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Geochemistry and Tectonic Setting of the Volcanics of the Carolina Slate Belt

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Abstract

The Carolina slate belt consists of Precambrian-Cambrian, metamorphosed, mafic to felsic flows, volcaniclastics, and derived sediments which filled in a volcanic trough presumed to have formed along the leading edge of the North American continent during the early closing of the proto-Atlantic Ocean. Within the slate belt, in central North Carolina, South Carolina, and on the South Carolina-Georgia line, there are volcanigenic massive sulfide deposits of Kuroko affinities and their metamorphically remobilized sulfide and Au quartz deposits.

A total of 296 chemical analyses of volcanic rocks and associated dikes (of which 227 are in unpublished theses, dissertation, and reports) are plotted on alkali-SiO_2, K_2O-Na_2O, AFM, and Na_2O-K_2O-CaO diagrams. In addition, selected subsets are compared with standard discriminant plots, such as TiO_2-SiO_2, MgO-FeO_{total}-Al_2O_3, and Y-Zr-Ti. Generally speaking, the volcanics of the slate belt define a bimodal suite of calc-alkaline to tholeiitic rocks with strong affinities to volcanic suites described in the lesser Antilles and with the volcanics of the coastal volcanic belt of Maine. A subduction-related orogenic environment is most probable.

In addition, the major element analyses strongly suggest that a pervasive, postdepositional alteration process has taken place. In general, this alteration appears to have affected the fine-grained matrix of the volcaniclastics, but flows and dikes were not immune. An overall alkali depletion and MgO enrichment is characteristic, with significant, but variable, mobility of Na_2O, K_2O, CaO, and SiO_2. Thus, characterization of the magmatogenesis by major element composition alone is not easily done. Alteration associated with massive sulfide mineralization in the Gold Hill district, North Carolina, and the Lincolnton-McCormick district, South Carolina-Georgia, is similar to, but more intense than, the pervasive secondary alteration. Strong silicification, alkali addition or subtraction, and MgO enrichment is characteristic. In general, a significant proportion of the mineralization-associated alteration falls outside the normal range of compositional variability of typical slate belt suites and, thus, has a notable signature.

Introduction

THE Carolina slate belt (Fig. 1) is a complex volcanic basinal sequence which formed during later Precambrian to Cambrian time. It is at least 10,000 m thick, consisting of volcanics—both fragmentals and flows—and volcanically derived sediment. In general, these rocks are only mildly deformed and metamorphosed. The slate belt is, in general terms, the southern Appalachian correlative of the Caledonide rocks of New England, the Maritime Provinces, and northeastern Europe. The detailed geology of many areas within the slate belt is poorly known due to inadequate mapping, deep weathering, and the gently rolling topography of the southern Appalachian Piedmont province. Fresh exposures are rare and continuous sections are found only infrequently in manmade cuts. No significant metal mining has been carried out in the slate belt for several decades and currently only aluminosilicate refractory materials (i.e., kyanite and pyrophyllite) are mined in the metavolcanics.

However, there has been a significant history of metal mining in the slate belt and current interest in metals exploration is high. Metallic mineral deposits (see Fig. 2 for the location of some of the more significant districts) are of four distinct types (Feiss and Hauck, 1977; Bell et al., 1980; Feiss, 1982):

1. Polymetallic massive sulfides of "Kuroko affinities." Polymetallic massive sulfide deposits are found in the Cid and Gold Hill districts of central North Carolina, the Haile and Brewer deposits of central South Carolina, and the McCormick and Lincolnton districts of South Carolina and Georgia. These are galena-sphalerite-chalcopyrite-pyrite deposits which are strata-bound and stratiform within sequences of extrusive, predominantly felsic, volcanics. They show typical Pb-Zn, Cu-Zn, and Pb-Cu zoning and are associated with extensive hydrothermal alteration as well as exhalites, including iron-formation and barite. Especially in the Lincolnton-McCormick area, the deposits are also associated with apparently subvolcanic intrusives similar to the quartz-eye porphyries of the Archean. Variations in detail of these deposits are predominantly due to differences in relative proximity to volcanic centers or details of depositional basin dynamics. None appear large by the standards of Buchans, Newfoundland, or Bathurst, New Brunswick, but clusters of small, high-grade deposits are

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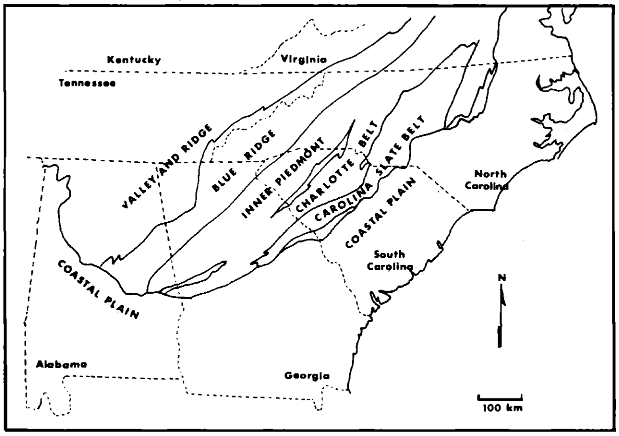

FIG. 1. Generalized map of southeastern U. S. Appalachians showing major geologic provinces.

known, as, for example, in the East and West Cid and Gold Hill districts in North Carolina and the Haile-Brewer district, South Carolina.

2. Remobilized massive sulfide deposits. A second characteristic occurrence are the remobilized sulfide deposits which are presumed to have been originally similar to those described above. At least in North Carolina, the slate belt shows a general increase in metamorphic grade to the west and, near the somewhat enigmatic border with the metaigneous terrain of the Charlotte belt, the Carolina slate belt rocks become ductilely sheared and may show evidence of multiple deformation (Unger, 1982). In these latter areas, there are mineral deposits, such as in the Gold Hill district in central North Carolina and the Smyrna district in South Carolina (J. R. Butler, pers. commun.), which suggest metamorphic remobilization, including recrystallization and hydrothermal mobility, and deformation. The deposits become lozenge shaped and pitch steeply into the nose of possible folds or into the plane of ductile shear. As indicated, recrystallization textures are common, as are locally discordant veins.

3. Vein mineralization. The end members of the process of metamorphic remobilization of presumed syngenetic mineralization are, in the central North Carolina part of the belt, the quartz vein deposits with gold and minor base metal sulfides and the chalcocite-bornite-quartz-epidote veins of the Virgilina district on the North Carolina-Virginia line. Stein and Kish (1978) have shown that the copper in the veins at Virgilina is leached from the surrounding mafic volcanics during an epidotization event associated with regional metamorphism. In the Au quartz veins of central North Carolina, recent fluid inclusion studies (Ford, 1981) strongly indicate that the filling temperatures of primary fluid inclusions in Au-bearing veins match the temperatures expected from the prograde metamorphic event in the Carolina slate belt. This is entirely consistent with the Pb isotopic evidence presented by Kish and Feiss (1982).

4. Postmagmatic hydrothermal veins. In several areas in the Carolina slate belt and its correlatives, metal-bearing veins are associated with granitoid intrusives. Examples include the Hamme tungsten district (Foose et al., 1980) and molybdenum mineralization associated with the Hercynian granites in North Carolina and South Carolina (Speer, 1978). None of these latter have been studied in any detail, as none are of any significant extent or grade. No disseminated, porphyry-type mineralization has been reported from premetamorphic granites in the belt.

The volcanic rocks that host these deposits have been described in several studies in recent years. Two unpublished M.S. theses (Hauck, 1976; Wilkenson, 1978), two Ph.D. dissertations (Black, 1977; Bland, 1978), and a number of other papers (Conley, 1962; Conley and Bain, 1965; Allen and Wilson, 1968; Butler and Ragland, 1969; Stromquist and Sundelius, 1969; Hadley, 1973; Seiders, 1978) have reviewed the stratigraphy, petrology, and petrochemistry of portions of the North Carolina part of the belt. Whitney et al. (1977) have reviewed the correlative units of the Little River Series in South Carolina and Georgia. Rogers (1982), drawing on these same sources, has reviewed the general character of the Carolina slate belt volcanics. These authors generally agree, on petrologic grounds, that the volcanics of the belt were laid down in a volcanic island arc. There the consensus ends. These rocks have been variously character-

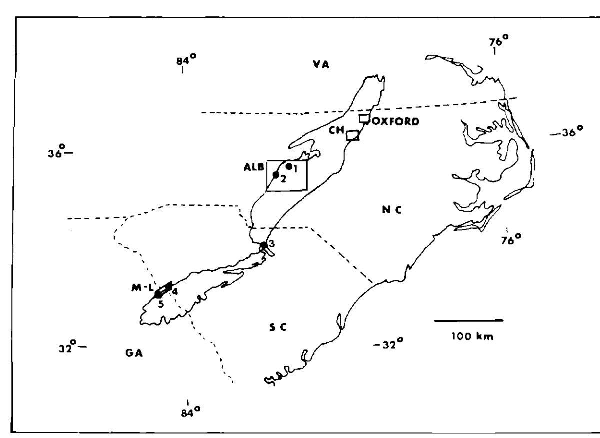

FIG. 2. Location map showing areas being studied. CH = Chapel Hill area, ALB = Albemarle area, M-L = McCormick-Lincolnton area. Also shown are major massive sulfide districts: 1 = Cid district, 2 = Gold Hill district, 3 = Haile-Brewer district, 4 = McCormick district, 5 = Lincolnton district. Outline is the approximate boundary of the Carolina slate belt lithologies, although isolated correlative areas exist in North Carolina, South Carolina, and Georgia.

ized as being produced in a primitive ocean-ocean arc system, a thin transitional crustal margin, and a continental trailing margin.

It is the goal of this study to characterize the Carolina slate belt volcanics which are the hosts of, and possible source for, volcanogenic massive sulfide deposits in the belt and to compare them with other Caledonide massive sulfide-generating environments. A review will be made of the petrochemical data (over 250 analyses) for the belt from the Virginia-North Carolina state line to the southernmost areas that have been studied in the Lincolnton quadrangle of Georgia. This data will be compared to that for the chemistry of other Caledonide and worldwide volcano-sedimentary suites which host massive sulfide mineralization. An effort will also be made to investigate the nature and magnitude of major element mobility during postdepositional alteration of the volcanics.

Petrology and Petrochemistry

The volcanics of the slate belt in central North Carolina have been variously called "Aleutian-type" arc volcanism (Butler and Ragland, 1969), a bimodal calc-alkaline suite (Seiders, 1978), and a continental margin, calc-alkaline suite with sufficient thin continental crust to permit oceanic affinities (Rogers, 1982). Whitney et al. (1979) have suggested a primitive, tholeiitic island-arc origin for the slate belt volcanics in South Carolina and Georgia. The possibility is very real that in some manner all of these models are correct and that the belt was produced in a very hybrid marginal-arc system where no single set of conditions prevailed for very long along the more than 800 km of known strike length and during the more than 100 million years of evolution. It may well be that the goal of defining a single environment is unattainable, but nonetheless this section will try to consider the geochemical and petrologic data as a whole and attempt a characterization of this environment.

The following observations appear to be universally accepted:

1. The Carolina slate belt is a mixed section with as much as 50 percent of the stratigraphic section consisting of volcanically derived sediments and the balance being flows and pyroclastics. Most of these epiclastic rocks are well-laminated, fine-grained mudstones and siltstones ("argillites"). They are remarkably unfossiliferous and often graded. At higher grades of metamorphism, they are typically a monotonous suite of sericite phyllites.

2. The volcanics themselves are dominated by fragmental rocks. Tuffs, with varying proportions of crystals and lapilli and breccia fragments, are the dominant rock type. While indicating a predominance of explosive volcanism during belt evolution, this presents a significant goechemical problem due to the relative ease with which such rocks can be altered in a subqueous environment.

3. The bulk of deposition appears to be subaqueous, in all likelihood submarine. Clear evidence for subaerial deposition is rare and the fact that interbeds of well-laminated, continuous siltstones and mudstones without evidence of channel fill deposits are present throughout the section greatly favors a subaqueous origin. This, too, increases the likelihood of postdepositional alteration.

4. The slate belt volcanic section is dominated by felsic volcanics. For central North Carolina, Seiders (1978) estimates 17 percent mafic, 3 percent intermediate, and 80 percent felsic compositions, based on point counting the geologic maps of three 15 minute quadrangles. Even Whitney et al. (1977), while arguing for a primitive tholeiitic origin for the volcanics in the South Carolina-Georgia portions of the belt, note that the Lincolnton, Georgia, section is dominantly felsic, with only thin, mafic flows. It appears that mafic-dominated regimes occurred in local terrains in the Virgilina synclinorium and in the Chopawamsic Formation in central and southern Virginia, which may or may not directly correlate with the belt.

Areas sampled

The analyses employed in this study come from five areas within the belt. The sources for these analyses are listed in Table 1. The five areas are:

1. The Oxford quadrangle, North Carolina (number of analyses = 6). The northernmost set of analyses used in this study are from the Oxford quadrangle, only several kilometers south of the Virginia-North Carolina state line. The southeastern portion of the quadrangle is dominated by granitic intrusive rocks, while the northeastern portion contains some slate belt rocks. The volcanics consist of mafic, intermediate, and felsic pyroclastics and flows with numerous dikes and small plutons. Immediately west of the quadrangle, one passes into the Virgilina synclinorium (Laney, 1910)—a mafic-dominated greenstone sequence whose relationship to the belt proper is problematic. Of the 25 analyses reported by Hadley (1973), only six are volcanics of the belt. The age of these units is not known, but U/Pb dates on zircons in volcanics of the Virgilina synclinorium in the Roxboro quadrangle, immediately west of the Oxford quadrangle, give an age of 620 m.y. (Glover and Sinha, 1973). Regional metamorphic grade is lower greenschist facies. For the sake of simplicity, these samples will be included with those of the Chapel Hill area (see below).

TABLE 1. Sources of Analyses Used in this Study

Location°	Number of analyses (dikes in parentheses)	Source
Carolina slate belt		
Oxford quadrangle, Granville County, North Carolina	6	Hadley, 1973
Chapel Hill area		
Bynum quadrangle, Chatham, Orange, and Alamance Counties, North Carolina	30 (9)	Hauck, unpublished data
Orange County, North Carolina	13	Allen and Wilson, 1968
Albemarle area		
Albemarle quadrangle Stanly and Montgomery Counties, and Denton quadrangle, Rowan, Davidson, and Randolph Counties, North Carolina	23 (9)	Butler and Ragland, 1969, with trace element data from Black, 1977
Asheboro quadrangle, Randolph County, North Carolina	24 (6)	Seiders, 1978
Albemarle quadrangle, Stanly and Montgomery Counties, North Carolina	27 (6)	Weigand, 1969
Albemarle and Denton quadrangles, North Carolina	27	Paulson, 1980
Union Copper mine, Gold Hill district	25	Unger, 1982
Lancaster County, South Carolina	6	Black, 1977
South Carolina-Georgia area		
Lincolnton-McCormick districts, Georgia-South Carolina	27 (12)	Whitney, 1978
	44	Paulson, 1980
Dorn Mine, McCormick, South Carolina	24 (4)	Guthrie, 1980
Civil War mine, Lincolnton, Georgia	20 (5)	Goldstein, 1980
Total	296 (51)	
Coastal volcanic belt of New England		
Machias-Eastport area, Maine	25 (1)	Gates and Moench, 1981

° Carolina state belt localities shown in Figure 2.

2. Chapel Hill area, North Carolina (number of analyses = 54). The immediate area of Chapel Hill, Orange County, North Carolina, has been mapped by a number of investigators, including Mann et al. (1965) and Allen and Wilson (1968). The area consists of numerous plutons ranging in composition from diorite to adamellite intruded into a sequence of subaerial and subaqueous, mafic to felsic pyroclastics, flows, and fine-grained epiclastic sediments of the slate belt. The area is bounded on the east by the north-northeast-trending Triassic border fault of the Durham basin. Allen and Wilson (1968) give 13 analyses used in this study, and the balance of the analyses are from unpublished work by S. A. Hauck and W. W. Black performed in the Geochemistry Laboratory at University of North Carolina at Chapel Hill. The absolute age of the volcanics presents some problems. Black (1977) obtains an Rb/Sr whole-rock age of 613 m.y. on a dacite crystal tuff in the area. This age cannot be correct, however, as these units and their correlatives are cut by the 638 m.y. is old Meadow Flats pluton and the 705 m.y. Chapel Hill pluton. Thus, a minimum age of 705 m.y. is commonly reported, although Black has suggested an age of 750 m.y. based on a speculative "Piedmont volcanic growth curve" for the $^{87}Sr/^{86}Sr$ ratios. All the $^{87}Sr/^{86}Sr$ ratios for the Chapel Hill area are uniformly low, ranging from 0.7025 to 0.7047. This has led two investigators, Fullagar (1971) and Black (1977), to suggest an upper mantle or lower crustal origin for the magmas which gave rise to the slate belt volcanics. Metamorphism in the Chapel Hill area is no higher than lower greenschist facies.

3. Albemarle area, North Carolina (number of analyses = 127). The Asheboro, Denton, and Albemarle quadrangles of the central North Carolina part of the Carolina slate belt and the adjacent Mount Pleasant, Troy, and Gold Hill quadrangles are the best studied portion of the northern part of the slate belt. The classic work of Conley (1962), Stromquist and Sundelius (1969), Sundelius (1970), and Stromquist et al. (1971) sets the regional geologic context in which the first comprehensive study of the Carolina slate belt lithogeochemistry (Butler and Ragland, 1969) and the more recent work by Seiders and Wright (1977) and Seiders (1978) have been conducted. The currently accepted stratigraphic column for this area is shown in Figure 3 and consists of greater than 3,500 m of dominantly felsic Uwharrie Formation overlain by at least 5,000 m of the Albe-

marle Group. The Albemarle Group is the more complex volcanic sequence with significant mafic and intermediate components, in addition to the felsics, and with a generally increasing proportion of epiclastic sediments in the upper units. In addition to the published analyses of Butler and Ragland (1969) and Seiders (1978), unpublished analyses from Weigand (1969) and Paulsen (1980) are used. Black (1977) provides some trace element data on the samples originally analyzed by Butler and Ragland. U/Pb dates on zircon fractions from felsic volcanic rocks in the upper Uwharrie Formation yield ages of approximately 580 m.y. (Wright and Seiders, 1977). This age corresponds well to the early to middle Cambrian age assigned to *Paradoxides carolinaensis*, the only dated fossil find in the Carolina slate belt (St. Jean, 1973). This fossil locality is in the Floyd Church Member of the Millingport Formation of the Albemarle Group from the Stanfield quadrangle (D. J. Milton, pers. commun.). The metamorphic grade in the area is lower to middle greenschist facies, increasing generally to the northeast.

4. Lancaster area, South Carolina (number of analyses = 6). In the Taxahaw quadrangle, Lancaster County, South Carolina, a predominantly felsic sequence with a few mafic and intermediate pyroclastics is exposed. Black (1977) gives a few analyses of the felsic units in this area. Their stratigraphic relationship to the Albemarle and Chapel Hill area rocks is uncertain and no age data is available. They are chemically indistinguishable from the Albemarle, North Crolina, rocks, and their analyses have been included with these for brevity's sake.

5. McCormick area, South Carolina, and Lincolnton area, Georgia (number of analyses = 113). The recent compilation of the volcanic geology and chemistry by Whitney et al. (1977) summarized the regional geology of the McCormick, South Carolina-Lincolnton, Georgia, area. This area is unique in relation to the other four areas in that the volcanics and sediments overlie a quartz porphyry (the Lincolnton metadacite) which is, presumably, subvolcanic to volcanic in setting. The overall stratigraphy is shown in Figure 3, with upward of 1,200 m of fragmental rocks and epiclastics in the Lincolnton area. Carpenter et al. (1978) report an age on the Lincolnton metadacite of between 560 to 570 m.y., making it roughly time correlative to the upper Uwharrie Formation in North Carolina. Presumably on that basis, Paulson (1980) and Guthrie (1980) make an age correlation of the fragmental rocks in the McCormick-Lincolnton area with the lower Albemarle Group of central North Carolina. The metamorphic grade in the area is upper greenschist facies.

In addition to the analyses described above, geochemical data are available from detailed studies made immediately adjacent to areas of known massive sulfide mineralization. These include 25 analyses from the Gold Hill district in the Albemarle area, North Carolina (Unger, 1982), 24 analyses from the Dorn mine, McCormick district, South Carolina (Guthrie, 1980), and 20 analyses from the Civil War mine, Lincolnton district, Georgia (Goldstein, 1980). These analyses are not included in the regional compilation in order to avoid skewing the data with data sets collected from very limited areas that undoubtedly underwent extensive hydrothermal alteration associated with mineralization. These data will be discussed in the section on alteration.

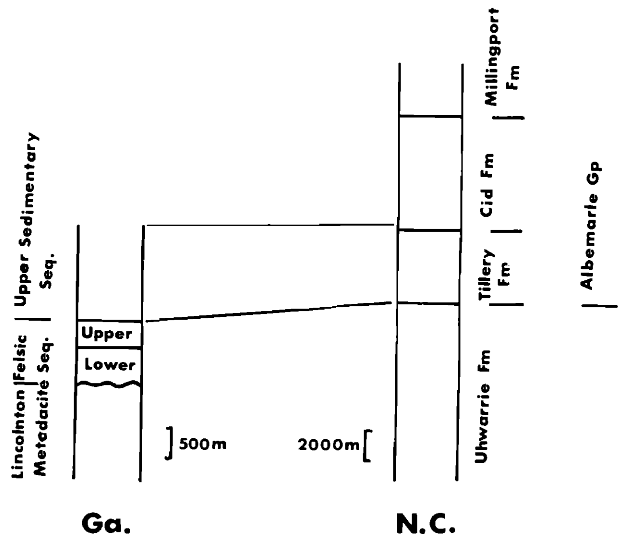

FIG. 3. Stratigraphic sections for Lincolnton-McCormick areas, South Carolina-Georgia (Ga.) from Whitney et al. (1978) and for Albemarle quadrangle, North Carolina (N.C.) from Seiders (1978). Note different vertical scales. Correlation is based on a suggestion by Paulson (1980) of the equivalence of the Uwharrie-Albemarle contact with the boundary between the felsic pyroclastic sequence (Felsic Seq.) and the upper sedimentary sequence. The stratigraphy in the Chapel Hill area is not as well defined and correlations are uncertain.

For this study, major element analyses of 296 volcanic rocks, both flows and pyroclastics, and 50 contemporaneous dikes have been compiled. Of these, 203 volcanic and 24 dike analyses are from unpublished data, including M.S. and Ph.D. theses. The unpublished analyses from the Geochemistry Laboratory at the University of North Carolina are available from the author on request. In addition, selected trace element data have been compiled from unpublished analyses carried out by S. A. Hauck and W. W. Black. These data will be compared with 25 recent analyses of volcanic rocks from the Coastal volcanic belt of Maine (Gates and Moench, 1981) and with selected averages from mineralized volcanic belts elsewhere in the Caledonides and worldwide.

Major element geochemistry

The vast majority of the volcanic rocks in the Carolina slate belt are volcaniclastic. In the Albemarle area, North Carolina, for example, 83 percent of the analyses represent tuffs. This dominance of pyroclastic rocks does not change significantly with composition. On the whole, the tuffs and flows are viewed as submarine, though specific criteria for such a classification are frequently absent. In the vicinity of known volcanic centers, e.g., Collins Mountain, Bynum quadrangle, North Carolina (Hauck, 1977), subaerial flows, breccias, and ash falls are seen. In general, however, the interstratification of finely laminated and often graded epiclastic siltstones and mudstones and the absence of pumice strongly favor a submarine origin for the Carolina slate belt volcanics. This, as we have stated previously, raises the probability of submarine alteration, a subject to be addressed in a subsequent section.

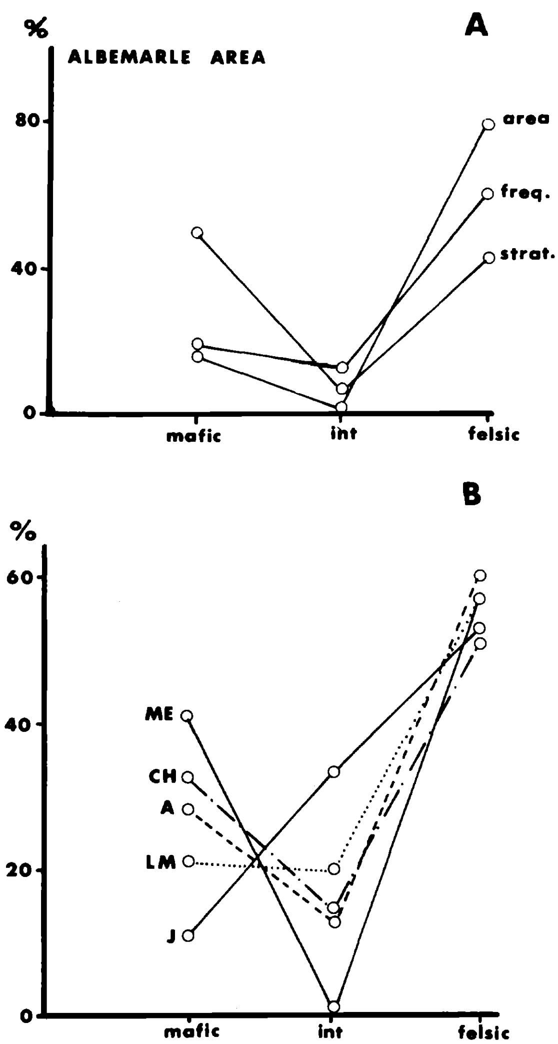

FIG. 4. A. Frequency distribution of mafic, intermediate (int), and felsic rocks in the Albemarle area, North Carolina. Area = percentage of rock types based on point counts of geologic quadrangle maps by Seiders (1978), freq. = distribution of each rock type as a percentage on 127 random chemical analyses from the same area (see Table 1 for sources of analyses), strat. = distribution of rock types based on detailed stratigraphic section of Seiders (1978).

B. Frequency distribution of rock types from the Carolina slate belt and comparable areas as a percentage of total number of available chemical analyses. CH = Chapel Hill area, North Carolina (number of analyses = 49); A = Albemarle area, North Carolina (number of analyses = 127); LM = Lincolnton, Georgia-McCormick, South Carolina, area (number of analyses = 110); ME = Coastal volcanic belt of Maine (number of analyses = 25). Sources of data listed in Table 1. J = distribution of rock types in Miocene Green Tuffs in Japan, based on stratigraphic section of Ishihara, 1974.

SiO_2 content: Seiders (1978) emphasized the bimodal character of the Carolina slate belt volcanics in the Albemarle, North Carolina, area. He based his estimate on point counts of selected quadrangle geologic maps. As such maps are not available for all the areas under consideration in this study, it was deemed worthwile to compare abundance estimates based on his point counts with estimates based on stratigraphic thickness and on pure percentages of the available analyses. This latter estimate is the one readily available for this study but is of use only if such data are a relatively systematic representation of the distribution of rock types. Obviously, there is no statistically sound way to evaluate this for the slate belt as a whole, but it is felt that if the estimations of rock abundance in the Albemarle area are relatively independent of method of estimation, then, at least, we can be confident that there is nothing in the nature of exposure of slate belt rocks that would introduce a sampling bias—assuming random and nonselective sampling. Figure 4A demonstrates the relative abundance of mafic, intermediate, and felsic works in the Albemarle area based on three independent techniques. They are: (1) as a percentage of the total chemical analyses available, rocks being classified by the method of Irvine and Baragar (1971), (2) as a percentage of known exposure (Seiders, 1978, table B), and (3) as a percentage of the detailed stratigraphic column for the area (Seiders, 1978). It is obvious that, while some sampling error may exist, there is no significant qualitative difference between the distribution of rock types as a function of the technique used to estimate abundance. Thus, we feel justified in treating the analytical data sets as essentially representative, in a statistical sense, of the type and abundances of the rocks in these areas. Figure 4B, then, shows the distribution of rock types for all portions of the Carolina slate belt on the basis of the available rock analyses. Clearly, the bimodal distribution is a consistent pattern within the belt.

Figure 5 demonstrates the bimodality on a frequency histogram for SiO_2 content. In spite of the

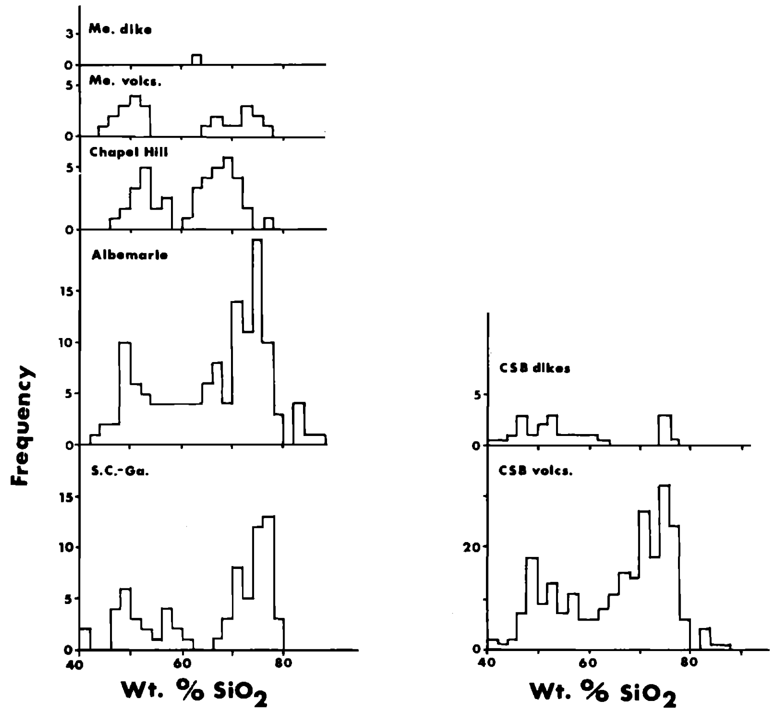

FIG. 5. SiO_2 frequency histograms for Carolina slate belt and Coastal belt volcanics and dikes. Sources of data given in Table 1. Slate belt volcanics includes all analyses in the Chapel Hill, Albemarle, and South Carolina-Georgia areas.

possibility of blurring the relationships by silica mobility during alteration, the marked absence of intermediate compositions (SiO_2 = 58–62%) is consistent both locally and regionally. In addition, an overall dominance of 2–3 to 1 of felsic over mafic compositions is shown. The possibility of sampling bias in the deeply weathered terrains of the Piedmont cannot be dismissed in discussing this felsic dominance. One would expect a bias toward felsic compositions due to the more resistant weathering behavior of siliceous rocks. While this might mute the felsic preeminence or even explain it away, it can have little effect on the bimodality. This conclusion is supported by the map point counting of Seiders and by the bimodal character of the dike analyses as well.

Gates and Moench (1981) have emphasized the bimodal character of the Silurian-Devonian metavolcanics of the Coastal volcanic belt in Maine and the Maritime Provinces. This bimodality is also shown in Figure 5, where it differs from the Carolina slate belt volcanics only in the relative equality of the number of felsic and mafic samples and the complete absence of intermediate compositions. Time correlative sequences from Newfoundland (Strong, 1977) show a similar bimodality but with significant volumes of intermediate compositions as well.

Major element geochemistry: For the sake of simplicity, the following discussion of major element chemistry will avoid any detailed discussion of alteration effects and will simply point out when such alteration appears to have an impact on the conclusions reached.

Figure 6 is an alkali-SiO_2 plot for the three areas in the Carolina slate belt and for the Coastal volcanic belt of Maine, for reference. In general, and assuming a limited alkali or silica mobility, the Chapel Hill area resembles a fairly typical calc-alkaline suite—as do the Coastal belt volcanics of Maine. The Albemarle and South Carolina-Georgia data suggest a more transitional range of compositions between calc-alkaline and tholeiitic, as has been suggested by Bland and Blackburn (1980) and by Paulson (1980). However, the extreme scatter of the data points raises the concern that the apparent tholeiitic character of these rocks is an artifact of alteration. Figure 7 shows the K_2O-Na_2O relationship for the volcanics in these areas. In the Coastal volcanic belt, there is no direct correlation of Na_2O and K_2O, except in the potash-rich rocks, which may reflect some alkali exchange. In the Chapel Hill area, the possibility of alkali exchange appears probable due to a vague negative correlation, whereas in the Albemarle and the South Carolina-Georgia areas, such exchange appears highly likely. It is clearly not possible with this representation to indicate whether this alkali exchange was one-for-

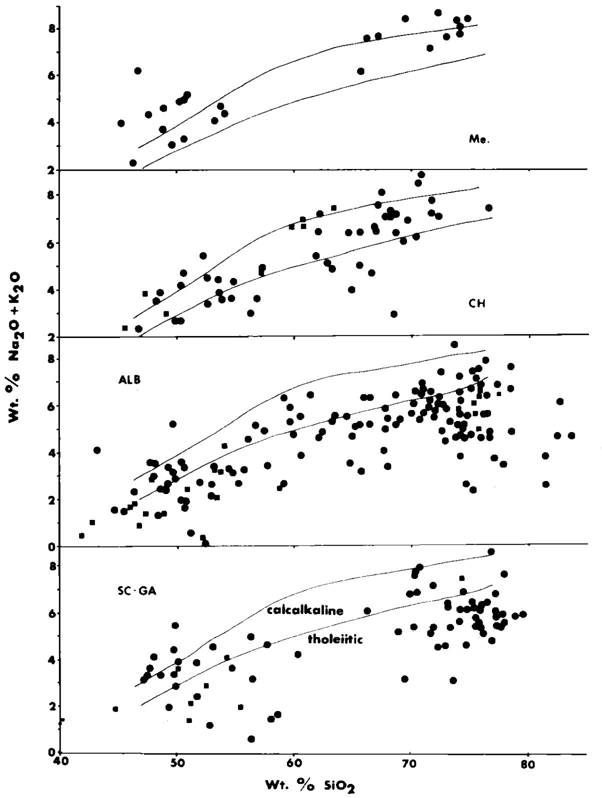

FIG. 6. Alkali-SiO_2 diagram for Carolina slate belt and Coastal volcanic belt dikes and volcanics. SC-GA = McCormick, South Carolina-Lincolnton, Georgia, area, Alb = Albemarle, North Carolina, area; CH = Chapel Hill, North Carolina, area, ME = Machias-Eastport, Maine, area; filled circles = volcanics; filled squares = dikes. Boundaries between alkalic, calc-alkaline, and tholeiitic fields from Kuno, 1969.

one, sodium for potassium, or whether net gains and losses of alkalis occurred. I must, however, conclude that, while there is a suggestion that the older, more northerly suite of the Carolina slate belt volcanics is calc-alkaline while the younger, southerly suites are of more tholeiitic affinities, the evidence for alkali mobility is such that correlating the alkali-silica content with age or tectonic setting is risky, at best.

Figure 8, a series of CaO-Na_2O-K_2O plots for the same areas, suggests, as one should suspect, that any effort to use these elements to classify the Carolina slate belt volcanics is doomed to failure. The extreme variability in their relative proportions is further confirmation of alkali and lime mobility during an apparently postdepositional alteration process. In general, one can conclude from Figure 8 that:

1. The South Carolina-Georgia rocks show a lower overall K_2O content, especially with respect to the rocks in the Chapel Hill area. There would appear also to be fewer rocks with very high K_2O/Na_2O ratios in South Carolina-Georgia. As will be shown in subsequent sections, however, very high K_2O volcanics in general are related to hydrothermal alteration associated with mineralization and that the low K_2O, mafic rocks may be a vestige of incipient spilitization.
2. The Chapel Hill area analyses suggest a more typically calc-alkaline trend (high K_2O) relative to the other areas.
3. Averages based on these analyses in CaO-Na_2O-K_2O space would be highly misleading without applying some unknown exclusionary criteria to eliminate the vestiges of secondary processes.

The diagrams in Figure 8 also show the dike analyses for these areas in order to determine if the dikes may be less variable than the extrusives. Except at the mafic end (Ca rich), there appears to be as much variability in dike composition as in the volcanics, suggesting that, if the scatter is induced by secondary processes, then these processes were sufficiently long-lived that they did not spare the intrusive equivalents of the volcanics. Butler and Ragland (1969) were able to place an upper limit on the Na_2O content of the Albemarle rocks by noting the higher Na_2O/K_2O ratio of the rhyolitic vitric tuffs vs. the rhyolitic flows. The field for their vitric tuffs is shown in Figure 8 and strongly suggests the probable largest primary Na_2O/K_2O ratio in the felsic rocks. Unfortunately, it is not possible to apply this criteria uniformly in the Carolina slate belt as detailed petrography is not available on all the samples analyzed.

AFM diagrams have, along with alkali-silica and alkali-lime plots, traditionally been used to distinguish between calc-alkaline and tholeiitic suites. Typically, tholeiitic suites show significantly more iron enrichment than their calc-alkaline analogs. The wide range in alkali values, which we have already suggested may represent a postdepositional mobility of alkalis, makes such a plot of questionable value in the slate belt, even without considering the likelihood of magnesium mobility. Figure 9 is an AFM diagram for the slate belt suites. As was the case with the alkali-SiO_2 plot, the data appear to straddle the calc-alkaline-tholeiitic boundary in AFM space. Equally significant is the fact that the dikes show, in general, as much scatter as the extrusives. Gates and Moench (1981) demonstrate the same scatter for the rocks of the Coastal volcanic belt. However, with their excellent fossil control, their diagram suggests that the Silurian suites are more calc-alkaline and the Devonian more tholeiitic. The Albemarle area is the only area sampled in the Carolina slate belt with sufficiently thick exposure to allow us, in the absence of fossil control, to attempt such a time analysis of the variability in one region, but there is no obviously discernible relationship between stratigraphic position and magmatic affinity in AFM space.

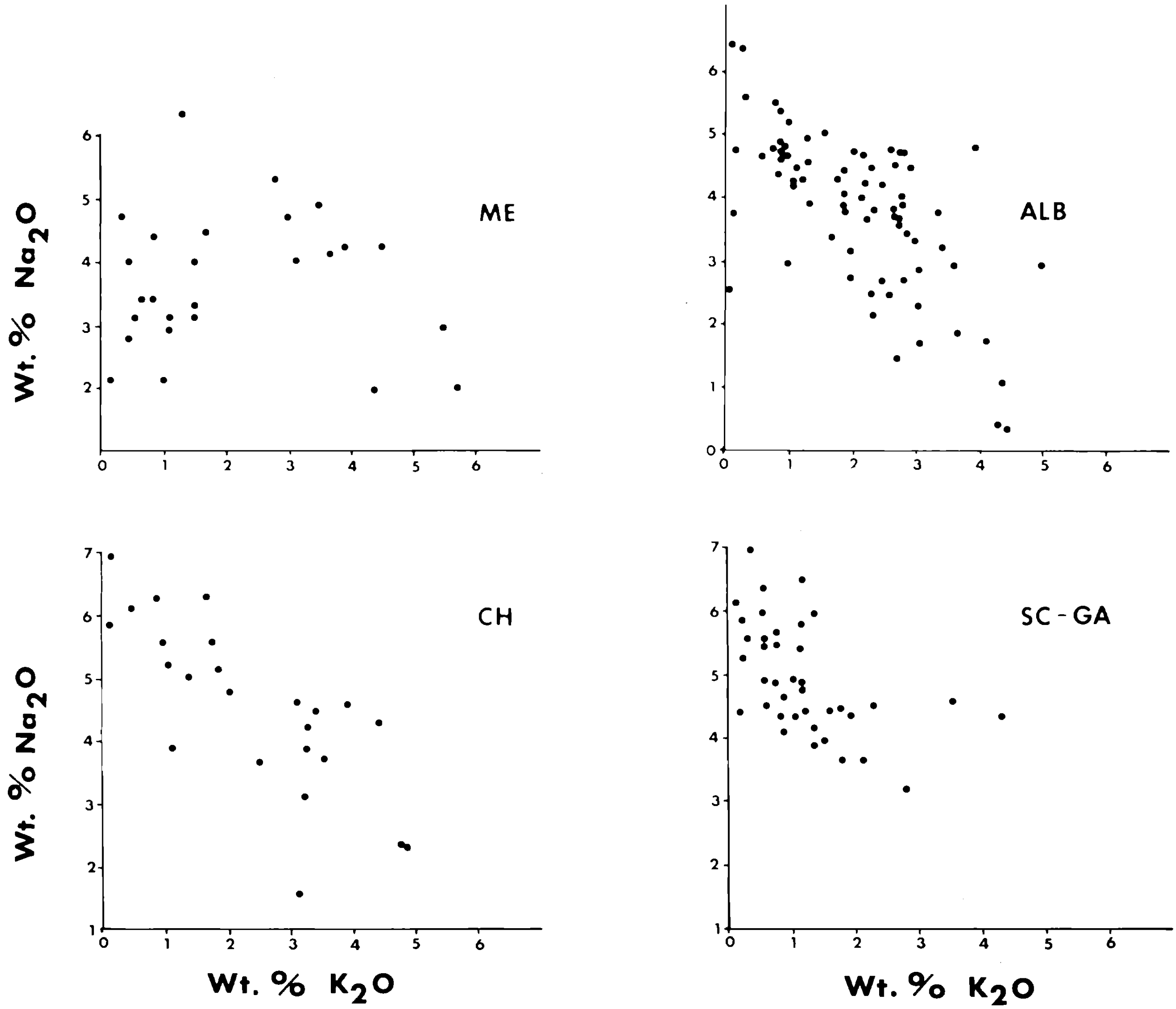

FIG. 7. Na_2O-K_2O variation for Carolina slate belt and Coastal volcanic belt volcanics. Abbreviations as in Figure 6.

Pearce et al. (1977) propose that using subalkaline, basaltic andesites (SiO_2 = 51–56%), one can distinguish between oceanic island, continental, spreading center, orogenic, and ocean ridge-floor basalts on a MgO-$Feo_{(total)}$-Al_2O_3 plot. This has the advantage over the previously employed diagrams because we are dealing with, at most, only one component normally viewed as highly mobile during secondary alteration, i.e., MgO. They only employed this diagram for Cenozoic volcanic rocks, however. Figure 10 shows their discriminate fields and the analyses from the Carolina slate belt that meet their exclusionary criteria (all samples were assumed to be subalkaline in primary composition). Clearly, it is impossible to characterize uniquely the tectonic setting of the slate belt volcanics on this basis alone. There is as much spread of the data points along the Al_2O_3-$FeO_{(total)}$ join as there is in the direction of increasing and decreasing MgO. The most likely classification for the slate belt volcanics, i.e., orogenic, only appears likely if there is significant MgO depletion and/or FeO or Al_2O_3 mobility. As we will see in a subsequent section, FeO and Al_2O_3 are very likely immobile and, if anything, we see significant MgO enrichment with alteration. It appears likely that this diagram is inapplicable to the Carolina slate belt.

Based on the ambiguous nature of the previously described classification schemes, the likelihood of extensive major element mobility during secondary postdepositional alteration is inescapable. Jensen

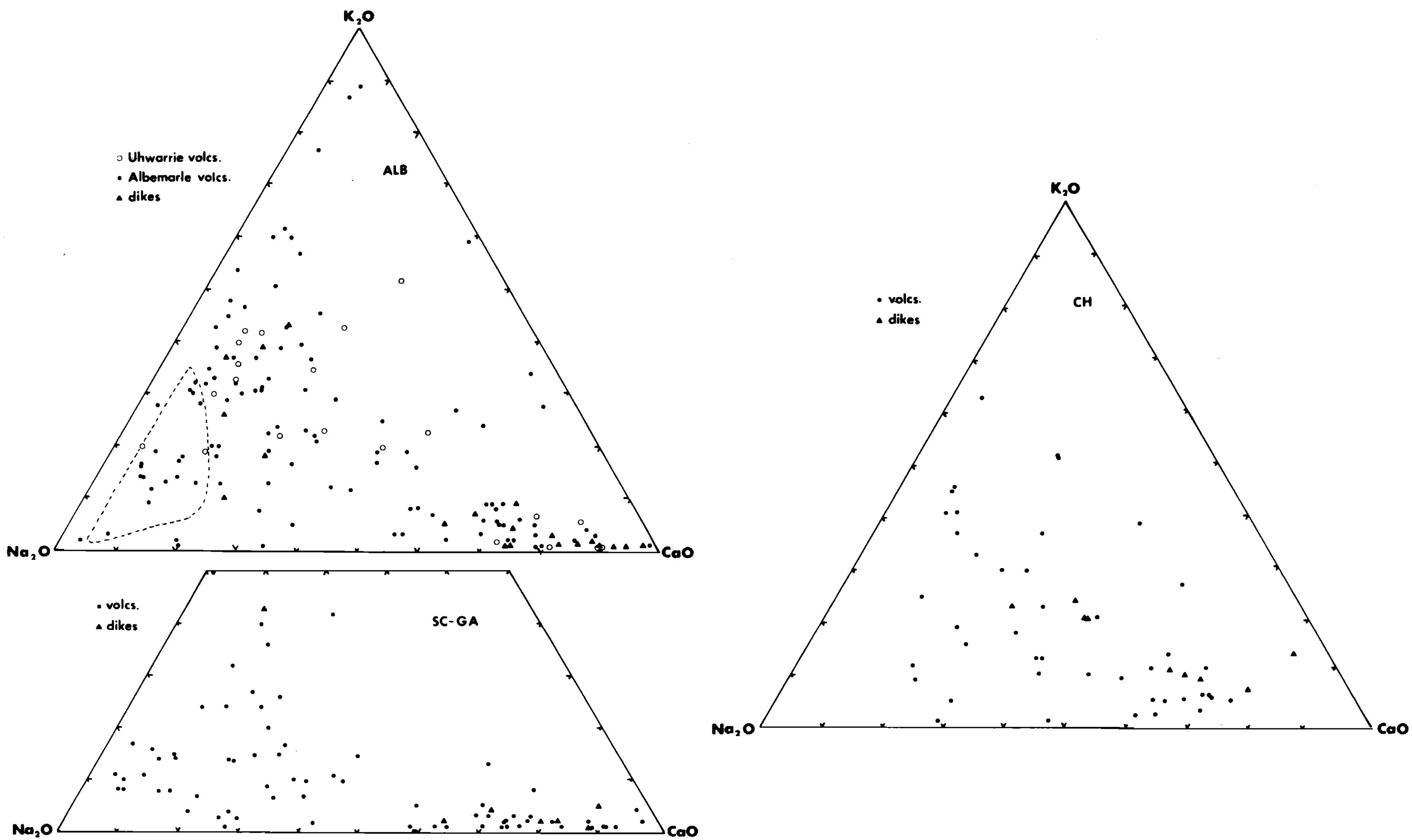

FIG. 8. Na_2O-K_2O-CaO plot of analyses from the Carolina slate belt. Abbreviations as in Figure 6. Dashed line represents the field of Na_2O/K_2O ratios for vitric tuffs from Butler and Ragland (1969).

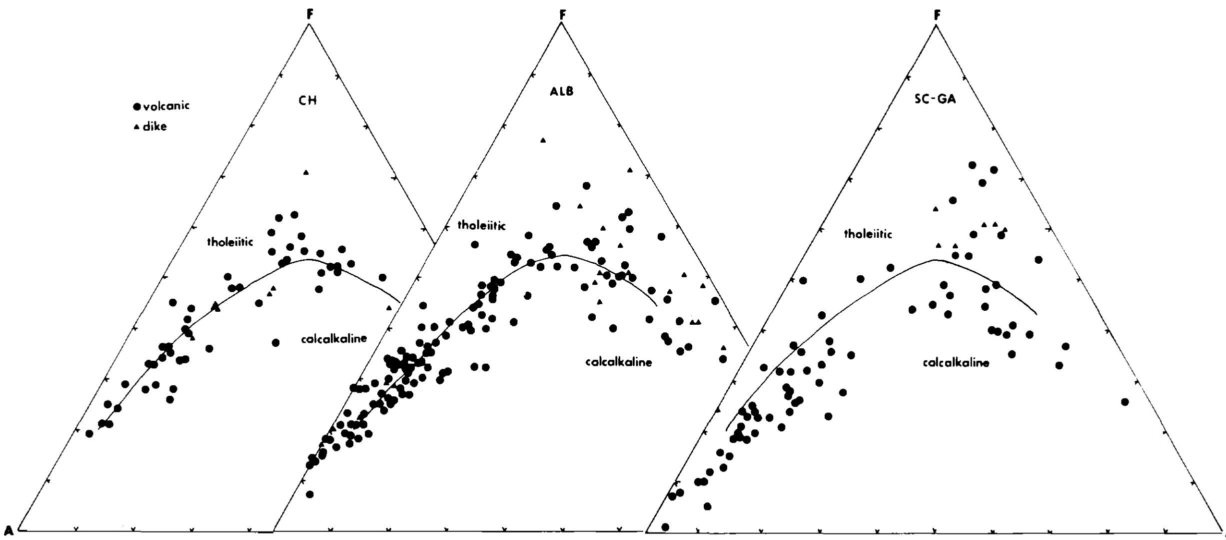

FIG. 9. AFM diagram for Carolina slate belt volcanics and dikes. Abbreviations as in Figure 6.

(1976), presented with the same problem in analyzing Precambrian volcanics in Ontario, devised the Jensen cation plot utilizing $(FeO_{(total)} + TiO_2)$-MgO-Al_2O_3. Using this system, he successfully distinguishes calc-alkaline from tholeiitic rocks and classifies the rock types as well. Use of his criteria suggests that all the Carolina slate belt volcanics in North Carolina are tholeiitic. On the whole, the same appears true for

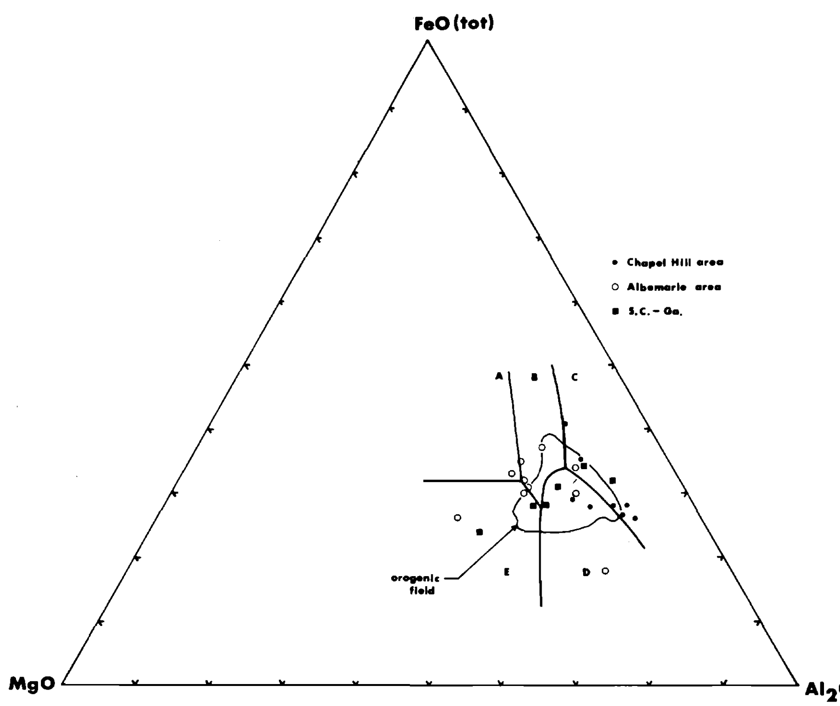

FIG. 10. MgO-$FeO_{(total)}$-Al_2O_3 diagram using the tectonic discriminant fields of Pearce et al. (1977). Compositions plotted are for subalkaline basaltic andesites (SiO_2 = 51-56%) from Carolina slate belt areas as indicated. Tectonic fields: A = oceanic islands, B = continental, C = spreading centers, D = orogenic belts, E = ocean ridges and floors. Area labeled orogenic field includes all orogenic basaltic-andesites of Pearce et al. (1977).

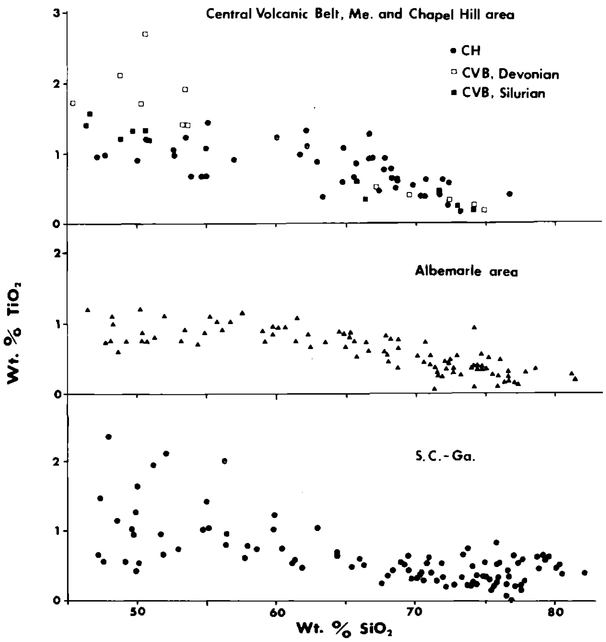

FIG. 11. SiO_2-TiO_2 plot for Carolina slate belt and Coastal volcanic belt volcanics.

South Carolina and Georgia, except that the more felsic units appear to be calc-alkaline. The possibility of MgO mobility continues to be present here, too.

The generally low TiO_2 content of subduction-related mafic to intermediate volcanics has been widely acknowledged (e.g., Jensen, 1976; Rogers, 1982). This can be clearly seen by analyzing the discriminant functions of Pearce (1976). Pearce's first discriminant function (F_1) is heavily TiO_2 weighted and clearly separates subduction-related basalts, i.e., calc-alkaline basalts and low potassium tholeiites, from within plate basalts. To separate the calc-alkaline basalts and the low potassium tholeiites, however, one must use his secondary and tertiary functions (F_2 and F_3) which are heavily alkali weighted, and thus inapplicable in the Carolina slate belt.

In general, TiO_2 contents of 1.0 to 1.3 or less, in mafic rocks, are typical of subduction zones. Figure 11 shows the strong negative correlation of TiO_2 with silica in the slate belt. In addition, with the exception of six analyses from South Carolina-Georgia and one from the Chapel Hill area, no samples have TiO_2 contents in excess of 1.3 percent, and only two are higher than 2 percent. This is in intriguing contrast to the mafic volcanics of the Coastal volcanic belt (Gates and Moench, 1981), none of which is lower than 1.3 percent. As is also shown in Figure 11, high TiO_2 values for mafic volcanics are characteristic of the coastal belt volcanics, especially the early to late Devonian rocks. Glazner (1981) has indicated that in the western United States, all subduction-generated mafic volcanic suites have uniformly low TiO_2 contents relative to postsubduction volcanics, with a critical TiO_2 content cutoff at TiO_2 equal 1.2 to 1.7 percent as an inverse function of SiO_2 content of mafic to intermediate rocks. Though it is clearly premature to extrapolate this relationship from the western United States to the coastal volcanic belt, the possibility exists that the Devonian volcanics represent a suite derived after the cessation of active subduction. The volcanics of the slate belt, on the other hand, by this criterion, are subduction related.

Trace element geochemistry: A very limited suite of Carolina slate belt volcanics has been analyzed for trace elements. Paulson (1980), Black (1977), and Hauck (unpub. data) provide the only sources of such data. The results of nearly all trace element plots are as ambiguous as the major element plots. This is particularly true for the alkaline earths, Sr, Rb, and Ba. This is not very surprising if the alkali data are interpreted as suggesting feldspar-destructive, secondary alteration. The most promising trace element relationship is the Zr-Ti-Y plot of Pearce and Cann (1973), as this discrimination of rock types is based on an extensive sample population and is dependent only on immobile elements. Figure 12 is the standard Zr-Ti-Y diagram with Pearce and Cann's discriminate fields and positions of the 48 basalt samples from the Carolina slate belt for which Zr and Y values are available. In addition, five samples from the Coastal volcanic belt in Maine are plotted. Twenty-eight of the slate belt samples plot in the calc-alkaline basalt field, nine are unclassified, and six and five samples plot within plate-contained basalts and low potassium tholeiite fields, respectively. In general, it is the Albemarle area volcanics which give the most spread, with only half of the analyzed samples falling within a calc-alkaline basalt field. All of the Coastal belt volcanics plot within a calc-alkaline basalt field.

Summary

The major element chemistry of the Carolina slate belt volcanics and associated dikes does not permit any significant limiting of the tectonic setting for the genesis of these volcanics. All the suites yield ambiguous results with respect to their calc-alkaline or tholeiitic affinities. The wide scatter in alkali and lime content strongly suggests feldspar-destructive alteration. In addition, silica, magnesia, and possibly even iron and aluminum have been remobilized during secondary alteration. The TiO_2 values strongly suggest a subduction-related tectonic setting.

The trace element data that are unaffected by remobilization indicate a calc-alkaline suite. The limited Sr isotopic data suggest a relatively primitive source for the magmas.

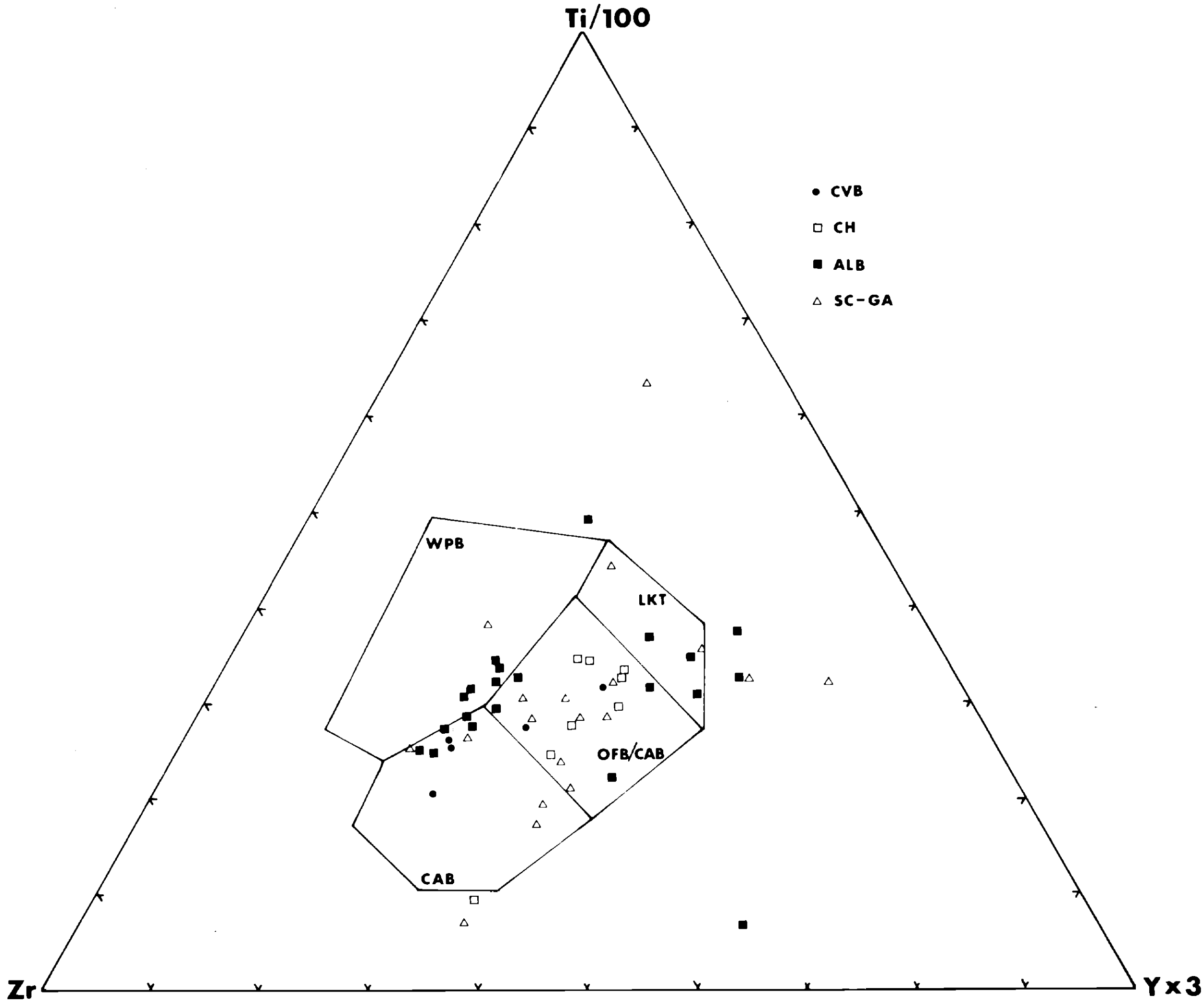

FIG. 12. Zr-Ti/100-Y × 3 plot for basalts from the Carolina slate belt and Coastal volcanic belt. Abbreviations as in Figure 6. Discriminant fields from Pearce and Cann (1973). WPB = within plate basalt, OFB = ocean floor basalt, CAB = calc-alkaline basalt, LKT = low potassium tholeiite.

One could conclude, then, that the volcanics of the Carolina slate belt represent a bimodal, calc-alkaline suite generated in a subduction zone. One cannot exclude the possibility of tholeiitic affinities for some (or all?) of the extrusives. Such a setting is not really coincident with Whitney et al.'s characterization of the South Carolina-Georgia part of the belt as a primitive arc sequence. Rogers (1981) suggests subduction on a thickening continental crustal margin, which might explain both the bimodality and the calc-alkaline character of the volcanics but does not explain the low Sr isotopic ratios.

Discussion

Gates and Moench (1981) propose a rift-related environment for the Silurian-Devonian Coastal belt volcanics. This does not seem appropriate for the slate belt due to the low TiO_2 contents, the Zr-Ti-Y values, and the uniformly subalkaline character of the rocks. Furthermore, the limited number Y/Nb ratios for all the slate belt rocks are uniformly greater than 2 to 4 (Paulson, 1980), much higher than typical rifting environments (Pearce and Cann, 1973). Bimodal, calc-alkaline suites have been described in oceanic, island-arc environments. Brown et al. (1977) point out that in the calc-alkaline suites of Dominica in the Lesser Antilles, there is a strong SiO_2 bimodality in a volcanic suite known to be approximately 100 to 120 km above the descending slab. Equally intriguing in the Lesser Antilles is that the volcanic islands are all about the same distance above the descending slab, are all about the same age, and yet vary from alkaline

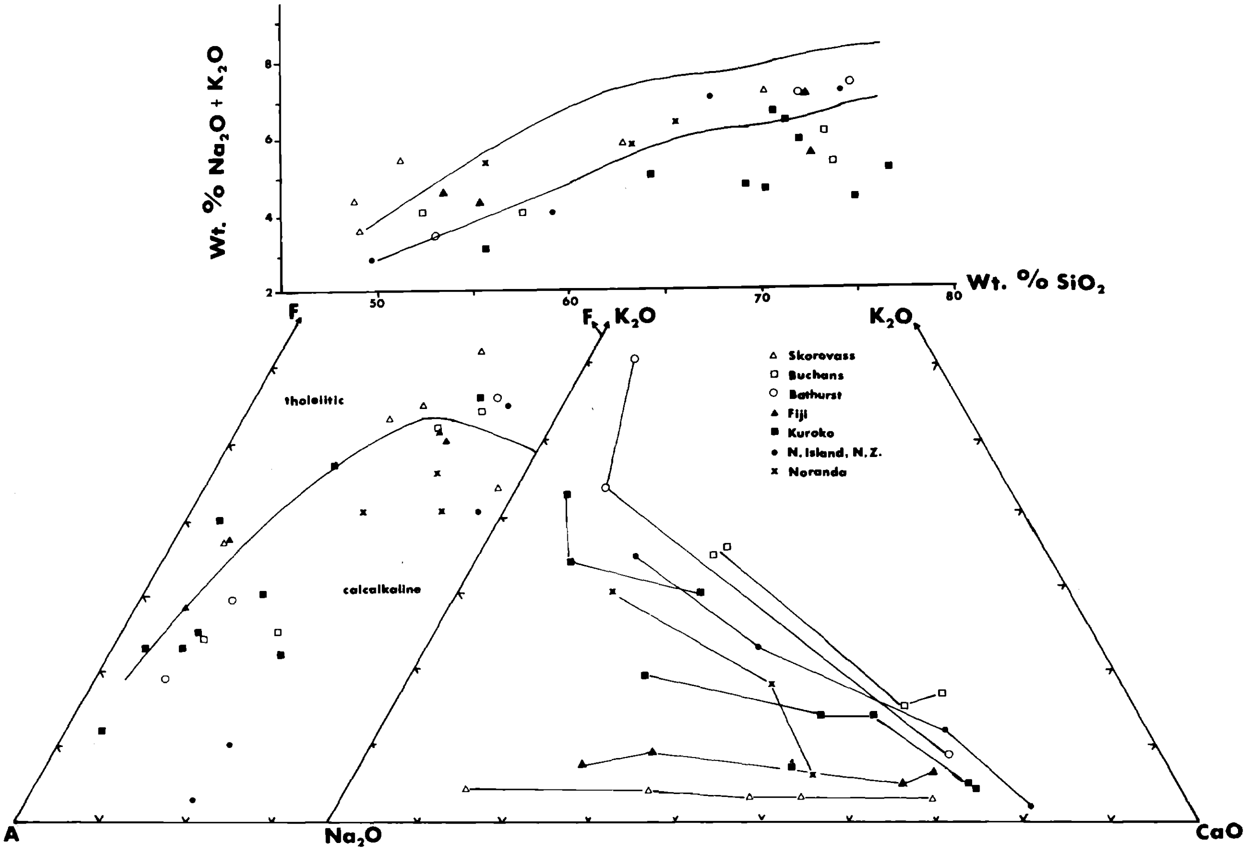

FIG. 13. AFM (on left), Na_2O-K_2O-CaO, and alkali-SiO_2 diagrams for average volcanics from other Caledonide ore districts (open symbols) and from other ore-hosting volcanic suites worldwide. Caledonide data from Reinsbakken (1980), Thurlow et al. (1975), and Whitehead and Goodfellow (1978). Other data sources: central North Island, New Zealand, Ewart et al. (1968); Kuroko, Matsukawa (1974), Date and Tanimura (1974), Tatsumi and Clark (1972), and Mukaiyama et al. (1974); Fiji, Colley and Greenbaum (1980); Noranda, Riverin and Hodgson (1980).

to tholeiitic as one proceeds north to south along the length of the arc, with Dominica sitting about the middle of the arc. The island of Grenada, at the southern, tholeiitic end of the Lesser Antilles also shows SiO_2 bimodality but with the modes shifted 5 to 6 wt percent toward the low SiO_2 end of the scale relative to the calc-alkaline volcanics on Dominica. Arculus and Johnson (1978) point out that, in several magmatic provinces in Papua New Guinea, andesite is absent to subordinate relative to mafic and felsic volcanics.

Comparison of Carolina slate belt lithogeochemistry with the host volcanics for other massive sulfide deposits

It is somewhat difficult to make direct comparisons of the Carlina slate belt volcanism with that of other ore-hosting Caledonide suites as the data reported in the literature are most often sets of averages for various rock types. Thus, one cannot subject these values to the kind of analysis with respect to scatter of the data that we have attempted here. Clearly, by inspection of the slate belt data and as has been suggested previously, such averages would be very misleading for the slate belt and, thus, we have not used them. Figure 13 shows the alkali-SiO_2, CaO-Na_2O-K_2O, and AFM diagrams for the averages of multiple analyses in the host sequences of several massive sulfide districts in the Caledonides, i.e., the Buchans Group which contains the deposit at Buchans, Newfoundland, the Tetagouche Group in New Brunswick which hosts the Bathurst district, and the volcanics of Skorovass in the Grong area of Norway. In addition several other suites are shown to indicate the range in the whole-rock geochemistry and tectonic setting of volcanics which host mineralization elsewhere in the world. These include: (1) the Miocene Green Tuffs on Honshu which host the Kuroko ores and

TABLE 2. Chemical Gains and Losses during Alteration of Caledonide Volcanics in the Appalachians (literature estimates)

Source	SiO_2	MgO	$FeO_{(total)}$	CaO	Na_2O	K_2O
Whitney et al., 1978	+	+	+	−	−	+
Weigand, 1969						
fold "troughs"	+					+
fold "flanks"					+	
Butler and Ragland, 1968	+				+	−
Seiders, 1978	0	0	0	0	0	0
Goldstein, 1980						
Lower volcanics		+		−	−	+
Upper volcanics		+		−	+	−
Guthrie, 1980		+	+	−	−	+
Gates and Moench, 1981		0	0	+−	+−	+−

Symbols: +, rock increases in component during alteration; −, rock decreases in component during alteration; 0, no change during alteration; +−, both enrichment and depletion observed; blank, study does not evaluate

which are thought to represent a transitional environment from continental to oceanic, (2) the primitive island-arc suite on Viti Levu in Fiji which contains massive sulfides, (3) the volcanics of central North Island, New Zealand, which represent a young intermediate-felsic suite assumed to be produced by partial fusion of a eugeosynclinical crustal source, and (4) the Black River Group at Noranda, Quebec. On the whole, the host volcanics for other Caledonide districts are of similar affinities in that they tend to bridge the traditional calc-alkaline-tholeiitic boundaries. Furthermore, the Caledonide volcanics, in general, show as much range in composition as the highly varied suites from Fiji, Japan, Canada, and New Zealand. Perhaps it is significant that to explain the range of compositions which have been observed in the Caledonides as a whole, one is required to consider chemical data from such disparate tectonic environments.

Whether any of these other suites, as shown in Figure 13, conform in detail with the bimodal, calc-alkaline-trending suite of the Carolina slate belt is not clear. The Miocene Green Tuffs are definitely not bimodal (see Fig. 4B), nor apparently are the suites from Viti Levu or North Island, New Zealand. On the other hand, based on descriptions of the Tetagouche Group (Strong, 1977), the volcanics of the Carolina slate belt may be very similar in chemistry to those in the Ordovician-Silurian volcanics of the western Maritimes. We suggest that there is no known significant difference in chemistry, tectonic setting, or magmatic affinity between the slate belt volcanics and the volcanics which host other Caledonide massive sulfides. Thus, other explanations—such as basin dynamics, thermal history, depth of erosion, or human error—will need consideration in the future to explain the absence of a Buchans or Bathurst in the slate belt.

Effects of Alteration on Major Element Chemistry in the Carolina Slate Belt

As the analysis of the major element chemistry has implied, wide-scale alteration of the Carolina slate belt volcanics and associated dikes has occurred. Table 2 indicates the nature of compositional changes that various previous investigations have proposed in the slate belt. About the only consistent observations in these many studies are that SiO_2 and MgO increase during postdepositional alteration, though whether this is a numerically significant increase is not known, and that alkalies and CaO behave in highly unpredictable fashion. Gates and Moench (1981) raise the strong likelihood, confirmed by Figure 7 in this study, that sodium and potassium negatively covary during alteration.

This section of the present study will address two related questions: first, whether any consistent patterns of slate belt alteration can be discerned and whether these patterns correlate with other studies and, second, what is the nature of the alteration associated with mineralization itself.

Regional alteration in the Carolina slate belt

Without some means of evaluating the composition of unaltered slate belt volcanics or their equivalents, there is no direct way of estimating how much of the observed variation in chemistry is due to primary and how much to secondary processes. Associated intru-

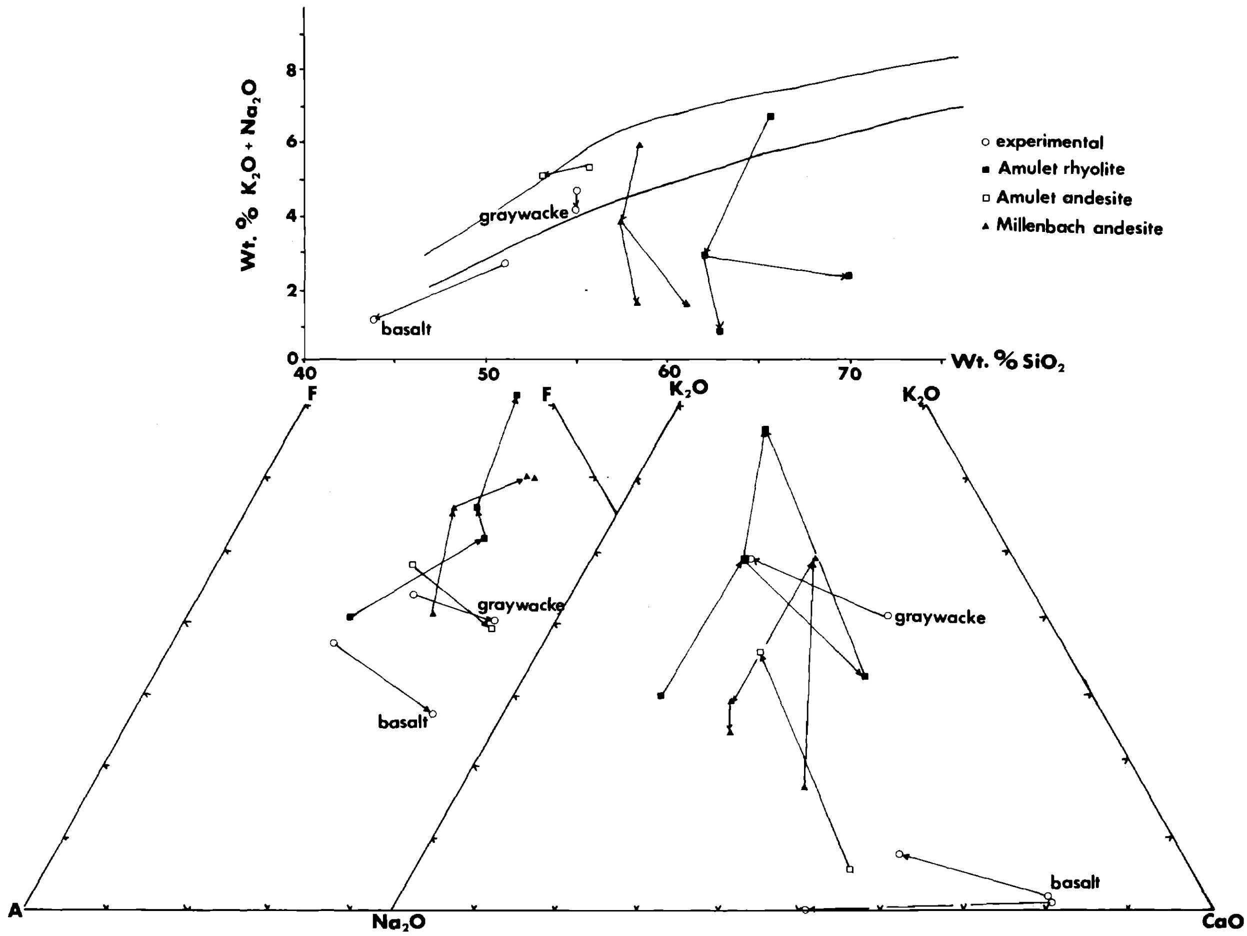

FIG. 14. AFM (on left), Na_2O-K_2O-CaO, and alkali-SiO_2 diagrams showing the effect of alteration processes on major element chemistry. Experimental results from Bischoff et al. (1981) for graywacke. Values for Amulet and Millenback Formations from Noranda, Quebec (Riverin and Hodgson, 1980).

sive rocks (see Figs. 6, 8, and 9) commonly show as much chemical variability as the volcanics themselves. The flows, as a rule, are as variable in composition as the fragmental rocks. In thin section, the feldspar phenocrysts in crystal tuffs, flows, and dikes appear fresh, even in rocks which yield analytical results suggestive of alteration. While the recrystallization and reequilibrium of altered feldspar during regional metamorphism cannot be ruled out, it appears probable that the bulk of chemical modification is restricted to the fine-grained matrix of the volcanics.

The observations of other investigators suggest that nearly all major elements are mobile. Figure 14 demonstrates the effect of alteration experiments on the composition of basalt and graywacke (Bischoff et al., 1981). These major element effects are plotted on the same diagrams that were used to characterize and classify the volcanics in previous sections. Under experimental conditions, the following generalization with respect to element mobility can be made: (1) in basalt-sea water interactions, there is SiO_2 depletion, total alkali depletion, K_2O and CaO loss, Na_2O gain, and MgO enrichment; and (2) in graywacke-sea water interaction, there is no significant SiO_2 mobility, slight alkali depletion, CaO loss, and MgO enrichment. Also shown in Figure 14 is the effect of alteration on composition from a study in the Noranda district, Quebec (Riverin and Hodgson, 1980). This is alteration associated with mineralization and, presumably, more intense than the regional, all-pervasive postdepositional alteration that we are describing in this section. Looking only at their "weakly altered" volcanics as a possible analog to the regional alteration, one sees: (1) for andesites: slight to significant SiO_2 depletion; slight to significant alkali depletion; K_2O enrichment, Na_2O loss, and minimal CaO mobility; and MgO enrichment and depletion; and (2) for rhyolites: slight

TABLE 3. Chemical Gains and Losses in Hydrothermal Alteration Associated with Massive Sulfide Mineralization

Location	SiO_2	MgO	$FeO_{(total)}$	CaO	Na_2O	K_2O	Reference
Buchans, Newfoundland	+	+	+	−	−	−	Thurlow et al., 1975
Skorovass, Norway	−	+		−	−	+	Gjelsik, 1968
Lake Dufault, Quebec	−	+	+	−	−		Sakrisson, 1967
Timmons, Ontario		+			−	+	Bennett and Rose, 1972
Noranda, Quebec	0	+	+	−	−	−	Riverin and Hodgson, 1980

See Table 2 for symbols

SiO_2 loss; alkali depletion; significant Na_2O depletion, lesser CaO and K_2O loss; and MgO loss.

In general, then, the experimental studies roughly confirm what is seen in such environments as Noranda, where detailed studies permit characterization of elemental gains and losses. Applying these models to the Carolina slate belt, wholesale matrix alteration would make the typical slate belt volcanic rock appear more tholeiitic by alkali depletion. The significant Na_2O enrichment trend for mafic rocks could easily mask a more typically calc-alkaline trend of K_2O enrichment and, thus, suggest a primitive tectonic setting for magma genesis. In an AFM diagram, the highly variable MgO behavior with significant alkali mobility could easily mask primary magmatic trends.

Alteration associated with mineralization

Any number of studies have been conducted which evaluate the more extreme alteration typically associated with volcanogenic massive sulfide deposits. Table 3 shows several examples. Three recent studies provide a data base for evaluating this alteration in the Carolina slate belt (Goldstein, 1980; Guthrie, 1980; Unger, 1981). Generally speaking, the alteration associated with mineral deposits is similar to the previously characterized regional alteration but produces greater extremes of elemental variability. As noted in the Albemarle and South Carolina-Georgia areas (Fig. 7), there is a very significant range in the K_2O/Na_2O ratio. However, as can be seen in Figure 15, for mineralized areas this variation is even more extreme. In North Carolina, very K_2O-rich and Na_2O-depleted rocks are characteristic of the hydrothermal alteration associated with metallogenesis at the Union Copper mine, Gold Hill district, with K_2O contents as high as 9 percent. In South Carolina-Georgia, this same extreme K_2O enrichment-Na_2O depletion is observed but so, too, is a very Na_2O enriched, K_2O depleted alteration. As can be seen in Figure 16, on an alkali-silica plot one again sees extremes of alkali leaching or enrichment, as well as SiO_2 addition to the siliceous rocks. In the South Carolina-Georgia area, there has been sufficient SiO_2 mobility to generate a range of SiO_2 contents that fall in the 61 to 66 percent SiO_2 gap in the regional sampling suite. On the ternary diagram, $CaO-Na_2O-K_2O$, this effect is even more pronounced, with well over half of the rock analyses from mineralized districts plotting to the K_2O-rich side of the field which contains most of the rest of the Carolina slate belt suite. In AFM space, the mineralization-associated alteration is also more

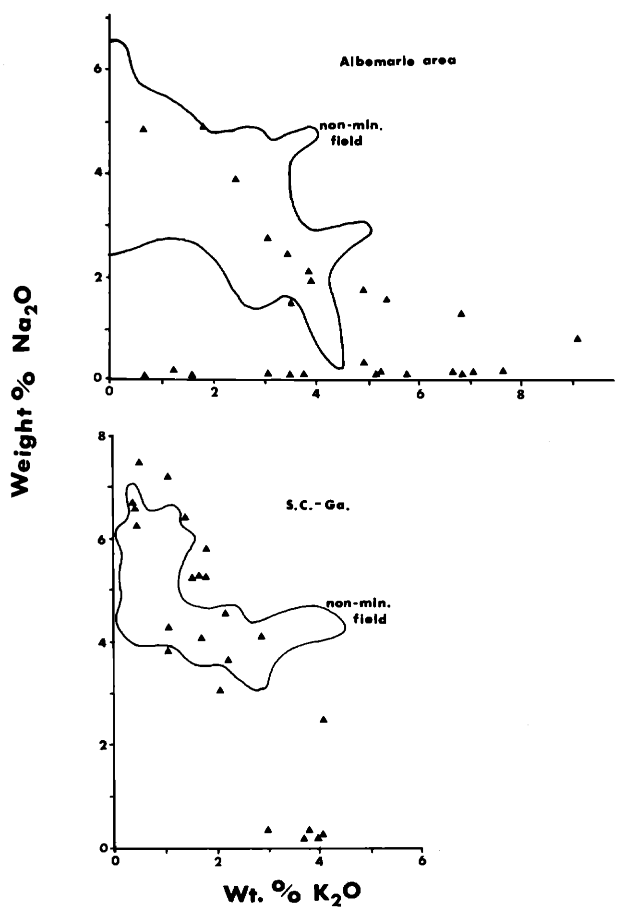

FIG. 15. K_2O-Na_2O diagram showing range of compositions for Carolina slate belt volcanics not associated with mineralization compared with analyses from mineralized areas (Guthrie, 1980; Goldstein, 1980; Unger, 1981).

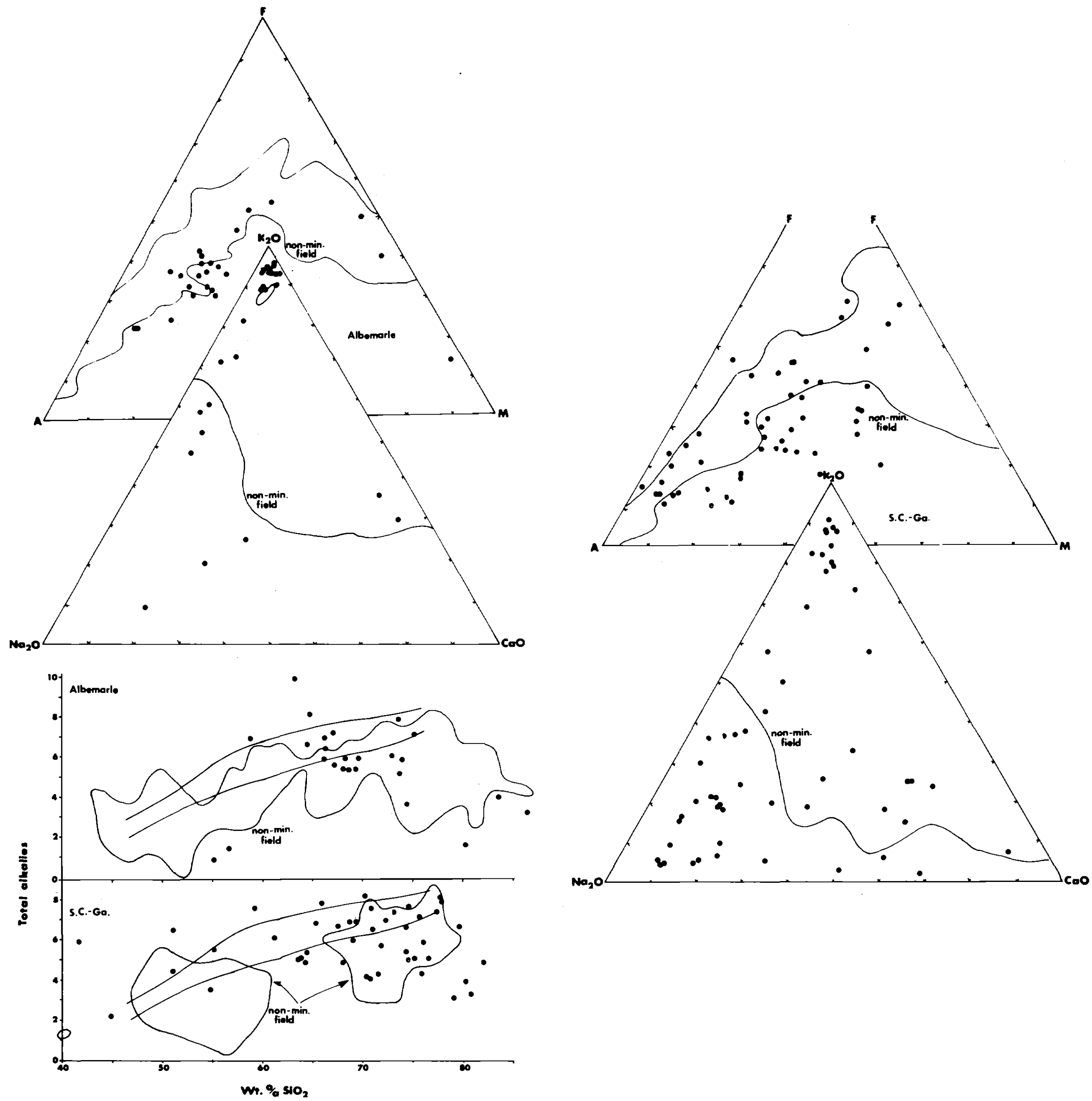

FIG. 16. Variation diagrams for mineralized, altered areas as compared to the range of compositions of typical Carolina slate belt volcanics from the Albemarle, North Carolina, area and the Lincolnton, Georgia-McCormick, South Carolina, areas.

extreme in terms of MgO mobility, but the effect is more subdued due to the previously described alkali mobility. Nonetheless, mineralization-associated volcanic rocks plot on the MgO-rich side of the general trend of the slate belt volcanics. The addition of TiO_2 to the AFM, the Jensen cation plot, suppresses the MgO-enrichment effect, as presumbly it was intended to do.

The conclusions reached above are similar to those based on the data collected by Riverin and Hodgson (1980) at Noranda and shown in Figure 14. As in the slate belt, hydrothermal alteration at Noranda has made calc-alkaline andesites and rhyolites appear, on a Kuno diagram, to be tholeiitic and, due to the SiO_2 mobility, has increased the potential spread in silica values. Furthermore, at least some of the altered rocks at Noranda show significant K_2O and MgO-enrichment trends. As in the slate belt, the MgO-enrichment trend in AFM space is very much suppressed by alkali mobility.

Summary and Conclusions

1. Given the degree and character of the alteration of the typical Carolina slate belt volcanic rock, it appers unlikely that major element chemistry can give unequivocal answers to the tectonic setting and petrologic history of the belt. Based on immobile trace elements and a somewhat conservative evaluation of the major element chemistry, it appears likely that the slate belt volcanics are a bimodal, calc-alkaline suite generated over a subduction zone. This volcanic arc was active over a period of about 150 million years beginning in the late Precambrian. It was similar in many important respects to the younger volcanics of the Coastal volcanic belt in Maine and in roughly correlative volcanic belts in the Maritimes. Most reconstructions of the Wilson cycle for eastern North America at this time would place the Carolina slate belt volcanic arc on the west side of the closing Iapetus ocean, constructed on an unknown crustal substrate. The Sr isotopes would suggest that this substrate was a relatively primitive, nonevolved crust. The bimodal, calc-alkaline character of the slate belt is a puzzle, although modern analogs in the Lesser Antilles and portions of Papua New Guinea do exist. None, however, has the geographical extent nor the time duration of the Carolina slate belt. Several possible explanations can be suggested:

a. The Carolina slate belt volcanic arc is not analogous to modern arc systems in some essential and fundamental way.

b. Characterizations of modern arcs are flawed by sampling problems (see, e.g., Arculus and Johnson, 1977). This would imply that, when one investigates a significant cross section of an ancient arc system such as the Carolina slate belt, one is not correct in directly comparing its chemistry to that of the exposed and younger portions of modern arcs.

c. The Carolina slate belt volcanics preserve either a transitional environment (Rogers, 1982) in which the volcanics were constructed on a thickening continental crust above oceanic subduction, thus possessing a certain "hybrid" character, or they preserve a two-stage process of oceanic (subduction) magma genesis followed by a continental (postsubduction) magma genesis (Jakes and White, 1971). The latter concept, while fitting the TiO_2 data for the Coastal volcanic belt, presents a problem in the Carolina slate belt because the thickest felsic sequence, the Uwharrie Formation, underlies the more mafic-intermediate, mixed volcanic sequences of the Albemarle Group. Furthermore, if the alteration is not totally masking the calc-alkaline character of the volcanics in the Albemarle and South Carolina-Georgia areas, then these more tholeiitic-trending suites are actually younger than the more characteristic postsubduction suite in the Chapel Hill area.

2. There is nothing unique or distinctive about Carolina slate belt volcanic chemistry when it is compared with the available averages for volcanic suites which host massive sulfide deposits eleswhere in the Caledonides. The issue as to whether other bimodal, calc-alkaline subduction-related suites are likely hosts for volcanogenic massive sulfide deposits requires additional study. Clearly, this is not the same suite, on a petrochemical basis, as the felsic-dominated, mafic-poor Miocene Green Tuffs of Japan. However, the slate belt does bear some striking resemblances to the volcanic host rocks of Archean massive sulfide deposits.

3. The entire Carolina slate belt volcanic suite appears to have been subjected to greater or lesser amounts of postdepositional alteration. Whether this is analogous to submarine weathering, spilitization, or hydrothermal alteration is not known. The alteration would appear to affect the fine-grained matrices of the flows and fragmental rocks to a preferential degree, though one cannot discount the possibility of alkali exchange in the feldspar phenocrysts. The alteration, in general, appears to result in an overall alkali depletion and MgO enrichment with significant and variable amounts of K_2O, CaO, Na_2O, and SiO_2 mobility into and out of the system.

4. Hydrothermal alteration associated with mineralization is intense and results in extremes of alkali addition and subtraction as well as MgO enrichment. Relatively massive Mg talc is reported in the Union Copper deposit in the Gold Hill district (Unger, 1981). Most rocks show clear evidence of silicification. These altered rocks fall well "outside" the normal ranges of Carolina slate belt rocks in alkali-silica, CaO-Na_2O-K_2O, and AFM space.

5. It is apparent that the extreme variability in the composition, H_2O content, grain size, and distribution of volcanic and epiclastic rocks that were encountered by circulating sea water during postdepositional alteration results in a highly varied, unpredictable, and unsystematic alteration chemistry. The varying depth of burial and proximity to volcanic centers could produce as well a potentially significant range in alteration temperatures in time and space. Thus, it is hardly surprising that, in detail, the alteration chemistry appears so varied. Perhaps most significant is the fact that there appears to be a characteristic alkali variation and SiO_2 and MgO enrichment associated with volcanogenic massive sulfide mineralization.

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