High-Alumina Hydrothermal Systems in Volcanic Rocks and their Significance to Mineral Prospecting in the Carolina Slate Belt

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By ROBERT G. SCHMIDT

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Large alteration systems in the slate belt have many of the characteristics of high-alumina copper-, molybdenum-, and gold-bearing deposits in other regions of the world

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HIGH-ALUMINA HYDROTHERMAL SYSTEMS IN VOLCANIC ROCKS AND THEIR SIGNIFICANCE TO MINERAL PROSPECTING IN THE CAROLINA SLATE BELT

By Robert G. Schmidt

ABSTRACT

Large subvolcanic to solfataric hydrothermal systems characterized by an abundance of high-alumina minerals, very intense alteration by strong acids acting through large volumes of rock, and profound changes in bulk composition are found at many localities worldwide, and can be considered to form a separate sub-class of alteration system. The altered zones at many of the localities contain widespread disseminated pyrite, and may contain from traces to economically extractable quantities of gold, silver, copper, molybdenum, tin and other metals. Fluorine is commonly but not always more abundant than boron, and topaz is a widespread major mineral. Bismuth, arsenic, lead, and zinc are also present in many of the deposits. Characteristics of these systems are transitional to shallower solfataric and hot spring deposits, and with greater K-silicate alteration into classical subvolcanic porphyry copper deposits.

One major area of high-alumina deposits is in the Southeastern United States. At least 40 large bodies of aluminous rock within volcanic rocks of the Carolina slate belt have been identified. Some bodies have many features of porphyry copper systems but others do not; the two types must have originated under somewhat different conditions of pressure and (or) temperature. Characterized by some or all of the minerals kaolinite, sericite, pyrophyllite, and rutile, and locally abundant disseminated sulfide, parts of some bodies are even more aluminous with abundant andalusite and topaz and traces of diaspore. These deposits are interpreted to be the result of intense hydrothermal alteration of predominantly andesitic eruptive rocks. Several are presently mined for andalusite and pyrophyllite. Although no metallic ores have been identified, copper, molybdenum, bismuth, arsenic, or tin are locally present in minor amounts. Gold has been mined at five aluminous deposits and may be associated with a few more. Two areas of former gold mines in large siliceous pyrophyllite-andalusite-topaz-bearing systems--the Brewer, in Chesterfield County, S.C., and Pilot Mountain, in Randolph County, N.C.--are tentatively classified as porphyry gold systems. Of 40 aluminous deposits, most occurring in North Carolina, at least 14 are topographically positive, and some have associated unique depleted floral suites and stunted trees. Aluminous deposits, especially kyanite deposits of the more metamorphosed Charlotte and Kings Mountain belts were not considered here.

Analogous deposits in other regions have economically minable metals associated with them and these call attention to the possible importance of the major systems in the Carolina slate belt. Other deposits that help us understand those in the slate belt include Mount Pleasant in New Brunswick, Canada, and scattered porphyry copper deposits in the North and South American Cordillera, and in southeast Asia. The Kounrad and certain other deposits in central Kazakhstan, U.S.S.R, are major porphyry copper systems where abundant andalusite and pyrophyllite closely associated with the ore zone have formed by hydrothermal action. Comparisons with Kazakh orebodies suggest that several Carolina deposits may be variations of true porphyry-type systems, that alteration mineral zonation is a potential tool to identify the part of a greater system represented by the surface exposures that we see, and that the systems deserve consideration for their copper and molybdenum potential.

Many major problems concerning the relationships of the deposits to their enclosing rocks remain unresolved because the geologic history of the enclosing units is exceedingly complex and few features of the rocks have been mapped. Many of the deposits have granitic plutons nearby, but it is not clear whether a genetic relationship exists between them. A major objective of current studies in the area is the ordering of successive geologic events and the selecting of rock units for age dating in order to yield geologically significant values. More information on the ages and compositions of plutonic rocks may make it possible to assume that the volcanism took place on continental crust, that is, at a continental margin rather than on an island arc. Such new data are expected to help construct a probable model of a high- alumina alteration system in the Carolina slate belt and to select the best places for metal exploration.

INTRODUCTION

The Carolina slate belt, a thick sequence of metamorphic rocks derived from volcanic tuffs, flows, and tuffaceous sediments was probably formed in a volcanic arc environment in late Precambrian and early Paleozoic time. Extending about 650 km from Georgia to Virginia, some of these rocks are similiar to and might be related to the Avalon zone rocks of Newfoundland.

Within the Carolina slate belt, at least 40 large bodies of aluminous rock have been identified; part of them are shown on figure 1. Characterized by some or all of the minerals kaolinite, sericite, andalusite, pyrophyllite, topaz, rutile, and diaspore, these deposits are interpreted to be the result of intense hydrothermal alteration of predominantly andesitic pyroclastic rocks by strongly reactive acidic fluids or gases acting at high temperatures and low pressures. While most or all of these deposits include abundant kaolinite, sericite, and pyrophyllite, and traces of rutile, about one-quarter of the deposits also have abundant andalusite and topaz, and minor diaspore, which I have designated a high-alumina assemblage. The latter tend to be enclosed by large envelopes of highly silicified rocks and to cut across stratigraphic layers. The subject of this report is this smaller group of crosscutting deposits generally containing andalusite and topaz and sometimes diaspore, in what is probably a high temperature mineral suite. The same group of deposits was designated "replacement

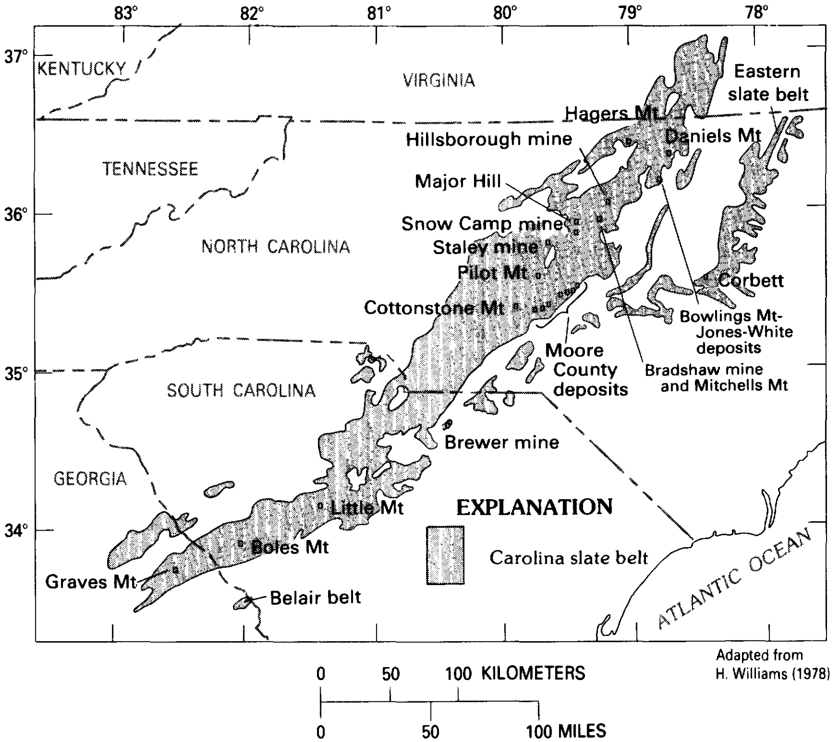

FIGURE 1. High-alumina alteration systems in the Carolina slate belt.

deposits" by Espenshade and Potter (1960), who differentiated them from the more abundant, lower temperature and perhaps stratabound deposits. A separation of the high-alumina bodies by mineral suite and structural form has not been attempted by most authors in describing the deposits. Although metallic ores have not been found in association with most of these aluminous deposits, gold is associated with some and may be inferred to be related to several more. Copper, molybdenum, and tin are locally present in minor amounts (table 1). The Brewer and Pilot Mountain deposits, where gold has been mined from large high-alumina alteration zones, are tentatively classified as porphyry gold systems (Schmidt, 1982).

The deposits of pyrophyllite and andalusite, and the topaz that accompanies many of them, have been considered to have various origins by previous workers. Pardee and others (1937, p. 1064), after topaz was recognized as an important rock-forming mineral at the Brewer deposit, considered quartz, topaz, and pyrite to be the products of hydrothermal alteration of quartz-sericite schist by flourine-rich

TABLE 1.—*Metals associated with selected pyrophyllite deposits*

Name of deposit	County	State of development	How disseminated sulfide is present
Brewer mine	Chesterfield, S.C.	Former gold mine	Widespread disseminated pyrite, 5–15 percent
Pilot mountain	Randolph, N.C.	Undeveloped	Disseminated pyrite widespread, sparse molybdenite in Pine Hill mine dump
Fox Mt./Iron Mt.	Randolph, N.C.	Undeveloped	Pyrite probably common before oxidation
Standard Minerals	Moore, N.C.	Operating pyrophyllite mine	Present
Glendron Pyrophyllite	Moore, N.C.	Operating pyrophyllite mine	Abundantly disseminated in north wall of mine
Staley mine	Randolph, N.C.	Former pyrophyllite mine	Only seen in blocks of waste rock
Snow Camp mine	Alamance, N.C.	Former pyrophyllite mine	Common in mine walls and floor
Hillsborough mine	Granville, N.C.	Operating pyrophyllite mine	Present in local masses
Bowlings Mountain	Granville, N.C.	Small pyrophyllite production	Observed in waste rock
White deposits	Granville, N.C.	Undeveloped	Widespread in deposit
Daniels Mountain	Granville, N.C.	Undeveloped	Relict textures indicate sulfide common below zone of oxidation
Limonite from Gossan, Ore Hill, Mt. Vernon Springs	Chatham, N.C.	Former iron ore mines	Lenses, pods (now all oxidized)
Ammons (Comer-Aumen) mine	Montgomery, N.C.	Former pyrophyllite mine	Disseminated in wall rock
Average, 12 samples, unmineralized hilltop sites (see Table 3)	Mostly Randolph, N.C.	------------------------------	Sparse dissemination in bedrock at part of sites

TABLE 1.—*Metals associated with selected pyrophyllite deposits*—Continued

Name of deposit	Numbers of samples		Maximum analytical values, rocks (Cu, Mo, and Sn analyses by emmission specroscopy; Au by atomic absorption)							Maximum analytical values, soil and saprolite				Mines and prospects nearby	
	Rock	Soil or Saprolite	Cu	Mo	Sn	Au	As	Bi	Ag	Cu	Mo	Sn	Au	Au	Cu
Brewer mine	44	>400	10,000	700	200	-----	3,000	500	-----	900	80	-----	.44	X	-----
Pilot mountain	3	60	[1] 2,200	[2] 66	[2] 25	-----	[3] 200	-----	.69	88	21	16	-----	X	-----
Fox Mt./Iron Mt.	0	10	-----	-----	-----	-----	-----	-----	-----	94	< 1.	4	-----	X	-----
Standard Minerals	10	5	20	8	-----	0.68	-----	-----	-----	10	4	-----	0.24	X	-----
Glendron Pyrophyllite	16	4	1,100	500	-----	0.04	-----	-----	-----	30	10	-----	0.04	-----	X
Staley mine	1	0	26	22	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Snow Camp mine	2	7	25	1.8	3.6	-----	-----	-----	-----	49	6.2	2.1	-----	-----	-----
Hillsborough mine	1	1	6.0	-----	4.6	-----	-----	-----	-----	6.6	< 1.0	3.1	-----	-----	-----
Bowlings Mountain	0	4	-----	-----	-----	-----	-----	-----	-----	8.6	2.8	7.0	-----	-----	-----
White deposits	0	1	-----	-----	-----	-----	-----	-----	-----	7.5	< 1.0	5.4	-----	-----	-----
Daniels Mountain	0	4	-----	-----	-----	-----	-----	-----	-----	31	< 1.0	< 1.5	-----	-----	-----
Limonite from Gossan, Ore Hill, Mt. Vernon Springs	2	--------------	200	51	-----	-----	460	-----	3	-----	-----	-----	-----	-----	-----
Ammons (Comer-Aumen) mine	2	--------------	12	61	6.5	-----	-----	-----	.16	-----	-----	-----	-----	-----	-----
Average, 12 samples, unmineralized hilltop sites (see Table 3)	---	10	-----	-----	-----	-----	-----	-----	-----	Ave. 11.7	All 1.0	Ave. [4] 2.1	-----	-----	-----

[1]Sulfide-bearing rock from dump of old Pine Hill mine.
[2]Analyses of three leached cap rocks.
[3]Analyses of limonite gossan from prospect pit; also contains 91 ppm Pb and 110 ppm Zn.
[4]Average was calculated using 1 ppm for samples below level of detection.

solutions. Broadhurst and Councill (1953, p. 10) considered the high-alumina minerals to be products of mineralizing solutions associated with a shallow magma. Espenshade and Potter (1960, p. 25-27) believed that deposits of high-alumina minerals in the different geologic terranes of the Southeastern United States might have had different origins and that some of the andalusite-pyrophyllite deposits, which are most characteristically developed in the slate belt, might have formed in the deeper zones of extensive solfataric centers. Zen (1961) reasoned that, because of an excessive number of phases for the phase rule, the mineral assemblages present in the deposits required that the fugacity of H_2O be internally defined by the assemblage. This would be inconsistent with a hydrothermal origin. He suggested instead that the deposits originated by metamorphism of aluminous saprolite bodies. Spence (1975) proposed that kaolinitic clays formed by hot springs and (or) fumarolic alteration of the volcanic rocks, and that the transformation to pyrophyllite (and presumably andalusite and diaspore as well) took place during regional metamorphism. Sykes and Moody (1978) showed H_2O to be a variable or externally defined component and held that the andalusite formed as the result of metamorphism. They demonstrated from field and microscopic studies that there were not, in fact, an excessive number of phases for the phase rule (that is, kaolinite formed later and cut andalusite-bearing assemblages). They felt flourine was supplied by a hydrothermal event earlier than and distinct from the metamorphism, but gave no substantiating evidence. Worthington and others (1978) attributed the gold mineralization of the Brewer mine and presumably the accompanying pyrophyllite, andalusite, and topaz to alteration of volcanic rocks by a hot spring or fumarolic system.

Allard and Carpenter have studied high-alumina alteration systems in the slate belt at Graves Mountain, Ga., and other sites, and at several more-metamorphosed deposits as well (Allard and Carpenter, 1981. 1982a. 1982b, 1983; Carpenter and Allard, 1980a, 1980b). They have concluded that the hydrothermal systems have formed in submarine felsic volcanic piles by fumarolic action and that the quartz-rich high-alumina rocks and the quartz-sericite-pyrite rocks formed as separate parts of such systems. Though individual alteration types may cross- cut strata, the overall stratiform nature of the deposits was stressed (Carpenter and Allard, 1982, p. 20). The major high-alumina alteration minerals as well as certain alteration and metamorphic accessories such as hogbomite, sapphirine, tourmaline, dumortierite, lazulite, apatite, barite, rutile, nigerite, cassiterite, kornerupine, and gold were proposed as indictors that might be used to delineate prospective exploration areas (Allard and

Carpenter, 1983). Parallels were drawn with deposits in other regions that have associated high-alumina minerals, such as Boliden, Sweden, and Kounrad, Kazakhstan, U.S.S.R.

The results of this study also indicate that the large andalusite-bearing high-alumina deposits in the Carolina slate belt had a subvolcanic hydrothermal origin. Deposits that we see probably represent a range in depths of formation, the shallower more fumarolic ones tend to be stratiform in shape, and the deeper ones cross-cutting and more pipe-like. It is the deeper systems which I have tried to study most extensively. Hydrothermal alteration accounts for both the high-alumina and associated high-SiO_2 rocks and for the specific mineral suites present; the widespread association of contemporaneous andalusite-topaz-quartz bodies enclosed in large highly silicic zones with later diaspore, pyrophyllite, and kaolinite cutting the andalusite are interpreted to have formed during a single high-temperature low-pressure event and its waning or collapse stages, without any significant changes wrought by later metamorphism. I believe these interpretations to be compatible with what has been established for the phase relations in the system Al_2O_3-SiO_2-H_2O by Hemley and others (1980).

The subvolcanic hydrothermal hypothesis proposed in this article is generally compatible with the ideas of origin proposed by Pardee and others (1937) and Espenshade and Potter (1960). It differs only slightly from the interpretation of Worthington and others (1978), mainly in the depth of formation in the volcanic system and the origin assumed for the siliceous rocks (those they have called sinters). Earlier workers have not generally emphasized the size and characteristics of the whole alteration system, nor the prevalence of high-alumina minerals such as topaz, andalusite, and diaspore, factors important in understanding the system. I believe that current studies by Carpenter and Allard deal primarily with shallower systems as indicated by the generally stratiform nature of the deposits they describe (Carpenter and Allard, 1982, p. 20); but my general conclusions regarding the hydrothermal process are very similar to theirs and the studies complement each other. The deposits I have examined lack evidence indicating a submarine origin, however.

Like Espenshade and Potter (1960, p. 25-27), I believe that all of the slate-belt high-alumina deposits did not originate in the same manner. I have tentatively selected those with large envelopes of hydrothermally altered rock enclosing pods of high-alumina minerals as significant hydrothermal deposits with the most economic metallic mineral potential, and deserving of further study (Schmidt, 1982).

It is the purpose of this article to explore the possibility that some of these deposits form a transition to a tvpe of major porphyry copper-molybdenum deposit that includes widespread silicification plus pyrophyllite or andalusite as a major alteration mineral intimately associated with hypogene sulfide ores. Comprehensive comparisons are neither possible nor intended at this time because adequate mineral assemblage data are available for only a few of the major foreign deposits, and studies comparing the various deposits of the Carolina slate belt are only beginning. Instead, my intention is to emphasize the possible significance of certain of the slate belt systems and to urge that they be given much more attention in mineral exploration.

Studies made elsewhere that bear on the possible relationship of high-alumina alteration to porphyry-type systems include those of Hemley and others (1980), Knight (1977), Wallace (1979), and Sillitoe (1973). Hemley and others (1980) experimentally investigated and thermodynamically treated the chemistry of phase relations in the Al_2O_3-SiO_2-H_2O system and briefly discussed the implications to porphyry copper alteration-mineralization systems and to other systems as well. Similarity of the North Carolina pyrophyllite deposits to altered rock in certain parts of the greater Butte orebody was noted by the same authors (Hemley and others, 1980, p. 226). Knight (1977) conducted a number of thermochemical calculations in order to better interpret the alteration mineralogy above buried copper deposits; his results showed general consistency with published descriptions of deposits in other regions. Wallace (1979) developed a working model for the upper levels of porphyry copper systems to serve as an exploration guide to porphyry-type deposits not yet exposed by erosion. Sillitoe (1973) prepared an early synthesis of information obtained mostly from Andean examples to model the upper part of a porphyry system in a stratovolcano. Advanced argillic alteration, in places including andalusite and other high-alumina minerals, is definitely present in the upper part of some examples, as demonstrated by the detailed work of Gustafson and Hunt (1975) on the El Savador, Chile, deposit.

Meyer and Hemley (1967, p. 170) pointed out that andalusite-bearing alteration assemblages are high-temperature equivalents of what they termed advanced argillic. I have used the term high-alumina alteration to distinguish assemblages with abundant topaz, andalusite, diaspore or corundum from advanced argillic alteration, containing mostly kaolinite or alunite; furthermore, many of the deposits discussed here contain only volumetrically minor amounts of true clay minerals. High-alumina alteration is typically accompanied by widespread highly silicified rocks for which I use the term quartz granofels. These siliceous rocks have been called secondary quartzites in Soviet literature, and altered rocks with over 90 percent quartz have been termed monoquartzites. I have not used the latter terms to avoid confusion with metasedimentary rocks.

The more highly metamorphosed high-alumina deposits, especially the kyanite deposits of the Charlotte and Kings Mountain belts are geologically more complex and have not been considered at this time.

Descriptions have been collected of deposits in other regions that may be analogous to the aluminous deposits in the Carolinas and can therefore help in understanding their origins. The Mount Pleasant deposit in New Brunswick is outstanding among these. Descriptions of hydrothermal andalusite-pyrophyllite clay deposits of Japan and mineralogic data from active geothermal fields provide valuable information on the probable environment in which deposits like these formed. Several deposits of the porphyry-copper type are characterized by andalusite and pyrophyllite in zones of intense hydrothermal alteration; among them, the Kounrad and other deposits in Kazakhstan, U.S.S.R., the Tapadaa and Tombuililato copper districts, North Sulawesi, Indonesia, and the El Salvador deposit, Chile. The porphyry gold mineralization at Vunda, Fiji, has quartz-diaspore rock as one accompanying alteration phase (Lawrence, 1978, p. 26).

This study grew out of a project conducted to evaluate favorable areas in the Eastern United States for the occurrence of porphyry-type copper deposits. The Mount Pleasant deposit, New Brunswick, Canada, was visited and the study of drill cores from the Brewer mine begun in 1973. Field examination of the Pilot Mountain area was first undertaken in 1978, with a brief field visit to the Brewer mine vicinity at the same time. Preliminary conclusions regarding the mineral potential of this area were presented at that time (Schmidt, 1979). Subsequently, information for preparation of this report was obtained from field examination of many aluminous deposits in North and South Carolina, together with the search of geologic literature for data on other localities. Geochemical sampling, especially soil sampling, was carried out at many places in North Carolina, and sample data obtained by other members of the U.S. Geological Survey were used in conjunction with my own. A detailed map of Pilot Mountain was prepared, and reconnaissance geologic mapping was carried out in the Ramseur and adjacent 7-1/2 minute quadrangles, North Carolina.

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The author is very grateful for the cooperation of Piedmont Minerals Co., Inc ; to Tom R. Kleeburg, consulting geologist working with them; and to Glendon Pyrophyllite Company for their help in making this study possible. My interpretations of the geology of the deposits have been greatly sharpened by many discussions with Tom Kleeburg; he has found some of my ideas less acceptable than others, as I expect certain readers will as well. Grayson Byrd, an owner of land in the western part of the Pilot Mountain alteration zone, has shown a continuing interest in this study and his kindness in showing us outcrops is appreciated.

I have drawn heavily upon the results of detailed mapping and mineralogical studies by Terry L. Klein, U.S. Geological Survey, in the mines of Glendon Pyrophyllite Company and on parts of Pilot Mountain. Our many discussions have been most useful in shaping the concepts presented here. Special thanks are due to Dr. Shuichi Iwao, Professor Emeritus, University of Tokyo, for calling my attention to the geologic significance of the Ashio copper-tin mine, Honshu, among the many high-alumina hydrothermal clay deposits of Japan, and to Henry Bell III for the loan of 29 thin sections of Brewer mine rocks. I wish especially to thank J. J. Hemley, T. L. Klein, and Henry Bell III for their reviews and suggestions for improvement of this paper.

METAL DEPOSITS WITH ASSOCIATED ZONES OF ALUMINOUS ALTERATIONS IN OTHER REGIONS

Alteration zones containing significant amounts of the aluminous minerals kaolinite and pyrophyllite, and particularly the high-alumina minerals andalusite, diaspore, and corundum have been described from major porphyry copper deposits at several locations worldwide, including especially Kazakhstan in the U.S.S.R., and from one hydrothermal system described as a porphyry-gold deposit. Brief summaries of published descriptions of metal-bearing deposits with significant aluminous hydrothermal alteration follow.

EXAMPLES IN NORTH AMERICA

Few porphyry-type deposits of Western United States and Canada have much associated aluminous alteration other than kaolinite; of these Butte, Mont., and Island Copper, British Columbia, are the best known. The minerals that characterize aluminous alteration may have been overlooked at some porphyry deposits, and I may have failed to find references to the aluminous minerals in recent publications, but the occurrences north of Mexico must certainly be few.

The polymetallic deposit at Mount Pleasant, New Brunswick, is a major metal deposit that contains abundant aluminous alteration. High-alumina deposits without much associated sulfide ore minerals are present in Avalonian rocks of Newfoundland (Papezik and others, 1978) and in Mesozoic volcanic rocks of Puerto Rico (Hildebrand, 1961a, 1961b).

Butte, Mont.--Widespread andalusite and corundum are present in the alteration envelopes surrounding pre-main-stage ore veins in the Butte district (Brimhall, 1977), and considerable pyrophyllite is known to be associated with sericite in the Berkeley pit in the same district (Guilbert and Zeihen, 1964). Assemblages recognized in 1964 included pyrophyllite-topaz, sericite-topaz, sericite-zunyite, and topaz-zunyite. High-sulfur vein assemblages containing pyrite, covellite, digenite, and enargite are found only in the zone of pervasive sericitization, and are particularly associated with high-alumina alteration minerals (Meyer and Hemley, 1967, p. 193). The control of H^+ activity in shifting equilibria toward high sulfur fugacity, as discussed by Meyer and Hemley, is thus illustrated at Butte and in many other examples of these deposits presented in this paper.

Island Copper, British Columbia--The Island Copper deposit, British Columbia, formed in andesitic pyroclastic rocks in breccia zones along the sides of a large quartz-feldspar porphyry dike of granodiorite composition (Cargill and others, 1976). Plagioclase, mafic minerals, and matrix material have been extensively altered to pyrophyllite and lesser amounts of dumortierite in breccia zones above the dike and in zones that extend downward on the sides of the dike along the contacts. Copper concentrates from this deposit contain gold (7-10 ppm) and silver (35-40 ppm), and the molybdenum concentrates contain 1400 ppm rhenium, a relatively high rhenium content (Sutulov, 1970, p. 223).

Kyuquot Sound, British Columbia--An alunite-pyrophyllite deposit containing sericite, kaolinite, and diaspore has been mined at Kyuquot Sound on Vancouver Island, about 50 km south of the Island Copper deposit. There, rocks in a thick series of interbedded amygdaloidal, porphyriic, and fragmental feldspathic andesites and dacites are altered to an aluminous mineral suite close to an intrusion of feldspathic quartz diorite (Clapp, 1915). Pyrite is disseminated through much of the altered rock, especially below the zone of oxidation, and minor amounts of copper, gold, and silver are present. Chalcopyrite is the only copper mineral described. The deposit is not the same locality as the Kyuquot porphyry-type Cu-Mo-W "showing" of Pilcher and McDougall (1975, table 2, map B).

Other Western North American examples--Aluminous alteration minerals are also associated with a major porphyry-type hydrothermal system at the Warren-Bisbee district, Arizona, where quartz porphyry of the Sacramento stock has altered to quartz and pyrophyllite with dickite, alunite, rutile, and zircon (Bryant and Metz, 1966, p. 196).

Wallace (1979), building on the work of Gustafson and Hunt (1975) at El Salvador, various papers by Meyer and others at Butte, and Knight (1977), has proposed applying the presence of pyrophyllite-dominated advanced argillic alteration to indicate possible upper levels of porphyry-copper systems in the western Great Basin of Nevada. Knight (1977) had used certain mineral assemblages, especially alunite, pyrophyllite, and copper-arsenic sulfosalts, to suggest that alteration has taken place above a sulfur-rich pluton.

Mount Pleasant, New Brunswick--Porphyrylike deposits of tungsten, molybdenum, copper, tin, and bismuth are located in volcanic rocks of a caldera of Mississippian age at Mount Pleasant, New Brunswick (Ruitenberg, 1967; van de Poll, 1967). The aluminous minerals kaolinite, topaz, and dickite have been formed by intensive hydrothermal alteration related to volcanism (Petruck, 1964, p. 29); neither pyrophyllite nor andalusite has been described from these deposits.

The geology of the large and complex Mount Pleasant hydrothermal system has been described by McAllister and Lamarch (1972, p. 82-89) and Dagger (1972). Mineralization and intense alteration are related to two pluglike bodies that are interpreted to be erosional remnants of volcanoes. The plugs are highly altered felsite, tuff, and breccia; intruded rocks are mosty felsic ash-flow tuffs. Three overlapping zones of hydrothermal alteration are concentric about the plugs (Ruitenberg, 1967, 1972) within which the original felsic vent rock is mostly replaced by quartz and has not been a particularly favorable host for mineralization.

Intense alteration has destroyed much of the primary rock texture, and locally it is difficult to interpret what the original rock may have been. Volcanics adjacent to the plugs have been more favorable hosts partly because they are more fractured and tend to form more vugs. Intense hydrothermal alteration of these rocks has resulted in some nearly complete replacement by quartz, but mostly the formation of a mixture of quartz, fine mica, flourite, topaz, and kaolinite. Less altered rocks are sercitized, silicified, and chloritized. A bright green "chlorite," shown to be a mixture of kaolinite and chlorite, is common with metallic mineralization. Chlorite extends beyond the other alteration products to form the outermost alteration zone with a total mapped length of 2.6 km (Ruitenberg, 1967). Kaolinite and hydromica are common widespread products of hydrothermal alteration, either mixed or in separate form, and dickite has been found within kaolinized zones. Steeply plunging kaolinite pipes 2 to 7 m in diameter have been described by Ruitenberg (1967, p. 107); the pipes contain abundant large pale-green flourite crystals and large blocks of wall rock.

Mineralization has taken place in individual veins, complex veins or narrow vein swarms, isolated pods, stockworks of numerous fine irregular veinlets, and disseminated patches; some breccia pipes are well mineralized. Feldspar porphyries are the best hosts for metallic minerals. Mineralized veins are associated with greisen zones of quartz, flourite, kaolinite, topaz, hematite, and chlorite. Most intense mineralization tends to be in breccia zones of dike or pipelike shape; the origin of these breccias is in dispute.

The principle ore minerals at Mount Pleasant are molybdenite, wolframite, native bismuth, bismuthinite, chalcopyrite, cassiterite, stannite, spalerite, and galena. Economic minerals in minor quantities include scheelite, chalcocite, tennantite, tetrahedrite, covellite, wittichenite, native gold, glaucodot, arsenobismite, and malachite; other significant associated minerals are pyrite, marcasite, pyrrhotite, arsenopyrite, flourite, topaz, zircon, rutile, quartz, sericite, kaolinite, chlorite, calcite, siderite, hematite, and goethite (Petruk, 1964).

Foxtrap deposit, Newfoundland--The Foxtrap pyrophyllite deposit, in the Avalon Peninsula of Newfoundland, is located in rhyolitic flows and pyroclastics of the Avalon zone, a sequence of volcanic rocks generally considered to be related to the Carolina slate belt. Pyrophyllite, muscovite, diaspore, barite, and rutile have formed along a shear or fracture zone close to the contact of an intrusive granitoid rock; it has been suggested that the alteration was produced by hydrothermal fluid related to the granitoid (Papezik and others, 1978).

EXAMPLES IN SOUTH AMERICA

El Salvador, Chile--As much as 40 percent andalusite, pyrophyllite in significant amounts, and lesser amounts of diaspore and corundum have been described in parts of the porphyry copper deposit at El Salvador, Chile (Gustafson and Hunt, 1975). During the complex alteration and mineralization history of this large orebody, high-alumina and advanced argillic alteration minerals formed at two stages; the first in the upper part of the system overlapping the top of the main ore zone, and the last above the main ore occupying a space mostly in the present leached cap.

According to the model proposed by Gustafson and Hunt (1975), andalusite and corundum were important constituents of alteration zones that formed after intrusion of the last major porphyry body (the L Porphyry) and are thus genetically related to the pyrite-bornite mineralizations that formed at the same stage; both formed in similar high-sulfur strongly hydrolytic environments. The deepest andalusite and corundum alteration occurs with the assemblage K-feldpar-Na-plagioclase-anhydrite plus biotite or sericite. Gradationally upward, the high-alumina altered zone changes to the assemblage andalusite-sericite-quartz and minor to trace amounts of pyrophyllite, diaspore, or alunite at the erosion surface. Outward at the surface, the assemblage grades to sericite-pyrite with local alunite and (or) pyrophyllite; at a greater distance, this is surrounded by propylitic alteration. Gold values in excess of 0.1 g/T are restricted almost exclusively to a central chalcopyrite-bornite zone which is beneath and extends upward into the center of the high-alumina alteration (Gustafson and Hunt, 1975, p. 886 and fig. 28). The copper-gold mineralization is interpreted to have formed before the high-alumina alteration, however.

The second high alumina alteration, being generally later than other alteration processes, overprinted the upper part of earlier alteration zones. It was restricted to a high level in the system but spread laterally beyond the ore and is now mostly within the leached capping (Gustafson and Hunt, 1975, p. 900 and fig. 28). The assemblages contain pyrophyllite and a variety of associated minerals such as diaspore, primary alunite, andalusite, sericite, and local corundum, but no kaolinite. This alteration is interpreted to be the product of a very late post-mineral hot spring stage, albeit formed as much as 600 m below the present erosion surface.

Boron, present in tourmaline, is locally abundant in the El Salvador deposit, but I have found no reference to flourine-bearing minerals there.

La Granja porphyry copper deposit, Peru--The recent discovery of this interesting deposit furnishes another important example of porphyry-type mineralization associated with a high-alumina hydrothermal alteration system in the American Cordillera (Schwartz, 1981, 1982). The copper-molybdenum deposit is situated in northern Peru in the Cordillera Occidental in an area of high relief, subtropical climate, and 800 mm of rainfall per year. Host rocks consist of quartzite and a clastic-calcareous sequence of Cretaceous age, and volcanic rocks of Tertiary age. A large intense alteration zone is associated with a feldspar-quartz porphyry intrusive. Less altered phases of the intrusive grade into biotite-granodiorite porphyry and hornblende-granodiorite porphyry. The central most altered area is a large roughly circular sericite-clay zone about 3 km in diameter, within which there are 3 patches of "advanced argillic" alteration, 2 of which form a rough half-ring that is both surrounded by and has within it alteration of the sericite-clay type (Schwarz, 1982, fig. 3). The "advanced argillic" zone is characterized by the mostly high-alumina mineral assemblages andalusite-quartz, andalusite-pyrophyllite-quartz, andalusite-sericite-quartz, diaspore-pyrophyllite-quartz, and sericite-pyrophyllite-quartz. The area of supergene ore with more than 0.7 percent copper occupies much of the sericite- clay zone inside the half-ring of high-alumina alteration; the high-alumina rock itself is low in copper.

Other South American examples--Both hypogene and supergene alunite have been identified at the Cerro Verde porphyry copper mine, Arequipa, Peru, and pyrophyllite is also an alteration mineral there (Cedillo and others, 1979). The zoning is similar to that in El Salvador, and kaolinite is common. Though tourmaline is the predominant boron mineral, especially in breccia pipes, dumortierite (an aluminum borosilicate) is also common at Cerro Verde. No flourine minerals have been reported.

LARGE HYDROTHERMAL ALTERATION ZONES AND PORPHYRY COPPER DEPOSITS OF KAZAKHSTAN

The major porphyry copper province in central Kazakhstan, U.S.S.R, includes the most important group of deposits of Paleozoic age in the world. Most of the hydrothermally altered bodies have been formed in felsic and intermediate volcanic rocks including tuffs, tuff-breccias and tuff-agglomerate-breccias. Many ore deposits are associated with extensive high-alumina rocks, and there are also many additional zones of highly aluminous rocks without significant metallic ores in them. Evaluation of these zones in a large and generally remote region has been carried out to varying degrees and on only a relatively few deposits (Nakovinik, 1968, p. 74).

Nakovnik (1968, p. 85-86) suggested that the Kazakhstan deposits might be better understood by comparison with other areas, such as the well studied sulfur-iron sulfide, alunite, and diaspore-pyrophyllite deposits of Japan. The association of major porphyry copper deposits with andalusite-pyrophyllite-diaspore alteration zones, with both related to widespread felsic and intermediate volcanism, makes the geologic history of this region particularly important to interpreting the significance of the hydrothermal systems of the Carolina slate belt.

Preliminary identification of the locations of zones of alteration has progressed far ahead of detailed evaluation and, whereas at least

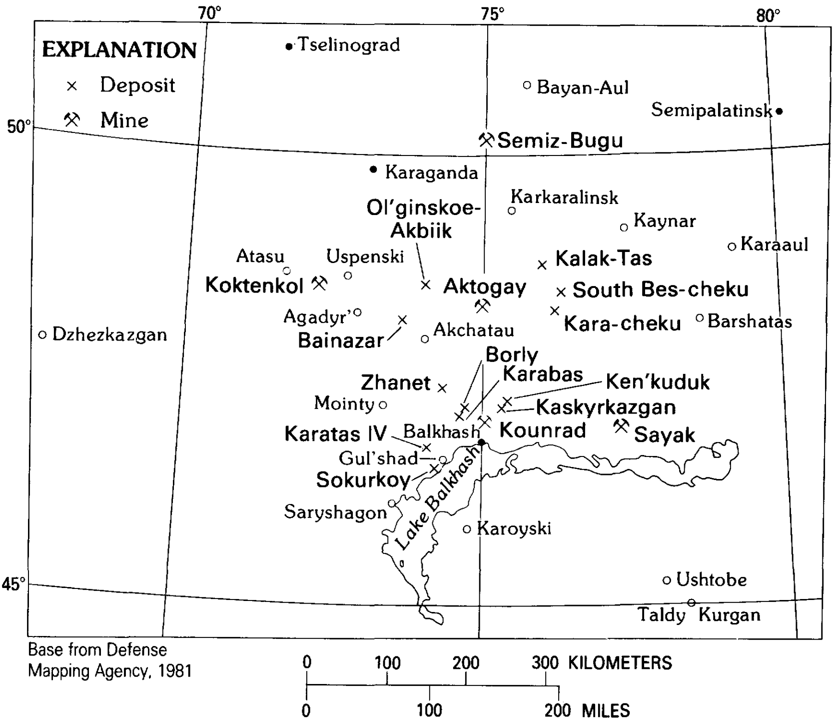


FIGURE 2. Porphyry copper deposits and other major hydrothermal alteration systems in central Kazakhstan, U.S.S.R.

235 alteration zones were known in 1959, only 43 bodies had been explored in even preliminary ways (Nakovnik, 1968, p. 74). As many as 2,000 siliceous alteration zones were attributed to the region by Shcherba in 1965, but this high number includes a large number of "aposedimentary" bodies that are not properly included with the hydrothermal alteration zones--the "secondary quartzites" of Soviet literature (Nakovnik, 1968, p. 74). It is not clear what these "aposedimentary" bodies are really like, which is most unfortunate because they might also have analogs among those pyrophyllite bodies of the Carolina slate belt that I interpret to be distal to or perhaps unrelated to porphyry systems.

I have been able to obtain limited geologic information for 18 copper, copper-molybdenum, and molybdenum porphyry deposits in central Kazakhstan. General locations for 12 of these, plus 5 alteration systems perhaps lacking significant metals are shown on figure 2. Geologic information is easier to obtain than information on exploitation and exact locations. Several of the deposits are being exploited including the Kounrad, Sayak, and Uspenski (this last may be the townsite and mill location for the Koktenkol' molybdenum-

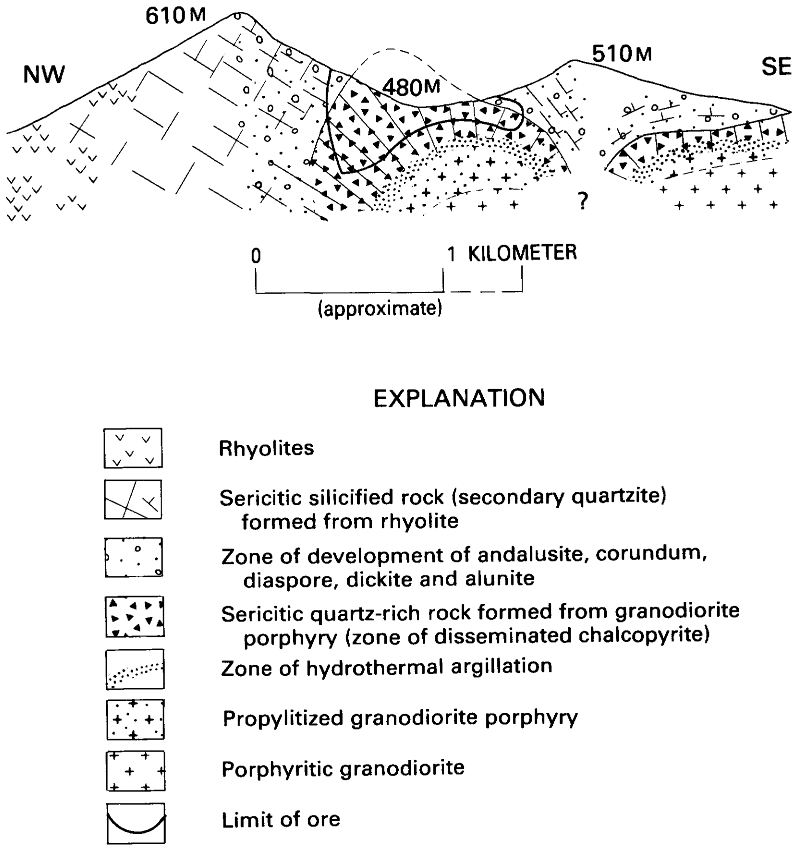


FIGURE 3. Schematic cross section of the North Kounrad alteration system and its copper orebody (after Nakovnik, 1958). Exaggerated vertical scale; no horizontal scale given on original.

bearing deposit); however, the status of most is unknown to me. Some are certainly too small or too low grade to be exploited but are metallogenically significant. It is hard to judge the completeness of descriptions of alteration minerals, but 6 of the 18 deposits are known to have high-alumina minerals, particularly andalusite, diaspore, pyrophyllite, corundum, dickite, alunite, and zunyite.

Kounrad deposit--The Kounrad (Kounradski) copper-molybdenum porphyry deposit is the best known Kazakhstan deposit and also one that contains substantial amounts of high-alumina minerals. Copper and molybdenum mineralization and some high-alumina alteration are located within the top of an intrusive granodiorite porphyry stock which seems to have been dated at 280 m.y. Mineralization is not limited to the intrusive; it extends a short distance into the adjacent hydrothermally altered rhyolites as well (fig. 3), but dies out rapidly away from the contact (Nakovnik, 1968, p. 164). Primary ore minerals are chalcopyrite, enargite, bornite, molybdenite, tennantite, tetrahedrite, and galena. Propylitic, quartz-sericitic, argillic, and high-alumina alteration zones have been described in relationship to the metallic mineralization (fig. 3). In the most-intensive high-alumina zone in the rhyolites close to the contact with the granodiorite porphyries, andalusite locally comprises 50 to 80 percent of the rock, plus lesser corundum, topaz, barite, and alunite (Magak'yan, 1961, p. 334) as well as dumortierite (Nakovnik, 1968). Mineral assemblages described include andalusite-quartz-sericite, andalusite-quartz, quartz-sericite-andalusite-cordundum, quartz-sericite-andalusite-alunite, and andalusite-corundum-diaspore, all of which can also include minor rutile and major pyrite (Nakovnik, 1968, p. 157-159). It seems curious to me that pyrophyllite is not mentioned in these assemblages. Explosion breccias are exposed at many places in the Kounrad mine (Smirnov, 1977, p. 124).

The exploitable copper orebody, 1,000 x 200 m on the exposed surface, is a thick blanket of secondary-enriched oxides and sulfides. The vertical zonation is well developed (Nakovnik, 1968, p. 164). The generalized thicknesses of the respective ore zones are as follows: oxidized zone, up to 60 m; mixed ores, up to 50 m; secondary sulfide enriched zone, up to 270 m, beneath which the primary sulfides extend to an undetermined depth as the deepest boreholes only reach 400 m. Leached cap rock is present in irregular pockets, some up to 30 m thick. Kaolinite, opal, limonite, malachite, and brochantite are the most widespread minerals in the oxidized zone. Jarosite, azurite, chalcanthite, cyanotrichite, chrysocolla, and copper-manganese pitch ore are of limited distribution.

This important copper-molybdenum (+gold?) deposit began production in 1940 and is still in operation. The total minable copper resource before mining began at the Kounrad deposit is reported to have been 10 million tons copper metal (Laznicka, 1976, p. B14).

Other porphyry copper deposits and prospects in Kazakhstan--Andalusite and dumortierite accompany the quartz and sericite of South Bes-cheku (Nakovnik, 1968, p. 75, 307), a porphyry copper deposit containing molybdenum. Kara-cheku, an alteration zone of about 5 km^2 containing copper and lead and the alteration minerals, quartz, andalusite, dickite, and sericite, is not of the porphyry type (Nakovnik, 1968, p. 84), although the size and mineralogy seem appropriate. Sokurkoy is a large porphyry copper-molybdenum deposit near Lake Balkhash, southwest of the Kounrad mine. Quartz, alunite, dickite, sercite, andalusite, and zunyite are present in an alteration zone of 6.5 km^2; there are four major breccia pipes within this zone (Nakovnik, 1968, p. 318; Puchkov and others, 1968, p. 68).

Karabas is another porphyry copper-molybdenum deposit about 28 km northwest of Kounrad; high-alumina parts of the altered rocks there contain the mineral suites quartz-diaspore, quartz-sericite-alunite, and zunyite (Puchkov and others, 1968, p. 68) formed by hydrothermal alteration of microgranite porphyry, granodiorite porphyry, granodiorite, and quartz diorite.

Names of other copper-molybdenum porphyry deposits in central Kazakhstan are Aktogay, Borly, Kaskyrkazgan, Ken'kuduk, Karatas IV, Kaindy-cheku, Sayak, Tologai (Tulagai), and Zheke-zhuvan. In addition, the Ol'ginskoe-Akbiik deposit is reported to be copper-bearing, and the Koktenkol' and Bainazar deposits are molybdenum-bearing porphyry deposits (Laznicka, 1976). Some of these deposits may have high-alumina alteration as well. Locations of only some of these are shown on figure 2.

Major high-alumina alteration zones--Of the 235 alteration zones in Kazakhstan tabulated by Nakovnik (1968), half were alunite bearing, and andalusite, dickite, diaspore, and corundum were present in 40 or more localities. Other minerals noted were dumortierite, barite, topaz, zunyite, tourmaline, lazulite, and augelite. Rather surprisingly, pyrophyllite was reported from a relatively small number of localities. The high-alumina minerals occur as nodules, pockets, pipes, veins, and lenses, the thickness of which is measured in tens of centimeters, less often in meters, and very rarely in tens of meters within the much more extensive highly siliceous "secondary quartzites," (Nakovnik, 1968, p. 83).

Nakovnik (1968) considered that gold, silver, lead, mercury, and zinc were potential resources of the unevaluated hydrothermal alteration zones. Gold is of particular interest to us because of its possible genetic relationship to the aluminous alteration zones of the Carolina slate belt. Sutulov (1973, p. 161) has reported that the porphyry copper deposits of Kazakhstan produce a significant amount of gold, but information regarding individual deposits is not given. In his tabulation of 235 alteration zones, Nakovnik (1968) shows the Tologoi (Tulagai) deposit to contain Cu, Mo, Au, and Pb, with molybdenum the most important, and the Kaindy-cheku deposit to contain Cu, Mo, Sr, and Au, with copper the most important. Major alteration minerals noted at the Tologai deposit are quartz, sericite, and muscovite, and at the Kaindy-cheku, quartz, andalusite, sericite, and muscovite. I cound not obtain locations for these deposits, and they are not shown on figure 2.

Four major high-alumina deposits with minor or no noted base metals, the Bol'shoy Semiz-Bugu, Malyy Semiz-Bugu, Zhanet, and Kalak-Tas, have also been described by Nakovnik (1968). All are associated with large zones of solfataric alteration in intermediate to felsic volcanic rocks. All have zones of silicification in the more highly altered parts, and all but the Malyy Semiz-Bugu deposits are probably enclosed in zones of sericitic alteration. Only the Zhanet deposit is discussed further here.

The Zhanet dumortierite-corundum-andalusite deposit is 75 km northwest of the Kounrad copper-molybdenum mine (fig. 2). High-alumina alteration zones have formed in Upper Devonian and Lower Carboniferous felsic volcanic rocks including ashy tuffs, lavas, and pyroclastics, all dipping southwest at a low angle (Nakovnik, 1968, p. 168). The volcanic pile has been intruded by a variety of shallow and subvolcanic granitic stocks and felsic volcanic plutons that breached the surface. An important dumortierite-corundum-andalusite deposit is present as a narrow belt trending northwest for 2 km parallel to the strike of individual flows. Though not specifically stated, the ore is presumably present as a lens or layer roughly parallel to the stratification of the silicified volcanic rocks. Thus the deposit is a possible analog to certain lenticular stratiform orebodies in the Southeastern United States, though Nakovnik (1968, p. 171) seemed to consider the Zhanet deposit to be exceptional for Kazakhstan.

The Zhanet altered rocks are mineralized mainly by sericite, andalusite, corundum, alunite, and dumortierite. Altered rocks locally consist of up to 70 percent hematite, which is present instead of the pyrite generally associated with deposits of this type. Diaspore, dickite(?), tourmaline, topaz, apatite, and perhaps some pyrite are also present. The corundum-rich zone is 50 to 60 m wide and 1 km long. Specific alteration zones above and below the ore may be present, but I could not work them out from the information available. Nakovnik (1968, p. 178) concluded that the alteration took place during intensive circulation of hot acid waters adjacent to a volcanic vent.

The examples of the Kazakhstan porphyry copper province are important in understanding the Carolina slate belt deposits. More than reminding us of the association of highly aluminous subvolcanic alteration with some exploitable hypogene copper and molybdenum deposits, these examples show that in this one region several copper and molybdenum porphyry deposits are intimately associated with just part of a much larger number of high-alumina alteration systems.

EXAMPLES IN SOUTH ASIA AND OCEANIA

North Sulawesi deposits--Widespread development of strong high-alumina alteration is a distinctive characteristic of the Tapadaa and Tombuililato copper-gold districts, North Sulawesi, Indonesia (Lowder and Dow, 1978), and andalusite, pyrophyllite, diaspore, and corundum are common in various mineral suites in the altered zones. At the Cabang Kiri prospect in the Tombuililato district, ore grade pyrite-bornite-chalcopyrite mineralization is associated with the assemblage quartz-diaspore-pyrophyllite; elsewhere in the same area high-alumina assemblages are not accompanied by ore-grade mineralization (Lowder and Dow, 1978, p. 638-639). It is important to note that the location of ore at the Cabang Kiri prospect is within the high-alumina alteration.

Vunda, Fiji, deposits--Sporadic gold mineralization in a 6 km^2 hydrothermal alteration zone at Vunda, Fiji, has been described by Lawrence (1978). Alteration takes several forms and neither meaningful zonation nor correlation of alteration type with alteration intensity and strength of mineralization has been found. Pyritic, potassic, quartz-sericitic (phyllic), argillic, and propylitic alteration have been described by Lawrence (1978, p. 25-27), but three gold-bearing alteration products are more important to this comparative study. These are quartz-sericite rock with traces of diaspore and gorceixite (a hydrous barium aluminum phosphate), quartz-sericite-kaolinite rock, and quartz-diaspore rock. Lawrence (1978) interprets the Vunda deposit to be a weakly mineralized porphyry gold system probably related to the nearby Kingston porphyry copper deposit. Because the Vunda deposit is associated with shoshonite, Lawrence regards it as analagous to those porphyry deposits of British Columbia associated with alkali rocks.

Tangse prospect, Sumatra, Indonesia--The Tangse copper-molybdenum prospect in Northern Sumatra is associated with a middle to late Miocene multiphase stock, consisting of various quartz diorite and dacite porphyries, that is intruded into a large composite middle-Eocene pluton of granitic to dioritic composition. As with the four porphyry occurrences in West Sumatra (Taylor and van Leeuwen, 1980, p. 106-107), the intrusions and mineralization at the Tangse prospect are closely associated with the major northwest-trending Sumatran fault system. The deposit has been described by Taylor and van Leeuwen (1980) and Force and others (1981) and the material presented here is mostly condensed from the latter source.

Hydrothermal alteration at Tangse is multistage and alteration types are telescoped. Early biotite alteration has affected almost all of the quartz diorite stock; late fracture controlled quartz-sericitic and high-alumina alteration characterized by andalusite have been superimposed on the early phase. The primary sulfide minerals pyrite, chalcopyrite, and molybdenite are present as disseminations and in veinlets. Chalcocite is generally present in a short interval directly below the oxidation zone. Lead and zinc are present as a well defined geochemical halo to the zone of copper and molybdenum mineralization. Gold is absent at Tangse, but substantial epithermal gold deposits are found along the fault zone further south in West Sumatra.

HYDROTHERMAL CLAY DEPOSITS OF JAPAN AND KOREA

High-alumina clays derived by hydrothermal alteration of volcanic rocks and some intrusive rocks are widespread in Japan and are also present in Korea. Deposits containing major pyrophyllite or andalusite, many of which are included in the type called Roseki clays, have features indicating that they formed close to the surface, yet have associated high-temperature minerals (Nakamura, 1954, p. 35, Iwao and Udagawa, 1969, p. 72, Kamitani, 1977, p. 50- 52). The largest hydrothermal clay deposits are in southwest Japan, where they are located in volcanic rocks of Cretaceous and early Tertiary age, but hydrothermal clays of Miocene through Quaternary age are also abundant, especially in central and northeast Japan (Iwao and Udagawa, 1969, p. 71-72). Hydrothermal kaolin deposits are still being formed in active geothermal areas (Fujii, 1976, p. 7.)

The high-alumina hydrothermal clays of Japan contain various combinations of the following minerals: alunite, andalusite, boehmite, chlorite, corundum, diaspore, dickite, dumortierite, halloysite, kaolinite, montmorillonite, pyrophyllite, sericite, sudoite (a dioctahedral aluminum-rich mineral of the chlorite group), topaz, and zunyite (Iwao and Udagawa, 1969, p. 76-78). In addition, quartz is a common constitutent and may be abundant. Gypsum, pyrite, hematite, and native sulfur may be present. Very few anomalous values of Cu, Mo, Bi, W, and Sn have been reported, though it may that few analyses were made for the trace metals in the clays.

The Ashio copper mine--The Ashio mine is located in Tochigi Prefecture, in central Japan north of Tokyo (36°38′N, 139°27′E). The mineralized zone is in an isolated mass of middle to upper Tertiary rhyolite that fills a funnel-shaped crater in Carboniferous and Permian sedimentary rocks (Nakamura, 1954, p. 36-38). Extensive hydrothermal alteration and polymetallic mineralization have taken place throughout much of this conical mass of rhyolite and to some extent in the surrounding Paleozoic rocks. The rhyolite funnel is elliptical in surface outline and 3.3 x 4.4 km (Kusanagi, 1955, p. 1).

Rhyolitic lavas and pyroclastic rocks of Miocene age (S. Iwao, 1980, written commun.) fill a conical depression and rise to form the peak Bizendate, 1,272 m above sea level. A breccia of diverse clasts lining the inner slopes of the crater is interpreted to be a talus; the crater filling is rhyolitic lava, volcanic breccia, and tuff, changing upward to tuff breccia, lapilli tuff, and welded tuff, interpreted to be the remnant of a stratovolcano, perhaps including a breccia pipe, (Kusanagi, 1955).

Silicification, sericitization, and chloritization are major products of hydrothermal alteration associated with the metal-bearing veins. Most of the early high-alumina alteration has taken place in the breccia pipe, and Imai and others (1975, p. 667) report the minerals pyrophyllite, topaz, diaspore, corundum, zunyite, and andalusite; however, most of the ores appear unrelated to the early stage of alteration (Kusanagi, 1955, Nakamura, 1961). Pyrophyllite and topaz are present locally in the altered rhyolitic rocks of the high grade tin and copper ores (Nakamura, 1961, p. 108); these ores are interpreted to have formed early. The possible relationships of metallic ores to high-alumina alteration had not been fully studied at the time of Nakamura's article.

Copper mineralization is present in an extensive stockwork of fissure veins that form a swarm about 2 km x 2 km in an area central in the crater, and extends downward 1 km. A few veins also extend outward into the surrounding Paleozoic rocks. Concentric mineral zones have been mapped by Nakamura (1954, fig. 1). A central Sn-W-Bi-Cu zone is present around the peak Bizendate; the grade of tin decreases abruptly downward. The intermediate zone contains Cu-As-Zn, and the marginal zone is Zn-Pb-Cu-As. Gold, silver, and selenium are also present in the deposit. Flourine and phosphorus are indicated by the minerals fluorite, apatite and vivianite (Fukuchi, 1926, p. 10), and topaz is also present (Imai and others, 1975, p. 667). Flourine, by inference, must have been an important component of some alteration stage, but no evidence of boron enrichment has been noted. The breccia pipe, site of high-alumina alteration, is not central to the metal zones (Nakamura, 1954, fig. 1), but is located in Nakamura's zone III of marginal Zn-Pb-As-Cu mineralization.

In addition to the vein swarm, massive replacement deposits and large disseminated orebodies also occur. Within the rhyolite these form crooked chimneys of sericitic and chloritic clay containing irregular masses of chalcopyrite (Fukuchi, 1926, p. 8-9). Bonanza deposits are also found as replacements in Paleozoic chert ("quartzite" of early authors) adjacent to the rhyolitic crater filling.

Some of the mineral zonation at the Ashio mine is interpreted to be reversed due to inward collapse of the hydrothermal system (Imai and others, 1975, p. 667).

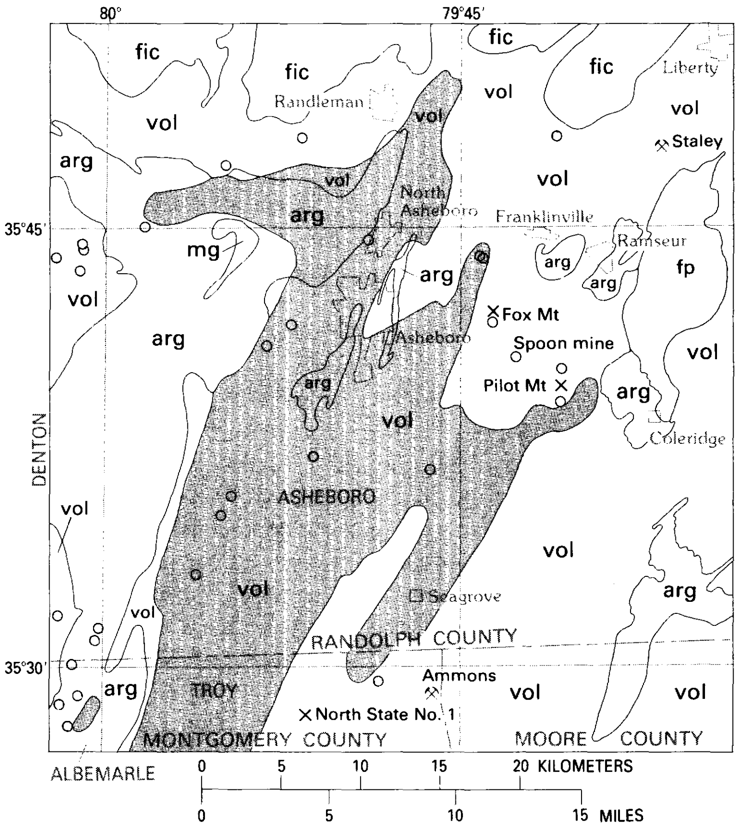
Guryong prospect, southeastern Korea--Several porphyry-type copper and molybdenum prospects have been recognized north and west of Pusan in southeastern Korea (Sillitoe, 1980). One among these, near the Guryong vein-copper mine, is associated with an aluminous hydrothermal alteration zone. At Guryong, the zone of hydrothermal alteration is developed mainly in Upper Cretaceous andesitic volcanic rocks near an adamellite pluton. The core of the alteration zone, about 2 x 1.2 km, contains pyrophyllite and lesser amounts of diaspore, unidentified white clays, chalcedony, and pyrite; silicification is locally dominant. Dumortierite was identified in one sample. Molybdenite, pyrite, and chalcopyrite are present in a stockwork of quartz veinlets that cut the aluminous altered rock beneath a thin leached capping. Pyrite and chalcopyrite are also present as exceptionally fine disseminations but disseminated molybdenite is rare. Sphalerite, galena, chalcopyrite, and pyrite were noted in a few late veinlets. At depth greater than 50 m, propylitic minerals and actinolite become more prevalent than aluminous minerals.

GENERAL GEOLOGY OF THE CAROLINA SLATE BELT

The main outcrop areas of rocks that are usually included in the Carolina slate belt extend 650 km (400 mi.) from central Georgia to southern Virginia in the Southeastern United States (fig. 1). Outlying localities and provisionally correlative areas can be included to make the belt even longer. The outcrop width is typically 40 to 80 km. More or less separated belts of similar rocks parallel the main slate belt to the northwest and southeast, such as the Belair belt on the Georgia-South Carolina border and the eastern slate belt in north-central North Carolina.

The slate belt in North Carolina has been mapped in detail in many local areas, and the rest has been completed on a reconnaissance scale. A recently completed map at approximately 1:125,000 covers six counties in north-central North Carolina, including the area around Asheboro (Carpenter, 1982). A preliminary geologic map at a scale of 1:250,000 has been released for the Charlotte 1°×2° quadrangle by Goldsmith and others (1982). Reconnaissance maps at a scale of 1:250,000 have been prepared for the Raleigh 1°×2° quadrangle by Wilson and others (1978) and for the Greensboro 1°×2° quadrangle by Jones and Ferguson (1978, pl. 1a). For some of the State, the general lithologic map by Conley and Bain (1965) is still the most widely available.

The volcanoclastic and epiclastic strata and a much lesser thickness of lava flows of the slate belt have been mapped in detail in the Denton, Albemarle, and Asheboro 15 min. quadrangles in central North Carolina, and in some adjacent areas (fig. 4). Stratigraphic and structural data have been recorded for this area (Conley, 1962; Seiders and Wright, 1977; Stromquist and Sundelius, 1969; Stromquist and others, 1971), although not all authors agree on major conclusions.



EXPLANATION

- Area of volcanic and argillaceous rocks in which hard, flint-like rhyolitic flow rocks and associated felsic volcaniclastic strata are present
- **arg** Fine-grained, thinly laminated argillite and mudstone; locally includes sandstone, conglomerate, and felsic volcanic rock
- **vol** Andesitic to rhyolitic volcanic and volcaniclastic rocks; largely lapilli tuffs, crystal tuffs, and volcanic arenites
- **fp** Felsic and intermediate plutonic rocks; probably includes intrusives of two or more ages
- **mg** Metagabbro
- **fic** Felsic intrusive complex; massive to foliated
- O Former gold mines and prospects
- ⚒ Former pyrophyllite mine
- × Pyrophyllite deposit

FIGURE 4. Generalized geologic map of the Asheboro area, central North Carolina. Geology modified from Carpenter (1982).

Part of the stratigraphic section here has been interpreted to be at least 25 km thick (Bell and others, 1980), and if this reconstruction is correct the total section could be even thicker, although there could also be undetected repetition. Black (1980, p. 271) has stressed that stratigraphic features can be expected to extend for only short distances in a volcanic arc environment of this type. Certainly little is known about the realiable extensions of facies and the distances over which reasonable stratigraphic correlations can be made. This is a major handicap in mineral resource studies as it is highly probable that several mineral commodities may be found here in environments that are essentially stratabound in distribution.

The volcanosedimentary, epiclastic, and volcanic rocks of the Carolina slate belt are now generally believed to have originated in late Precambrian to Middle Cambrian continental margins or island volcanic arcs (Butler and Ragland, 1969; Glover 1973; and many other authors). Black (1980) calculated titanium-zirconium ratios in the manner of Kean and Strong (1975) and showed that the compositions of some of these rocks indeed best fit a model for volcanic arc areas, and that using several compositional criteria together, the rocks he studied definitely comprise a continental margin suite developed where the crust ranged upwards in thickness from 20 km. In contrast, Whitney and others (1978) concluded that the portion of the Carolina slate belt in the Lincolnton, Georgia-McCormick, South Carolina, area formed in a primative island arc where no thick continental crust is present, and may represent the earliest stage of island arc development found in the slate belt. They consider the formations in the upper part of the stratigraphic section in the Albemarle area, central North Carolina, to represent a later more calc-alkaline stage in arc development. With the limited geologic information now available, the position and dip direction of subduction zones associated with the original arc or arcs is highly problematic, but much discussed (Glover, 1976; Spence and Carpenter, 1976; Black and Fullargar, 1976; and several others).

Many persons now recognize that earlier interpretations of Carolina slate belt structure and stratigraphy have been too simplistic (Secor and others, 1983). It is generally known that different segments of the belt are characterized by widely divergent ages, structural styles, and metamorphic grades. The possibility that the belt is a complex assemblage of accreted terranes will certainly be considered in the near future, but truly reliable tests of interpretations of this sort are seriously limited by the dearth of detailed geologic mapping now available.

Ages of 705 ± 15 m.y. and 620 m.y. have been determined for rocks of the Carolina slate belt from Chapel Hill and Roxboro, N.C., respectively (Black, 1980). Rocks from the Albemarle area about 60 km southwest of Asheboro have yielded ages in the 530 to 560 m.y. range (Black, 1980), and trilobites collected from relatively high in the stratigraphic section in the same general have been assigned an Early to Middle Cambrian age (St. Jean, 1973). Middle Cambrian trilobites from metamudstone in the Richtex Formation in the upper part of the slate belt section near Batesburg, S.C., 250 km southwest of Asheboro (Samson and others, 1982; Secor and others, 1983) have been described.

Both radiometric and paleontologic ages in the Albemarle area relate to rock strata that are structurally high in the stratigraphic section; rocks that may be many kilometers lower in the section in this area are undated. Black (1979) concluded that slate belt rocks southwestward from Albemarle as far as the Georgia-South Carolina border are of the younger ages.

Plutons have invaded the slate belt at many places; their ages have been shown to fall into two age brackets: 595 to 520 m.y. and about 300 m.y. (Fullagar and others 1973; Fullagar and Butler, 1979; and Speer and others, 1980). Thus, the older intrusions overlapped in time the deposition of many of the volcanic strata, and the possibility of a genetic relationship exists.

Carolina slate belt strata range from gently folded and little deformed to very tightly folded and intensely sheared. In less well mapped areas, few top directions are know, but in many places the folding style can be surmised from the traces of resistant fold limbs that form hogback ridges many kilometers long. Abundant transverse faults and fractures are clearly expressed in drainage patterns. Regional metamorphism pervades the entire belt, the facies is mostly lower or middle greenschist. The gradation northwestward to gneisses of the Charlotte belt is essentially a metamorphic facies boundary (Secor and others, 1983). The time of deformation is bracketed by the ages of prekinematic plutons, about 560 m.y., and postkinematic plutons, about 400 and 300 m.y. (Kish and others, 1979), the main tectonic event having been "Taconic" (Kish and Fullagar, 1978). This places no limit on the number of orogenic events within the time bracketed by these dates, however. As the absolute ages of slate belt rocks range from about 740 m.y. (Glover, 1973) to 500 m.y. (Butler, 1979), it seems most unlikely that the slate belt strata were deposited in an unbroken continuum, and little is known about unconformities within the sequence, although one has been proposed in the Ramseur area (Harris, 1982).

A volcanic belt, either at a continental margin or an island arc, is a highly favorable environment for the development of large vigorous hydrothermal systems and the formation of metal deposits of the porphyry-copper and porphyry-gold types. On the basis of volcanic and volcaniclastic rock suites, it should be possible to classify most areas in the Carolina slate belt as having formed near, at an intermediate distance, or far from volcanic sources. Assuming that porphyry alteration and mineralization systems form close to areas of eruption, the slate belt areas with coarse pyroclastic rocks and felsic flows should have formed closest to volcanic centers and, I think, be the most favorable prospecting areas.

DESCRIPTIONS OF SELECTED HIGH-ALUMINA DEPOSITS IN THE CAROLINA SLATE BELT

Three deposits have been selected for further description because more geologic information regarding them is presently available. The Brewer mine in Chesterfield County, northeastern South Carolina, is presently inactive, has a long though intermittent history as a gold mine, and has many features of a porphyry-type deposit (fig. 1). The Pilot Mountain deposit in Randolph County, N.C., has been explored by Piedmont Minerals Co., Inc., as a potential pyrophyllite-andalusite-sericite resource and has several substantial gold prospects or small abandoned mines at its margins (fig. 4). The mines operated by the Glendon Pyrophyllite Company in Moore County, N.C., are significant producers of pyrophyllite and other aluminous mineral products. They lack the widespread silification so strongly developed at the Brewer and Pilot Mountain deposits, which may indicate a different formative process.

Each of these deposits is interpreted to be the site of major hydrothermal alteration of intermediate to felsic volcanic rocks. Each has significant amounts of iron sulfide associated with the altered rock and there are also various amounts of associated Cu, Mo, Sn, Au, and other metals. However, there is much difference in the total extent of alteration outside the orebodies and of general alteration style. The Brewer and Pilot Mountain alteration systems are mostly crosscutting in relationship to rock strata and structures while other deposits such as Hillsborough, and perhaps much of the Bowlings Mountain-Jones-White deposit group may be generally stratiform; all of the deposits in Moore County seem generally stratiform, though cross- cutting features are present. These differences suggest that we may be dealing with very different types of hydrothermal systems, each yielding large bodies of high-alumina rock, but necessitating different interpretations for mineral exploration.

Most of the high-alumina deposits of both types are present along two northeast-trending belts (fig. 1). The major belt extends for 170 km from near Troy in Montgomery County, N.C., to near Oxford in

Granville County, N.C. The Brewer mine near Jefferson in Chesterfield County, S.C., may belong in this belt as well, but is separated by a gap of 100 km. Other widely scattered monadnocks of high-alumina rocks in the slate belt include Little Mountain and Boles Mountain, farther southwest in South Carolina, and Graves Mountain, in Georgia (Espenshade and Potter, 1968). Several important pyrophyllite deposits are located in a lesser 20 km belt in Moore County, N.C., that trends a little more northeasterly than the major belt. The trend in Moore County seems to be approximately parallel to the strike of sedimentary layering but, lacking reliable stratigraphic markers, it is hard to know how stratabound the deposits actually are. It is very important to understand the structural or stratigraphic control that has caused these deposits to form mostly in narrow belts, but explanations are limited to speculations thus far.

It is possible that the high-alumina deposits in both belts are subjected to certain lithologic controls. They seem to occur only in coarser pyroclastic materials such as lapilli tuffs and crystal tuffs or, as in Moore County, in pebbley volcaniclastic rocks and overlying fine sandstone and argillite. Near Asheboro, the deposits seem to be limited to areas of strongly deformed andesitic volcanic rocks. Elsewhere the stratigraphic section is less well known, but volcanic rocks of intermediate composition close to the Snow Camp and Glendon deposits are rather similar to rocks near Pilot Mountain. Volcanic and volcanosedimentary rocks north of Pilot Mountain were recently described by Harris (1982).

Hydrothermal alteration at the Pilot Mountain deposit is believed to be related to a dacite porphyry stock and its dikelike apophyses. Subvolcanic dikes seem to have produced minor alteration effects in adjacent volcanic rocks at the Brewer mine but no specific source for major hydrothermal alteration effects has been identified there. The degree of hydrothermal alteration measured in terms of profound compositional change and near destruction of original volcanic textural features throughout surface areas measured in square kilometers at Pilot Mountain, the Brewer mine area, and several other deposits exceed that generally seen in porphyry copper systems.

THE BREWER PORPHYRY GOLD DEPOSIT

The alteration zone at this deposit is very large and has a polymetallic suite associated with it that seems characteristic of high-flourine subvolcanic alteration at several known deposits in other regions. The mine produced gold intermittently from about 1828 until 1939 or 1940; further evaluation of the deposit has been resumed (1980-84). Part of the following description has been modified from Schmidt (1978, p. E-24--E-25).

The Brewer deposit is located near Jefferson in Chesterfield County, S.C. Gold mining was done first by placer in coastal plain sediments and saprolitic material, and later by openpit and underground methods in unweathered bedrock. The mining has been described by Leiber (1858, p. 63-68), Nitze and Wilkens (1896, p. 762-767), and McCauley and Butler (1966, p. 36-40).

The identification of topaz in the mine led to a drilling program by the U.S. Bureau of Mines in 1951-52 to determine the extent of the topaz reserve and the possibility of the use of the topaz for the production of calcium flouride with mullite as a coproduct. The results of this exploration program were described by Peyton and Lynch (1953). The cores of the 10 holes drilled on this program, retained by the U.S. Bureau of Mines, are the best source of information on the nature and extent of the rock alteration northwest of the old mine workings. The locations of part of the holes are shown in figure 5.

General geology--The Brewer mine area is in felsic volcanic rocks of the Carolina slate belt close to and partly under the thin edge of the overlapping Coastal Plain strata. Minard (1971) and Nystrom (1972) divided the slate belt rocks present here into two units, one of volcaniclastic rocks, mainly felsic tuffs and flows but also some interbedded mafic units, and the second of gray and greenish gray thinly bedded argillite and slate.

Geology of the Brewer alteration system--In the area close to the mine (fig. 5), the rocks that have been mapped by Minard (1971) as the volcaniclastic unit and by Nystrom (1972) as the felsic volcanic unit also include laminated argillite, as at point B-7 in the Tanyard Pit, as well as quartz-sercite schist and phyllite, sericitic argillite, porphyritic sulfide-bearing flow, various fragmental pyroclastic rocks, hard greenish-gray hornfelses, and three or more different kinds of probably hypabyssal porphyries. Country rock within the Brewer mine was described by Kinkel (written commun., 1968) as strongly silicified rhyolite, part of which is tectonic breccia, part pyroclastic breccia, and part tuff. Very recent work by Cherrywell and Butler (1984) provides additional data on the nature of this system.

Over a large area near the old mines, including the areas explored by the U.S. Bureau of Mines core drilling, the rock has been so vigorously altered by hydrothermal action that in much of it the original rock textures have been destroyed. Although volcanic textures and bedding were noted in the mine, primary textures were widely destroyed there as well. Kinkel (written commun., 1968) described a variety of breccias in the dark gray chertlike rocks in the walls of the mine, and breccias were common in three drill holes. Some of these had pyrite as the major cementing mineral. Some of the breccias may have been related to hydrothermal explosion events but data are now too scant to show this with certainty. The relative abundance of breccias in altered quartz rock was noted by Pardee and Park (1948, p. 107). Hypabyssal intrusive rocks have been recognized within the zone of strong hydrothermal alteration in the Tanyard pit, where a small dike of porphyritic rock penetrates laminated argillite in a thoroughly saprolitized exposure (point B-7, fig. 5). A zone of hematite-stained argillite saprolite about 5 m thick rims the porphyry intrusive, which is several meters thick. Xenoliths are common in the porphyry. The hematitic zone is interpreted to have been sulfide-bearing before weathering.

Scattered outcrops and float boulders along highway 110 about 1.5 km west of the Brewer pit (fig. 5) include several porphyritic rocks that I believe to be other hypabyssal intrusive rocks (points B-13, B-14 and B-16, fig. 5). Secondary hornblende has formed in argillaceous rocks at points B-16 through B-18, presumably by contact effects of the Pageland pluton about 0.5 km to the north. A dark gray porphyritic trachyte at point B-16 has been affected by this contact metamorphism, indicating that at least some of the hypabyssal rocks are older than the Pageland pluton.

Two zones of hydrothermal alteration were first mapped by Nystrom (1972), an inner zone of quartz granofels, which he called "massive quartzite", and a surrounding zone of siliceous sericite-pyrite schist that grades outward to unaltered laminated argillite and felsic volcanics (fig. 5).

The quartz granofels is a fine-grained, dense, and compact quartz rock, very light to dark gray and bluish gray. The color is at least partly controlled by small amounts of included sericite or pyrophyllite, and disseminated pyrite, and local significant admixtures of topaz. Traces of relict breccia textures are widespread in the granofels; some rock preserves sedimentary or volcanic textures, but much of the rock retains the forms of neither clasts nor beds. Nystrom (1972, p. 16) emphasized the massiveness of this rock, "without bedding, cleavage, foliation, or any other planar or linear feature." Fresh rock contains from minor traces to over 15 volume percent sulfide, mainly pyrite. In the zone of oxidation this has been altered to iron oxide yielding a reddish or brown- stained quartz rock, or, where sulfide was most abundant, a gossan.

In the quartz granofels adjoining the mined areas radial clusters of pyrophyllite as much as 5 cm across are common, and smaller grains of pyrophyllite and kyanite are present in the gold ore (Kinkel, written commun., 1968). Pyrophyllite, andalusite, and lesser kyanite were common minerals in the tunnel draining the Brewer pit, in a drift extending northward from that pit, and also in the U.S. Bureau of Mines drill cores. Some of the highly altered rock is more than 95

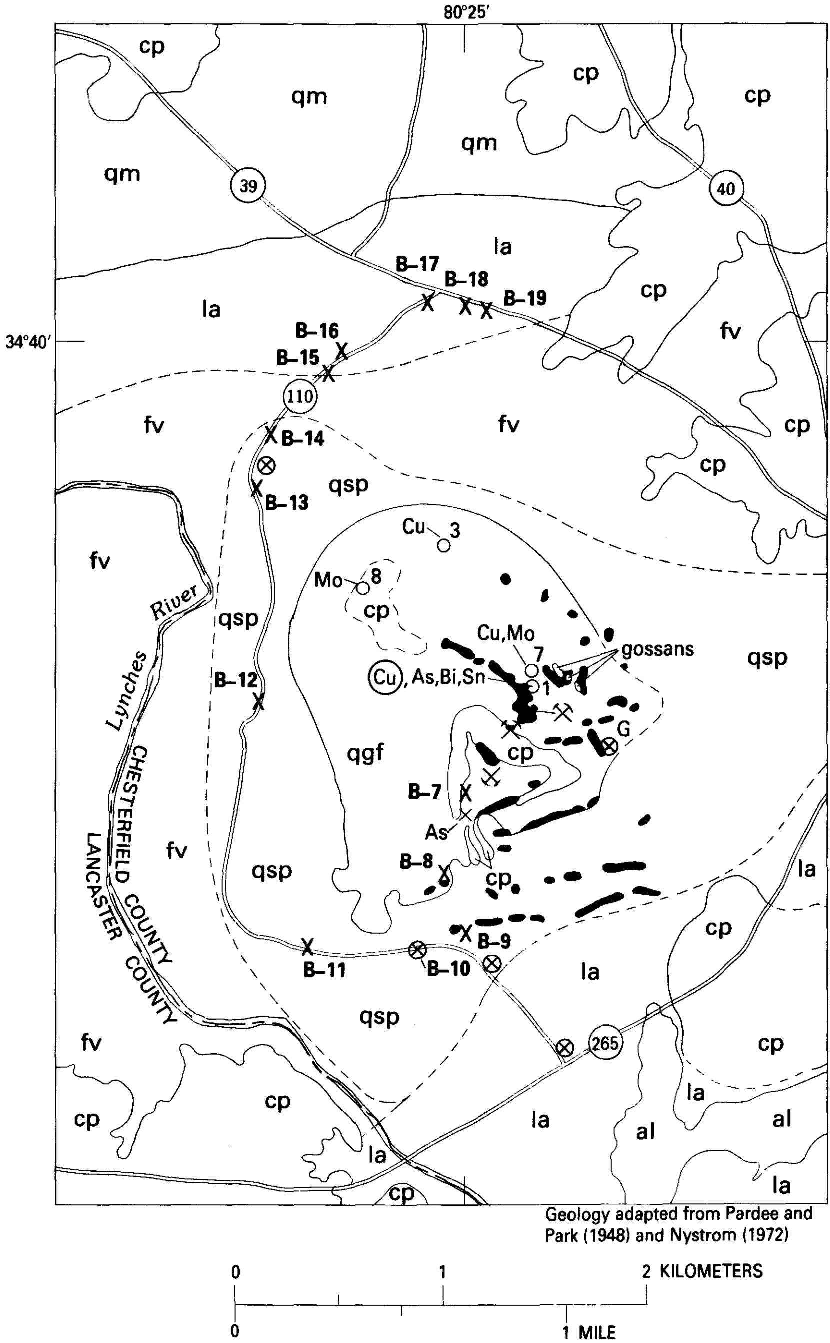


FIGURE 5. Hydrothermal alteration at the Brewer mine, Chesterfield County, S.C.

EXPLANATION[1]

al	Alluvium—Includes sand, gravel, silt, clay, and mine tailings
cp	Coastal plain sediments
la	Laminated argillite and slate—Fine-grained, greenish- and brownish-gray, probably tuffaceous
fv	Felsic volcanic rocks—Includes rhyolitic tuff, rhyolite porphyry, lapillite, hornblende plagioclase schist, and muscovite schist
qm	Quartz monzonite—Coarse-grained, pink and gray, porphyritic. Intrusive into rocks of Carolina slate belt
qgf	Quartz granofels—Intensely silicified rock, quartz content commonly exceeds 80 percent; includes locally abundant andalusite, pyrophyllite and topaz. Areas of outcrop shown shaded
qsp	Quartz-sericite-pyrite schist—Light-toned to white schist and phyllite, weathers white with patches of iron-oxide stain. Includes layers of quartz granofels south of the Brewer mine, shown shaded
——---	Contact—Dashed where gradational or inferred
o3	U.S. Bureau of Mines cored drill hole
X B-9	Field sample site and number
⊗	Copper 100 ppm or more in soil sample
⊗G	Copper 100 ppm or more in gossan sample
As—×	Arsenic 300 ppm in saprolite sample
7 o Cu / Mo	Copper 100 ppm or more in drill core Molybdenum 300 ppm or more in drill core
8 o (Cu) / Sn	Copper 10,000 ppm in drill core Tin 150 ppm or more in drill core
1 o As / Bi	Arsenic 3000 ppm in drill core Bismuth 500 ppm or more in drill core
⚒	Hard rock gold mine, abandoned
⚔	Placer gold mine, abandoned

[1]Analyses from A. R. Kinkle, Jr. (written communication, 1967) and from samples of drill core collected by Henry Bell, III, 1973.

FIGURE 5. Continued

percent quartz and some contains as much as 80 percent andalusite. Rocks are commonly made up of only two or three hydrothermal alteration minerals; the assemblages most frequently noted are quartz-pyrophyllite, quartz-muscovite, andalusite-quartz-pyrophyllite, pyrophyllite-diaspore-kaolinite, and quartz-topaz. Pyrophyllite is commonly found forming a sheath around andalusite grains and isolating them from quartz. Rutile is a widespread trace mineral in the altered rock. There were minor amounts of several other minerals that I was not able to identify in a thin section.

Topaz was identified in the altered volcanic rocks of the Brewer mine by Pardee and others (1937). These authors found the topaz to contain only 13.23 percent flourine and to have a correspondingly low specific gravity of 3.509. As in many other Carolina deposits, the topaz-rich material here is difficult to distinguish from dense siliceous quartz granofels rocks unless the high specific gravity is noted. The material was generally called flinty quartz or blue hornstone in the reports of pre-1937 examinations, and the high area around the mine was called Blue Flint Hill (Leiber, 1858, p. 65). The topaz occurs as disseminated fine grains, as patches and streaks of aggregates, and as masses of microcrystalline grains. All these are made up of rounded individual grains only a few microns in diameter. Pardee and others (1937, p. 1062) reported that only a few grains had an euhedral form. I observed only rounded shapes. The composition of one sample of topaz-rich rock is given in table 2.

A shell or band of siliceous sericite-pyrite schist completely surrounds the quartz granofels; Nystrom (1972) mapped this as a unit and called it sericite phyllite. Mostly moderately to strongly foliated, some phases of the schist retain faint to well-preserved textures of fine volcaniclastic sediments, tuffs, and coarse fragmental material. Traces to several percent of disseminated fine pyrite grains or small voids marking the former locations of sulfide grains are present in all of this rock. The extent to which siliceous sericite-pyrite schist may be present in the inner quartz granofels zone between outcrops of the weathering-resistant quartz-rich rocks is not clear, but none was penetrated by any of the U.S. Bureau of Mines drill holes.

Primary gold ore, all within the area mapped as quartz granofels, consists of silicified topaz-pyrite altered rhyolite, in which local areas several centimeters across consist entirely of fine-grained granular pyrite (A. R. Kinkel, Jr., 1968, written commun.). Kinkel further stated in regard to mineralization in the Brewer pit and adjacent workings, "All of the pit walls were equally mineralized and to about the same degree as the few exposures in the bottom of the pits. Mining has certainly not reached the limits of the deposit in any of the pits, and there may be a considerable amount of unmined ore horizontally

TABLE 2.—*Rapid rock analysis of topaz-rich hydrothermally altered rock from drill hole 8, 13.4 to 19.5 meters depth, Brewer mine area, South Carolina.*

[Lab no., W-180860; field no., B-8-44-64. Hole was drilled by U.S. Bureau of Mines, and the sample for analysis was kindly furnished by them. Analytical methods used are supplemented by atomic absorption; P. L. D. Elmore, analyst. Cu, Bi, Mo, and W were obtained by activation analysis; P. Aruscavage, E. Lillie, and L. Mei, analysts].

Constituent	Percent or parts per million
SiO_2	76.0
Al_2O_4	16.0
Fe_2O_3	.43
FeO	.08
MgO	.02
CaO	.32
Na_2O	.09
K_2O	.52
H_2O^+	1.2
H_2O^-	.00
TiO_2	.45
P_2O_5	.09
MnO	.02
CO_2	<.05
F	4.0
Cu	63 ppm
Bi	.41 ppm
Mo	23 ppm
W	4.2 ppm

as well as in depth." He found gold in flakes several millimeters across, both in the granular pyrite and on joints. Kinkel was impressed with the copper content of considerable areas in the pits (table 3); enargite was the principal copper mineral he observed.

Much of the gold mined at the Brewer during early years of operation came from the placer working of overlying gravelly sediments of Cretaceous age and from supergene enriched deposits in saprolite (Nitze and Wilkins, 1896, p. 764).

A diverse suite of metallic elements that tends to occur together at other subvolcanic hydrothermal ore deposits worldwide is found in the Brewer mine area. The presence of the metal suite Cu, Mo, Bi, W, Sn, As, and Au has been confirmed by recent chemical analyses, and the presence of Ag indicated (tables 3, 4). Minerals containing these metals were reported by various authors, mostly before 1895; these include chalcopyrite and enargite, (Lieber, 1856) covellite (Becker, 1895, p. 295), and bismuth ochre (bismite) and native bismuth (Tuomey, 1848, p. 97). Cassiterite has been identified only in black sands associated with placer mining at the Brewer mine, but it was present "in some quantity" and crystals as large as 1 cm. (one-half

TABLE 3.—*Analyses of hard rock with fresh pyrite from the Brewer mine area, South Carolina.*

[Traces of tin and bismuth were detected in a few samples. From A. R. Kinkle, Jr. (written commun., 1968). All values in parts per million].

	Field no.	Lab no.	Au	Cu	As
Brewer pit	SC JM 261	ABV 667	12.0	400	
Brewer pit	K 289	ABP 310	4.5	800	700
Topaz pit	K 356	ABX 023	3.9	20	20
Topaz pit	K 1458	ABX 972	0.56	500	200
Hartman pit	K 358	ABX 025	.64	< 10	20
Hartman pit	K 359	ABX 026	1.9	< 10	< 10
Hartman pit	K 361	ABX 028	.22	< 10	< 10

inch) were collected (Clark and Chatard, 1884, p. 25). In addition, chalcanthite and rutile were listed by Peyton and Lynch (1953, p. 3).

Sulfides make up an estimated 1 to 5 volume percent of all rock in the cores from 9 of the 10 U.S. Bureau of Mines drill holes. In two cores taken near the old Brewer pit, average sulfide content was close to 5 volume percent. In one hole (No. 1) the estimated sulfide content over an interval of 33.2 m was 15 volume percent.

Potassium-argon ages of muscovite-pyrophyllite rock at the Brewer pit were determined to be 430 ± 15 m.y. and 401 ± 14 m.y. (Bell and others, 1972).

GENERAL GEOLOGY OF THE PILOT MOUNTAIN-FOX MOUNTAIN REGION (RAMSEUR 7½' QUADRANGLE)

The area of figure 4 surrounding Pilot Mountain and Fox Mountain is underlain by a complex thick sequence of andesitic to felsic lapilli tuffs, interpreted to be a relatively older and more deformed part of the slate belt. I have not assigned these rocks to any formational unit, but a thesis by Harris (1982) proposes correlations with the Hyco and Aaron Formations of the Roxboro-Durham, N. C., area. West of Pilot Mountain, the strata of the Asheboro area have been divided into the Tillery Formation, largely thinly laminated siltstone and claystone, and the underlying Uwharrie Formation, chiefly felsic volcaniclastic rocks (Conley and Bain, 1965). Several small bodies of mafic-rich plutonic and porphyritic rocks (not shown on figure 4) crop out north and south of Pilot Mountain, and a felsic intrusive complex, the Parks Crossroads granodiorite of Tingle (1982), is present southeast and east of Ramseur.

This larger area of plutonic rock southeast and east of Ramseur consists of several phases of two rock types, a mafic-rich foliated

TABLE 4.—*Semiquantitative spectrographic analyses of selected chip samples from U.S. Bureau of Mines drill holes, Brewer mine area, South Carolina*

[N=not detected at limit of detection; L=detected, but below limit of determination; G=greater than 1 percent. All values except TiO_2 in parts per million. In addition to values shown in table, all samples were analyzed for the following elements: Fe, all samples, 2-20 percent; B, Mg, all samples, detected but below limit of determinations; Au, Cd, Zn, all samples, not detected at limit of detection; W, all samples "N" except hole 9, 24.4 meters, which is 70 ppm. Samples selected and analyses requested by Henry Bell; analyses by G. W. Day, U.S. Geological Survey, November 6, 1973]

Hole No.	Depth (meters)	Ti (percent)		Mn		Ag		As		Ba		Bi		Co		Cr		Cu		La		Mo	
1	32.0		1		10		1		700		20		30	N		N			50	N			50
1	36.3		.7		15	N			200		100		500	N		N			700		20		50
1	58.2		.5	L			.5		3,000		50		200		30	N			10,000		50		30
1	78.9		.3		10		2	N			50		100		30		10		700		20		30
7	45.1		.7	L			10	N			300		500		5		10		200		200		70
9	24.4	G		L		N		N			70	N			10		15		150	N			700
Limit of Detection			.002				.5		200		20		10		5		10		5		20		5

Hole No.	Depth (meters)	Nb		Ni		Pb		Sb		Sc		Sn		Sr		V		Y		Zr	
1	32.0	L			5	L			100		15		200	N			20		10		500
1	36.3	N		L			30	N			15		30		1,000		50		10		300
1	58.2	N			20		100		200		10		150		100		30		10		300
1	78.9	N			30		15	N			7		15	N			15	N			200
7	45.1	N		L			500	N			15		150		1,000		30		15		500
9	24.4		30		5		30	N			30		70	N			150		30		1,000
Limit of Detection			20		5		10		100		5		10		100		10		10		10

quartz-diorite and a potassic mafic-poor granitic porphyry. The relationship between the two has not been determined.

The quartz-diorite contains 10 to 25 percent quartz, 50 to 65 percent plagioclase, a trace of potassic feldspar and 10 to 40 percent mafic minerals. The latter are mixtures of relict shreds of chlorite, biotite, epidote, and amphibole; the texture suggests that foliated amphibole was the principal mineral at an earlier stage in the metamorphic history of the rock, and that biotite, epidote, and chlorite are products of the last greenschist-facies event. Thus the quartz-diorite may have undergone an earlier and higher grade period of metamorphism than other rocks of the area, including slate belt volcanic rocks from outcrops only a few meters distant. No certain aureole effects have been observed in slate belt rocks adjacent to this plutonic phase. The quartz diorite phase of this rock has been radiometrically dated by the Rb/Sr method as 566 ± 46 m.y. (Tingle, 1982).

Quartz monzonitic and quartz dioritic rocks unmapped north of Pilot Mountain and others shown on figure 6 south of Pilot Mountain appear to be various phases of this same general type of plutonic rock.

The second plutonic rock type, a fine-grained granitic porphyry, is found in an area of unknown size east of Ramseur. The rock is light gray with a salt and pepper appearance; matrix grains are up to 0.5 mm in greatest dimension, and relatively sparse plagioclase phenocrysts are about 5 mm long. The rock is quartz-rich, containing 50 percent of that mineral, 35 percent potassic feldspar, and 15 percent plagioclase. Sparse biotite was the predominant or only mafic mineral prior to metamorphism; its positions are now occupied by chlorite and epidote. Epidote is common as a metamorphic alteration product in many plagioclase grains. There are traces of fluorite present. Two-phase and gas-filled inclusions are common to abundant in quartz grains; cubic crystals presumed to be halite are present in a few inclusions. Minerals and textures in this rock do not seem to indicate more than one period of metamorphism, and it is tentatively interpreted to be younger than the nearby quartz diorite. It is not known if this granitic porphyry is unconformably overlain by the volcanic strata or if it is intrusive into them. I have not yet found places where a contact between the two plutonic rocks or between a plutonic rock and fresh slate belt rocks is exposed.

The unnamed largely andesitic rocks near Ramseur, Pilot Mountain, and Fox Mountain consist of lapilli tuff, tuff breccia, and crystal tuff, with lesser flow rocks and locally extensive volcaniclastic materials. Their abundant chlorite and epidote suggest a more generally andesitic composition. The andesitic rocks also seem somewhat more deformed, but this may be a result of their greater mafic mineral content. Exposures of dominantly andesitic volcanic rock alternate with intervals of dacitic to rhyolitic volcanics in abundant outcrops in the bed of Deep River and along the abandoned railroad grade that runs close to the river from Cedar Falls to Ramseur. Many good outcrops, mostly andesitic, are also present in the bed of Richland Creek, and to a lesser extent along the smaller streams. Studies of bedrock at about 50 sites in the Ramseur quadrangle have suggested no simple subdivisions according to composition or texture, except that sandstone and mudstone seem to be more abundant close to the contact with the pluton east of Ramseur. The rocks between Cedar Falls and Ramseur have been divided into two major units and correlated with the Hyco and Aaron Formations of the Roxboro-Durham area by Harris (1982).

Within the town of Ramseur, water-laid volcaniclastic arenite beds are common, though they are locally present farther west as well. These arenites and some silty argillites may comprise a stratigraphic thickness of several hundred meters in the easternmost 1,000 m of the formation. Close to the contact of the volcanic sequence with plutonic rocks, porphyritic rocks that I interpret to be dacite or latite flows are common. If the andesitic strata were deposited unconformably on the plutonic rocks, these flows and arenite beds may form the lowermost strata in the andesitic sequence.

The Uwharrie Formation in the Asheboro 15-min. quadrangle was mapped and described by Seiders (1981) as consisting of felsic volcaniclastic rock and lava and subordinate mafic volcanic rock. The predominant rock is thin to thick bedded light to dark gray and part pale green lapilli tuff, tuff, and tuff breccia; clasts in these volcanic rocks are very rarely as long as a meter; generally they do not exceed 2 cm and are angular to subrounded, or sometimes well rounded. Some clasts with poorly preserved lenticular textures may have been collapsed pumice. Local light to dark gray felsites are flow-layered and (or) spherulitic. Parts of the felsites have abundant phenocrysts of albite and quartz. Many felsite layers are closely associated with felsic arenite and volcaniclastic conglomerate. Strata of the Uwharrie Formation are considered to be of Cambrian and (or) Proterozoic Z age (Seiders, 1981).

The volcanic rock strata are folded along northeast trending axes and near-vertical dips with strikes about N50° E characterize the bedding near Ramseur. The felsic volcanic bodies included within slate belt rocks west and south of Asheboro trend about N25° E. Many of these have shapes that suggest folds plunging both northeast and southwest, and fold axes plunging each of these directions have been identified in the field.

Only one period of regional metamorphism can be distinguished for most slate belt rocks, but some of the quartz monzonite and quartz diorite southeast of Ramseur (fig. 4) may have been subjected to at least two periods of regional metamorphism, the first to amphibolite facies and the last to midgreenschist facies. Rocks of the andesitic volcanic sequence seem generally uniformly metamorphosed to the midgreenschist facies, with abundant chlorite and epidote. Penetrative deformation ranges from very strongly developed to moderate, but it is not certain whether this indicates different deformational histories or is a function of rock composition. Rocks mapped as Uwharrie Formation are also modified by metamorphism to the midgreenschist facies, with sparse fresh metamorphic biotite in the felsic volcanics and abundant biotite, epidote, and actinolite in nearby mafic strata. Pentrative deformation in the Uwharrie may be mostly moderately developed; some related porphyritic rocks with barely detectable foliation remain a puzzle.

PILOT MOUNTAIN PORPHYRY GOLD SYSTEM

Pilot Mountain is a prominent isolated monadnock 279 m above sea level, located 13 km southeast of Asheboro, N.C., in Randolph County (fig. 4). All of the monadnock is made up of hydrothermally altered rock and there are at least four groups of long-abandoned gold mines and prospects on the flanks of Pilot Mountain. A pyrophyllite-andalusite body northwest of the crest has been evaluated for mining several times, the latest in 1978-83 by Piedmont Minerals Co., Inc. Additional concentrations of pyrophyllite and lesser amounts of andalusite scattered within quartz granofels and quartz-sericite-pyrite schist extend westward from the mountain, altogether occupying an area 4.5 km long in an east-west direction and 2 km wide (fig. 6). All of the exposures of altered rock are presumed to be part of the same hydrothermal alteration system, but this is not proved. The system is also marked by a 4 km^2 area of low-level but anomalous amounts of copper, molybdenum, and tin in soils (fig. 7, table 1).

Geology of Pilot Mountain--The nature of most of the bedrock of Pilot Mountain prior to alteration is hard to determine because hydrothermal alteration has modified both composition and texture of the rocks. From sparse exposures of incompletely modified rocks around the edges of the zone of alteration and by projections of the trends of rock units present a few kilometers away, it is possible to conclude that most of the altered rock was formerly andesitic lapilli tuff plus smaller amounts of laminated argillite, volcanic-rich sediment, crystal tuff, and flows; but along the southeastern flank of Pilot Mountain the protolith was part of a subvolcanic(?) dacite porphyry body containing abundant rounded quartz grains up to 5 mm long.

The area of hydrothermal alteration grades outward on the southwest, west, and north to metamorphosed andesitic and dacitic volcanic rock and laminated tuffaceous argillite, but the outcrops are sparse in these directions. Three different rock types bound the hydrothermal alteration on the southern and southeastern sides where the margin is more closely controlled. These include quartz monzonitic and dioritic plutonic rocks, gray felsic volcaniclastic rock, and subvolcanic dacite porphyry (fig. 6).

The quartz monzonitic and dioritic rocks south of Pilot Mountain include a variety of generally foliated dark chloritic granitic rocks with both plutonic and porphyritic textures. Compositions also tend to differ considerably within each outcrop area as well as between areas. Textures range from faintly to distinctly porphyritic with largest feldspar grains ranging from 2 to 5 mm long. Quartz comprises 10 to 30 percent in rounded grains or subhedral crystals. Some of the rounded grains are probably embayed and some of the porphyritic phases may include volcanic material. Plagioclase exceeds potassic feldspar by 3 to 4 times; the plagioclase is extensively altered to sericite and epidote. Biotite has been the principal or only mafic mineral and may have been as abundant as 30 percent of some phases but was much less common in others. It is now partly to entirely altered to chlorite and epidote. Most of the porphyritic rocks contain small pyrite cubes. Some small areas of porphyritic quartz monzonitic rock are included in the northern part of the area shown on figure 6 as gray felsic volcaniclastic rock. Part of the quartz monzonite there has been intensely altered to quartz and sericite and contains 15 to 20 percent pyrite. At other localities the quartz monzonite and dacite lack effects of hydrothermal alteration, even when close to highly altered parts of the Pilot Mountain system, leading one to the conclusion that the contact may locally be a fault surface younger than the alteration.

Gray felsic tuff and felsic arenite outcrops are common in a km^2 area southwest of Pilot Mountain and south of the zone of hydrothermal alteration (fig. 6). The outcrops include light to dark gray probably dacitic and rhyolitic rocks. Megacrysts of quartz and plagioclase are generally smaller than 2 mm and are not abundant. Isolated outcrops of similar rocks are found within the highly altered rocks, and these are interpreted to be unconformable younger strata infolded with the altered rocks. Tentatively, I interpret the outcrop area of gray felsic volcaniclastic rocks and felsite porphyry shown on figure 6 to be an extension along strike of the layered rocks of Needhams Mountain 10 km to the southwest, and thus a part of the Uwharrie Formation. I believe that this volcanic unit laps

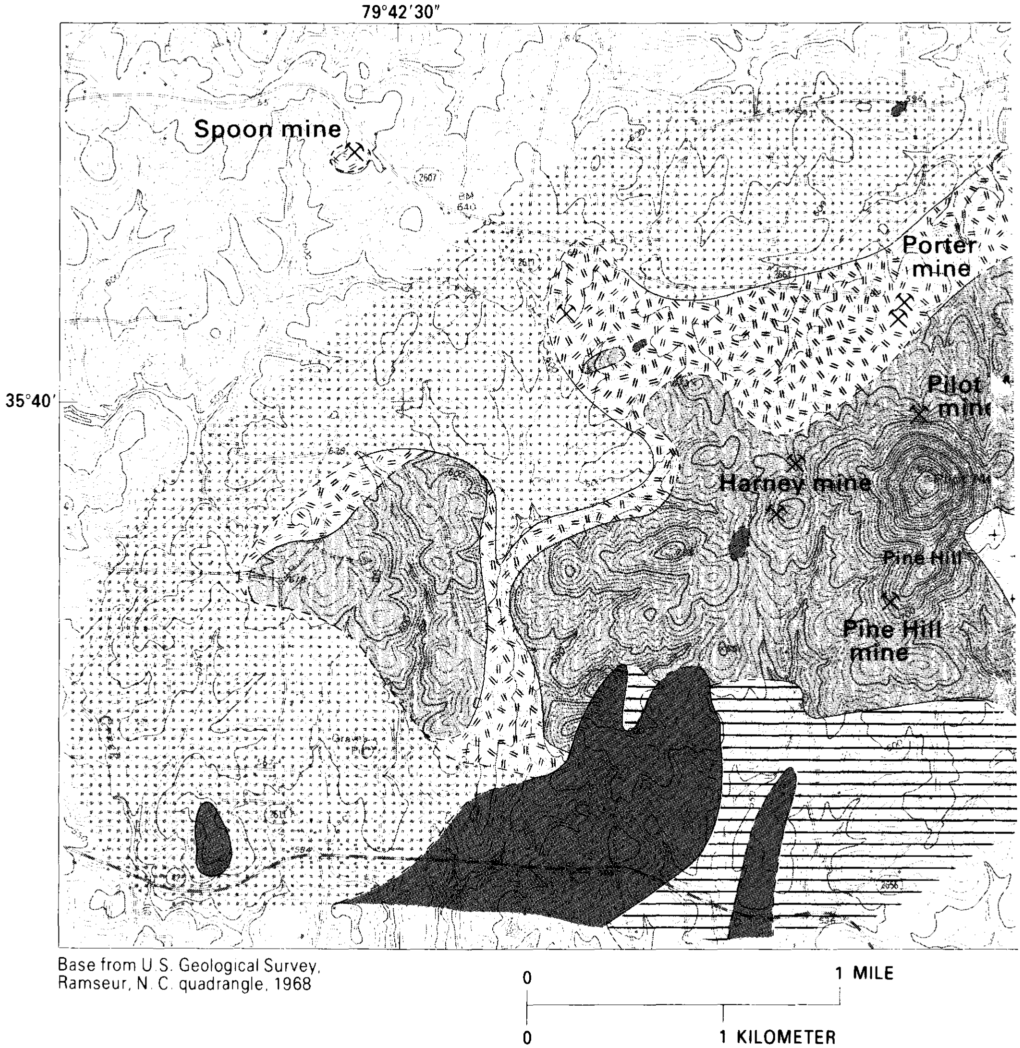
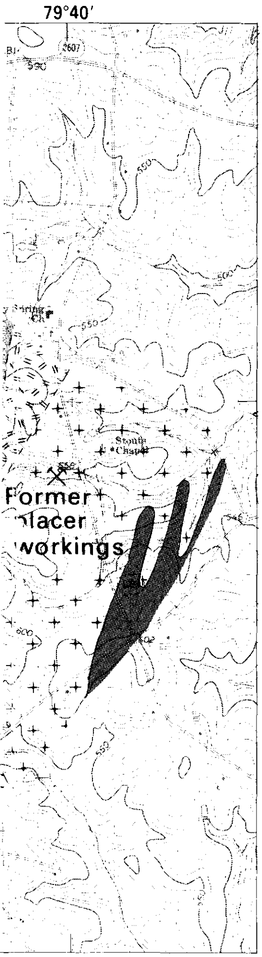


FIGURE 6. Hydrothermal alteration at Pilot Mountain, Randolph County, N.C.



Geology by R. G. Schmidt and T. L. Klein, 1978–82
Adapted from Milton and others, 1983

EXPLANATION

Gray felsic volcaniclastic rocks and felsic porphyry or crystal tuff—Light- to dark-gray felsic arenite and porphyritic dacite and rhyolite; megacrysts of quartz and plagioclase generally smaller than 2 mm, not abundant. Unit probably unaffected by hydrothermal alteration.

Andesitic and dacitic volcanic rocks—Largely lapilli tuffs and crystal tuffs or porphyritic flows, probably includes volcaniclastic units. Light- to dark-greenish-gray, chloritic. Probably a major protolith of hydrothermally altered rocks

Dacite porphyry— Generally light-gray; abundant quartz and plagioclase phenocrysts up to 5 mm across. Generally hydrothermally altered; contains pervasive disseminated pyrite

Quartz monzonitic and dioritic plutonic rocks—Dark-greenish-gray; chlorite and epidote rich. Local porphyritic phases, some of which may include volcanic material. Generally foliated. No gradation to hydrothermally altered rocks recognized

Quartz granofels and quartz-sericite-pyrite schist with high-alumina pods— Moderately to intensely silicified rock; quartz content commonly over 80 percent, especially on Pilot Mountain and Pine Hill. Generally contains sparse pyrophyllite and a few percent of disseminated sulfide. Encloses unknown amount of silicified argillite and quartz-sericite-pyrite schist which does not commonly form outcrops. Includes pods containing abundant pyrophillite, andalusite, topaz, and pyrite. Textural features of protolith mostly obliterated except for quartz phenocrysts

Quartz-sericite-pyrite schist—Includes small pods of quartz granofels and lenses of chloritic volcanic rocks. Pyrite content generally 2–10 percent. Gradational to unaltered andesitic and dacitic volcanic rocks

Contact—Dashed where inferred

Gold mines and prospects, abandoned

FIGURE 6. Continued

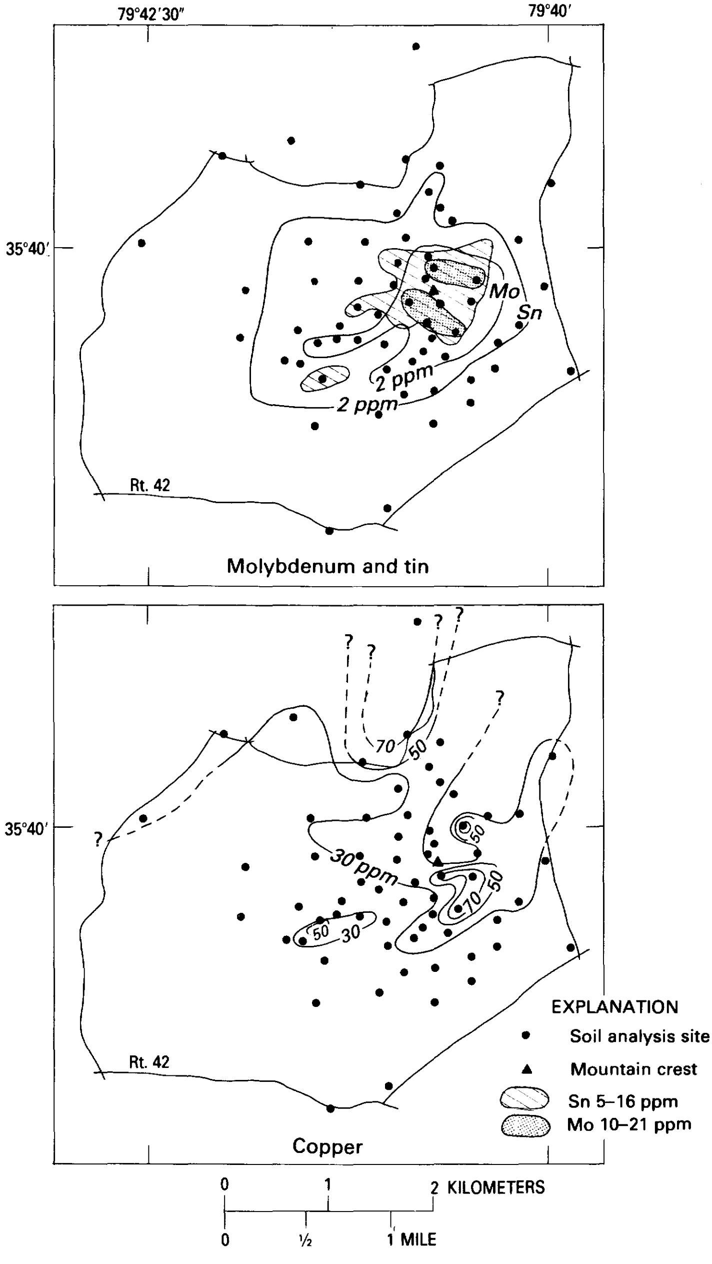


FIGURE 7. Soil sample analyses, Pilot Mountain area. Adapted from Milton and others (1983).

unconformably onto the altered rock southwest of Pilot and was deposited after alteration.

Dacite porphyry is present in a 2 km^2 area east and southeast of Pilot Mountain. This generally gray rock has abundant phenocrysts of quartz and plagioclase up to 5 mm across, but in some places the phenocrysts are less than 2 mm. Much or all of the porphyry, especially the coarse-phenocryst phase, has undergone strong hydrothermal alteration. Outcrops are generally poor and much weathered and do not permit easy interpretation of variations in texture, composition, and degree of hydrothermal alteration. In many weathered exposures and float blocks the abundant quartz phenocrysts are the only identifying feature. Southeast of Pilot Mountain the alteration is to quartz-sericite-pyrite rock with potassium feldspar in some samples. On the southeast slope of the mountain intense alteration has converted the porphyry to quartz granofels and only the phenocrysts remain to identify the protolith. Isolated occurrences of quartz granofels containing 3 to 5 mm relict quartz phenocrysts near the top and on the north slope of Pilot Mountain suggest the presence of dacite apophyses away from the main stock.

Hydrothermal alteration--The hydrothermal alteration zone that includes Pilot Mountain is over 4.5 km long and as much as 2 km wide (fig. 6), and within this zone the composition and textures of much of the pre-existing rock have been profoundly changed. The rock with strongest alteration contains masses, lenses, and pods of high-alumina minerals enclosed in quartz granofels and quartz-sericite-pyrite schist. The enclosing rock in the eastern end of the zone, especially on Pilot Mountain and Pine Hill, contains much quartz granofels, and most of the topaz recognized in the system is located there. Westward from Pilot Mountain quartz-sericite-pyrite schist encloses the pods and lenses of high-alumina minerals that characterize the innermost strongly altered zone, and quartz granofels is much less abundant. The high-alumina pods are made up of different proportions of pyrophyllite, andalusite, kaolinite, pyrite, chloritoid, and rutile; topaz is common at many locations on the west slope of Pilot Mountain and only a little has been identified west of there. Diaspore and lazulite were not observed although they occur in many similar deposits in the region.

Quartz-sericite-pyrite schist without associated high-alumina pods has been mapped as a separate unit peripheral to the most strongly altered zone (fig. 6). The appearance of this unit contrasts sharply with the surrounding andesitic lapilli tuffs and greenstones. The schists appear considerably deformed and strongly hydrothermally altered. Pyrite is present mostly in disseminated grains a few of which are as large as 1 mm, but most of which are less than 0.5 mm and less commonly in small wispy stringers. The fine size makes abundance difficult to estimate, but the sulfide content in some phases may be as great as 30 percent. Near large masses of quartz granofels, the quartz-sericite-pyrite schist includes minor lenses or pods of the granofels, commonly pyrophyllite-bearing; near the gradational contact with surrounding andesitic volcanics, the quartz-sericite-pyrite schist may contain small isolated pods of andesite or be quite intermixed with the less altered rock.

Quartz-rich granofels with minor pyrophyllite and pervasive minor sulfide is the most prevalent type of altered rock throughout the eastern part of the zone of intense alteration and thus enclosing the high-alumina layers on the northwest slope of Pilot Mountain. It comprises most of the large outcrop area on the south slope of Pilot Mountain, especially on the low knob known as Pine Hill.

Outcrops and large residual boulders on the crest and northwest slope for 100 m from the crest of Pilot Mountain include the following: (1) massive pyrophyllite rock made up of an intergrowth of radiating crystalline clusters up to 1 cm in diameter, light gray to white, and with no other mineral in significant amount; (2) pyrophyllite-andalusite-quartz rock in which the andalusite is present in rounded grains and knots, each commonly sheathed in a 0.5-2.0 mm layer of pyrophyllite, and set in a matrix of quartz and pyrophyllite; (3) topaz-quartz rock consisting of irregular nearly pure masses of each mineral a few millimeters to a few centimeters across; the quartz in mosaics of very fine grains up to 0.1 mm across, the topaz in mats of grainlets so fine as to be barely resolvable in a 0.3 mm thin section; and (4) quartz-pyrophyllite-sulfide granofels in which the quartz generally comprises 80 to 95 percent of the rock, and the spaces formerly occupied by 2 to 5 percent sulfide are now voids partly filled by encrustations of hematite or goethite. Core drilling on the northwest slope of Pilot Mountain indicates the presence in the subsurface of several rock types not seen in outcrop, including laminated argillite, crystal and lapilli tuff, mafic flow rock and soft clay of unknown origin.

There is little doubt that Pilot Mountain stands as an erosion-resistant monadnock because of the highly aluminous and siliceous rocks present; still, the detailed physiography of the mountain and the outcrop patterns there tell us little about the sizes and shapes of the andalusite-pyrophyllite masses and of various other mineral facies of the quartz granofels. From the experience of mining other deposits with similar mineral suites but perhaps not identical formational history, masses rich in ore mineral species such as pyrophyllite are believed to form lenticular bodies several meters thick and tens of meters long. These lenses may be elongated in the general direction of the layers of volcanic rocks. In the mine at Hillsborough, N.C., the individual lenses seem to be arranged in a shingled or en echelon fashion rather than strictly parallel to the bedding strike. Elongate resistant outcrops of quartz granofels that are almost pure quartz are present on the low knob called Pine Hill on the south flank of Pilot Mountain. These outcrops trend about N.55°E. Elsewhere on Pilot Mountain low outcrops of quartz granofels, pyrophyllite-rich rock, or pyrophyllite-andalusite rock give little indication of the actual extent of these phases in the bedrock.

Float material on the crest of the mountain includes pieces of quartz granofels with brecciated texture, but the origin of the breccia has not been determined. A type of rock common on the northwest slope of the mountain has 3 to 5 mm andalusite grains in a fine matrix distributed in a manner that resembles the texture of a porphyry. The porphyrylike texture may be only coincidence, but I believe that in a few of the rocks the andalusite grains have replaced the sites of former plagioclase phenocrysts.

Metallic mineralization--In addition to widespread pyritization in the zones of hydrothermal alteration, anomalous amounts of copper, molybdenum, and tin are present in the overlying soils (fig. 7 and Milton and others, 1983). Gold was sought in several prospects within the alteration zones and three operations, the Pilot Mountain, Harney, and Pine Hill mines, may have yielded a profit, but there are no records of production. Nothing is known of the way the gold occurred.

Pyrite is disseminated through much of the high-quartz and pyrophyllite-andalusite altered rock, and quartz-sericite-pyrite schist, but has been leached to such depths that it is not generally seen in outcrops and prospect trenches; however, surface rocks have abundant voids left by dissolution of the sulfide. Some voids contain linings of iron oxide or the surrounding rock is stained, but in others most of the iron oxide has been leached out as well. Fresh pyritic rock has been penetrated by exploration drilling on the northwest slope of the mountain, and is present in dump material at the old Pine Hill gold mine on the south flank and at old prospects on the north slope. Locally abundant small flakes of molybdenite were also found disseminated and in small veinlets in quartzose rock on the Pine Hill mine dump. Neither copper nor tin minerals were observed on the surface or in mine dumps. Very small patches stained by secondary copper minerals are present at many places in drill cores.

Small but distinctly anomalous amounts of copper, molybdenum, and tin are present in soils on Pilot Mountain within the quartz granofels area known to have undergone strongest hydrothermal alteration, and anomalous copper is found in an adjacent area of sulfide-bearing quartz-sericite schist north of Pilot Mountain (fig. 7) also interpreted to be altered. Soils of most of the anomalous area are believed to overlie rock that was formerly sulfide-bearing. The soils are residual and have been subjected to strong acid leaching by H_2SO_4 formed on oxidation of the widespread sulfide; organic acids produced by the decomposition of forest litter, largely oak leaves, provided leachants over long periods of time. Values for tin and molybdenum are highest near the area where andalusite and pyrophyllite are most developed and drop significantly away from the alteration area on Pilot Mountain; copper values decrease eastward and southward, but copper relationships to the north and west beyond the edge of the quartz-sericite-pyrite schist are not clear. Control soil samples were taken on other high rock ridges, some of them with small amounts of disseminated sulfide in the bedrock; analyses of copper, molybdenum, and tin from these control samples were very low (table 5).

Hydrothermal alteration at Fox Mountain and Iron Mountain--Fox and Iron Mountains are two monadnocks separated by a low saddle, 8 km east of Asheboro and 6 km northwest of the crest of Pilot Mountain (fig. 4). Surrounding rocks are believed to be andesitic lapilli tuffs but, as at Pilot Mountain, many of the rocks on these monadnocks are so altered that original characters are difficult to determine. Pyrophyllite is abundant near the crest of Fox Mountain, and especially down the southern flank; it is also present along the east side of the saddle and to some extent on the east slope of Iron Mountain, forming a zone elongate in a north-south direction about 1 km long. Several long-abandoned mine workings and prospect pits on the east side of Iron Mountain appear to have been developed for gold or perhaps iron ore close to outcrops of pyrophyllite rock. The dump rock at the mines includes lapilli tuff, white quartz, gray metallic specularite, siliceous rock with 3 to 4 mm pyrite cubes, and pieces of limonitic gossan. Examination of what I believe to be a small ore pile suggests that mining was mostly in quartz veins in a zone of partial oxidation. A small prospect shaft on the southeast slope of Fox Mountain followed a weakly magnetic hematitic zone in siliceous coarse lapilli tuff or breccia. Breccia on the top of Fox Mountain consists of abundant small light gray fragments in a black matrix, and gray schistose rocks from the same area contain as much as 5 percent disseminated fine- grained pyrite.

The Fox Mountain-Iron Mountain area has been tested using only ten soil samples. One sample from Iron Mountain contained an anomalous amount of copper (94 ppm) and three samples contained 3 to 4 ppm of tin. All samples contained less than the detectable limit of molybdenum. Association of low levels of anomalous copper and tin, probably some gold ores, and extensive development of pyrophyllite

TABLE 5.—*Analyses of 12 soil samples from unaltered felsic rock monadnocks*
[In ppm. Emission spectrographic analyses by J. L. Harris and Leung Mei. After Milton and others, 1983]

Monadnock	Latitude north	Longitude west	Sample No.	Cu	Mo	Sn
Shepherd Mt.	35°45.11′	79°57.0′	27	9.4	<1.0	3.2
	35°45.25′	79°57.0′	28	24.	<1.0	3.4
	35°45.32′	79°57.2′	30	7.	<1.0	2.0
	35°45.05′	79°57.3′	33	17.	<1.0	3.8
	35°45.27′	79°57.1′	68	6.2	<1.0	1.9
	35°45.06′	79°56.9′	69	3.9	<1.0	1.8
Stackrock Mt.	35°39.8′	79°48.3′	66	6.5	<1.0	1.6
Caraway Mt.	35°45.1′	79°53.4′	67	6.3	<1.0	1.6
Buck Mt.	35°24.4′	79°59.9′	71	8.	<1.0	<1.5
"Pine Mt."	35°30.65′	79°29.5′	73	13.	<1.0	<1.5
	35°30.58′	79°29.6′	74	26.	<1.0	3.1
Worth Mt.	35°46.2′	79°46.9′	79	13.	<1.0	<1.5

and disseminated sulfide suggests a hydrothermal system similar to that at Pilot Mountain, though smaller in scale. The hypothesis that the Fox Mountain-Iron Mountain alteration is part of a much larger Pilot Mountain system is a tentative working model that can only be tested by much more field work.

HIGH-ALUMINA DEPOSITS IN MOORE COUNTY

The Standard Mineral Company mines and Glendon Pyrophyllite Company mines of Moore County form a secondary linear trend separate from the major deposit trend (fig. 1). There is enough difference between the Brewer and Pilot Mountain systems in the northwestern major trend and the minor trend in Moore County to suggest origins under somewhat different physical conditions, but there are also features in common, such as the widespread association of gold and of minor amounts of copper and molybdenum (table 1).

The deposits of Moore County are alined along a trend generally corresponding to sedimentary strike for a distance of 20 km. In addition to major deposits and many prospects along this line, there are several small deposits and prospects a few kilometers to the south. High-alumina minerals are present in pod-shaped masses of pyrophyllite and kaolinite or sericite are locally abundant as well. Chloritoid and pyrite are abundant in the rocks adjacent to the ores; andalusite and diaspore are rare or absent. Major quartz veins are common within the ores, but silification of host rock, so important in certain deposits in the major trend, is minor or wholly lacking. The effects of hydrothermal alteration do not extend far beyond the ores and may be limited to an additional volume of rock little greater than the ores themselves. A little flourite is present but neither topaz nor tourmaline has been reported.

In the part of the Moore County trend north of Glendon, unpublished detailed studies by T. L. Klein show that high-alumina deposits have formed close to the sedimentary transition from lapilli breccia and conglomeratic mudstone to an overlying fine-bedded tuffaceous argillite and lapillite. Both units have been altered to high-alumina minerals and the alteration cuts across the bedding. There appear to be segments of volcanic rocks and sediments along strike between orebodies where little or no alteration has taken place.

The volcaniclastic rocks have been affected by pervasive strong penetrative deformation, perhaps stronger here than in the Asheboro area. Many drag folds can be seen in the mines, and it is possible that folds are most intense in the zone favored by the ore deposits; exposures are much poorer away from the mines, however, and the regional distribution of drag folding is insufficiently known.

Strike faulting and axial plane displacements on drag folds can be seen at several places in the mines. Faulting in several mines, interpreted as a single major strike fault, was held by Stuckey (1967, p. 29) to be an important control of hydrothermal solutions. Prominent quartz veins appear to occupy some of the fault planes and may well represent former solution channel ways.

Many problems regarding ore controls and temporal relationships of ore-forming processes to deformational history remain, but the deposits in Moore County probably represent orebodies formed under different physical conditions from such deposits as the Brewer and Pilot Mountain. The Moore County deposits may represent lower temperature parts of similar systems and hence may have been more distant from the heat source. Lack of evidence that andalusite was ever abundant here and the absence of large silicified zones suggest a lower formational temperature, or less acid solutions in a weaker part of a hydrothermal system.

OTHER DEPOSITS IN NORTH CAROLINA

Data on metal content of soils, veins, or associated sulfides have been obtained as part of this study, or earlier by Lesure (1981), for 10 other pyrophyllite prospects and mines (fig. 1), and I have briefly visited at 15 more. All of these deposits are located in lapilli-bearing or tuffaceous volcanic strata and are known to have masses of rock containing disseminated sulfide associated with them in some way (table 1). Sulfide-bearing bedrock zones and associated soils were sampled for metal analysis. Two mine areas yielded soil and rock samples containing slightly anomalous amounts of copper and two areas had molybdenum analyses greater than background.

ORIGIN AND SIGNIFICANCE OF THE HIGH-ALUMINA ALTERATION SYSTEMS

Hydrothermal alteration has produced at least 40 large bodies of aluminous rock in andesitic to rhyolitic mostly pyroclastic volcanic rocks in the Carolina slate belt. Part of these include areas of silificied rock that may be as large as 4.5 km long and 2.5 km wide. Within the silicified bodies, pods and lenses of pyrophyllite have formed; these pods commonly include also andalusite, diaspore, topaz, and kaolinite. In some deposits the vicinity of some of the high-alumina mineralization is marked by anomalous amounts of copper, molybdenum, and tin in the residual soils. Gold has been mined from locations within the silicified zone of at least 5 of the deposits, but there are also many others from which no gold occurrences have been reported. In addition to the previously mentioned metals, arsenic and silver are present in anomalous amounts at several places within the Pilot Mountain alteration system, and arsenic, bismuth, and tungsten occur in small amounts at the Brewer deposit.

Topaz is known to be present at many of the major deposits and may well be present though unreported at the rest. Tourmaline has been observed in patches in only one deposit, and being much easier to spot in the field, must be generally rare or absent. Thus, flourine is known to have been introduced by hydrothermal alteration in many of the systems while boron was probably not commonly present. Phosphorus-bearing minerals are widespread but are always very minor in amount. In rocks interpreted to have been hydrothermally altered, rutile as widespread very small grainlets is the most common titanium-bearing mineral recognized.

The minerals present and the configurations of the Brewer and Pilot Mountain deposits suggest that these two systems formed under generally similar conditions of pressure, temperature, and solution chemistry. The widespread presence of andalusite and the absence of kyanite except for local concentrations at the Brewer deposit imply formation at relatively low pressures--less than 2 kilobars--and temperatures ranging 300 to 400°C. The temperature precludes deposition under atmospheric pressure and the deposits cannot be said to be spring-related in the sense of being almost at the surface, but low pressure required by the absence of kyanite in many deposits implies relatively shallow depth and a high geothermal gradient. For Graves

Mountain, Ga., and Willis Mountain, Va., Allard and Carpenter (1981) have described generally stratiform zones of high-alumina alteration, and by analogy to the Otake geothermal field of Japan, refer the origins of these deposits to shallower, more truly fumarolic systems. Less metamorphosed examples of such shallower systems in North Carolina may include the Moore County deposits, the Hillsborough deposit, and perhaps the more stratiform parts of the Bowlings Mountain-Jones-White deposit area as well.

The capacity to alter large amounts of volcanic rock drastically, moving silica freely and leaching all other contituents except alumina from certain zones, required a strongly acid solution in large volumes. From the minerals present we can assume that flourine was probably an important constituent of the solution.

Shallow but vigorous hydrothermal systems in volcanic rocks such as these in the slate belt are commonly associated with subvolcanic intrusive rocks as in the widely occurring subvolcanic types of porphyry copper deposits. Shallow intrusive bodies, mostly with porphyritic textures, are the heat engines that drive the hydrothermal circulation. In many porphyry copper deposits successive intrusive phases including both stocklike masses and dike swarms have contributed to the total alteration history and the successive intrusives of these sequences tend to cut and cause alteration of the earlier bodies. Subvolcanic intrusives are interpreted to have been major altering agents in the Pilot Mountain deposit. Several porphyritic dikes have been noted within the Brewer system, but too little is known about them to specifically relate them to the major alteration.

Examples of copper and molybdenum porphyry deposits associated with high- alumina alteration are scattered from Canada to Chile, and several porphyries with high-alumina alteration occur in east and southeast Asia, some having gold associated with them. However, the most important analog is the major Paleozoic porphyry copper province of central Kazakhstan in the Soviet Union. Of several hundred mapped highly-silicic alteration zones in felsic and intermediate volcanic rocks, many have strong high-alumina components. Several are larger than 30 km^2, and many form monadnocks. In these relatively unmetamorphosed deposits, the minerals pyrophyllite, andalusite, diaspore, corundum, alunite, dickite, sericite, topaz, and abundant highly silicified rock are considered by Nakovnik (1968) and other workers to be hydrothermal in origin. Of 18 copper, copper-molybdenum and molybdenum porphyries there, at least 6 are related to high- alumina systems. The largest and best known, the Kounrad Mine, with 10 mil tons of copper metal, is a good example of a subvolcanic alteration system in volcanic rocks with an alteration suite similar to certain of the Carolina deposits, but with copper and molybdenum in economic quantity.

SUMMARY

I believe it is reasonable to conclude that the large alteration systems in the Carolina slate belt with widespread quartzification and development of pyrophyllite, andalusite, and pervasive disseminated sulfides are variations of porphyry copper and (or) gold systems and, as a consequence, deserve careful consideration for their mineral resource potential. The pressure-temperature specific alteration suites indicate relatively shallow formation of the altered rocks now exposed. The Brewer deposit may represent a somewhat deeper level of erosion into the system; it also has the greatest amount of copper, molybdenum, and tin. Pilot Mountain and other large andalusite-bearing deposits with large highly-silicified alteration envelopes are interpreted to be similar systems eroded to a slightly lesser depth than the Brewer. The Moore County deposits and perhaps other generally stratiform systems may be either considerably shallower, or the result of much smaller and weaker systems.

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