND AGE OF THE PLUTONS

The crystalline portion of the southern Appalachians has been divided into a series of northeast-southwest-trending geologic belts, of which the Charlotte Belt (Fig. 1) is the main region of igneous intrusion (17). The country rock of the Charlotte Belt consists of moderate- to high-grade regionally meta-morphosed sedimentary and igneous rocks having a schistosity that regionally strikes N 32° E (18). Rubidium-strontium whole-rock ages (where necessary these ages have been recalculated using $\lambda = 1.42 \times 10^{-11}$ yr^{-1}) on plutonic rocks from the Piedmont suggest three intrusive episodes at 582-509 Ma, 406-377 Ma, and about 294 Ma (14), and all units from the second episode, of particular interest to this study, are found within the Charlotte Belt. Butler and Ragland (17) have divided these plutons into pre-metamorphic and syn- or post-metamorphic groups. The last regional metamorphic event in the Charlotte Belt ended more than 372-392 Ma ago in South Carolina and possibly more than 401 Ma ago in North Carolina (14,19). The complex character of this event is indicated by the variation in time of its maximum intensity from place to place within the Charlotte Belt (14).

The isotopic ages assigned to the seven plutons of this study are given in Table 1. The Salisbury and Yadkin plutons, both highly leucocratic albite adamellites, are believed to be genetically related because of their similar chemical attributes and Rb-Sr whole-rock ages, and close spatial proximity (20). Classified as pre-metamorphic (17), these plutons contain rocks that range in texture from massive to distinctly foliated. The foliations trend to the northeast, dip steeply, and are concordant with the foliation of the country rock, both probably having formed during low-rank regional metamorphism (20). In these and the other plutons, only rocks that appeared massive in outcrop were sampled. The other plutons included in this study (Concord complex, Newberry granite, Lowrys granite, Bald Rock granite, and Mount Carmel diorite) are all considered to be post-metamorphic (17). Rb-Sr biotite ages on the Newberry, Lowrys, and Bald Rock granites (21, 22) group around 300 Ma, indicating that the mineral was re-equilibrated at about that time. However, the good fits of the whole-rock isochrons for these rocks suggest that the overall rock systems have remained closed and that the whole-rock ages probably correspond more closely to the initial crystallization of the rock units. The Concord complex of North Carolina consists of a coarse-grained syenite ring dike enclosing a gabbro-diorite intrusion (both phases were sampled for this study). Chemical, petrographic, and field evidence, as well as nearly identical initial Sr^{87}/Sr^{86} ratios, suggest a close genetic relation between the two (14), the syenite possibly being a differentiation product derived from the gabbroic magma (17). Of a similar description is the Mount Carmel complex of South Carolina. K-Ar ages on the diorite phase of the complex (23) imply a minimum age for the time of intrusion of this unit at approximately 384 Ma, although Fullagar (14) dated (assuming an initial Sr^{87}/Sr^{86} ratio of 0.704) an aplite dike found cutting the diorite at about 303 Ma.

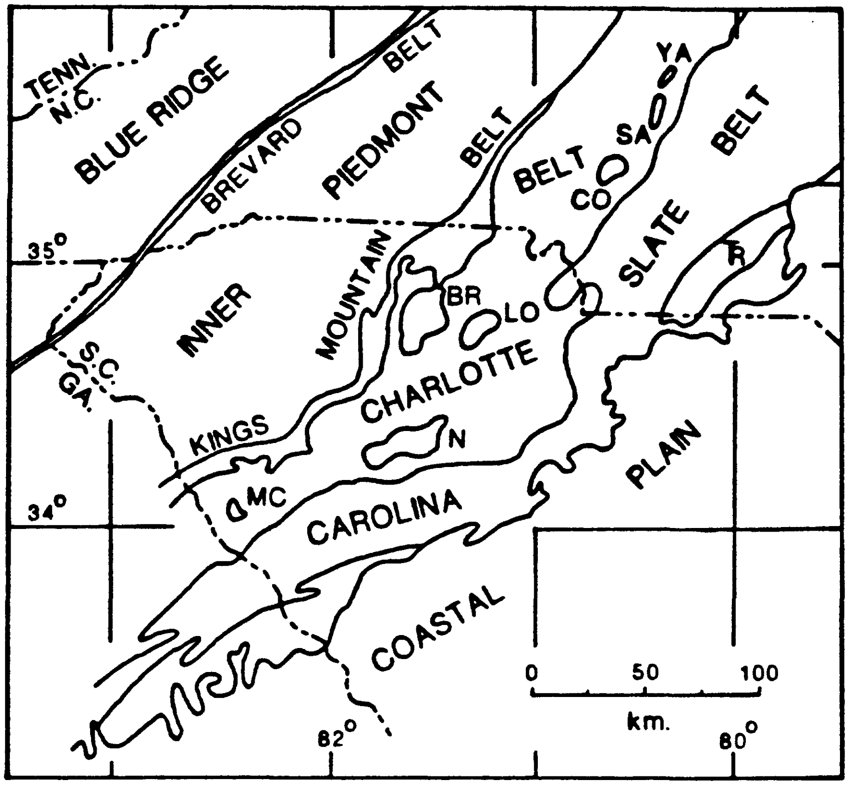

Fig. 1. Schematic geologic setting and locations of the plutons sampled for this study. SA, Salisbury adamellite; YA, Yadkin adamellite; CO, Concord complex; LO, Lowrys granite; BR, Bald Rock granite; N, Newberry granite; and MC, Mount Carmel diorite.

TABLE 1
Radiometric ages of the plutons

Unit	(abbreviation)	Age (Ma)	Method	Reference
Salisbury adamellite	(SA)	404 ± 4*	Rb-Sr whole-rock	(14)
Yadkin adamellite	(YA)	378 ± 8*	Rb-Sr whole-rock	(20)
Concord complex	(CO)	404 ± 21*	Rb-Sr whole-rock	(14)
Lowrys granite	(LO)	399 ± 4	Rb-Sr whole-rock	(15)
Bald Rock granite	(BR)	388 ± 6	Rb-Sr whole-rock	(15)
Newberry granite	(N)	415 ± 9	Rb-Sr whole-rock	(15)
Mt. Carmel diorite	(MC)	387,386,380	K-Ar (biotites)	(21)

* recalculated with $\lambda = 1.42 \times 10^{-11}$ yr^{-1}

3. EXPERIMENTAL PROCEDURE

A total of 185 independently oriented drill-core samples were collected from 15 sites in the seven plutons. Sampling localities (Table 2) were restricted to large artificial exposures (quarries, roadcuts) or the freshest natural exposures (stream-bank cuts, hillside outcrop). At Mount Carmel (MC1), where only a single suitable site could be located, more samples (25) were taken.

All samples were subjected to either progressive thermal or alternating-field (AF) demagnetization, averaging about 9 steps per specimen. Almost half of the samples were thermally demagnetized employing a shielded, non-inductively wound electrical furnace. AF demagnetizations were done with a commercial single-axis demagnetizer and measurements of magnetization were made with a digital spinner magnetometer, also of commercial design.

Demagnetization data for each specimen were plotted using orthogonal vector diagrams and equal-area plots. A component search through the demagnetization data was then made using a least-squares method based on principal-component analysis developed by Kirschvink (24). In this method, lines and planes are fitted to the endpoints of the successive magnetization vectors in three-dimensional space. Collinearity of these points usually suggests the removal of a single magnetic vector component during demagnetization, whereas coplanarity indicates the simultaneous removal of two magnetic vector components in differing ratios. The intersection of two of these demagnetization planes within a single speciman can be used to define an intermediate magnetic vector component or "Hoffman-Day" direction (25). Should the origin fall within the line or plane error limits, it was included as a data point representing the theoretical final demagmetization value "anchoring" the fit to the origin, implying that the components removed by this fit were the only ones remaining in the rock specimen. A minimum of three points are needed to check for collinearity and four points for coplanarity, and an estimate of the precision of the fit given by Kirschvink's method is the maximum angular deviation (24). Selection of directions and planes for statistical analysis from those generated by the component search was done on the basis of visual graphical identification, a maximum number of points included in the fit, and a minimum maximum angular deviation assigned to the fit.

Important to this study is the analysis of converging remagnetization circles (26). Remagnetization circles on equal-area plots correspond to demagnetization planes in space in which overprinting magnetic vectors of variable direction are removed preferentially to a common magnetic component within a given sample set. Because poles to the remagnetization circles form an equatorial girdle about the common direction, corresponding to a Bingham distribution (27), Bingham statistics (28) are reported for those sites exhibiting intersecting demagnetization planes. The more commonly used Fisherian statistics (29) are reported in the analysis of the other paleomagnetic directions.

TABLE 2

Summary of paleomagnetic results

Site	N. Lat/ W. Long	N/n	Declin- ation	Inclin- ation	k	α_{95}
SA1	35.60°/80.44°	9/6L	72.7°	74.1°	32.0	12.0
SA2	35.63°/80.42°	10/9L	37.8°	45.5°	54.7	7.0
YA1	35.72°/80.39°	9/6L	46.8°	52.4°	15.6	17.5
CO1	35.40°/80.61°	11/11L	62.8°	80.5°	41.8	7.1
CO2	35.36°/80.60°	11/10L	326.8°	54.2°	26.9	9.5
CO3	35.34°/80.64°	8/4P,1L,1H	82.1°	-41.4°	-235.1/-1.5	4.0/5.7
LO1	34.83°/81.27°	21/16L	352.0°	53.1°	4.0	21.2
LO2	34.81°/81.28°	9/5L,2P	34.2°	-54.9°	43.6	11.7
BR3	34.86°/81.51°	8/5P,1L	257.3°	42.8°	-36.2/-1.3	9.3/13.1
N1	34.33°/81.54°	12/11L	359.1°	74.4°	53.2	6.3
N2	34.25°/81.67°	19/17L	72.6°	63.2°	15.7	9.3
MC1	34.03°/82.47°	25/14P,9L	140.9°	22.0°	-29.5/-2.5	5.7/11.0

N is the number of samples collected and n is the number of lines (L) or planes (P) or Hoffman-Day directions (H) included in the mean, the most populous group being used in the calculation (see text); k is the Fisher precision parameter (28) for lines if one value or the Bingham concentration parameters (27) for converging planes if two; and α_{95} is the semi-angle of the cone of confidence at the 95% probability level or the minor/major semi-axes of the ellipse of 95% confidence (26) in degrees around the site mean.

4. PALEOMAGNETIC RESULTS

The sample directions of natural remanent magnetization (NRM) for a given site are either largely dispersed with both positive and negative inclinations, or show more consistent clusters, generally with northeasterly declinations and steep downward inclinations. The average NRM intensities for the plutons range in value from 10 to 10^{-2} Am^{-1}, corresponding to their compositional range from gabbro to granite. However, the Bald Rock granite and site LO2 in the Lowrys granite, both distinctly mesocratic, give higher NRM intensities than the other leucocratic rocks and site LO1, respectively. Thermal demagnetization, performed on all rock units, mostly yielded characteristic directions consistent with those isolated by AF treatment. Both thermal and AF demagnetizations to as high as 650°C or 100 mT indicate the magnetic carrier in the rock units to be primarily magnetite. Hematite appears to be present within many of the samples in small amounts, probably associated with the weathering of titanomagnetite.

Two types of remanence behavior were observed. The first is characterized by a single component of magnetization identified as a linear demagnetization trend on a vector diagram (Fig. 2a). Rocks exhibiting solely this type of behavior include the SA granite, YA granite, CO syenite, LO granite, and N granite with the exceptions of sites CO3 (gabbro) and LO2 (mesocratic phase). The single components commonly reside in lower coercivity and blocking temperature ranges than those of the more mesocratic rock samples, being for the most part almost entirely removed (>90%) by 30 mT or 400°C. The maximum demagnetization values for the magnetic component in the N granite and sites LO1 and CO2 are usually less than these.

The second type of remanence behavior is distinguished by the simultaneous removal of two vector components during demagnetization, represented by a curved demagnetization trajectory on a vector diagram (Fig. 2b) and, for anchored planes, by a great-circle arc on an equal-area plot. (Free demagnetization planes that are not place constrained to pass through the origin also form arcs on equal-area plots but cannot be rigorously fitted to a great circle.) Samples exhibiting demagnetization planes are from sites MC1, BR3, CO3, and LO2. These rocks are distinct from the rock units of the single-component group in their more mafic composition, higher NRM intensities, and generally more dispersed NRM directions. In addition, the planes (and lines) fitted to the demagnetization vector endpoints for these rocks tend to reside in coercivity and blocking temperature ranges higher than those of the first group, and commonly include the origin.

Figure 3 shows the convergence of the anchored demagnetization planes, or remagnetization circles, for site BR3. Individual demagnetization vectors are also plotted to illustrate the fit of the remagnetization planes to these points. Demagnetization lines were also found in samples from sites yielding demagnetization planes that are similar to the direction on which the planes converge. The lines presumably are from samples that either had no significant secondary component superimposed on the characteristic component for the site, or reach an endpoint away from the characteristic direction due apparently to the lack of a part of the samples' magnetization spectra in which the characteristic component resides alone. The site mean was calculated in the former case (LO2) from the more numerous line directions and in the latter (MC1, CO3, BR3) from the converging planes, as they are considered to show more accurately the partially overprinted characteristic direction (Table 2).

The site means given in Table 2 are plotted, with their approximate 95% confidence limits (or averaged values for Bingham statistics), in Fig. 4. Because demagnetization behavior was erratic within samples and inconsistent between samples, three sites (BR1,

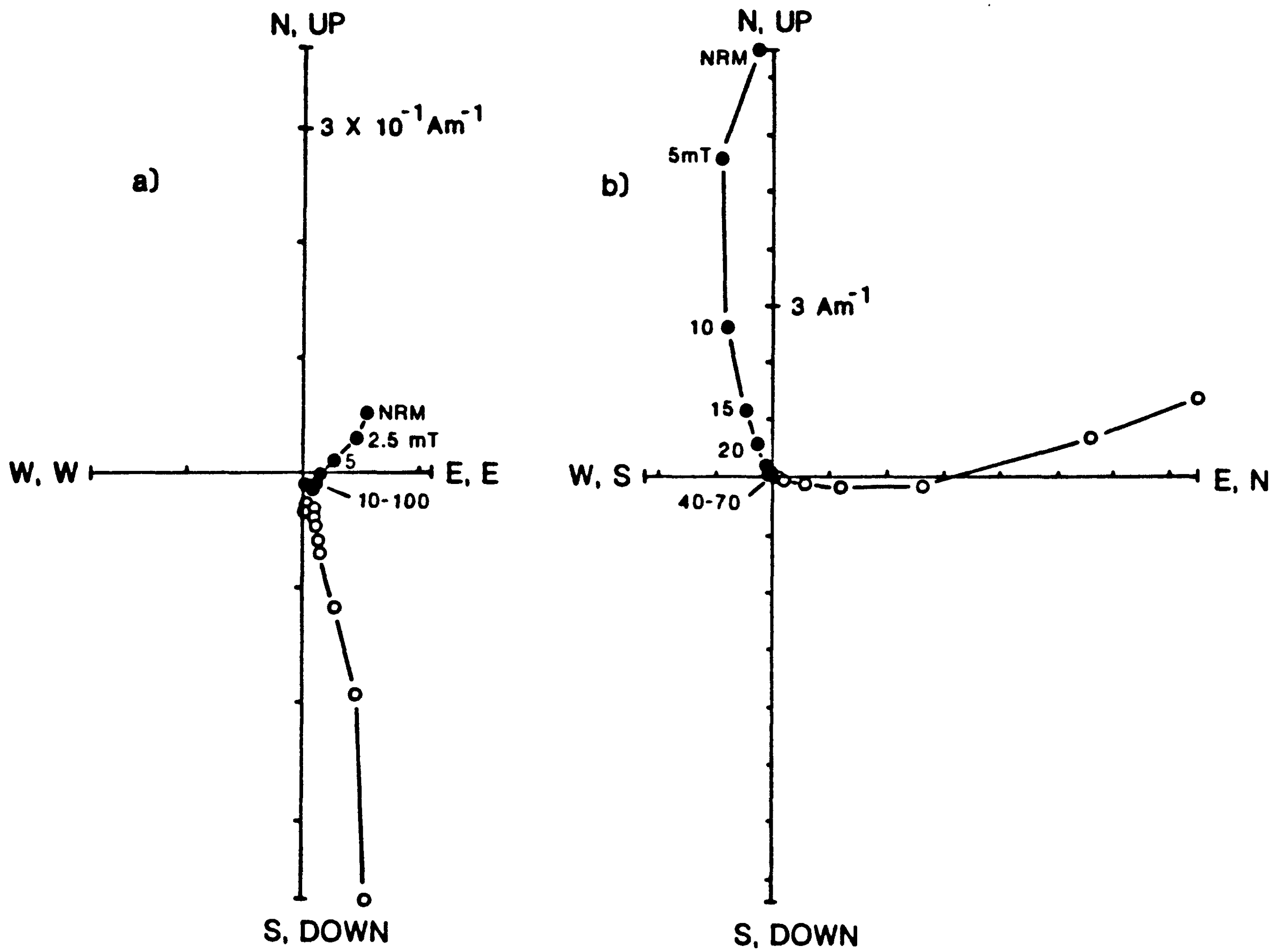

Fig. 2. Orthogonal demagnetization projections of the successive endpoints of the magnetization vector during progressive AF demagnetization showing (a) representative single-component behavior in a sample from site CO1, and (b) representative multicomponent behavior in a sample from site BR3. The convergence of the projections on a point away from the origin in (a), indicates that a small remanence remains in the sample after AF treatment that is most likely associated with hematite. Open circles indicate projections onto the vertical plane, and closed symbols onto the horizontal plane.

BR2, SA3) were dropped from further consideration. Similarly, individual samples from the other sites that showed unstable behavior during demagnetization or disagreed with consistent results from other samples at the site were excluded from the site means. A common cause for exclusion was that a sample exhibited a line direction far from the characteristic direction shown by the convergence of planes from a majority of the other samples at the site. Results from site LO1 show a wide scatter, perhaps the result of repeated overprinting, but generally consistent with results from the other rocks of similar composition and magnetic remanence behavior.

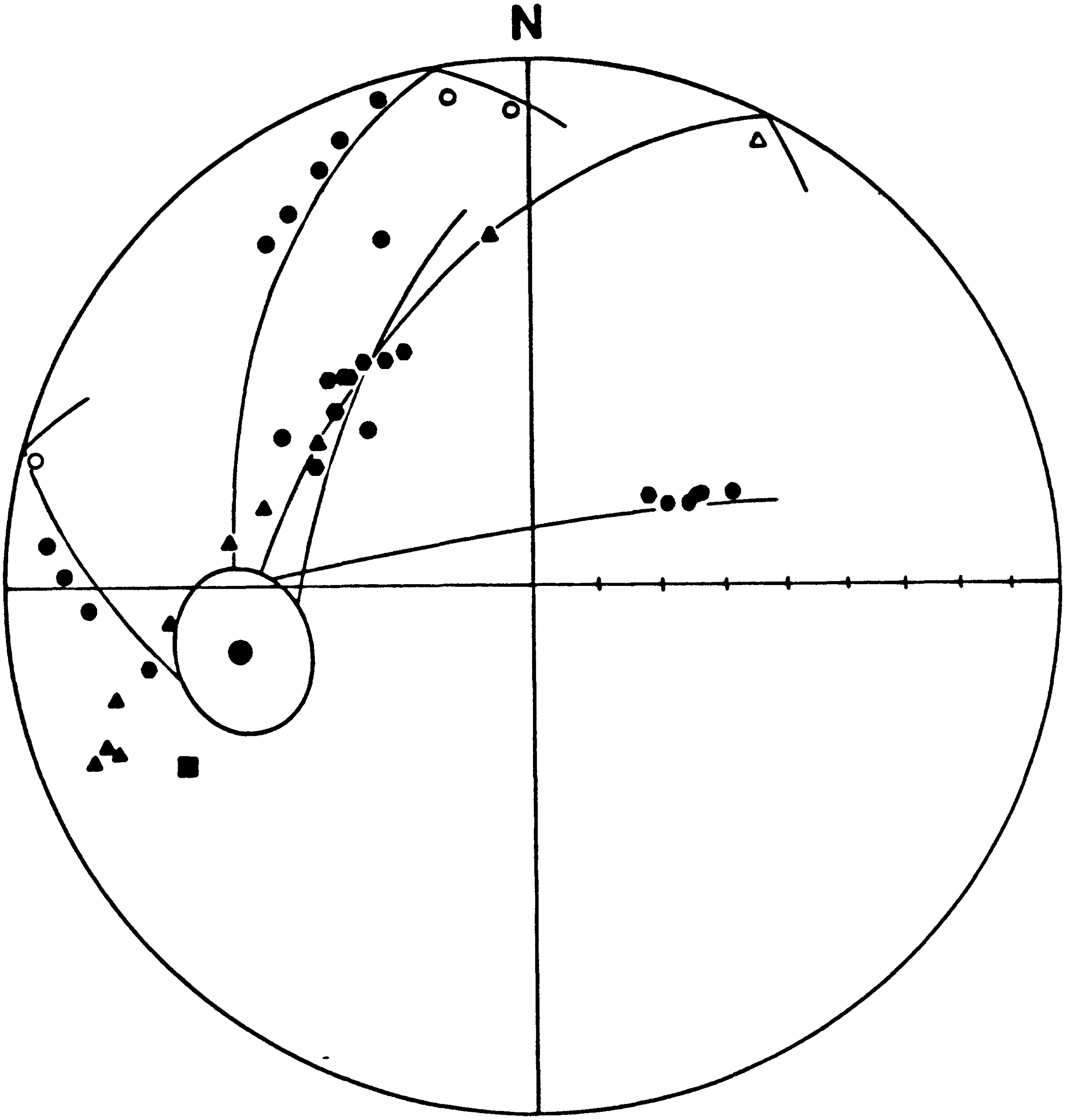

Fig. 3. Equal-area projection of successive magnetization vector endpoints, extended to unit length, and their fitted planes for 5 samples from site BR3. The site mean and the approximate limit of 95% confidence calculated from these planes is also shown. The square symbol represents a characteristic line direction for a sixth sample from BR3. Open symbols indicate projection from the upper hemisphere and closed symbols from the lower hemisphere.

5. DISCUSSION

The paleomagnetic results from sites characterized by a single component of magnetization show them to be dominated by the direction of the present Earth's field (PEF) for this region of the southern Appalachian Piedmont (Fig. 4). Because this remanent magnetization is usually associated with generally low coercivities and blocking temperatures, it is inferred to be of a recent viscous origin. The more shallow inclinations and northeasterly declinations of two sites in the SA and YA granites (SA2, YA1) could reflect a magnetic anisotropy coincident with the regional foliation inherent in these pre-metamorphic rocks. Apart from these, there is a noticeable trend within the PEF-overprinted site mean directions toward steeper downward inclinations and more easterly declinations in the general direction of the MC1 site mean.

The MC diorite yields a mean direction, from converging demagnetization planes, singularly southeasterly in declination with a shallow downward inclination. A paleomagnetic pole calculated from this direction is roughly similar to the poles determined for the North American craton ranging in age from early Devonian to late Carboniferous (Table 3). A late Carboniferous age for this characteristic magnetization of the MC diorite is preferred as it would correspond to the 303 Ma date on the aplite dike (14) cutting the diorite. The emplacement of this dike was part of the last major episode of igneous intrusion in the southern Piedmont (14). It is inferred that this episode of intrusion is responsible for the remagnetization of at least the MC diorite, possibly having had a significant effect on many other rocks in the Piedmont as evidenced in part by the reset biotite ages in the granites from South Carolina. If so, perhaps it is relicts of this remagnetization that contribute to the steeper inclinations observed in the single-component PEF-overprinted rocks.

The characteristic magnetizations from the remaining sites (CO3, LO2, BR3), determined in part from converging demagnetization planes, give paleomagnetic pole positions displaced to the south of those reported for North America in the Devonian (Table 3) and are considered reliable (Table 2). Because poles calculated for these sites do not correspond with the North American apparent polar wander path since the Devonian, the characteristic magnetic directions of these rocks could have been acquired during their initial crystallization and cooling when the southern Appalachian Piedmont was not a part of North America but was located approximately 30° to the south, perhaps with Gondwana affinity (7,8,10). This albeit tenuous assertion is supported by the general equivalence of the site directions and by the presence of site means of both normal and reversed polarity. Also, the southward displacement suggested by their Devonian paleomagnetic poles is intermediate to that inferred for the northern Piedmont in the Ordovician (10) and the presumed suturing of the Piedmont to North America in the Carboniferous (7,8). An alternative explanation to southward displacement for the Piedmont would be a post-magnetization southward tilting of these sites by about 30°. Mildly deformed Triassic sediments and the undisturbed Cretaceous strata of the coastal plain (32) indicate that a large southward tilt of the Piedmont would have to predate the Triassic. And furthermore, this explanation requires that a large portion of the southern Piedmont show a uniform southward tilt that is inconsistent with the northeast-southwest structural trends for the region.

In summary, this study has demonstrated the difficulties encountered in conducting paleomagnetic investigations on middle Paleozoic (400 Ma) rocks in as complex an area as the southern Appalachian Piedmont. From 15 sites (185 samples) in 7 plutons, only 3 sites (CO3, LO2, BR3) have yielded reliable mean directions, another (MC1) appears completely remagnetized, 3 sites (SA3, BR1, BR2) give unreliable results and were discarded, and the remaining 9 sites give apparently viscous PEF magnetizations

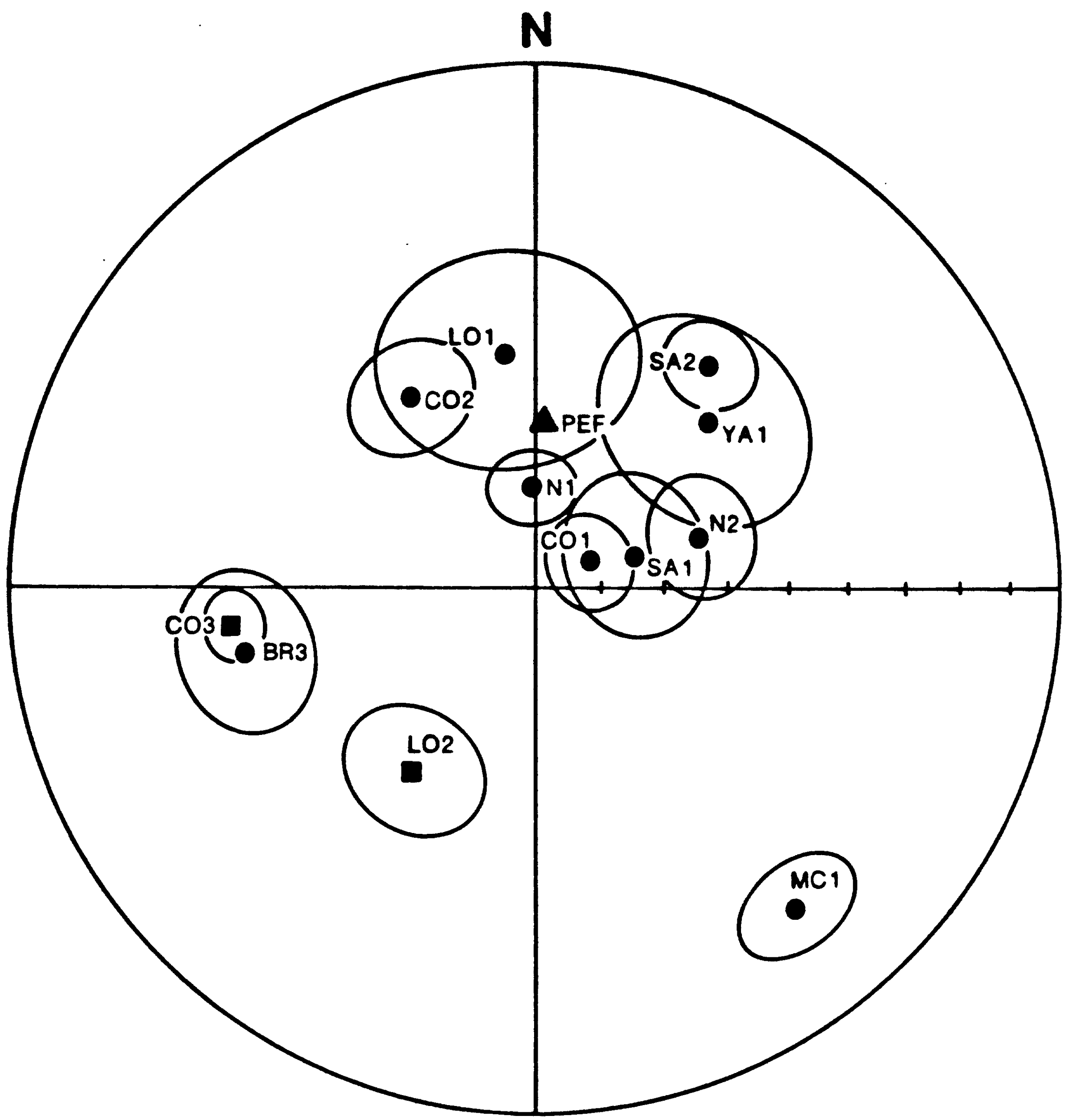

Fig. 4. Equal-area projection of 12 site means from the 7 units with their approximate 95% confidence limits. The square symbols indicate reversed south-seeking directions. The large triangular symbol represents the magnetic direction of the present Earth's field (PEF) in the region of this study.

TABLE 3

Mid-Paleozoic paleomagnetic poles

Unit/Formation	Locality	Pole Position	Age	References
average	N. America	39,N, 126,E	Late Carboniferous	(7)
Mt. Carmel diorite	Piedmont	31,N, 144,E	303 Ma	This study
Catskill Formation	N. America	47,N, 117,E	Middle to Late Devonian	(4)
Columbus Limestone	N. America	45,N, 120,E	Early Devonian	(29)
Bloomsburg Red Beds	N. America	32,N, 102,E	Late Silurian	(30)
Bald Rock granite	Piedmont	4,N, 216,E	388 Ma	This study
Lowrys granite	Piedmont	13,N, 71,E	399 Ma	This study
Concord gabbro	Piedmont	8,N, 213,E	404 Ma	This study

indicating their unsuitability for paleomagnetism. However, these data show some promise and, moreover, suggest guidelines for continued work in the older rocks of the Piedmont. More sites in these and older units of middle Paleozoic age are needed to substantiate the results of this study. A greater number of sites from a single unit may increase the chances of finding those retaining a potentially primary magnetization that could be isolated, if applicable, through demagnetization-plane analysis. Partial to complete remagnetization of units could prove troublesome, especially in the vicinity of younger igneous rocks emplaced in the Carboniferous. And, if possible, the more leucocratic, particularly pre-metamorphic, plutons should be avoided in preference to the more iron-rich mesocratic and melanocratic rocks of higher magnetic stability.

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