The Potential for Porphyry Copper-Molybdenum Deposits in the Eastern United States

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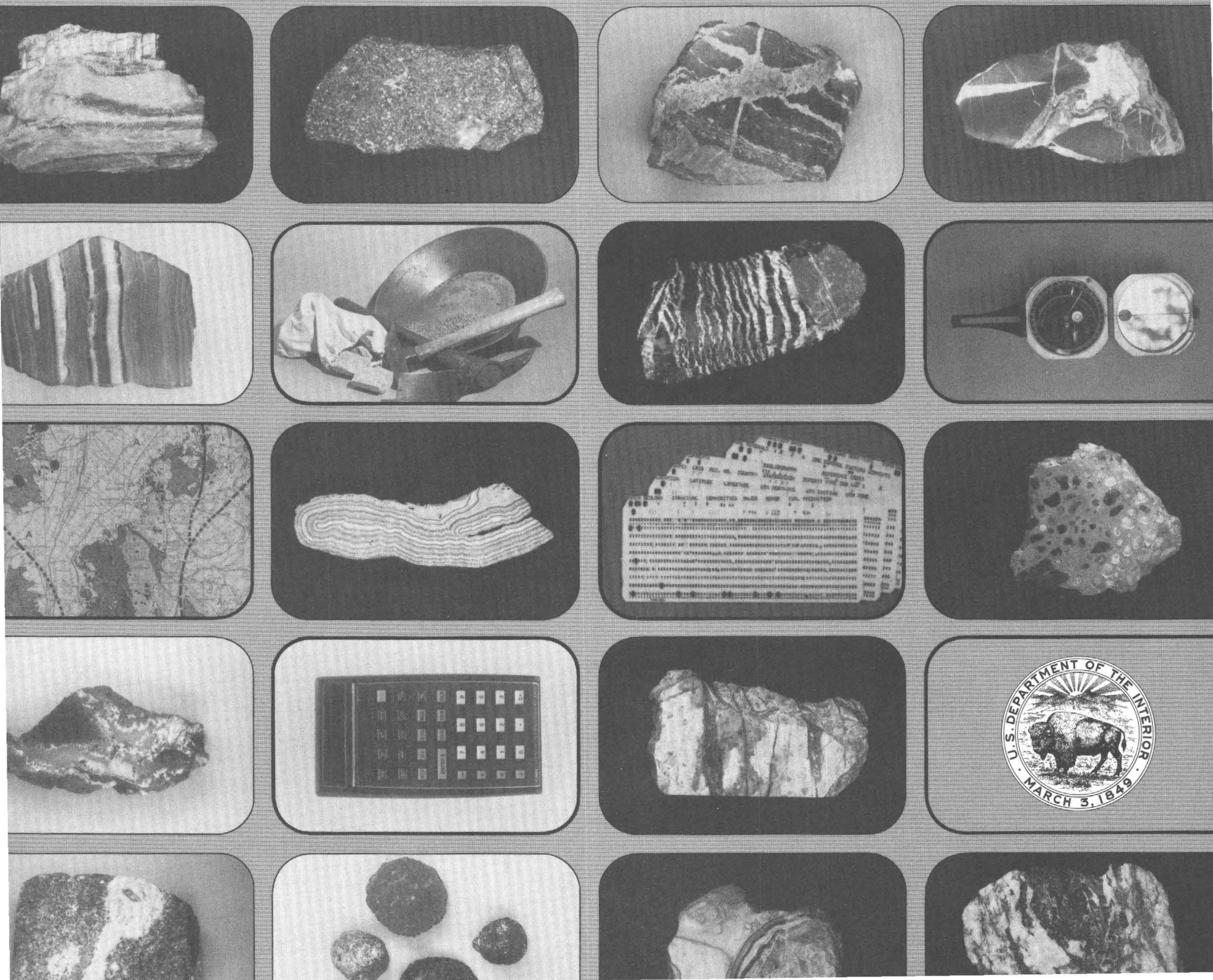

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1. Asbestos ore
2. Lead ore, Balmat mine, N. Y.
3. Chromite-chromium ore, Washington
4. Zinc ore, Friedensville, Pa.
5. Banded iron-formation, Palmer, Mich.
6. Ribbon asbestos ore, Quebec, Canada
7. Manganese ore, banded rhodochrosite
8. Aluminum ore, bauxite, Georgia
9. Native copper ore, Keweenawan Peninsula, Mich.
10. Porphyry molybdenum ore, Colorado
11. Zinc ore, Edwards, N. Y.
12. Manganese nodules, ocean floor
13. Botryoidal fluorite ore, Poncha Springs, Colo.
14. Tungsten ore, North Carolina

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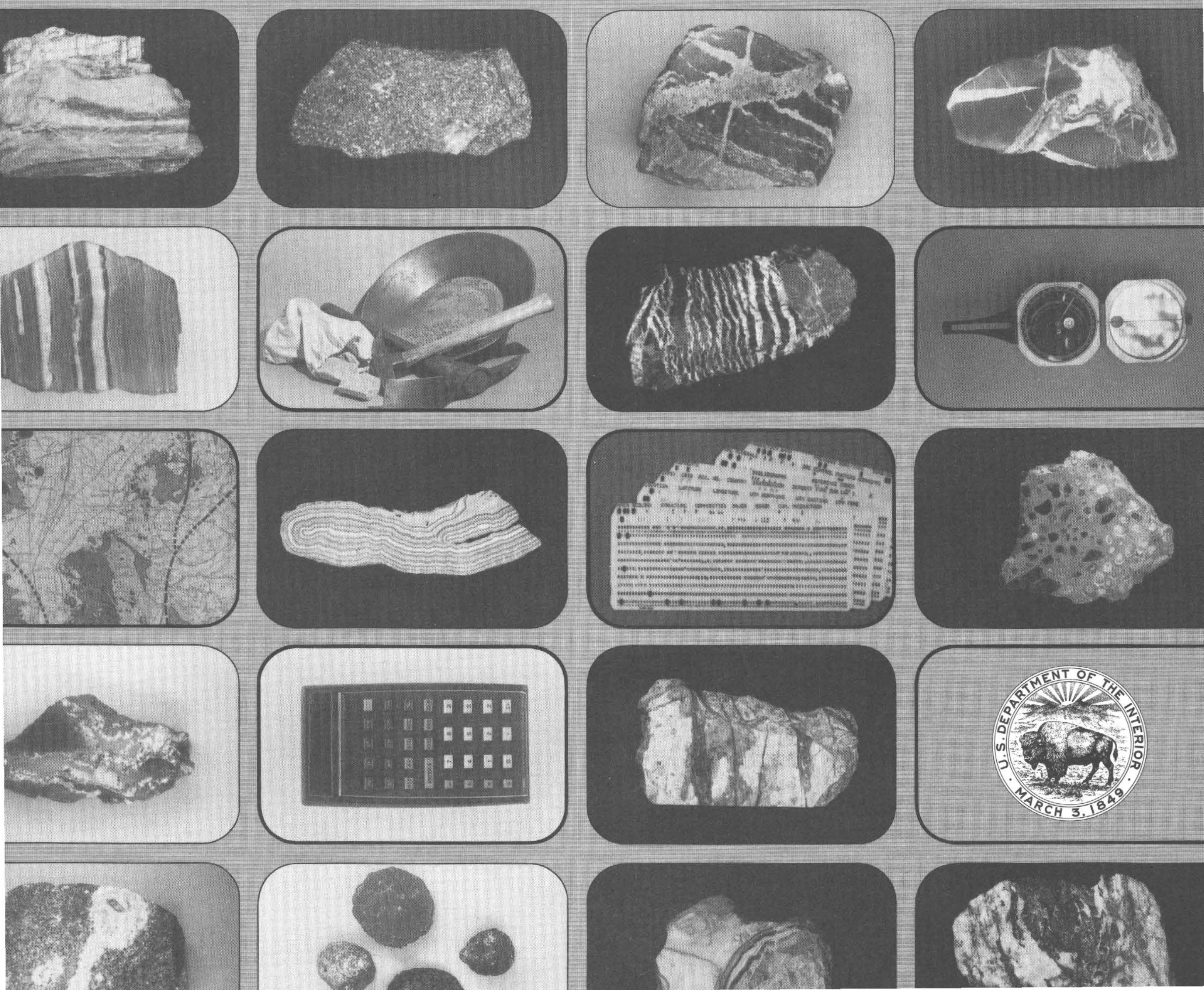

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The Potential for Porphyry Copper-Molybdenum Deposits in the Eastern United States

By ROBERT GORDON SCHMIDT

GEOLOGY AND RESOURCES OF COPPER DEPOSITS

GEOLOGICAL SURVEY PROFESSIONAL PAPER 907-E

A descriptive resumé of deposits of the porphyry type and an evaluation of potential areas for discovery of new deposits

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APPRAISAL OF MINERAL RESOURCES

Continuing appraisal of the mineral resources of the United States is conducted by the U.S. Geological Survey in accordance with the provisions of the Mining and Minerals Policy Act of 1970 (Public Law 91-631, Dec. 31, 1970). Total resources for purposes of these appraisal estimates include currently minable resources (*reserves*) as well as those resources not yet discovered or not currently profitable to mine.

The mining of mineral deposits, once discovered, depends on geologic, economic, and technologic factors; however, identification of many deposits yet to be discovered, owing to incomplete knowledge of their distribution in the Earth's crust, depends greatly on geologic availability and man's ingenuity. Consequently, appraisal of mineral resources results in approximations, subject to constant change as known deposits are depleted, new deposits are found, new extractive technology and uses are developed, and new geologic knowledge and theories indicate new areas favorable for exploration.

This Professional Paper discusses aspects of the geology of copper as a framework for appraising resources of this commodity in the light of today's technology, economics, and geologic knowledge.

Other Geological Survey publications relating to the appraisal of resources of specific mineral commodities include the following:

Professional Paper 820—"United States Mineral Resources"
Professional Paper 926—"Geology and Resources of Vanadium Deposits"
Professional Paper 933—"Geology and Resources of Fluorine in the United States"
Professional Paper 959—"Geology and Resources of Titanium in the United States"

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GEOLOGY AND RESOURCES OF COPPER DEPOSITS

THE POTENTIAL FOR PORPHYRY COPPER-MOLYBDENUM DEPOSITS IN THE EASTERN UNITED STATES

By Robert Gordon Schmidt

ABSTRACT

Several significant porphyry-type deposits of Paleozoic age are known in New England and eastern Canada. Disseminated copper-molybdenum deposits of Paleozoic age are in the Southeastern United States, and copper is produced from porphyry-type deposits of both Precambrian and Paleozoic age in eastern Canada. Although these old deposits are surely less abundant than those in Cenozoic and Tertiary porphyry belts, the known Precambrian and Paleozoic deposits in Eastern North America appear to be valid exploration targets. The difficult of prospecting in drift-covered and saprolite-mantled terrains suggests that all such deposits probably have not been discovered. Although such deposits are more costly to discover in this region than a massive sulfide deposit, the total amount of copper in even a medium-sized porphyry copper deposit is much greater than in most massive sulfide deposits.

This report summarizes current knowledge of porphyry copper-molybdenum-type deposits in the Eastern United States and suggests more favorable areas for mineral exploration. Selected Canadian deposits are discussed because of their bearing on planning exploration in this country.

Porphyry copper deposits are here defined as deposits of widely dispersed copper sulfide related to a felsic intrusive body and associated with a major system of hydrothermal alteration.

Four deposits that are regarded as porphyry type have been identified in the Precambrian shield of Canada; copper is mined from two of these, McIntyre mine (Timmins) and Batchawana area, Ontario. Five deposits of Paleozoic age are here regarded as certainly of the porphyry copper type, Copper Mountain, Needle Mountain, and Pekan in the Gaspé Peninsula, the Woodstock prospect in New Brunswick, and the Catheart Mountain deposit in Maine. In addition, one deposit in the Southeastern United States, the Conner-Neverson quarry prospect in North Carolina, is probably of the porphyry type. The Copper Mountain and Needle Mountain deposits, Quebec, are now mined. Several copper and (or) molybdenum prospects and deposits classed by others as porphyry-type occurrences are not included here. Inclusion or exclusion of these has a profound effect on metallogenic modeling of New England and Southeastern United States.

Catheart Mountain, Maine, the most significant porphyry-type deposit known in the Eastern United States, covers an area of about 1.5 km^2 of intensely hydrothermally altered rock. A substantial but subeconomic body of copper-molybdenum ore is found on the fringe of the alteration system. The southern and northwestern fringes of the system have been only partly explored and remain as favorable drilling targets.

I believe that the known Paleozoic porphyry-type deposits in New England and eastern Canada are in Middle Devonian subvolcanic intrusive rocks in a narrow northeast-trending belt in northwestern Maine, New Brunswick, and southeastern Quebec, and perhaps also in New Hampshire. I propose that these porphyry copper-molybdenum deposits are related to a northwest-dipping Acadian subduction zone located near the Maine and New Brunswick coasts, and that a broad belt in western New Hampshire, northwestern Maine, and southeastern Quebec is the most favorable for further discoveries in this region.

Only one deposit, in the Conner-Neverson quarry area, that is probably of the porphyry type, is now known in the Southeastern United States, but the upper Precambrian or lower Paleozoic thick volcanic successions included in the Carolina slate belt are considered to be favorable prospecting areas. Though only partly mapped on an adequate scale, the volcanic rocks are known to include several small plutonic intrusive bodies but surprisingly few subvolcanic intrusive bodies. Neither the existent mapping scale over much of the area nor the deep saprolitic weathering favor easy identification of small felsic porphyry bodies in felsic volcanic rocks, so I consider that the exploration conducted so far has not adequately tested the region.

The area surrounding the Brewer mine in Chesterfield County, S.C., is not a typical prophyry copper system, but it has some of the same features. The old gold mines are in part of a much larger zone of highly altered copper-bismuth-tin-bearing volcanic rocks, part of which are now quartz-andalusite and quartz-topaz rocks. The large alteration zone, evidence for a subvolcanic origin, and the metal suite provide only a sketchy picture of the whole hydrothermal system, but permit comparison with the large systems at Mount Pleasant, New Brunswick, and some of the deposits of Cornwall. The whole area of alteration and mineralization may be several kilometers in each dimension, and until the perimeters are defined and variations in both alteration and mineralization style are known, the Brewer area cannot be fully evaluated for its base-metal potential.

The possibility of finding porphyry copper deposits of exploitable size in Eastern United States is good, although not as good as in the high-potential regions of parts of the Western States. Initial exploration should be concentrated in those parts of New England and the Southeastern States that seem to be the most favorable. Problems of detection of porphyry deposits in drift-covered regions and in areas having deep saprolitic soils offer a great challenge to exploration geologists. The combined use of geological, geophysical, and geochemical methods will almost surely be needed for successful exploration programs in these places.

INTRODUCTION

Although most economic geologists recognized no copper or molybdenum deposits of the porphyry type in eastern North America only a decade ago, several deposits are now known that fit the porphyry model well, and many more can be cited as probable or possible porphyry type. These deposits range in age from Archean to middle Paleozoic, possibly to Mississippian. The several deposits that are being mined at this time are all in Canada, but the ore body that is perhaps the best example of a porphyry deposit is at Catheart Mountain in Maine. Although the exploited ore bodies and the known prospects are small compared to many Cordilleran and Arizona porphyries, their discovery opens up new regions for potential discoveries. As our domestic copper is consumed, we must evaluate fully our remaining copper resources. The porphyry copper resources of the Eastern States probably never will exceed a few percent of our total minable copper, but a reasonable assumption is that one to five deposits, each containing 100–300 million tons of low-grade copper ore, exist in the Appalachian region.

In this report, a porphyry copper- (or porphyry molybdenum-) type deposit is defined as a deposit of widely dispersed copper sulfide related to a felsic intrusive body and associated with a major system of hydrothermal alteration. A widely occurring porphyry type is typically subvolcanic and has many characteristics indicating formation close to the surface; however, some deposits clearly formed at depths as great as several kilometers. In many porphyry deposits, particularly those formed close to the surface, the hydrothermal rock alteration and the sulfides deposited tend to be arranged in symmetrical zones such as those described by Lowell and Guilbert (1970). Some near-surface porphyry deposits formed in association with volcanoes (Sillitoe, 1975). Pipelike breccia bodies, many containing tourmaline, are associated with many porphyry copper deposits. Sulfides may occur mainly as veinlet fillings or as disseminated grains in different parts of the same deposit, generally in a systematic relationship to zonation. In the selection of deposits to be regarded as porphyries in this study, overall size was considered not as important as the presence of widely distributed sulfide accompanied by extensive hydrothermal rock alteration. Fluid inclusion studies in porphyry deposits (Nash and Theodore, 1971; Takenouchi and Imai, 1975, p. 769; Nash, 1976) have shown that halide-bearing inclusions are common in porphyritic bodies related genetically to mineralization, especially in the cores of porphyry copper deposits. In this study, abundant halide-bearing inclusions are considered a strongly favorable factor in classifying mineralized localities as porphyry copper-type deposits, but the apparent absence of such inclusions is weighted less heavily in a negative sense.

Global tectonic principles may have been important controlling factors in the formation of Paleozoic porphyries, just as they seem to have been in Tertiary and Quarternary porphyries, and, therefore, appropriate plate tectonic models form a reasonable basis for selecting general regions for further prospecting. The relationship of porphyry copper deposits to the plate tectonic model has been described by Sillitoe (1970) and by others in more recent articles. Application of these principles to the search for additional Paleozoic porphyries in the complex Appalachian geological environment requires caution as well as good regional mapping and structural and stratigraphic analysis. The role of plate tectonics in Precambrian time, however, is still not clear. The tectonic history of the Appalachian region as reinterpreted according to "the new tectonics" is still hypothetical and subject to multiple interpretations, and the theoretical model of a relatively simple plate margin and its related mineralized porphyry intrusions is also interpreted in different ways. The attempt to use paleo-plate tectonics in the search for copper-molybdenum porphyry deposits in the complex Appalachian environment may now seem premature, but thought is being given to exactly this idea by exploration geologists, and exploration decisions have probably been based on these principles already.

Porphyry copper-molybdenum deposits probably formed close to the surface; furthermore, many or most of them probably formed in terrains that were undergoing simultaneous rapid erosion. Thus, many older porphyry deposits have been eroded away entirely, or only the deepest parts have been left; we do not expect porphyry deposits to be nearly as abundant in Paleozoic and Precambrian as in younger rocks. However, some deposits have been found, and the existence of these older minable ore bodies confirms that the older rocks are a legitimate exploration target.

The Mount Pleasant deposit in New Brunswick has been variously regarded as one of porphyry type (Hollister, Potter, and Barker, 1974) or as one having affinities to a porphyry-type deposit (Kirkham and Soregaroli, 1975). It resembles a porphyry copper deposit in its subvolcanic setting, large size, and structural control. The complex metal suite including tin, tungsten, and bismuth, the complex mineralogy, telescoped mineral zones, and areas of intense fluorine metasomatism are unlike typical porphyry copper systems, but some of these features are also found in the Climax and Henderson porphyry molybdenum deposits, Colorado, and I believe also in certain of the tin-copper deposits of Cornwall, England. Mount Pleasant is of the same general age as the Cornwall deposits. The Brewer Mine area, South Carolina, has a large zone of intense alteration, fluorine metasomatism, and a metal suite that includes copper, gold, tin, bismuth, arsenic, and molybdenum. The possibility that the Mount Pleasant and the Brewer Mine deposits have a similar origin and are also similar to the deposits of Cornwall may be important in determining how they should be evaluated and in searching for additional deposits of similar type.

This report is a summary of current knowledge of porphyry copper- (and molybdenum-) type deposits in the Eastern United States and a preliminary attempt at placing the Paleozoic deposits in a metallogenic model; more favorable areas for further mineral exploration are suggested. Selected deposits in Canada are also included in the summary because of their significance in developing metallogenic models and planning exploration in this country.

In addition to the collection of information from published reports, this investigation included a detailed study of the Catheart Mountain deposit in Maine, examination of drill cores from the Newell and Ellis prospects in North Carolina and from the Brewer mine in South Carolina, and brief field visits to most of the other New England prospects described, as well as to the Woodstock prospect and the Mount Pleasant deposit in New Brunswick.

The cooperation of many companies and individuals who gave permission to publish new data and who helped to provide the information in this report is gratefully acknowledged, especially the following: Scott Paper Co.; Noranda Exploration Co., Ltd.; A. W. Lockhart; Humble Oil and Refining Co.; Mrs. Harold Pelkey; Mr. and Mrs. John Sprague; Lindgren Exploration Co.; Bear Creek Mining Co.; and Perry, Knox, Kaufman, Inc.

I am grateful to Paul Josefson of the U.S. Geological Survey for translation of part of the Russian article by Khrushchov (1959).

PORPHYRY COPPER DEPOSITS IN PRECAMBRIAN ROCKS

At least four known mineral deposits in the Canadian shield are now considered to be of the porphyry copper-molybdenum type, and additional ones should be identified when this type of deposit becomes better known among prospectors and geologists working in Precambrian rocks. In evaluating the potential of the Canadian shield for discovery of porphyry deposits, Kirkham (1973) described similarities to younger porphyries: "close spacial associations with felsic and intermediate epizonal plutons, some of which may have been feeders for their host calc-alkaline and alkaline volcanic piles." He said further that "many of the deposits and areas still show a zonal distribution of alteration minerals, sulfides and metals which could be useful in exploration."

Kirkham stated that most known Precambrian porphyry deposits are of minor economic importance; however, some presently support operating mines or contribute to production of mines based mostly on ores of other types.

The following deposits (three Precambrian W and one Precambrian Y) have been selected from a much larger number of deposits and prospects in Canada because they are considered to be among the best examples of Precambrian porphyry copper systems. No examples are known in the United States, but large areas of Precambrian rocks in Minnesota, Wisconsin, and Michigan are generally similar to the areas where the Canadian deposits are known.

McINTYRE PORPHYRY COPPER DEPOSIT

A copper deposit in the McIntyre (now called Pamour) gold mine at Timmins in the Porcupine district, Ontario, contains 8 million tons of 0.7 percent copper ore (Pyke and Middleton, 1971, p. 61) in rocks of Precambrian W age. Production of gold and silver at this mine started about 1912; mining of the copper ore body began in 1963. The operations are underground.

The copper ore is associated with a sericitized and sheared leucocratic quartz feldspar porphyry, the Pearl Lake porphyry. Pyritization is extensive, and copper is in chalcopyrite and bornite. Some molybdenum and silver are also present; tungsten, zinc, and lead are associated with the gold ores. The geology as described by Pyke and Middleton (1971, p. 61) is as follows:

> The porphyry is about 5,000 feet long, 1,500 feet wide and plunges 50 degrees east, parallel to the pronounced lineation

so common in all the rocks in this part of the Timmins area. The porphyry is extensively sheared and sericitized and contains abundant gypsum, anhydrite and locally hematite around the ore zones. A 400-foot-wide zone characterized by extensive pyritization, contains disseminated chalcopyrite-bornite mineralization (minor tetrahedrite, tennantite, molybdenite and native silver are also present) and has been traced vertically for 5,000 feet (Griffis, 1962). Ore-grade material is confined to a zone about 1,200 feet long and 300 feet wide, and extends vertically from the 1,100-foot to the 3,600-foot elevation (Carter, 1967). The ore zone has the same plunge as the porphyry. Typically, the mineralization is concentrated along slip surfaces which plunge at the same angle as the porphyry. Less commonly, the sulphides are finely disseminated in non-sheared massive sections of the porphyry. The concentration of the sulphides along slip surfaces in the porphyry suggests a redistribution of the mineralization during shearing and hydrothermal alteration of the porphyry. That disseminated copper mineralization is present in massive porphyry suggests that the sulphides are indigenous to the porphyry.

I wish to emphasize the statement by Pyke and Middleton (1971, p. 61) that the identification of the mineralized Pearl Lake porphyry in the McIntyre mine is very important because the deposit "demonstrates not only porphyry copper deposits formed during Early Precambrian times, but that the level of erosion has not been so great as to remove these deposits."

SETTING NET LAKE PORPHYRY MOLYBDENUM DEPOSIT

This low-grade molybdenum deposit in northwest Ontario, about 400 km northeast of Winnipeg, is associated with an epizonal lower Precambrian porphyritic granodiorite-quartz monzonite stock where four intrusive phases have been recognized (Ayres, Wolfe, and Averill, 1973; Wolfe, 1974). The mineralized zone, in altered quartz monzonite in the northern part of the pluton, consists of closely spaced 1- to 2-mm-wide molybdenite-coated quartz veinlets and associated sericitic and chloritic alteration and pyritization. The highest grade material, occupying about half a square kilometer, contains about 0.06 percent molybdenite and minor amounts of copper (Wolfe, 1974, p. 28, and fig. 4, p. 33).

PORPHYRY COPPER DEPOSITS IN THE CHIBOUGAMAU AREA, QUEBEC

A porphyry-type copper deposit has been reported from Precambrian rocks near Chibougamau in northern Quebec by Jules Cimon (oral commun., March 1973). Mineralized areas are associated with several magnetic anomalies in the southwestern part of the tonalite-diorite Chibougamau pluton, a felsic body 65 km long by 2–16 km wide. The pluton occupies the center of the Chibougamau anticline within the Lac Doré layered mafic complex (Duquette, 1970, p. 10).

The six magnetic anomalies are related to stockworks of magnetite-chalcopyrite formed along what Cimon (oral commun., March 1973) called strongly metasomatized zones. In the most important localities, designated areas 3 and 4, the mineralization is confined to zones that are intensely intruded by a complex system of felsic porphyry dikes. The most common type of dike is a green aphanitic rock containing quartz phenocrysts, and other types are feldspar porphyry and quartz-feldspar porphyry. The intruded zones are locally highly brecciated, and some of the breccia has fine-grained tourmaline in the matrix material.

Potassic alteration is reported to be ubiquitous close to sulfide-magnetite mineralization (Cimon, oral commun., March 1973). Primary plagioclase has been altered to potassium feldspar, either evenly or in patches, and secondary biotite is present in a few places. The increase in total K_2O content is as much as 3 percent. Potassic alteration is of variable width along fractures. Outside the areas of potassic alteration, sericitization and chloritization are widespread, but the areas of these zones have not been defined. Regional greenschist facies metamorphism makes it impossible to delimit propylitic alteration related to the mineralization.

Magnetite is the most important iron oxide, but exploration drilling has penetrated some hematite zones, suggesting that perhaps part of the deposits was formed at relatively shallow depths (Cimon, oral commun., March 1973). Pyrite is commonly disseminated, and locally it is abundant.

Although still in a stage of preliminary investigation, this porphyry area is perhaps as important as the Pearl Lake porphyry at the McIntyre mine, Ontario, in establishing the concept of deposits of the porphyry type in rocks of Precambrian X age.

BRECCIA PIPES AND MINERALIZED PROPHYRY OF THE BATCHAWANA AREA, ONTARIO

Five known breccia pipes in the Batchawana area, 64 km north of Sault Ste. Marie, Ontario, are presumed to have a common origin, and the Jogran porphyry stock, several kilometers to the southwest, may also be related. Two of the pipes are being mined by the Tribag Mining Co. for copper and silver; a third contains disseminated copper and molybdenum sulfide, as does the porphyry stock. One of the deposits now being mined, the Breton zone breccia, is underlain by a highly altered feldspar porphyry.

The geology of the area has been described by Blecha (1965, 1973, 1974). The deposits are near the northern edge of a northeast-trending belt of Precambrian W greenstones, sedimentary rocks, and mafic intrusive rocks. Granitic rocks underlie the area both north and south of the belt. Five breccia pipes are at, or close to, the granite contact; two of these are entirely within volcanic rocks and diabase of the greenstone sequence, and one is surrounded mostly by granite. The locations of the breccias are probably structurally controlled and related to lineaments (Blecha, 1965, p. 1079). Blecha (1965, p. 1079–1080) stated: "The breccia consists of angular fragments of granite, diabase and basic volcanics, and of basic and acidic dyke material. Each of these rock types occurs in the immediate vicinity of the breccia and no fragments truly foreign to the area have been found within it." However, Blecha (1973) further stated: "The pipes contain a high proportion of felsophyric fragments which suggest the presence of a deep-seated porphyry intrusive."

Sulfides are most abundant in a vuggy quartz-carbonate matrix in open breccias, generally within distinct alteration halos as much as 46 m wide (Blecha, 1965, p. 1081) that have been used as guides in exploration. The alteration minerals are mainly sericite, chlorite, and clay minerals, depending on the composition of the original rock. Sulfide minerals are mainly pyrite and chalcopyrite and subordinate galena, molybdenite, chalcocite, and scheelite. Silver is an important product of ore concentration, but no silver mineral has been identified. The greatest alteration and the best ore are associated with domal fractures that are probably related to upward-propagating collapse.

Sericite from the Breton breccia zone has been dated by K-Ar methods as 1.055 b.y. (Roscoe, 1965). Fluid inclusion studies by Norman (1974) indicate that there were five stages in the brecciation, void filling, and mineralization of the five breccias.

These copper-molybdenum-bearing breccia pipes probably share many features with much younger breccia ore bodies, such as those described by Sillitoe and Sawkins (1971), but the Batchawana deposits lack the tourmaline and specularite common in many of the younger ones.

The Jogran quartz-feldspar porphyry stock, 6 km southwest of the breccia pipes, is partly altered and contains disseminated chalcopyrite, pyrite, and molybdenite (Blecha, 1974, p. 75). Giblin (1974) and Blecha (1973) suggested that the mineralized stock is of the porphyry copper type.

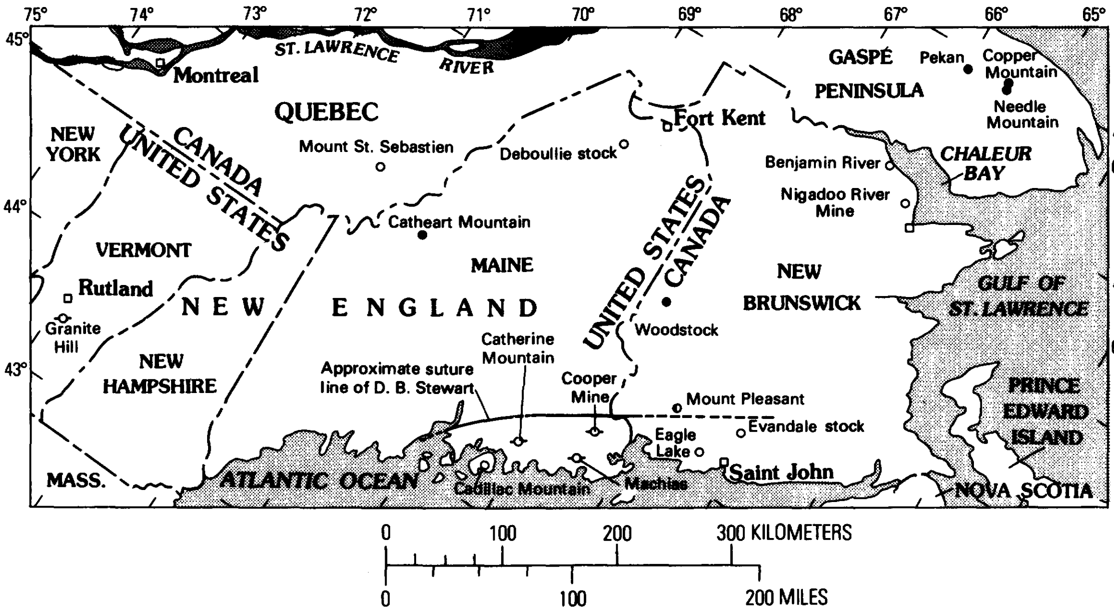
PORPHYRY COPPER AND MOLYBDENUM DEPOSITS IN PALEOZOIC ROCKS OF NEW ENGLAND, THE GASPE PENINSULA, AND NEW BRUNSWICK

The New England-Maritime Provinces-Gaspé area contains many deposits and prospects of disseminated copper and molybdenum sulfides. All, or only a few, of these deposits may be classed as the porphyry type depending on the definition or model used. The types of deposits tend to be grouped into types by region, and the inclusiveness of the definition that one uses for a porphyry system strongly biases the pattern of regional distribution.

As explained in the introduction, the major criteria applied in this report for classifying deposits as porphyry-type were the presence of widely distributed copper (or molybdenum) sulfide and also the presence of extensive hydrothermal rock alteration. Some prospects regarded by other writers (such as Hollister, Potter, and Barker, 1974) as porphyries have been omitted here because they are only locally mineralized and (or) lack sufficient rock alteration.

One deposit in Maine, one in New Brunswick, and three in the Gaspé Peninsula are, I believe, certainly members of the porphyry type (fig. 1). In addition, the Mount Pleasant deposit in New Brunswick has close affinity to the porphyry type and has been classed as a porphyry by Sillitoe, Halls, and Grant (1975, p. 925). Information sufficient for classification of a few other prospects is not available at this time.

Of particular importance in metallogenic modeling is the classification of several prospects along the Maine and New Brunswick coast (fig. 1). Inclusion of the prospects in a model of porphyry-type copper deposits greatly extends the area of potential porphyry occurrence and is, I believe, very misleading. These coastal prospects fit well into the "molybdenite" class or type as defined by Khrushchov (1959), and he states that few of this type are known to be exploitable. The molybdenite type of molybdenum deposit (I hereafter refer to it as molybdenitic), as described by Khrushchov (1959), results from post-consolidation autometamorphism of plutonic rocks, essentially deuteric alteration. The molybdenum generally occurs as sparse disseminated molybdenite flakes in felsic rocks, characterized by lack of associated vein-type minerals and metallic sulfides, and lack of rock alteration of the enclosing rocks. The intrusive rocks include granite (perhaps interpreted broadly as quartz-monzonite to granite), aplite, and syenite. Some molybdenitic deposits cited by



EXPLANATION

- ● Porphyry copper-molybdenum deposit
- ◐ Deposit of porphyry-copper affinity
- -o- Lean mineral occurrence of molybdenitic type
- o Uncategorized copper and(or) molybdenum deposit

FIGURE 1.—Index map showing porphyry copper-molybdenum deposits and certain other mineralized localities in New England, New Brunswick, and Quebec.

Khrushchov are near the contacts with country rocks, similar to the Cooper Mine and Quarry Hill prospect in New England; it is not clear to me if any of his molybdenitic examples are within the central parts of plutons. Small bodies up to a few meters across within one of the Soviet molybdenitic deposits contain as much as 10 percent molybdenum, and similarly, the Quarry Hill prospect may have yielded samples that analyzed as much as 30 percent molybdenum, but total molybdenum resources of deposits of this type are interpreted to be small.

The geology of the northern Appalachian orogen has been interpreted by Bird and Dewey (1970) in terms of plate tectonics theory. Although the general concept, to say nothing of specific local details, remains controversial among geologists, new ideas on distribution of porphyry-type deposits are closely tied to the theory and may help to explain the distribution of the ore deposits in this area, as suggested by Halls and Simpson (1972, p. B180). Ore deposits at Catheart Mountain, Maine, and the Gaspé copper mines (Copper Mountain and Needle Mountain), Quebec (fig. 1), and other mines and prospects are associated with postorogenic shallow or subvolcanic plutons, probably of late Acadian age (table 1). Other intrusive bodies of this type seem to be the most promising loci for new porphyry copper prospects in the region. D. B. Stewart (oral commun., 1975) identified an "Ellsworth block" of European-African continental crust in the Maine coast area that collided with the North American continent during the Devonian Period. The approximate line or suture along which this collision took place is shown on figure 1. Although the exact location is still open to dispute, this approximate location is more than adequate for metallogenic modeling, and may have considerable implication in selecting areas for prospecting for porphyry copper deposits. Porphyry-type and other hydrothermal mineral occurrences, all of Devonian age, include Catheart Mountain, Maine, the Pekan, Copper Mountain, and Needle Mountain deposits, Quebec, and the Nigadoo River mine, New Brunswick, and form a broad northeast-trending belt (fig. 1). If the mineralized felsic intrusive bodies were related to subduction during the Devonian continental collision along the line suggested by Stewart, then the five mineralized localities listed above range from 100

TABLE 1.—*The ages or age limits of Paleozoic base metal deposits in New England and eastern Canada*

Locality	Age	Reference
Keene Dome, N.H	373±15 m.y. (on related muscovite)	Foss, Scherffius, and Gaudette, oral commun., 1975.
Catheart Mountain, Maine	Late Ordovician	Boone, Boudette, and Moench, 1970, p. 19.
Mount St. Sebastien, Quebec [1]	Devonian	Kirkham and Soregaroli, 1975, p. 251.
Deboullie stock, Maine [1]	Later than stock which is post-Middle Devonian	Boone, 1962, p. 1453.
Pekan deposit, Quebec	Later than Silurian and Devonian sedimentary rocks.	Pérusse, 1969.
Gaspé copper mines (Needle Mt. and Copper Mt.).	Later than Middle Devonian sedimentary rocks	McAllister and Lamarche, 1972.
Mount Pleasant deposits	Mississippian	McAllister and Lamarche, 1972, p. 85.
Woodstock, New Brunswick	In rocks that that cut pre-Silurian strata	Anderson, 1954, p. 2.
Nigadoo River mine, New Brunswick.[1]	Acadian or shortly after	Suensilpong and Stumpfl, 1971, p. B105.
Cooper mine, Maine [1]	Within rocks of Devonian age	Hussey and others, 1967.
Catherine Mountain, Maine [1]	do	Do.

[1] I did not include in porphyry-type deposits as defined in this paper.

to 320 km in distance northwestward from it. (As the position of volcanism is believed related to the Benioff zone in the depth range of 100–200 km, the horizontal distance from the suture is a function of the dip of the Benioff zone. The average distance of volcanism and porphyry development from Benioff zones of intermediate dips is 200 km (Mitchell and Garson, 1972, p. B12).) Thus, the distribution of the several porphyry copper and copper-molybdenum deposits in this region permits the construction of a hypothetical metallogenic model showing a broad belt that includes parts of western New Hampshire, northwestern Maine, and southeastern Quebec as much more favorable for further discoveries than areas to the northwest and southeast of the belt.

Moench and Gates (1976) examined the chemical compositions of the volcanic rocks in the Maine and New Brunswick coastal belts and concluded that the volcanism had been bimodal, not andesitic; therefore, it was probably not an island-arc suite. Acceptance of this conclusion does not preclude application of the continental-collision model to the origin of the porphyry-type deposits, however, as subduction and collision may have occurred without formation of an arc.

KNOWN DEPOSITS OF PORPHYRY TYPE

CATHEART MOUNTAIN EXPLORATION

The porphyry copper-molybdenum deposit at Catheart Mountain, Maine (fig. 1), is in a large complex hydrothermal alteration system. To the extent that they have been identified, alteration and mineralization zones are moderately well developed on an overall scale as well as on smaller scales related to individual porphyry bodies and mineral veins. Mineralization is related to several subvolcanic porphyry intrusives, and copper and molybdenum occur within the porphyry as well as in a medium-fine-grained quartz monzonite country rock.

The Catheart Mountain deposit is on land owned by the Scott Paper Co. It was discovered in 1963 and has been entensively explored by the Noranda Exploration Co., Ltd. A study of mineral and alteration zonation was started by the U.S. Geological Survey in 1970. Results of examination of drill cores from an ore body were described in an earlier report (Schmidt, 1974).

Country rock in the vicinity of the Catheart Mountain deposit is gray uniform medium-fine-grained quartz monzonite that occurs within the much larger pluton of Attean Quartz Monzonite (Lower Ordovician). No well-exposed contacts between the two rock types have been seen, and the relationships of the two are not clear. The quartz monzonite of Catheart Mountain is distinguished by the generally finer grain size and by the absence of the 1- to 2-cm feldspar megacrysts so characteristic of the Attean Quartz Monzonite. The Attean Quartz Monzonite was described by Albee and Boudette (1972), and chemical analyses of the two rocks were tabulated for comparative purposes by Schmidt (1974, p. 191).

The hydrothermal alteration zones have been mapped from outcrop information and exploration drill cores (fig. 2). Despite gaps in some boundaries, the zonation pattern follows the well-known form of many other porphyry systems (Lowell and Guilbert, 1970).

Copper and molybdenum sulfides are present in most of the altered rock in the large hydrothermal system, but they have been identified in potentially extractable amounts in only a limited area on the southwest flank of the mountain (hereafter called the ore body) and in small masses or pods at other localities.

There are also two subsidiary nodes of potassic alteration on the southwestern flank, and one of these is the location of the known ore body; thus, the only sizable mass of potentially extractable ore is associated with its own small zonation pattern but is located well down on the flank of the main zone system. Folding later than formation of the deposit, as recorded in Devonian strata, 4 km to the east, may have rotated the zonal system from its original position. The most probable rotation seems to be downward to the southeast—perhaps as much as 60°—around an axis that trends northeastward and may plunge northeastward at a low angle. If rotation has occurred in this fashion, it does not significantly change the conclusion about the position of the ore body on the flank of the system, but it may have made great changes in the apparent position of the features on the northwest and southeast sides of the system. Exploration of the southwest flank of the system has been thorough only close to the known ore body; parts of the northeast, northwest, and south flanks are covered by glacial drift and remain untested.

A well-developed pyrite zone (mostly 2–5 percent sulfide) is present within the quartz-sericitic and potassic alteration zones of the main alteration system. Along the southeast side of the alteration

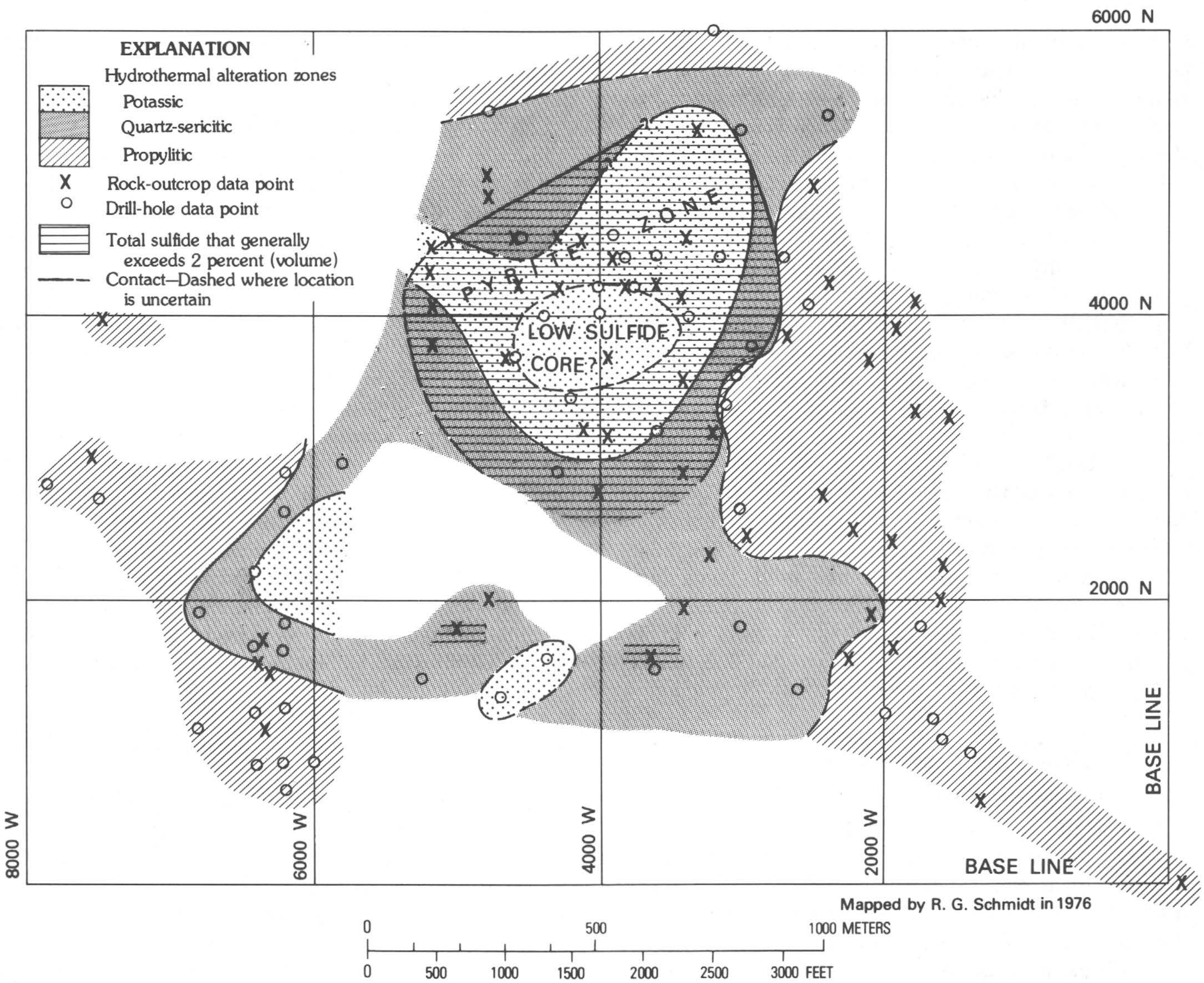
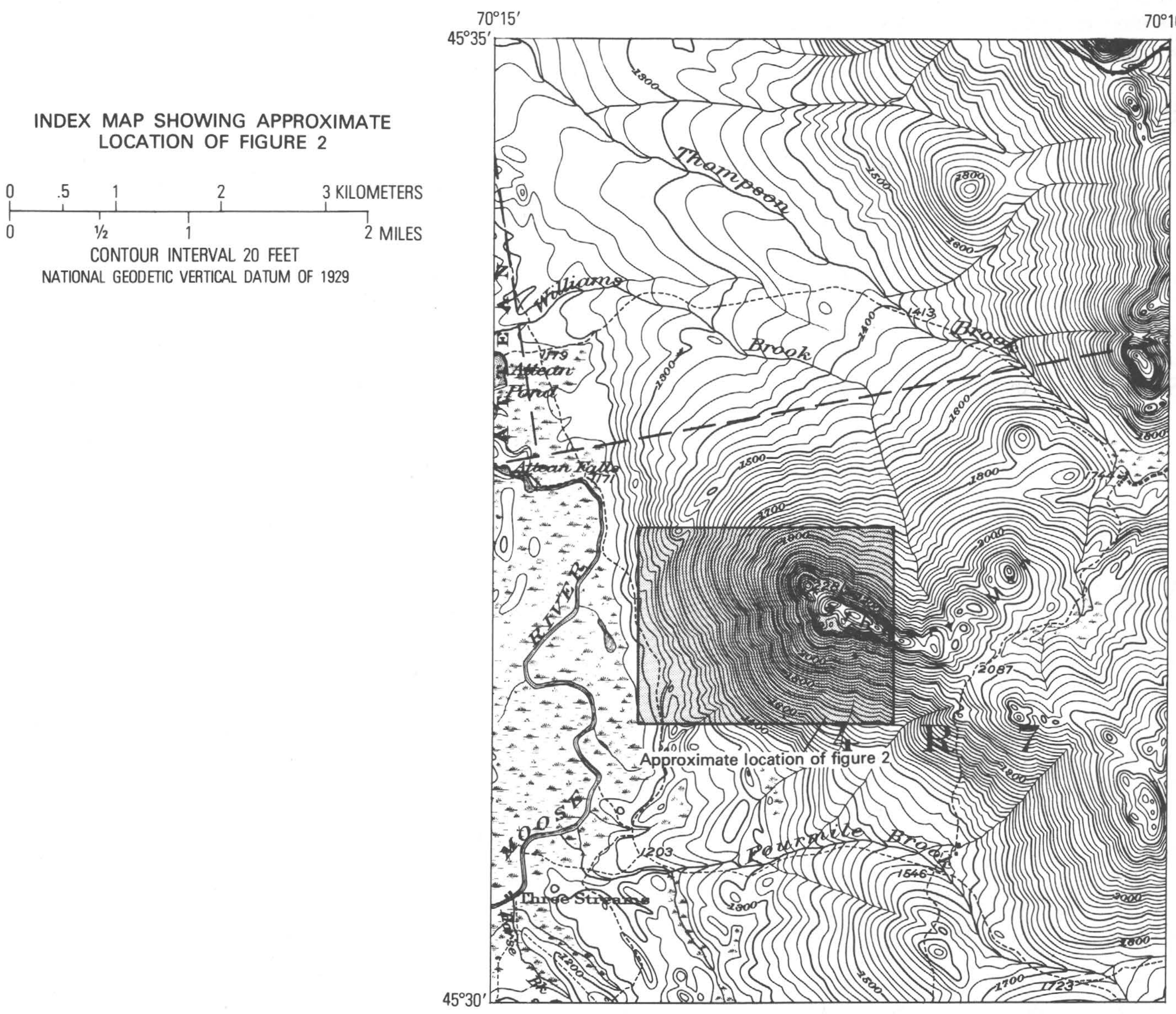


FIGURE 2.—Sketch map showing hydrothermal alteration zones and sulfide content at Catheart Mountain, Somerset County, Maine.

model, limits of the pyrite zone are close to the edge of the quartz-sericitic (phyllic) alteration zone, much like the "typical porphyry" as described by Lowell and Guilbert (1970, p. 379), but elsewhere the edge of the pyrite zone falls 500 m and more inside the limit of the quartz sericitic zone, and overlaps most of the central potassic zone, unlike the ideal Lowell-Guilbert model. Most of the rock associated with the ore body contains no more than 2.3 percent sulfide (Schmidt, 1974, p. 193).

Within the ore body, overall zonation is similar to the main system but on a smaller scale. The details of zonation are very complex and seem to be related to small dikes of porphyry and to veins and veinlets. In examination of drill-hole cores, most rock was assigned to one of seven alteration types, but the data did not generally permit interpretation of the alteration as simple successive zones. The average analyses of copper and molybdenum and the total contained sulfides in the rocks were found to be systematically different in the main alteration types (Schmidt, 1974, p. 193). When the alteration types were arranged on a chart in a sequence based on a combination of increasing copper plus molybdenum values and decreasing copper-molybdenum ratios, the resulting synthetic zonation was similar



Base from U.S. Geological Survey, 1:62,500, Long Pond, Maine, 1922

FIGURE 2.—Continued.

to that in the main Catheart Mountain system and in porphyry copper deposits elsewhere.

Examination of fluid inclusions in hydrothermally altered rock from Catheart Mountain indicates that strong brines were present in at least part of the hydrothermal system. Relatively small bubbles in gas-liquid inclusions suggest that the part of the system we now see never closely approached a boiling condition. Local explosion breccias and a fine groundmass in the porphyry bodies indicate that the system was probably not more than a few kilometers deep at time of formation. Thus, these sparse depth indicators suggest an intermediate (perhaps 2–5 km) depth of formation for the part of the deposit we now see. This contrasts with the relatively deeper burial during mineralization ascribed by Hollister, Potter, and Barker (1974, p. 627–628), and with my own earlier interpretations.

A small exposure of sulfide-bearing pebbly siltite containing fragments of quartz and assorted volcanic porphyry is in the northeast part of Catheart Mountain. This exposure is probably bedrock outcrop, and the sulfide in it roughly corresponds to the sulfide content of rocks in other nearby outcrops, but it is also possible that this is a float boulder. This sedimentary rock, if it is local bedrock, suggests that some generally contemporaneous extrusive volcanic material was included in the zone of mineralization and supports the idea of formation of the deposit at a relatively shallow depth.

The Catheart Mountain deposit is in the altered rock produced by a large hydrothermal system, and the altered area may extend outward beneath the glacial drift cover to the northeast, to the northwest, and perhaps also to the south into areas where there has been partial evaluation (northeast and south) or essentially no evaluation (northwest) by exploration drilling. It is my opinion that peripheral exploration will probably further extend the area of known alteration. The known ore body is peripheral to the central alteration system and therefore the remaining flanking areas seem at least as attractive for exploration as the center, if not more so.

THE GASPE COPPER DEPOSITS

The Copper Mountain and Needle Mountain deposits (fig. 1) at Gaspé Copper Mines, Ltd., Murdochville, Quebec, represent contrasting types of "typical" porphyry mineralization within a 6.5-km^2 zone of intense hydrothermal alteration believed related to small quartz-feldspar porphyry bodies. The deposits have been described by MacIsaac (1969), and McAllister and Lamarche (1972, p. 38–45). Mining at Needle Mountain began in 1955 and at Copper Mountain in 1968. Together they form the largest porphyry-type deposit in production in eastern North America and the largest of Paleozoic age known in the Americas.

The Gaspé deposits are in an area of Lower and Middle Devonian sedimentary rocks, especially calcareous shale, siliceous limestone, siliceous shale, siltstone, and sandstone. Contact metamorphism and hydrothermal alteration have converted these strata to a variety of hornfels and skarns (MacIsaac, 1969, p. 831; Allcock, 1974) in the area surrounding small intrusive bodies of quartz-feldspar porphyry. Hollister, Potter, and Barker (1974, p. 624) cited a K/Ar age af 346 m.y. for intrusive rock here.

The Copper Mountain deposit is a large low-grade stockwork ore body (230 million tons, 0.40 percent Cu (McAllister and LaMarche, 1972, p. 43)) in which chalcopyrite, the major copper mineral, occurs in fractures, veins, replacements, and as disseminated grains (MacIsaac, 1969). The ore body is closely related in space to a large plug and many dikes and sills of quartz-feldspar porphyry, but especially to one east-trending dike. Ore occurs both around and in the intrusive bodies, and favors certain stratigraphic layers. The pyrite zone occupies much of the alteration zone; within the ore body the pyrite-chalcopyrite ratio is about 3:1. Sparse molybdenite is distributed widely, mostly in veins, and is most abundant in the center of the ore body. Bismuth, silver, gold, selenium, and tellurium are other associated metals.

The nature of rock alteration in sedimentary host rock is different from that in intrusive rocks. The sedimentary rocks have been intensely silicified and bleached, and diopside and garnet were formed. The porphyries are kaolinized, although it is not clear how much of this alteration may be supergene (MacIsaac, 1969, p. 834).

The Needle Mountain deposit is primarily a skarn-type replacement ore body in sedimentary strata without known close spatial relationship to an intrusive body, but its occurrence within the same alteration zone as the Copper Mountain ore body suggests a common source of mineralizing solutions. Ores have been formed by selective replacement of four layers of calcareous sediments, separated by less calcareous units. Faults provided channels for solutions to reach the favorable layers, and faulting was an important ore control.

THE PEKAN DEPOSIT

Located about 35 km southwest of Copper Mountain and Needle Mountain, this is also a disseminated copper-molybdenum deposit related to felsic subvolcanic intrusive bodies (Pérusse, 1969). The intrusive bodies are a variety of small stocks, dikes, and sills of granodiorite and felsic porphyries that have different texture, color, and phenocryst composition. A breccia pipe about 300 m in diameter was described by Pérusse (1969, p. 825), but he did not indicate that the pipe was mineralized. Copper occurs mainly as chalcopyrite and bornite in skarns that have formed in Silurian and Devonian limestone and siltstone. Molybdenum is present mostly as coatings on fractures in the porphyries and in quartz veinlets.

WOODSTOCK, NEW BRUNSWICK, PROSPECT

Extensive exploration for disseminated copper sulfide has been carried out on a complex of small felsic intrusive bodies and hornfelsic country rock near Woodstock in west-central New Brunswick. Appreciable copper mineralization is present in several localities within an area of 21 km^2, and trace amounts of molybdenite are also present in parts of the deposits. Reports on the copper grade, though not contradictory, give somewhat different impressions of the potential of the deposit. Lockhart (1976, p. 13) stated, "Significant areas containing 0.3 to 1.0 per cent copper were discovered, but no orebody has been outlined to date."

According to Kirkham and Soregaroli (1975, p. 249), recent exploration "has indicated a large tonnage of very low grade copper mineralization."

Fine-grained porphyritic rocks, probably hypabyssal, are present within at least part of the mineralized area, although I cannot determine if the mineralization is related to them. Rock alteration, sulfide mineralization, and possibly some post-mineralization metamorphism have acted on quartz diorite and dioritic plutonic rocks and on hornfelsic quartzite and argillite of Cambrian and Orodovician age. Potassium feldspar is generally absent, but muscovite is very common in some of the rocks and may indicate potassium enrichment. I have insufficient data to determine if any zoning patterns can be mapped.

Fluid inclusions are relatively abundant in quartz grains, but halide crystal-bearing inclusions are sparse in the few specimens I examined, and there is no evidence for any particularly "potent" hydrothermal fluids in the system using the criteria described by Nash (1976). No gas-rich inclusions suggesting boiling fluids were seen.

Most rocks from the area contain chlorite and epidote, the result of low-grade metamorphism or propylitic alteration, and perhaps both. It is not clear whether or not some secondary biotite formed during potassic alteration, later to be changed to chlorite during low grade metamorphism. We cannot assume that the widespread presence of chlorite and epidote indicate that no quartz-sericite zone or quartz-sericite-potassium feldspar zone was present.

Although I have not seen evidence of zonation at the Woodstock deposit, I believe that the deposit represents an upper part of a major porphyry system. Old prospects for lead, zinc, and copper in the vicinity (Anderson, 1954) may represent peripheral veins related to the same hydrothermal system.

PORPHYRYLIKE MINERAL PROSPECTS

Kirkham and Soregaroli (1975) described two Canadian prospects that may be of the porphyry-copper type. The Benjamin River deposit, near New Mills, New Brunswick, consists of sparse pyrite, chalcopyrite, and trace amounts of molybdenite in fractures and disseminated in quartz monzonite dikes and hornfelsic volcanic rocks. The intrusive rocks are interpreted to be of Devonian age. The Mount St. Sebastien, Quebec, prospect is 70 km northwest of Catheart Mountain, Maine. Pyrrhotite, molybdenite, and minor chalcopyrite occur in small quartz veins in hornfels adjacent to a biotite quartz monzonite intrusive body. Kirkham and Soregaroli (1975, p. 251) stated that "the intrusions in the area have been dated as Devonian by K/Ar methods."

KNOWN DEPOSITS OF PORPHYRY COPPER AFFINITY

MOUNT PLEASANT DEPOSITS

Although mainly of interest for their tin, tungsten, and molybdenum, the deposits of Mount Pleasant in southwest New Brunswick are also partly copper bearing. These deposits, in the volcanic rocks of a caldera of Mississippian age, have been described by McAllister and LaMarche (1972, p. 82–89) and Dagger (1972). The deposits probably most closely resemble the tin-copper deposits of Cornwall, and suggest that additional deposits of this type may be present along the eastern margin of North America.

A mixed assemblage of volcanic rocks is present at Mount Pleasant. The mineralization is related to two pluglike bodies that are interpreted to be erosional remnants of volcanoes. The plugs are highly altered felsite, tuff, and breccia; the intruded rocks are primarily felsic ash-flow tuffs. Three overlapping but distinct zones of hydrothermal alteration concentric about the two plugs were mapped and described by Ruitenberg (1963; 1972, p. 442). The mineralized "greisen" zone consists of quartz, fluorite, kaolinite, topaz, hematite, and chlorite. This is surrounded by a zone of intense silicification accompanied by kaolinization. The lowest grade alteration is weak pervasive silicification, sericitization, and chloritization (the report of chlorite in the most intensely altered central zone has a parallel in the chlorite of the deep central core of the porphyry copper model proposed by Lowell (1968, p. 652)).

Two types of metallic deposits are present at Mount Pleasant. The most important consists of Mo, W, and Bi sulfides and lesser As, Zn, Cu, Sn, and Pb. The main deposit of this type is in the core of the southern volcano remnant. The Cu-Sn-Zn deposits (they also contain some Bi, In, Cd, W, and Ag) are small compared to the main Mo-W-Bi ore body. Three main Cu-Sn-Zn bodies are known, one near the northern volcano and two near the south vent (McAllister and LaMarche, 1972, p. 89).

HYDROTHERMAL MINERALIZATION RELATED TO FELSIC STOCKS BUT NOT HERE INCLUDED WITH PORPHYRY-TYPE DEPOSITS

EVANDALE STOCK, NEW BRUNSWICK

A quartz monzonite stock of Devonian age (Potter, Rutenberg, and Davies, 1969, p. 72) about 5 km in diameter is west of the Saint John River (approximately lat 45°35′ N., long 66°05′ W., 35 km north of Saint John). Chalcopyrite and molybdenite occurrences were discovered in the stock in 1968, and much exploration has been conducted since.

The Evandale stock is medium to coarse grained, and gray to pink. Orthoclase and plagioclase are about equal in amount (Ruitenberg, 1970, p. 7). Red and buff aplite dikes up to 1.5 m wide trend north-northwest. The stock has intruded dark-gray slate, argillite, and siltstone of Ordovician or Silurian age; an aureole of dark-brown hornfels 60 m thick has formed next to the contacts.

Sulfide minerals, mostly chalcopyrite, have been discovered in fractures and quartz stringers in a zone 2,400×460 m in the northwestern part of the Evandale stock. Veinlets about 2 mm wide are spaced 2–15 cm apart and trend mostly north-northwest. Pink alteration of feldspars is up to 1 cm thick along the mineralized fractures. Abundant molybdenite is reported from only one locality (Ruitenberg, 1970, p. 8). No genetic relationship of the sulfide minerals to the aplitic intrusive rocks has been suggested in published accounts. Too little is known of the copper and molybdenum mineralization for me to include this as a porphyry-type deposit at this time.

NIGADOO RIVER MINE, NEW BRUNSWICK

The Nigadoo River mine is a vein deposit rather than a porphyry-type deposit, but the copper-lead-zinc-silver veins occur within and adjacent to a small quartz porphyry plug intruded as a late phase of, or shortly after, the Acadian orogeny. A detailed description of the ore body was given by Suensilpong and Stumpfl (1971). The mine is about 18 km northwest of Bathurst, New Brunswick, within the Tobique structural-metallogenic zone as defined by Potter, Ruitenberg, and Davies (1969). Sedimentary country rocks in the vicinity consist of "mainly gray-green, fossiliferous argillites and calcareous graywackes, with minor layers of conglomerate, slate and limestone" (McAllister and Lamarche, 1972, p. 73).

The quartz-feldspar porphyry is a rather narrow vertical pipe. Horizontal dimensions are roughly 240×790 m at the surface, but several dikelike apophyses make the outline quite irregular in plan view. The intrusive body had been explored to about 600 m in 1972 (McAllister and Lamarche, 1972, p. 73–74). The same authors (p. 73) described the porphyry as "pale greenish yellow to light grey rock, containing quartz, orthoclase and plagioclase phenocrysts in an aphanitic matrix. Sericite and kaolinite are ubiquitous alteration minerals but are particularly abundant near veins. The porphyry pipe is enclosed by a zone of breccia two or three feet (30 to 90 cm) wide, containing fragments of adjacent metasedimentary rocks and porphyry."

Ore minerals occur in three successive vein-fault systems, each having different structural and mineralogic characteristics (Suensilpong and Stumpfl, 1971, p. B98–B99), but ore is mainly in the second vein group. A close spatial relationship of the mineralized veins to the porphyry intrusive body exists. Suensilpong and Stumpfl (1971, p. B105) believed that the porphyry and ore are genetically related: either ore solutions came from the cooling, mostly solidified porphyry, or the mineralizing solutions were a late-stage consequence of the same Acadian orogeny that produced the felsic intrusive rock. The same authors believed that the ore mineral zonation in the ore veins relates to the higher vein temperature in the porphyry because the intrusive body was interpreted to be still cooling when the vein minerals formed.

DEBOULLIE STOCK, AROOSTOOK COUNTY, MAINE

A geologic description of this complex stock was published in 1962 (Boone, 1962), and a private exploration company began an extensive drilling program in 1971. I have not sought the results of the exploration program, and the following description is based on Boone's article plus a 1-day visit to the generally mineralized area of the prospect.

The Deboullie stock was described by Boone as a postorogenic composite pluton. The compositions of the main types of intrusive rock range from pyroxene-biotite syenodiorite and monzonite to hornblende-biotite granodiorite. The stock is elliptical, the long axis is 5.5 km, trending northeast, and the greatest width is a little less than 3.0 km. Boone divided the stock into a relatively simple granodiorite south half and a complex north half which consists of calc-alkaline syenite and screens of monzonite, and which includes masses of country rock. The northwestern part has most of the sulfide mineralization. Sparse chalcopyrite and molybdenite occur in small fractures and are perhaps disseminated also. The extent of hydrothermal alteration is not known to me. Contact metamorphism has converted the wall rock Seboomook Formation (Lower Devonian) to andalusite-cordierite-biotite hornfels around the stock and in the inclusions. Boone mapped two hornfels areas of relatively large size that are perhaps roof pendants; these contain fairly abundant pyrite. Dikes of quartz-bearing latite, dacite porphyry, aplite, and fine-grained pegmatite were identified. Some of the porphyritic dikes appear to be hypabyssal. The alteration present in the dikes is like that associated with greenschist facies metamorphism and there is no evidence to link them to mineralization.

EAGLE LAKE, NEW BRUNSWICK

Prospecting near Eagle Lake, New Brunswick (approximately 45°16′ N., 66°22′ W.), indicated that copper, molybdenum, and silver are concentrated along fracture zones in a highly altered quartz monzonite stock (Ruitenberg, 1969, p. 13; Potter, Ruitenberg, and Davies, 1969, p. 72). Kirkham and Soregaroli (1975, p. 250) regarded the mineralization at this prospect as far too sparse to justify calling it a porphyry deposit.

MOLYBDENUM PROSPECTS OF THE MOLYBDENITIC TYPE

Several prospects containing rather sparse molybdenite on fracture surfaces and disseminated in felsic plutons have been found along the Maine and New Brunswick coasts, and also at Quarry Hill, near Rutland County, Vt. (fig. 1). These are best classed in the molybdenic type as described by Khrushchov (1959). These prospects are generally lean, but local concentrations of material containing more than 1 percent molybdenum were extracted from the Quarry Hill and Cooper mine prospects. Neither these nor the Catherine Mountain prospect and Machias occurrence have rock alteration of the kind or intensity that I associate with a porphyry-type deposit, even if I interpreted them to represent deeply eroded zones of porphyry systems such as Hollister, Potter, and Barker (1974) have done.

COOPER MINE

The now abandoned Cooper mine in Washington County, Maine, was first operated about 1902 and is said to be one of the oldest molybdenite mines in the country; however, total production probably did not exceed a few tons of concentrate (Burbank, 1965, p. 61). Last mining seems to have been in 1919. The workings probably included an underground mine as well as the small flooded quarrylike open pit visible today. The mine has been described briefly by several authors; the most complete reports were by Hess (1908, p. 231–234), Young (1963, p. 67–68 and 83–85), and Burbank (1965, p. 61–62).

The country rock adjacent to the open pit is medium-fine-grained porphyritic quartz monzonite. In parts of the pit walls, some of the feldspar, presumably the potassium feldspar, is creamy yellow or pale brown, giving the rock a slightly buff color (not to be confused with patches of weak iron-oxide staining probably related to weathering). The feldspar phenocrysts are sparse and small, generally not exceeding 5 mm in length. Matrix plagioclase is more abundant than potassium feldspar and is mostly unaltered, but in thin section some grains are lightly dusted by "sericitic" alteration. Matrix potassium feldspar is mostly untwinned. Biotite is very darkly pleochroic. No rock alteration is present, and X-ray diffraction studies of the potassium feldspar by Mary Mrose and Patricia Loferski, U.S. Geological Survey, indicate that no clay mineral exceeds the detection limit of perhaps 5 weight percent.

Burbank (1965, p. 61) described three modes of molybdenite occurrence in the mine: (1) associated with narrow pegmatite dikes and quartz veins, (2) as nests or pockets, and (3) disseminated in granitic rock. The nests and pockets as well as most of the pegmatite and vein concentrations seem to have been exposed in a trench in the quarry floor that was under water when Burbank visited in 1942 and also when I was there in 1971. I noted neither pegmatite nor aplite in the walls of the open pit, but Burbank found that "small seams of pegmatitic quartz are exposed in outcrops north of the quarry, but the amount of molybdenite in them is insignificant."

Molybdenite in the pit walls is mostly in disseminated 1- to 2-mm grains, and in a few grains as large as 10 mm. Rock containing more molybdenite than can be seen in place today was removed during the active mining, as shown in old reports and by rock on the waste dump (Young, 1963, p. 68). I took representative chip samples from the pit walls in 1971. The locations of these samples are shown in figure 3, and the analyses are given in table 2. My samples are substantially lower grade than the one collected by Burbank (see table 2). Presumed mill feed at the mine is reported to have contained 1,060 ppm (0.106 percent) molybdenite (Young, 1963, p. 68).

Hess (1908, p. 232–233) noted small amounts of fluorite and one specimen of native bismuth in the deposit.

CATHERINE MOUNTAIN (TUNK LAKE) PROSPECTS

The Catherine Mountain prospects (fig. 1) are in the central part of the Tunk Lake pluton, a circular granitic to quartz monzonitic zoned intrusive body in Hancock County, Maine. Sparse molybdenite is present over an extensive area on Catherine Moun-

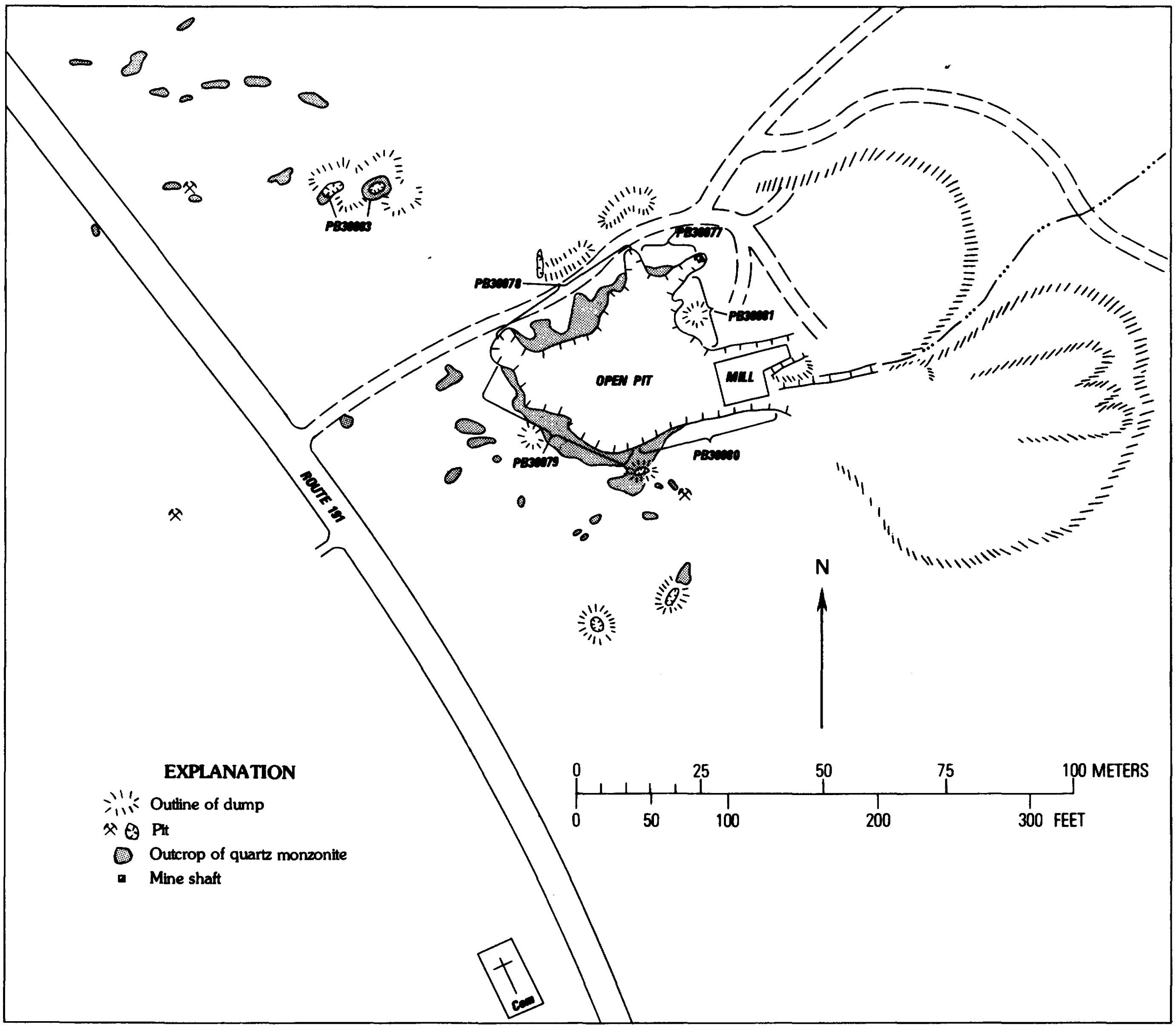


FIGURE 3.—Sketch map of Cooper mine, Washington County, Maine, showing locations of samples analyzed (see table 2). Map has been modified from Young (1963, p. 83).

TABLE 2.—*Analyses of composite samples from Cooper mine*

[Results in parts per million. Analyses by E. Y. Campbell, E. G. Lillie, and R. Moore, U.S. Geological Survey. Bismuth was determined by a substoichiometric isotope dilution technique; copper was determined by atomic absorption spectrometry; molybdenum and tungsten were determined by newly developed isotope dilution spectrophotometric techniques]

Sample No.	Cu	Mo	Bi	W
PB30077	10	110	75	26.5
78	11	36	120	92.
79	10	43	66	15.4
80	9.7	81	130	22.2
81	12	70	100	44
83	5.6	34	39	13.8
North wall[1]		720 (0.12 percent MoS_2)		
Ore pile[1]		720 (0.12 percent MoS_2)		
Crushed rock in mill bin[1]		180 (0.03 percent MoS_2)		

[1] From Burbank (1965, p. 62).

tain, but it nowhere exceeds trace amounts, and no hydrothermal rock alteration is associated with it. The prospects have been described by Hess (1908, p. 234–235), Trefethen and Miller (1947), and Young (1963, p. 65, 67, and 79–82). Composition zonation in the Tunk Lake pluton was described by Karner (1968) and by Karner and Helgeson (1970). I visited the prospect areas for 1 day in 1971.

The Tunk Lake pluton intrudes Ellsworth Schist (Upper Cambrian or Ordovician(?)), granite of Middle Devonian age, and various phases of rocks of the Bays-of-Maine complex (Karner, 1968, p. 195). Karner divided the pluton into six phases or types ranging from augite granite at the chilled margin to biotite monzonite in the interior. The best known molybdenum prospects are close to the northern edge of the innermost zone, where the quartz and oligoclase contents are relatively high and the total mafic mineral and potassium feldspar are low (Karner, 1968, p. 198, 203). Hess (1908, p. 236) was told of several other occurrences of molybdenite near Tunk Lake, but none of these are described in geologic literature.

The quartz monzonite on Catherine Mountain is a medium-coarse-grained gray granitic rock containing modal percentages of about 35 percent quartz, 25 percent plagioclase, 35 percent potassium feldspar, and a maximum of 5 percent biotite. In the vicinity of some of the prospects (probably those in area 5 of Young, 1963, p. 80), the texture is very uneven, for it includes patches of fine-grained as well as pegmatitic material. None of the rocks examined in the prospects show any evidence of hydrothermal alteration. The feldspar minerals are generally fresh, and most of the biotite is only 5 percent altered to chlorite. A specimen from a sparsely mineralized prospect (probably area 4 of Young) has a little clinozoisite developed in plagioclase grains, and about half the original biotite has been replaced by chlorite. This degree of alteration is so common in old granitic rocks that to consider it a result of a major hydrothermal process seems unrealistic.

Trefethen and Miller (1947, p. 55–56) described three modes for the molybdenum present: (1) as scattered crystals with pyrite on a few joint surfaces, mostly on the east-trending joint set; (2) with a few of the sparse small pegmatite bodies, also mostly with some associated pyrite; and (3) along the contact or in the gradational marginal zone of aplitic bodies, particularly at the eastern end of the mountain. Disseminated molybdenite was seen only within a few centimeters adjacent to pegmatite and aplite bodies. Young (1963, p. 65) described two modes of molybdenite occurrence: (1) disseminated with or without pegmatite, and (2) on joint surfaces accompanied by pyrite. The paucity of sulfides makes it difficult to classify some of the prospects, and I did not get an impression of clearly separate modes of occurrence when I visited the mountain.

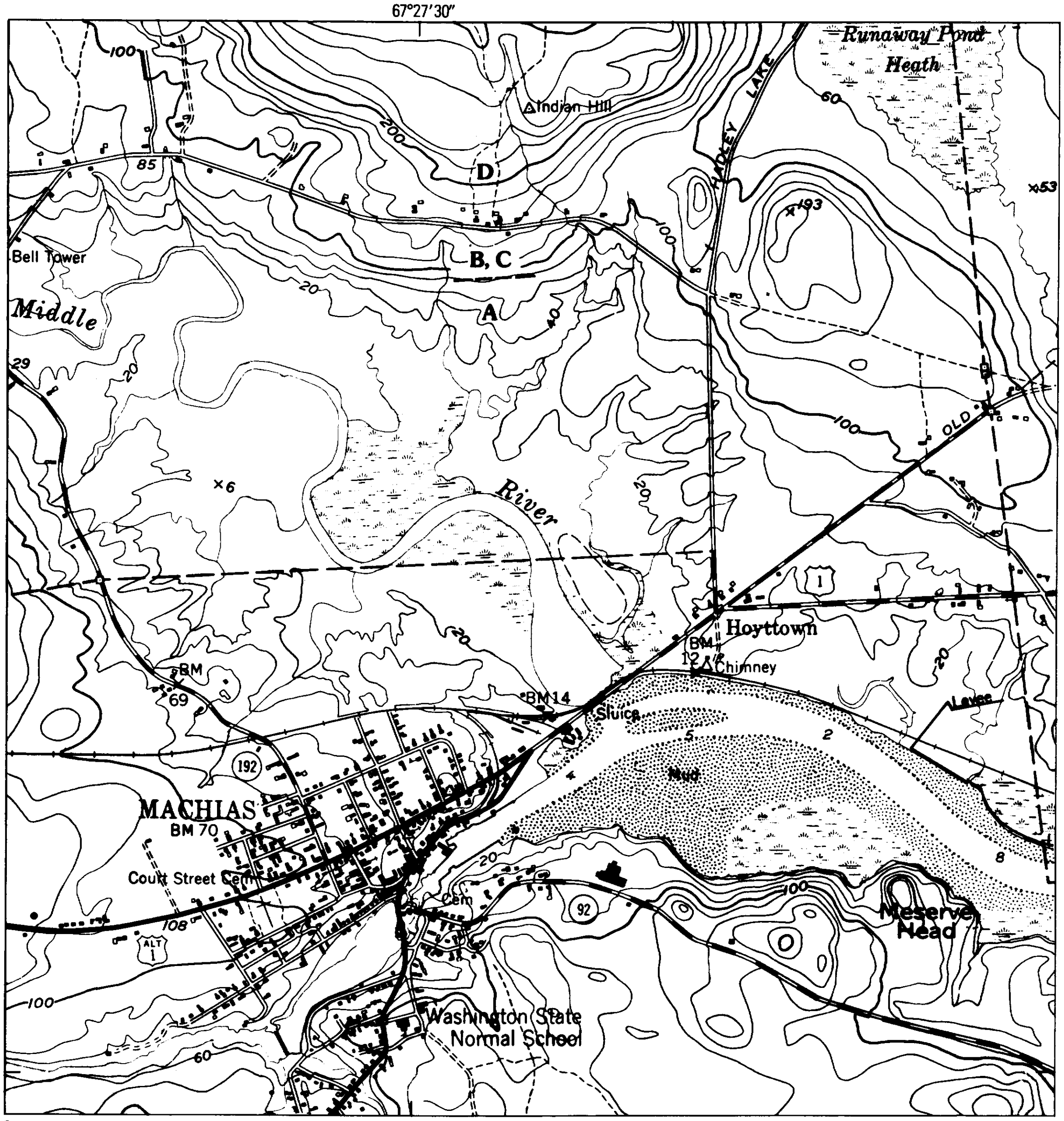
The meager sulfide and the lack of evidence of hydrothermal alteration at Catherine Mountain make it highly improbable that the molybdenite there represents any part of a porphyry-type hydrothermal system. This deposit was placed in the molybdenite class by Khrushchov (1959).

MACHIAS OCCURRENCE, WASHINGTON COUNTY, MAINE

Molybdenite on the Sprague-MacKenzie property near Machias, Maine, was discovered by Cornelia Cameron, U.S. Geological Survey, in 1973. The molybdenum occurs in a quartz monzonite pluton close to the contact of the pluton with metamorphosed lower Paleozoic felsic volcanic conglomerate. The pluton is of Devonian age (Hussey and others, 1967).

The contact of the intrusive and the volcanic conglomerate is in generally low, partly swampy ground near the Sprague-MacKenzie property, and I did not see the actual contact when I visited there. The conglomerate forms large rock knobs protruding above the swampy surface (point A, fig. 4). Most clasts in the felsic volcanic rock are less than 5 cm, but a few scattered boulders are as large as 40 cm. Metamorphism is presumably related to contact effects of the quartz monzonite pluton. Faint iron-

67°27'30"



44°42'30"

Base from U.S. Geological Survey, 1:24,000, Machias, Maine, 1949

0 .5 1 2 KILOMETERS

0 ½ 1 MILE

CONTOUR INTERVAL 20 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

EXPLANATION

A	Volcanic conglomerate	**D**	Medium-grained massive quartz monzonite
B, C	Fine-grained quartz monzonite containing molybdenite	----	Geologic contact—Approximately located

FIGURE 4.—Sketch map showing field localities described at the Machias occurrence, Washington County, Maine.

oxide staining in some of the larger clasts suggests traces of sulfide, but no fresh sulfide was observed.

The quartz monzonite crops out in a narrow east-trending band near the top of a short slope above the low and swampy land; the margin of the pluton probably parallels this outcrop near the foot of the slope. The rock at the top of the slope is a fine-grained quartz monzonite (points B and C, fig. 4). It contains 40–45 percent quartz, and potassium feldspar exceeds plagioclase by 1½ to 2 times. Plagioclase grains are partly clear and fresh, and partly light to densely sericitized. Dark minerals, mostly chlorite derived from alteration of biotite, make up perhaps 2–3 percent of the rock. Abundant low outcrops 300 m to the north (point D, fig. 4) are medium-grained massive quartz monzonite, noticeably coarser that the marginal rock at points B and C.

Molybdenite is present at points B and C (fig. 4) as 1-cm rosettes, especially along certain joints in the fine quartz monzonite, and also disseminated in the quartz monzonite for as much as 3 cm on each side of the joints. Limited rock alteration may also be in this 3-cm zone, but I have mode no petrographic study to substantiate this. The bulk of the rock has sericitization only in part of the plagioclase. Analyses for copper, bismuth, molybdenum, and tungsten in rock samples from points B and C are given in table 3.

No molybdenite mineralization was seen in the volcanic conglomerate (point A, fig. 4) nor in the quartz monzonite more distant from the margin (point D, fig. 4). This type of molybdenum occurrence is considered not likely to form deposits of exploitable size and grade, but examination of the rest of the periphery of this pluton seems advisable because experience in evaluating molybdenite deposits in North America is limited and the periphery is a clearly defined target for geochemical reconnaissance.

TABLE 3.—*Chemical analyses of two representative grab samples from the Machias occurrence, Washington County, Maine*

[Results in parts per million. Analyses by P. Aruscavage and L. Mei, U.S. Geological Survey]

Lab. No.	Field location	Cu	Bi	Mo	W
W–182107	B	28	2.7	93	1.3
W–182108	C	19	0.67	60	1.9

GRANITE (QUARRY) HILL MOLYBDENUM PROSPECT

Molybdenite ore in small quantities and extensive weak sulfide mineralization are present in the syenitic Cuttingsville pluton on Granite Hill, at Cuttingsville, near Rutland, Vt. To my knowledge, no radiometric dates have been obtained for the pluton, but Chapman (1968, p. 389) included the pluton in the White Mountain Plutonic Series of Early Jurassic or Late Triassic age.

The Cuttingsville pluton, a complex body mostly of potassic rocks about 2×2.5 km in size was described in detail by Eggleston (1918). Rock exposures were probably considerably better on much of Granite Hill when Eggleston mapped; the present dense woods and additional soil cover would make it difficult to reproduce his mapping today (fig. 5). The molybdenite prospect was merely mentioned by Eggleston (1918, p. 406), not surprising in a work that dealt mainly with the complex petrology of the pluton.

Jacobs (1937, p. 24) described the molybdenite as occurring in "a mineralized zone over 3100 feet long and some 125 feet wide." Weak sulfide mineralization is extensive, and perhaps even pervasive through much of the pluton, so that I found it difficult to define a specific mineralized zone in the field. Molybdenite occurs only locally in the more widespread sulfide-bearing rocks.

The pluton consists of five major rock types—in order of decreasing abundance, pulaskite, augite-syenite, essexite, hornblende-biotite syenite, and sodalite-nephelite syenite (Eggleston, 1918). Chemical analyses of four of these phases are shown in table 4. Hybrid rocks are found at many places where two phases adjoin.

TABLE 4.—*Chemical analyses of four phases of the Cuttingsville pluton, from Eggleston (1918)*

[Analyses of augite syenite by C. D. Test; other analyses of H. E. Merwin]

	Essexite	Hornblende-biotite syenite	Sodalite-nephelite syenite	Augite syenite
SiO_2	46.47	57.44	60.88	67.30
TiO_2	2.86	.69	.35	.17
Al_2O_3	16.86	21.60	20.75	17.44
Fe_2O_3	3.21	.20	.63	1.56
FeO	7.72	2.62	1.13	1.76
MnO	.23	.14	.22	.16
MgO	5.16	1.09	.17	.14
CaO	9.45	2.90	1.08	1.00
Na_2O	4.20	7.36	6.35	7.08
K_2O	1.35	4.12	5.57	4.78
H_2O+	.45	.58	.88	.05
H_2O-	.04	.03	.03	.05
P_2O_5	1.15	.38	Trace	.04
CO_2	Trace	.39	.61	-----
ZrO_2	None	.02	Trace	.08
SO_3	None	None	None	None
Cl	.06	.07	.18	-----
F	.10	.05	.05	-----
Cr_2O_3	None	None	None	-----
BaO	Trace	.26	.02	-----
SrO	.04	.04	Trace	-----
FeS_2	.21	.15	.61	-----
Fe_7S_8	.08	.14	.13	-----
Li_2O	None	None	None	-----
Total	99.64	100.27	99.64	101.61

The pulaskite occupies most of the southern two-thirds of the pluton (fig. 5). It is generally coarse grained and consists mostly of microperthitic feldspar and a little orthoclase; biotite is generally present (Eggleston, 1918, p. 395). Minor constituents and accessories are biotite, cancrinite(?), nephe-

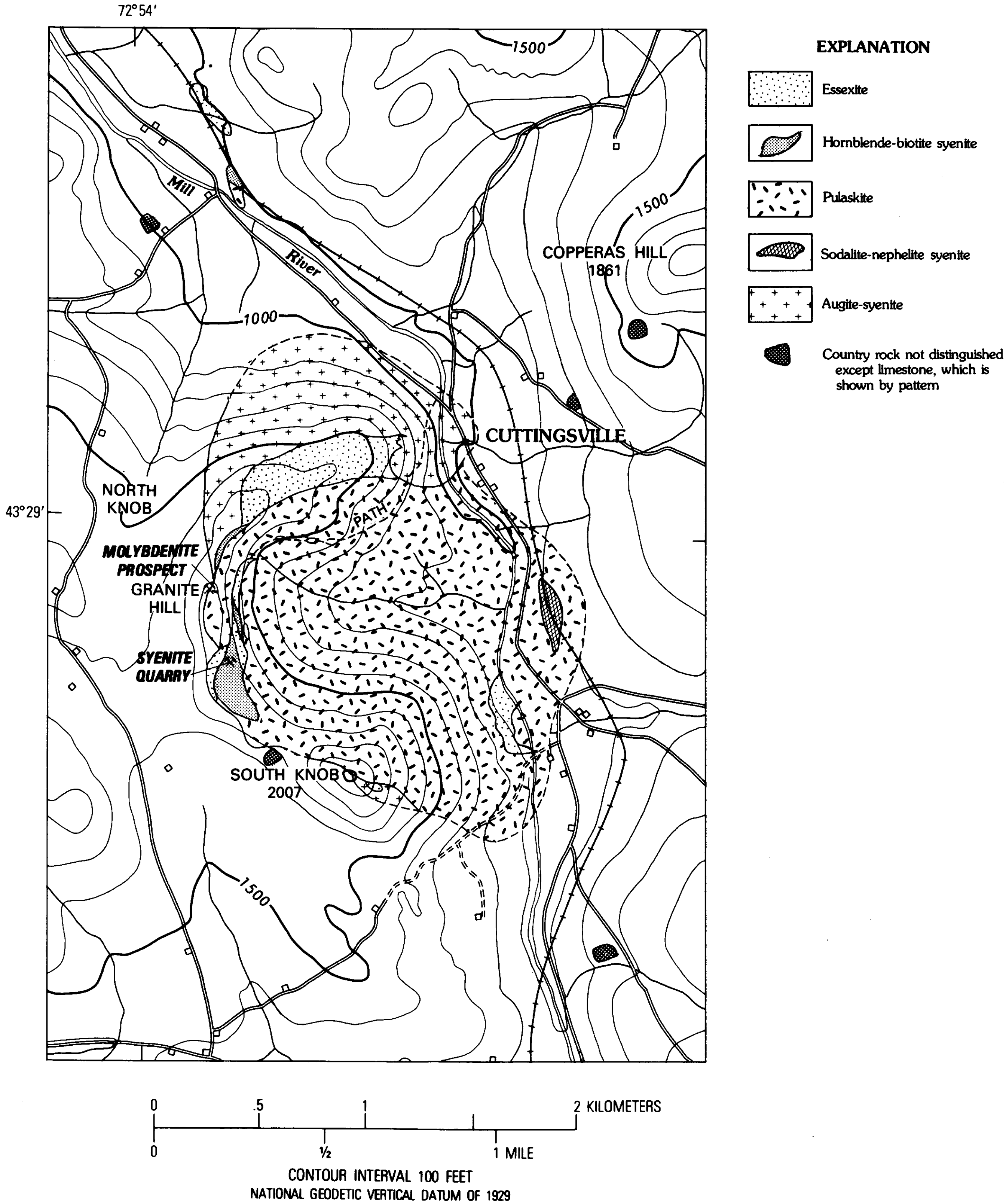


FIGURE 5.—Geologic map of the Cuttingsville pluton, Shrewsbury and Wallingford Townships, Rutland County, Vt., showing location of the Granite Hill molybdenum prospect. Modified from Eggleston (1918).

lite(?), titanite, magnetite, pyrrhotite, apatite, and zircon. The molybdenite prospect is along the western margin of the pulaskite phase and separated from the main pulaskite mass by a thin screen or lens of essexite (fig. 5). Northward-trending streaks of very coarse grained phases of pulaskite occur near the western edge of the pluton near the ridge crest of Granite Hill, including the vicinity of the molybdenite prospect. The pulaskite generally weathers to a rusty brown color that is locally related to the decomposition of sulfides; whether or not the brown color is everywhere related to disseminated sulfide is not certain. The analysis of copper and molybdenum in some of the coarse phase of the pulaskite is shown in table 5.

TABLE 5.—*Copper and molybdenum analyses of four samples from the Cuttingsville pluton, Rutland County, Vt.*

[Copper was determined by atomic absorption spectrometry. Molybdenum was determined photometrically. Analysts: P. Aruscavage and E. Campbell, U.S. Geological Survey]

Lab. No.	Field No.	Cu (ppm)	Mo (ppm)	Description
W-191906	JX20210	5	3.9	Hornblende biotite-syenite, grab sample from waste, quarry on Granite Hill (fig. 5).
7	5	6	5.8	Hornfels or border phase at edge of pluton, 30 m north of molybdenum prospect.
8	6	60	6.0	Hornfels near contact, crest of Granite Hill, 110 m north of prospect.
9	8	5	8.8	Coarse pulaskite, about 120 m north of quarry on Granite Hill.

Augite-syenite (nordmarkite) makes up the northern end of the Cuttingsville pluton (Eggleston, 1918, p. 398–401). Mostly medium grained, the grain ranges locally from fine to coarse. Seventy-five percent or more of the rock is feldspar, mostly microperthite, and also microcline, orthoclase, and albite. Green augite locally rimmed by green hornblende is the major dark mineral, and aegirite-augite, olivine, and primary quartz are minor constituents. Accessories are magnetite, zircon, apatite, and perhaps ilmenite. Although Eggleston detected no sulfide in the rock, he suspected it was there and reported that the rock gives a sulfurous odor on breaking, and weathers to a pale buff or very light brown.

Essexite occurs in a large patch between the pulaskite and the augite-syenite, and also in several small scattered lenses and pods (fig. 5). It is a dark rock containing hornblende, pyroxene, and biotite in about equal quantities, and 60 percent feldspar, most of which is plagioclase (An=30–70 percent) (Eggleston, 1918, p. 388). Accessory minerals are olivine (partly serpentinized), magnetite, titanite, apatite, pyrite, and probably pyrrhotite. Eggleston (1918, p. 388) considered this phase to have been the first to crystallize. It is not known to be sulfide bearing.

The hornblende-biotite syenite is a gray medium-grained rock consisting of light-gray feldspar speckled by hornblende and biotite (Eggleston, 1918, p. 392–395). More than half the feldspar is plagioclase, and most of the orthoclase is present as antiperthitic intergrowths in the plagioclase. Biotite and hornblende are about equal in quantity, and together make up about 10 percent of the rock. Accessories are apatite, titanite, magnetite, zircon, and pyrite. No quartz was noted. The biotite is fresh and no claylike alteration of the potassium feldspars is present. Pyrite is locally more abundant, making up perhaps as much as 0.5 percent of a few blocks in the waste dump of the old quarry (see fig. 5). The copper and molybdenum analysis of a sample of the hornblende-biotite syenite is shown on table 5.

The sodalite-nepheline syenite phase was described by Eggleston from only one relatively small lens near the east edge of the pluton. It is medium-coarse-grained gray rock consisting of 90 percent feldspar, and pyroxene, sodalite, and nepheline. More than half the feldspar is microperthite, orthoclase, and microcline, and the rest is plagioclase near albite in composition. Accessories are apatite, magnetite, titanite, and pyrite (Eggleston, 1918, p. 397).

Molybdenite occurs at one prospect at the west edge of the pluton (fig. 5); I know of no other occurrence in the vicinity. Jacobs (1937, p. 24) cited "a mineralized zone over 3100 feet long and some 125 feet wide," but I think that sparse pyrite rather than molybdenite probably determined the major boundaries of his zone. Sparse molybdenite can be seen in bedrock at the prospect. High-grade material in the dump probably came from the small shaft, which is too dangerous for thorough examination and is also flooded to perhaps 2 m from the surface. Relationships of the high-grade material to the enclosing rock must be deduced from the dump materials.

Country rock at the prospect consists of fine to coarse pulaskite, made up mostly of perthitic orthoclase, and a fine-grained sugary hornfelsic rock, probably mostly metamorphosed wall rock but perhaps partly a chilled marginal phase of the intrusive rock. Some specimens seem to be fine hornfels injected along and across foliation by abundant pulaskite, and some mixing of the two rocks has taken place in the contact zone. The molybdenite mineralization seems to be very close to, if not in, the contact zone, because both rock types are present in the sides of the small prospect shaft. The hornfelsic rock at the shaft and dump and also in nearby outcrop contains from a trace to 3 percent pyrite, and little molybdenite was observed in it. The copper and molybdenum content of two samples of the hornfels is shown in table 5.

Molybdenite is disseminated in irregular patches in fine and medium-grained biotite pulaskite fragments found on the dump of the prospect pit. Some material is estimated to contain more than 10 percent molybdenite, a few percent pyrite, and perhaps some chalcopyrite. The amount of this high-grade material on the dump is small but it probably has been preferentially removed by mineral collectors. It is assumed that the "analyses showing as much as 30 percent molybdenum" (Jacobs, 1937, p. 24) were made on selected pieces of material. Traces of secondary molybdenum minerals are present in weathered dump fragments, but no secondary copper minerals were observed. Hand specimens of the richest molybdenum-bearing pulaskite are weakly radioactive, but the source of the radiation has not been determined.

Although there is widespread weak sulfide mineralization and local high-grade molybdenum-bearing rocks, the Cuttingsville pluton completely lacks the pervasive hydrothermal alteration that one should expect in a porphyry-type deposit. It is proposed that the molybdenum is of the molybdenitic deposit type as defined by Khrushchov (1959). This type of deposit generally has a much lower potential for exploitation than a porphyry deposit, but a small high-grade deposit in the Cuttingsville pluton is still a possibility. Previous prospecting was probably controlled entirely by observations on natural outcrops, and I am not aware of any use of geochemical prospecting methods to explore the mineral potential of the pluton. Many unexposed areas are probably near the pluton margin that are large enough to obscure ore bodies of significant size. Drift cover is probably mostly thin, and geochemical soil sampling should be a rapid and efficient way to seek other molybdenum-bearing parts of the pluton.

OTHER MOLYBDENUM OCCURRENCES

Molybdenum has been reported from several other localities in southern and eastern Maine in addition to the Cooper mine and the Catherine Mountain deposit (King, 1970, p. 7). Although the brief descriptions given by King indicate that some of these are associated with pegmatites and small sulfide veins, some of them probably are deposits of the molybdenitic type. I know of no evidence that any of these localities are deposits of the porphyry type. Hollister, Potter, and Barker (1974, p. 625) discussed the sparse molybdenite mineralization that may be associated with a narrow breccia zone at Cadillac Mountain on Mount Desert Island, Hancock County, Maine.

PORPHYRY-TYPE DEPOSITS IN THE SOUTHEASTERN UNITED STATES

Several disseminated copper-molybdenum deposits associated with felsic stocks are known in eastern North and South Carolina, but information on them is somewhat limited. One prospect, the Conner-Neverson quarry area, is tentatively classified as the porphyry type, but none are proved to be of that type. These prospects are in, or close to, rocks of the Carolina slate belt, a sequence of metamorphic rocks derived from volcanic flows in tuffs intermixed and intercalated with rock waste. These slate-belt rocks and their presumed equivalents, extending from Alabama to Maryland, represent a very extensive belt of late Precambrian and early Paleozoic volcanism, perhaps related to an island arc or to the edge of a paleocontinent. One tectonic model for the southeastern Piedmont region would have had two continental masses collide about 450 m.y. ago (Glover, 1976), and the subduction zone dip southeastward. The distribution of small late-orogenic or postorogenic plutons in a thick sequence of volcanic sediments and volcanic tuffs and flows along the southeast edge of the Piedmont is compatible with this view. The subduction of oceanic crust prior to collision would have resulted in volcanism and perhaps the formation of porphyry copper-type deposits in a linear belt above the subduction zone. Small plutons within the slate belt may indicate the site of active volcanism and subvolcanic intrusion above the subduction zone, and I consider the small plutons to be the areas of highest potential for the occurrence of porphyry copper-type deposits.

In an alternate interpretation, Spence and Carpenter (1976) considered the western part of the slate belt as the site of a major volcanic island arc during late Precambrian and early Paleozoic time associated with an arc-trench gap and trench to the east, now hidden under Coastal Plain sedimentary strata, and a westward-dipping subduction zone. Black and Fullagar (1976) cited Rb/Sr age dates to indicate that subduction and volcanism began before 705 m.y. and ended 613 m.y. ago, then resumed in the early Paleozoic, and ended finally before the "Taconic" orogenic period. Presumably the interpretation by Black and Fullagar would permit more than one subduction zone, perhaps two of opposite dip.

The extensive belt of volcanic rocks in the Piedmont, though not well exposed in many areas, and as yet only partly mapped on an adequate scale, includes several small plutonic intrusive bodies, but has surprisingly few subvolcanic intrusive bodies known in it. The deep saprolitic weathering in the region does not favor the identification of felsic subvolcanic rocks in felsic volcanic country rock. There are many gold deposits and prospects, at least some of which are probably of volcanogenic origin (Worthington and Kiff, 1970), and some of these occurrences contained associated copper, lead, zinc, bismuth, and arsenic; a few such as the Haile and Blackmon mines, Lancaster County, S.C. (fig. 6), have associated potassic rocks that may indicate substantial hydrothermal potassic alteration (Pardee and Park, 1948, p. 112, 114).

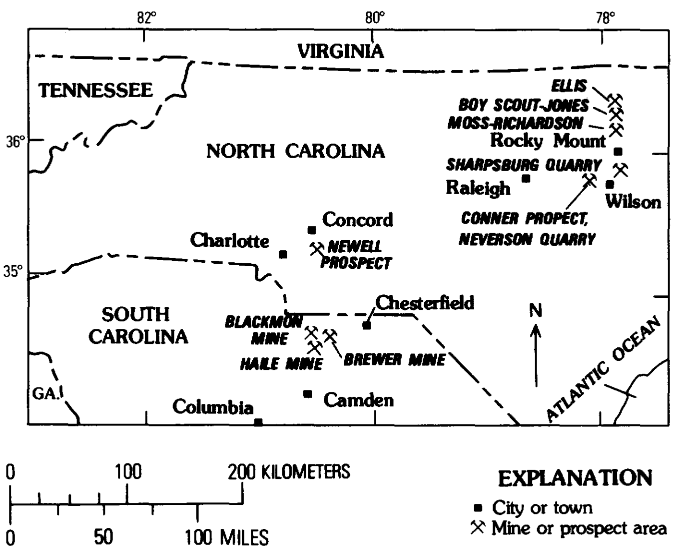


FIGURE 6.—Index map of mines and mineralized prospects in North and South Carolina. See text for discussion.

The disseminated molybdenum-copper mineralization at the Conner prospect and the Neverson quarry in North Carolina is sufficiently extensive to be of the porphyry copper type, but the intensity and extent of rock alteration are not known; hence the classification is tentative.

The Brewer mine, Chesterfield County, S.C. (fig. 6), is in a large zone of intense hydrothermal alteration that may be regarded as a deposit of porphyry copper affinity, possibly similar to the Mount Pleasant, New Brunswick, and the Cornwall, England, deposits.

Three prospects in Halifax County, N.C. (the Moss-Richardson, Boy Scout-Jones, and Ellis), are not now classified as porphyry-type deposits because rock alteration and mineralization seem too limited, but more information about these prospects could easily change their category.

Stratabound polymetallic mineralization of the type described by Maucher (1972) probably is present in the slate belt also (U.S. Geological Survey, 1973, p. 2). Perhaps this is related in some way to the probably volcanogenic gold-base metal deposits. Neither deposit type can be considered directly associated with or indicative of porphyry copper-type mineralization, but both suggest that this long volcanic belt had metal-bearing hydrothermal emanations associated with it.

Geologists working for private companies have searched for at least the last 10 years in the southeastern Piedmont for deposits of the porphyry type. Although none of the mineralized areas they found have yet proved to be minable, some may fit the porphyry model well enough to encourage further search. Six mineralized areas that I think deserve consideration as porphyry-type deposits are described here.

DEPOSITS THAT MAY BE OF THE PORPHYRY COPPER-TYPE

CONNER-NEVERSON QUARRY AREA

The Conner stock is in Wilson and Nash Counties, N.C., about 53 km east of Raleigh. Exploration at the Conner stock was described by Cook (1972). Porphyritic biotite granite has intruded argillite and tuff of the Carolina slate belt. Part of the stock is overlapped by thin sediments of the Coastal Plain.

Three areas of anomalous metal content were identified and two were explored. Two samples were taken and analyzed from the third area, the Neverson quarry near Sims, but no exploration was carried out.

The areas explored were on the northwest and west edges of the intrusive body. Pyrite-chalcopyrite-molybdenite mineralization was intersected in altered granite and in rock described as greisen. Quartz veins bearing minor galena, sphalerite, chalcopyrite, and pyrite were found at the granite-slate belt contact. All analyses of drill samples were less than 175 ppm Mo and 650 ppm Cu, averaged over 10-ft (3.05 m) intervals. Locally pyrite makes up as much as 15 percent of the "greisen" zone.

The most intriguing part of the pluton is the Neverson quarry where no drilling was done. Cook reported that argillic alteration is present here and alteration seems more intense than at the drilled locations. Some rock is abnormally red. According to Cook (1972), "Quarry blocks and greisen float contain up to 0.380 and 0.192 percent molybdenite re-

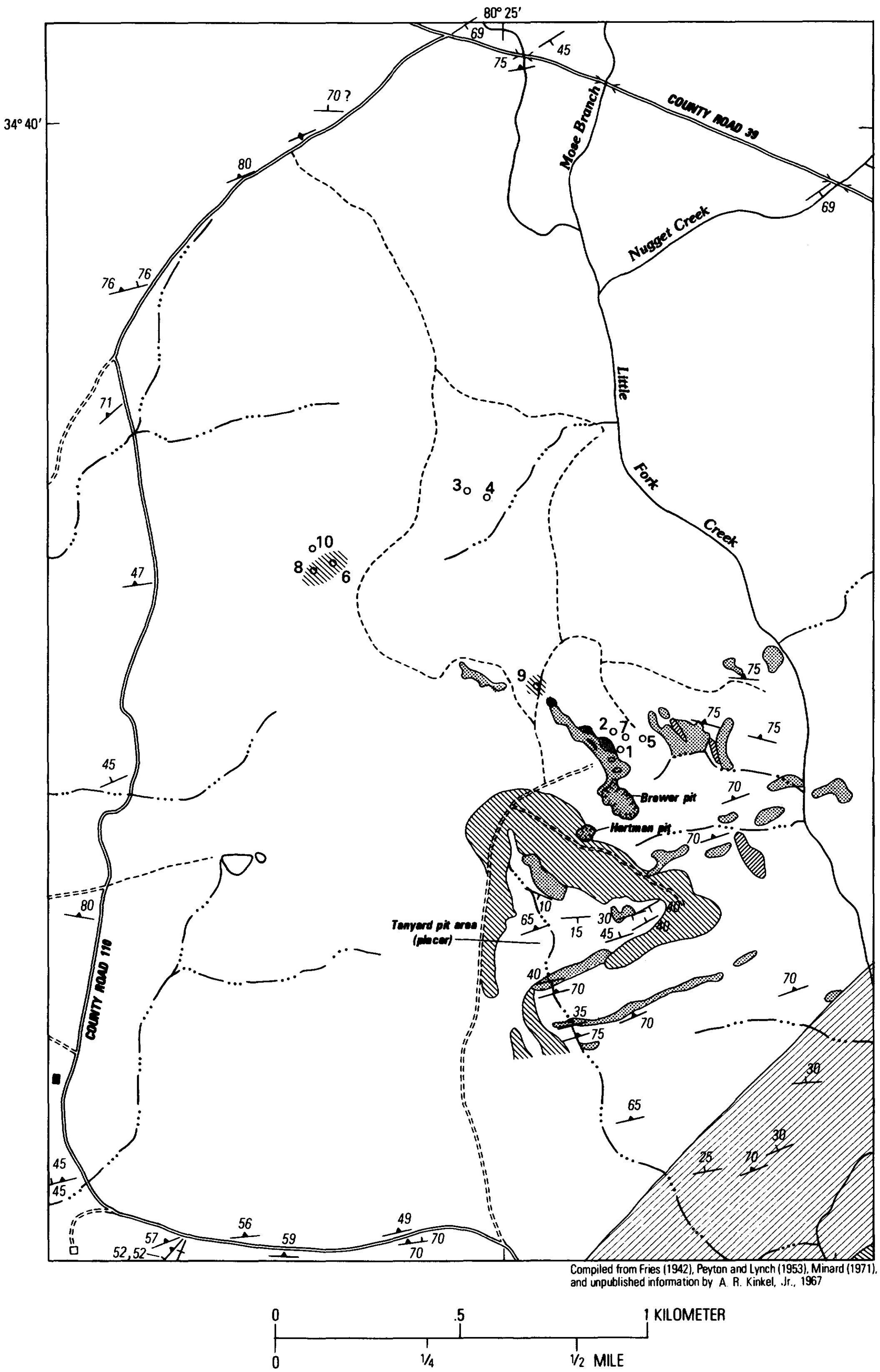


FIGURE 7.—Sketch map of the Brewer mine area, Chesterfield County, S.C.

EXPLANATION

MIDDENDORF(?) FORMATION (UPPER CRETACEOUS)—Unconsolidated light-gray, yellow-brown, and reddish-brown clay, silt, sand, and, especially at the base, gravel

METAMORPHOSED VOLCANOSEDIMENTARY ROCKS—Metamorphosed felsic tuff, tuffaceous sand and argillite, felsic porphyry, and volcanic breccia; metamorphosed rocks of undetermined origin include diabase, hornblende gneiss, and amphibolite. Some areas covered by Middendorf Formation are not delineated

ARGILLITE—Largely greenish-gray (brownish-gray when weathered) fine-grained laminated tuffaceous argillite

Contact

25 Strike and dip of bedding
Inclined
Vertical

70 Strike and dip of foliation
Inclined
Vertical

Gossan (data from J. T. Pardee in Fries, 1942, pl. 6)

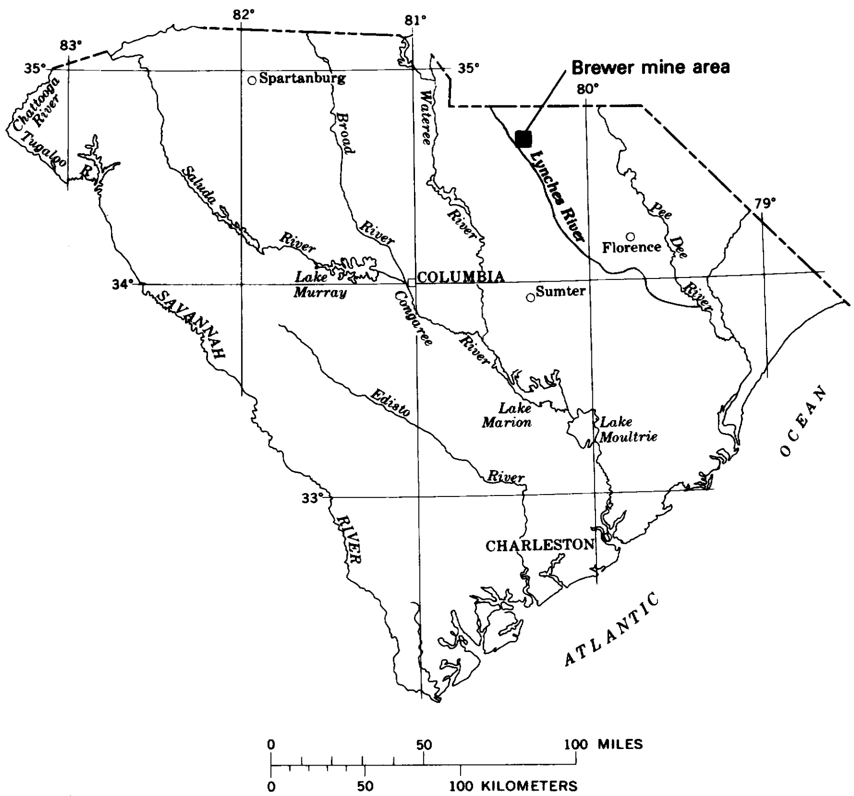
Topaz rock (data from J. T. Pardee in Fries, 1942, pl. 6)

Silicified rock (data from J. T. Pardee in Fries, 1942, pl. 6)

8 o U.S. Bureau of Mines diamond drill hole. All holes contain significant fluorine believed to be present only as topaz (Peyton and Lynch, 1953). Hole 8 contains the most topaz

Outline of open pit

---- Vehicle trail



INDEX MAP OF SOUTH CAROLINA, SHOWING BREWER MINE AREA

FIGURE 7.—Continued.

spectively." J. B. Mertie, U.S. Geological Survey, prepared a panned concentrate from finely crushed rock collected at the Neverson quarry crusher in 1947. Molybdenite is a major constituent of the heavy minerals in the concentrate.

I examined thin sections of five specimens of potassic quartz monzonite and granite taken from the Neverson quarry in 1949 by J. B. Mertie. Plagioclase appeared mostly unaltered, and biotite had been partly altered to chlorite and a little epidote. These mineral changes indicate rather weak alteration compared with major porphyry-type deposits elsewhere. The most reasonable alternate classification of the sulfide mineralization here is probably the molybdenitic type mineralization of Khrushchov (1959).

I also examined thin sections of two specimens collected by J. B. Mertie from a quarry about 4 km south-southwest of Sharpsburg in Wilson County, N.C. (about 23 km northeast of the Neverson quarry). The rock is very potassic, containing perhaps 50 percent potassium feldspar. Feldspars do not appear altered but the high potassium feldspar content may itself indicate a form of high-intensity potassic alteration. I know of no evaluation of the Sharpsburg quarry for contained sulfides.

DEPOSITS OF PORPHYRY COPPER AFFINITY

THE BREWER MINE AREA

The Brewer mine, a producer of gold from about 1828 until 1940, is in part of a much larger zone of highly altered copper-bismuth-tin-bearing volcanic rocks. The most outstanding alterations are quartz-andalusite and quartz-topaz greissens. The large alteration zone (a minimum of 1.4 km in one dimension), the evidence for a subvolcanic origin, and the metal suite provide only a sketchy picture of the overall geology of the hydrothermal system, but they suggest and permit consideration of a large system such as Mount Pleasant, New Brunswick, and some of the deposits of Cornwall, England. Although not a typical porphyry copper system, it has some features in common with one.

Gold-mining operations at the Brewer mine, near Jefferson in Chesterfield County, S.C. (fig. 7), at first by placer and later by openpit and underground, have been described by Leiber (1858, p. 63–68), Nitze and Wilkens (1896, p. 762–767), and McCauley and Butler (1966, p. 36–40).

The Brewer mine area is in felsic volcanic rocks of the Carolina slate belt, close to and partly under the overlap of Coastal Plain strata. Arthur R. Kinkel, Jr. (written commun., 1968) described the country rocks in the mine as strongly silicified rhyolite, part of which is tectonic breccia, part pyroclastic breccia, and part tuff. According to Kinkel, the gold ore consists of silicified topazized pyritized rhyolite, in which local areas several centimeters across consist entirely of fine-grained granular pyrite. Small grains of pyrite are widely disseminated in the rock associated with the gold deposit and may constitute 2–5 percent of the rock (Pardee, Glass, and Stevens, 1937, p. 1058).

Topaz was identified in the altered volcanic rocks of the Brewer mine by Pardee, Glass, and Stevens (1937). In general appearance, the topaz-rich material here is difficult to distinguish from dense siliceous rocks unless the high specific gravity is noted, and the material was generally called flinty quartz or blue hornstone in the reports of earlier examinations. The topaz occurs as disseminated grains, as patches and streaks of aggregates, and as massive topaz. All these are made up of rounded individual grains only a few microns in diameter. Pardee, Glass, and Stevens (1937, p. 1062) reported that only a few grains had a euhedral form. I observed only rounded shapes. 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 as mullite and for the production of calcium fluoride. 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 the holes are shown on figure 7.

Compilation of the full suite of base metals identified in the mine depends mainly on old reports. Pardee, Glass, and Stevens (1937, p. 1058) observed that "small grains of enargite are sparingly scattered through parts of the rock." Other authors noted covellite, cassiterite, bismite, native bismuth, chalcanthite, and chalcopyrite, but these were not seen by Pardee, Glass, and Stevens (1937). Grab samples of pyritic rock from drill hole 1 close to the old open pit (Brewer pit, fig. 7) contained as much as 0.3 percent arsenic, 1.0 percent copper, 500 ppm bismuth, and 200 ppm tin (analyses performed in laboratories of the U.S. Geological Survey). One sample in another hole near the mine contained 0.07 percent molybdenum.

Sulfides make up an estimated 1–5 volume percent of all the 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, and in one hole (No. 1) the estimated sulfide content over an interval of 33.2 m was 15 volume percent.

No primary rock textures seem to have survived the rock alteration in the Brewer drill cores. Although volcanic textures have been described from the mine, primary textures were probably not everywhere recognizable. Kinkel (written commun., 1968) described a variety of breccias in the mine, and breccias were common in three drill holes.

Much more needs to be known about the detailed geology of the area around the Brewer mine. Little has been described in earlier studies except the mine exposures and the occurrence of gold, but we know that strong hydrothermal alteration has affected a much larger area, accompanied by introduction of much disseminated sulfide, trace amounts of bismuth and tin, and as much as 0.3 percent arsenic, 0.07 percent molybdenum, and 1.0 percent copper. If the Brewer mine area is part of a large hydrothermal system of the Mount Pleasant type, the style of alteration and the associated metal suites may vary considerably in the different parts of a system that may be as large as several kilometers in each dimension. Until the perimeter of the alteration zone is defined, and variations in both alteration and mineralization style are known, the Brewer area cannot be said to be evaluated for its mineral potential.

PROSPECTS OF COPPER AND MOLYBDENUM NOT INCLUDED IN THE PORPHYRY TYPE

EASTERN HALIFAX COUNTY, NORTH CAROLINA, PROSPECTS

At least three copper-molybdenum prospects in Halifax County, N.C., have been explored by diamond drilling (fig. 6).

The Moss-Richardson and Boy Scout-Jones prospects were explored by the U.S. Bureau of Mines in 1942-46 (Robertson, McIntosh, and Ballard, 1947). The Ellis prospect was explored by Perry, Knox, Kaufman, Inc., about 1970. Cores from the latter exploration have been examined by the U.S. Geological Survey.

Mineralization at the Moss-Richardson and Boy Scout-Jones prospects is confined mostly to veins and is mostly near the contact between a small granitic body and siliceous chlorite slate, schist, and gneiss (Robertson, McIntosh, and Ballard, 1947). Sparse disseminated sulfide also occurs in wall rocks within 20–60 cm of the veins.

The ore minerals are molybdenite and chalcopyrite; some ferrimolybdite, chalcocite, and covellite are present as secondary minerals. Traces of lead, silver, and vanadium were detected spectrographically. The paucity of ore minerals, the seeming lack of extensive hydrothermal alteration, and the coarseness of the small intrusive body make it seem unlikely that these mineral occurrences have any relationship to a porphyry-type deposit, though molybdenum and copper are here associated with a felsic intrusive rock.

Drilling at the Ellis prospect was mostly in metamorphosed felsic volcanic rocks and small bodies of alaskite. Much of the volcanic rock that was drilled is silicic and probably rich in potassium feldspar, probably as a result of hydrothermal alteration. Some phyllic alteration is present also. The effects that I attribute to hydrothermal alteration are mostly in the volcanic rocks, as is most of the visible sulfide. Some alaskite is altered and sparsely mineralized, but much is fresh and contains only traces of sulfide.

Ore minerals are molybdenite, chalcopyrite, and scheelite; traces of lead, zinc, and bismuth are also present. The molybdenite and chalcopyrite are mainly disseminated and are probably most abundant where pyrite is locally as much as 2–5 percent. Some of the molybdenite and chalcopyrite are in films on fractures and in small veinlets. Both disseminated and fracture and vein sulfides seem to be more common where the quartz-potassic alteration is greatest. Rough visual estimates of chalcopyrite content indicate that of 1,003 m (3,291 ft) of core examined, 180 m (590 ft) probably contained more than 0.1 percent but less than 0.5 percent copper, and 18 m (59 ft) contained at least 0.5 percent copper. Because of their crudeness, these estimates must be used with caution. No estimates were made for molybdenum.

Scheelite was looked for only in relatively few pieces of core. The most abundant scheelite was in relatively unaltered laminated volcanoclastic rock, concentrated in a 2-mm-thick lamina and 2-cm-thick brecciated bed. The scheelite is probably volcanogenic, not hydrothermal, and resembles the widespread stratabound occurrences in mostly mafic metavolcanic rocks of Late Cambrian to Late Silurian age in Europe and Korea, as described by Maucher (1972).

NEWELL PROSPECT, NORTH CAROLINA

The Newell copper-molybdenum prospect is about 15 km south of Concord, in Cabarrus County, N.C.

(fig. 6), in the vicinity of the old Dixie Queen gold-copper mine. Anomalous amounts of copper in stream sediments led in 1964 to exploration for copper ore. More than 760 m of drilling was performed in exploring an area of weakly mineralized rock near the old Dixie Queen mine by Bear Creek Mining Co., and the results of this work have been described by Worthington and Lutz (1975). Worthington and Lutz interpreted the deposit of sparsely mineralized rock to be a lean porphyry copper-molybdenum deposit, in part because of what they believe to be extensive supergene sericite in saprolite. The drill core from this exploration is now in the collection of the U.S. Geological Survey and I have examined and logged the drill core.

The Newell prospect is in a region of gneiss and schist and felsic to mafic intrusive rocks generally known as the Charlotte belt. Country rocks at the prospect consist of diorite and several kinds of quartz monzonite (termed granite at Bogers Chapel by Bates and Bell, 1965) (fig. 8). Most of the mineralized rock is part of a pluton of quartz monzonite and alaskite about 1.2×2.4 km (Worthington and Lutz, 1975, p. 4–6) in which the weak mineralization (0.03–0.04 percent Cu, 0.01–0.02 percent Mo) outlined by the drilling is perhaps 600 m in diameter. Details of the company chemical analyses of drilling samples were not sought for this study.

Within the area of quartz monzonite and alaskite, metamorphosed potassium-rich granitic and rhyolitic rocks occur in several places, but I do not know their relationship to mineralization. Examination of thin sections shows that some of these rocks contain quartz, microcline, and biotite as major minerals, and plagioclase as only a minor constituent. In other specimens, part of the microcline seems to have been deposited as a late rim on the outside of plagioclase grains, suggesting potassium enrichment of the quartz monzonite toward the end of crystallization of the pluton. I observed no potassic feldspar that looks like the product of hydrothermal potassic alteration at typical porphyry copper deposits. The analyses for K_2O in the rocks at the Newell prospect range from 1.8 to 6.8 percent (table 6). I identified quartz-sericite and argillic alteration only in some very thin zones along fractures and veins.

The origin of the sulfides is not clear. There is no evidence for hydrothermal mineralization since the time of metamorphism. If some hydrothermal alteration took place before metamorphism, the metamorphic grade is high enough that the fabric may have been considerably altered and perhaps the origin disguised.

The association with a felsic pluton, the widely disseminated enrichment by potassium, copper, and molybdenum, and the quartz-sericite and argillic alterations are features characteristic of a porphyry alteration system, but the scantness of metal enrichment and quartz-sericite alteration makes the classification of the Newell prospect as a porphyry rather problematical. A zone of sericitic alteration based on clays that developed during formation of saprolite, as described by Worthington and Lutz (1975), does not, in my opinion, increase the likelihood of the prospect being of the porphyry type. Until more information about the geology of the Newell prospect is available, I prefer to not include the prospect with deposits of the porphyry type.

The interpretation of the origin of mineralization at the Newell prospect is more important than just for understanding of that prospect alone. It lies outside the Carolina slate belt, the area I think to be of highest potential, and, if the prospect is classified as one of the porphyry copper type, then the potential area for the occurrence of lower Paleozoic porphyry copper deposits is larger than I have postulated. There seems to be no good reason to change the prospecting model on the basis of present knowledge of the Newell prospect.

SUMMARY AND CONCLUSIONS

Past discoveries of porphyry copper deposits in eastern North America indicate that there is potential for finding new deposits of exploitable size, although the potential is considerably lower than in younger, less eroded, and less deformed porphyry-bearing regions.

I propose that porphyry-type mineralization in the New England-Maritime Provinces area is related to a northwest-dipping paleosubduction zone marking the line of collision of a European-African continent with North America during the Devonian Period. The collision line is near the Maine-New Brunswick coast; the most favorable structural zone for the occurrence of related porphyry copper deposits is parallel to the collision line and 130–320 km northwest of it, especially in western New Hampshire, northwestern Maine, and southeastern Quebec.

The upper Precambrian or lower Paleozoic volcanic piles included in the Carolina slate belt are proposed as favorable prospecting areas. Few subvolcanic intrusive rocks have been delineated in the metavolcanic rocks, but the geologic conditions are not favorable to easy recognition of such rocks. I believe that further detailed mapping and geochemical

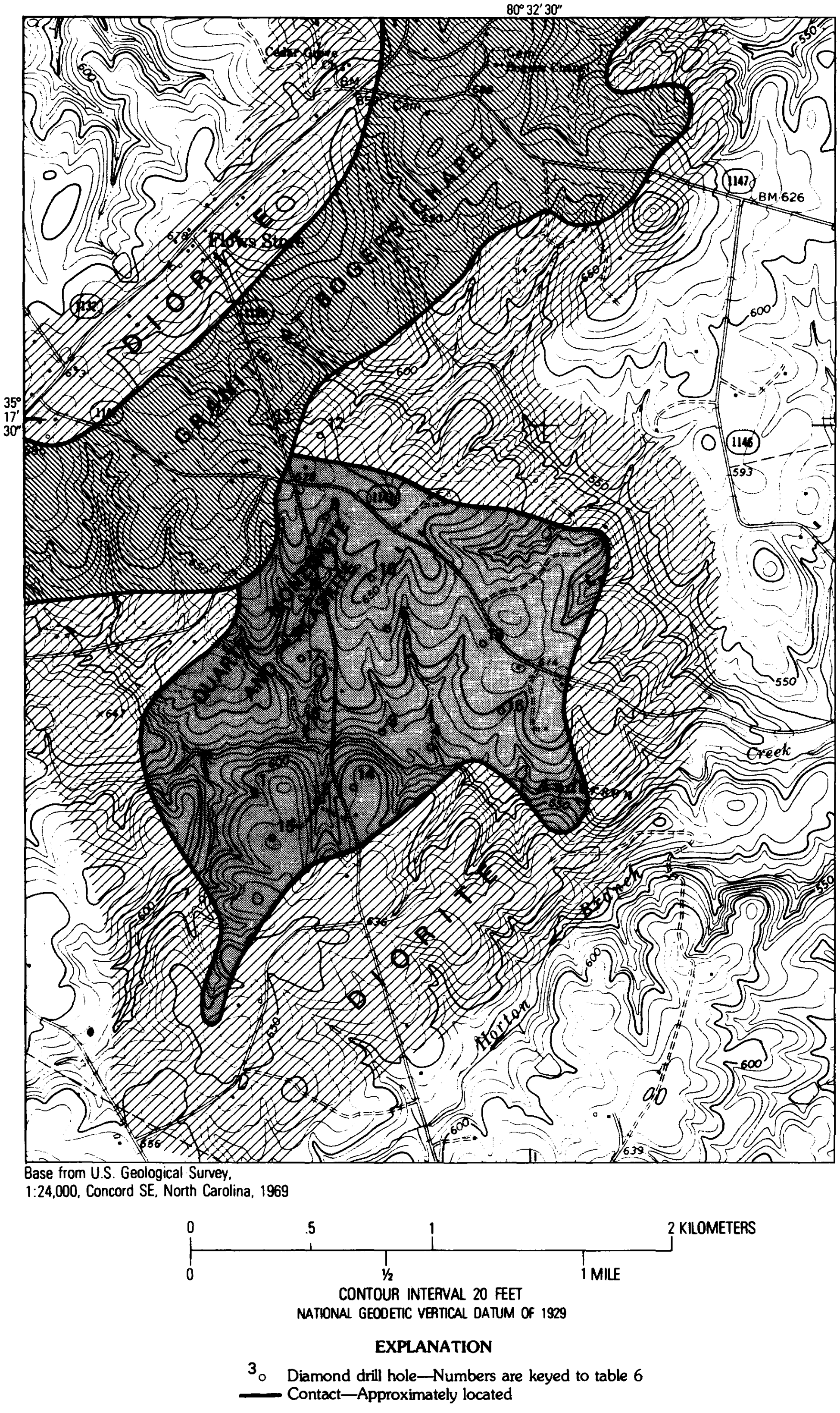


FIGURE 8.—General geologic map of the Newell prospect, Cabarrus County, N.C., showing the locations of the Newell mine shaft (old Dixie Queen mine shaft) and the exploration drill holes; modified from Worthington and Lutz (1975). The Newell mine is about 15 km south of Concord, N.C.

TABLE 6.—*Chemical analyses of 11 samples of drill core from the Newell prospect, Cabarrus County, N.C.*

[Results in percent except as indicated. Rapid-rock analyses (oxides and sulfur) by P. L. D. Elmore, Hezekiah Smith, J. L. Glenn, and James Kelsey. Bi, Mo, and W by isotope dilution spectrophotometric methods; CU by wet chemistry; analysts, E. G. Lillie and Leung Mei]

	W178523 Hole 3 (45.1–46.0 m) felsic metavolcanic rock	W178524 Hole 4 (44.5–45.1 m) metadiorite	W178525 Hole 5 (26.5–27.4 m) alaskite	W178526 Hole 6 (25.6–26.8 m) metadiorite	W178527 Hole 7 (17.0–19.2 m) diorite	W178528 Hole 10 (24.4–26.8 m) quartz monzonite	W178529 Hole 10 (43.6–46.3 m) alaskite	W178530 Hole 10 (54.3–57.3 m) alaskite	W178531 Hole 11 (32.6–34.4 m) gneissic quartz monzonite	W178532 Hole 15 (19.5–22.3 m) greenstone breccia	W178533 Hole 16 (37.2–39.9 m) hornblende-plagioclase-quartz schist
SiO_2	68.2	60.7	70.3	65.0	57.4	70.3	70.3	68.9	71.1	52.4	52.2
Al_2O_3	14.7	14.4	13.9	14.5	14.0	15.4	14.5	14.8	14.2	15.7	16.0
Fe_2O_3	1.3	1.7	2.3	2.5	4.2	1.7	1.4	2.2	1.2	4.7	3.2
FeO	1.6	3.2	1.2	3.0	5.7	.52	1.0	1.2	1.4	5.0	5.9
MgO	1.3	3.8	.50	2.2	3.9	.42	.33	.25	.62	5.2	6.2
CaO	2.5	5.0	.90	4.1	6.9	.73	.53	.54	2.3	7.9	8.7
Na_2O	3.3	3.0	3.2	3.6	2.7	3.7	3.1	3.6	3.9	2.7	2.8
K_2O	4.9	4.9	5.8	2.4	1.8	5.8	6.8	6.3	3.1	2.7	1.8
H_2O^+	1.1	.93	.72	1.0	1.0	.60	.44	.50	.73	1.7	1.2
H_2O^-	.26	.27	.21	.23	.11	.40	.32	.37	.11	.25	.15
TiO_2	.30	.77	.22	.66	.95	.22	.18	.14	.36	.69	.48
P_2O_5	.26	.69	.10	.24	.38	.07	.17	.08	.14	.17	.16
MnO	.04	.10	.03	.10	.17	.00	.00	.05	.07	.14	.14
CO_2	.11	.12	<.05	.35	.11	<.05	<.05	.21	.39	.22	.06
Total	100	100	99	100	99	100	99	99	100	99	99
S (percent)	.33	.21	.95	.53	.44	.13	.44	.56	.10	1.0	.89
Bi (ppm)	.076	.096	.22	.089	.31	.070	.12	.093	.050	.15	.13
Cu (ppm)	220	200	500.	360.	260.	480.	350.	320.	62.	510.	360.
Mo (ppm)	<.25	1.3	300.	18.	3.4	45.	110.	110.	.45	12.	43.
W (ppm)	<1.	1.6	1.5	2.6	2.2	<1.0	1.0	3.6	<1.0	<1.0	<1.0

sampling will locate more mineralized subvolcanic felsic intrusive bodies, and that some of them have a reasonable chance of being exploitable.

The extensive Pleistocene glacial drift on Precambrian rocks in Minnesota, Wisconsin, and Michigan handicaps prospecting for porphyry-type deposits in the covered areas to the extent that it does not seem advisable at the present time. However, if exploration for other types of mineral deposits reveals evidence for deposits of the porphyry copper type, this evidence should not be overlooked.

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