Shorter Contributions to General Geology 1966

GEOLOGICAL SURVEY PROFESSIONAL PAPER 554

This volume was published
as separate chapters A–G

U. S. DEPARTMENT OF THE INTERIOR
March 3, 1849

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[Letters designate the separately published chapters]

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By P. K. THEOBALD, JR., W. C. OVERSTREET, *and* C. E. THOMPSON

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GEOLOGICAL SURVEY PROFESSIONAL PAPER 554-A

Prepared on behalf of the
U.S. Atomic Energy Commission

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1967

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

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MINOR ELEMENTS IN ALLUVIAL MAGNETITE FROM THE INNER PIEDMONT BELT NORTH AND SOUTH CAROLINA

By P. K. Theobald, Jr., W. C. Overstreet, and C. E. Thompson

ABSTRACT

Chemical and spectrographic analyses were made for 15 minor elements in 291 samples of detrital magnetite from the Inner Piedmont belt of North and South Carolina. Lead and copper were determined in all samples; zinc in 283 samples; titanium, chromium, manganese, and tin in 284 samples; beryllium in 282 samples. These eight elements were detected in a large enough number of magnetite separates to allow the data to be analyzed statistically for geographic and geologic relations. Vanadium and barium were determined in 53 and 85 samples, respectively. Molybdenum and silver, sought in 282 samples, were detected in 8 and 2 samples, respectively. Arsenic, antimony, and tungsten, sought in 284 samples, were consistently below the lower limits of detection (1,000, 200, and 100 parts per million, respectively).

Manganese, titanium, chromium, zinc, and copper tend to group according to the four-coordinated bivalent, and the six-coordinated trivalent ionic radii, suggesting diadochic substitution in the magnetite lattice. Lead, tin, and beryllium also appear to be incorporated in the magnetite lattice, but their positions are not known.

The report area is divisible into southern, middle, and northern zones, each characterized by particular associations of minor elements in the magnetite. The middle zone is transitional between the northern and southern zones. In the northern zone, magnetite contains more chromium and less manganese and titanium than does that in the southern zone. Trends of high values for zinc and copper apparent in the northern and southern zones are abruptly interrupted at the middle zone, but high values for lead, tin, and beryllium persist throughout this zone.

The detrital magnetite is derived from metamorphosed sedimentary rocks, which cover about 85 percent of the source area; granitic rocks, which cover about 14 percent of the area; and amphibolite, gabbro, and syenite. Apparent regional variation in the bulk composition of the metamorphic rocks and regional increase in metamorphic grade are the principal factors determining the increase in abundance of manganese, titanium, chromium, and copper in the magnetite. The distribution of specific postkinematic granitic rocks rich in tin and beryllium controls the location of magnetite rich in those metals. Zinc- and lead-rich magnetite also is thought to come from particular granitic rocks, but the relations are not clear. Postkinematic granite and granodiorite in the southern zone contain abundant accessory magnetite that is lean in the minor elements. Where floods of this metal-poor magnetite enter the concentrate, the patterns of distribution of the minor elements in the metamorphic magnetite are strikingly disrupted.

The data demonstrate that the regional distribution of certain minor elements can be determined by analysis of detrital magnetite.

INTRODUCTION

This report is based on appraisals made during 1951–54 by Overstreet, Theobald, and others of fluviatile monazite placers in the western Piedmont of the Carolinas and on studies made in 1956–61 by Theobald and Thompson of trace elements in accessory magnetite from igneous rocks genetically related to ore deposits. During the latter investigation, Theobald decided to investigate the regional distribution of trace elements in magnetite. From the many thousands of heavy-mineral concentrates previously collected in the Carolinas, 289 magnetite separates were prepared by Overstreet and analyzed by Thompson. The text is largely the responsibility of Theobald and Overstreet.

The purpose of the work is to show the regional variations in the minor elements in magnetite in the western Piedmont of the Carolinas and to suggest how the procedures described here might be used in regional geochemical studies.

PREVIOUS WORK

Trace-element analyses of magnetites separated from igneous rocks or from ore deposits have been described in several recent papers. Wager and Mitchell (1951) and Vincent and others (1954) gave spectrographic and chemical analyses for several minor elements in magnetite concentrates from the Skaergaard intrusive. Theobald and Havens (1960) gave the copper, lead, and zinc contents of iron-bearing minerals and the alteration products of these minerals in the Swan Mountain intrusive. Green and Carpenter (1961) reviewed work on the thorium and uranium contents of magnetite from a variety of sources, principally ore deposits. Shrivastava and Proctor (1962) gave trace-element analyses of the rock-forming minerals of a quartz monzonite stock in Nevada. All these authors reported fairly high and fairly variable concentrations of several of the trace constituents. There is an evident partition of several trace constituents that favors magnetite, and this partition causes a more striking variation in trace-metal content of magnetite than that shown by comparative analyses of the whole rock. These considerations lead to the conclusion that regional minor-element variations can be elucidated by study of trace-element distribution in magnetite separates if representative composite separates can be obtained.

Concentrates obtained from alluvium seem to offer such a composite sample. A reconnaissance study of the distribution of zinc in alluvial-magnetite separates from the central part of the Front Range, Colo., successfully outlined the zinc-rich part of the Front Range mineral belt (Theobald and Thompson, 1959). Henry Bell 3d (1960), working near Concord, N.C., identified alluvium derived from a gabbro-syenite complex on the basis of the zinc content of alluvial-magnetite separates. To our knowledge there are no other published accounts of comprehensive studies of the trace-element composition of alluvial magnetites; however, several exploration and research groups associated with universities or mining companies are investigating the use of magnetite as an indirect medium for geochemical prospecting. These groups reportedly are obtaining favorable results, and their investigations have provided much of the impetus and, indirectly, much of the methodology for our work.

In the Front Range, local background appears to be about 200 ppm (parts per million) zinc, and anomalous values are usually greater than 1,000 ppm. Several samples collected near the periphery of that area contain less than 100 ppm, which suggests that the regional background for zinc is much less than the local background. To gain broader knowledge of the metal content of magnetite, the authors analyzed a large number of magnetite separates prepared during an appraisal of placer deposits in North Carolina and South Carolina.

The general methods of sample collection and preparation and the results of the placer appraisal and heavy-mineral studies in the Carolinas have been reported in several papers. Overstreet, Theobald, Whitlow, and Stone (1956) described methods for sample collection, sample preparation, mineralogic analysis, and data interpretation. Overstreet, Cuppels, and White (1956) reviewed the monazite distribution in the Southeastern States. Overstreet, Theobald, and Whitlow (1959) gave a more complete summary of the monazite resources in western North and South Carolina, the area of this report. Overstreet (1962) reviewed the heavy-mineral reconnaissance and the mineral suites and their distribution.

GEOGRAPHIC SETTING

The report area covers 5,200 square miles in the western Piedmont of North and South Carolina. It extends northeastward for 140 miles from the Savannah River at the South Carolina–Georgia border to the great bend in the Catawba River in west-central North Carolina. The altitude of the area is generally 700–1,100 feet. The area slopes gently toward the southeast and is characterized by low ridges, narrow valleys, and broad interfluves. The local relief is generally 100–200 feet, but it is as much as 1,700 feet at the west margin of the area, in the South Mountains and Blue Ridge.

The area is agricultural and industrial and includes some of the most heavily populated counties in North and South Carolina. The population density ranges from 44 to 309 persons per square mile and averages about 115. Because the area is heavily populated, most of it is easily accessible by a network of closely spaced roads. In general, the western part of the area is less populous and less accessible than the central and eastern parts.

From 30 to 70 percent of the land in the report area is cleared for farming (cotton, peaches, grain, or pasture), urban development, or industrial use. The uncleared land supports a luxuriant second growth of deciduous trees and conifers.

The climate is warm and humid; the annual average temperature ranges from 58.2°F at Morganton, N.C., to 62.1°F at Anderson, S.C. Annual precipitation ranges from 42.13 inches at Gaffney, S.C., to 53.18 inches at Greenville, S.C. Precipitation tends to increase westward; temperature, southward.

GEOLOGIC SETTING

The report area, a part of the Piedmont physiographic province, is underlain by metamorphic and igneous rocks of several ages. Little is known about these crystalline rocks, as surveys have been made of only four 15-minute quadrangles at Gaffney, Kings Mountain, Lincolnton, and Shelby, flanking the border between North and South Carolina (Keith and Sterrett, 1931; Sterrett, 1911; Overstreet and others, 1963); of one 30-minute quadrangle at Morganton, N.C. (Keith and Sterrett, 1907); and of Hart County, Ga., across the Savannah River from Anderson, S.C. (Grant, 1958). The part of the area in North Carolina has had better coverage by geologic mapping than the part in South Carolina. Syntheses of the regional geology of both States were prepared by Stuckey and Conrad (1958) and by Overstreet and Bell (1965a, b).

The report area is part of the Inner Piedmont belt as defined by King (1955, p. 352–356) and by Overstreet and Griffitts (1955, p. 549–577). This belt, one of 10 geologic belts into which the southern Appalachians have been divided (King, 1955, p. 337–338), includes the highest rank metamorphic rocks in the Southeastern States.

On the southeast the Inner Piedmont belt is bounded by the Kings Mountain belt, a narrow persistent zone of metasedimentary and metavolcanic rocks that is mainly at the greenschist and albite-epidote-amphibolite facies. The Kings Mountain belt extends southwestward along, and southeast of, the edge of the report area, from Lincolnton, N.C., to Gaffney, S.C. Southwest of Gaffney, the Kings Mountain belt lies a few miles southeast of the study area. The northwest edge of the Kings Mountain belt passes through the town of Laurens, S.C.; the belt reaches the Savannah River between the town of Abbeville and the Abbeville–Anderson County line.

At the northwest edge of the Inner Piedmont belt, there is a narrow zone of blastomylonite and phyllonite called the Brevard belt (Reed and others, 1961). This belt is a fault zone that crosses North and South Carolina southwestward from a point about 2 miles west of Marion, N.C., to a point on the South Carolina–Georgia border, about 23 miles upstream along the Tugaloo River from the Anderson–Oconee County line. Thus, the Brevard belt is northwest of the report area.

No certain stratigraphic succession or age assignments have been made for the rocks in the Inner Piedmont belt and, indeed, indisputable relic bedding is scarce west of the Kings Mountain belt. Locally, however, some of the sedimentary rocks exposed in the Kings Mountain belt can be traced into the Inner Piedmont.

The metamorphosed sedimentary rocks of the Inner Piedmont belt are inferred to consist of three sequences of graywacke, argillite, felsic and mafic tuffaceous argillite, tuff, and flows with sparse interbedded sandstone and limestone (Overstreet and Bell, 1965a). Erosional unconformities are postulated to separate the sequences, and to separate the oldest sequence from the basement schist and gneiss of early Precambrian age. This contact between the oldest sequence and the ancient basement rocks is probably exposed only locally in the Inner Piedmont. Ages of the three sequences of metasedimentary rocks overlying the early Precambrian basement are inferred to be late Precambrian and Cambrian, Ordovician to Devonian, and Carboniferous. Of the sequences of rocks above the basement, the older two probably constitute most of the metamorphic rocks in the Inner Piedmont belt.

A crude lithologic symmetry in the Inner Piedmont was inferred by Overstreet and Bell (1965a, p. 55–56) to represent repetition of stratigraphic units across a broad and complex anticlinorium. Hornblende gneiss, associated with biotite-muscovite schist and local layers of marble, occupies zones along the southeast and northwest flanks of the belt. Between the flanks the belt is underlain by biotite schist and gneiss, sillimanite schist and gneiss, and migmatite. Rocks in the core of the Inner Piedmont belt are less hornblendic and more highly metamorphosed than rocks on the flanks.

The decrease in the hornblendic component from the flanks toward the core probably results from original compositional differences in the sedimentary and pyroclastic rocks that now form the belt. The rocks in the core probably were deposited on the early Precambrian basement and were originally somewhat more aluminous than the rocks on the flanks. The rocks in the core were a stratified succession of shaly to sandy graywackes containing interbedded tuffaceous argillite and flows of intermediate to mafic composition. Rocks on the flanks of the Inner Piedmont belt were probably deposited on the succession exposed in the core of the belt. This overlying sequence seemingly contained more mafic volcanic tuffs and flows than did the core sequence. The overlying sequence also contained scattered layers of marl, dolomitic tuff, and dolomitic argillite that are now seen as layers of marble of different degrees of purity. Marble is virtually absent from the core sequence.

A northeastward regional decrease in the mafic character of the original sedimentary and pyroclastic rocks in the sequence overlying the core is evident on both flanks of the belt.

On the northwest flank of the belt, well beyond the report area, massive hornblende gneiss and intercalated marble are exposed in central Oconee and western Pickens Counties, S.C. These rocks may be correlative with massive hornblende gneiss and marble on the southeast flank in Laurens and Spartanburg Counties, S.C., in the extreme southeastern part of the report area. The hornblende gneiss in Oconee and Pickens Counties gives way northeastward to hornblende-biotite-oligoclase gneiss at the North Carolina–South Carolina line. The hornblende-biotite-oligoclase gneiss is more mafic than the rocks in the core of the Inner Piedmont belt, but less mafic than the hornblende gneiss in western Oconee and Pickens Counties. In Polk, Rutherford, and MacDowell Counties, N.C., outcrops of massive hornblende gneiss are sparse, but the hornblende-biotite-oligoclase gneiss is common eastward as far as central Rutherford County.

On the southeast flank of the belt, massive hornblende gneiss decreases northeastward from a point about 8 miles southwest of Gaffney, S.C. Staurolite-bearing schists, interbedded with subordinate hornblendic rocks, are abundant on the southeast flank and extend northeastward to the Catawba River. The counterparts of these staurolite schists have not been observed along the northwest side of the core of the belt in North Carolina, possibly because they were cut out by the Brevard fault west of Marion.

Thus, there seems to be a regional northeastward decrease in the original mafic component of the metasedimentary and metavolcanic rocks on the flanks of the belt.

The attitude of these rocks, inferred to be broadly anticlinorial, tends to expose the more argillaceous sequence in the core of the belt and the more tuffaceous sequence on the flanks of the belt. An unconformity probably separates the two sequences, but the detailed mapping needed to show the unconformity has not been done in South Carolina, and the maps that have been made in North Carolina do not show the stratigraphic sequence in the Inner Piedmont belt.

The metamorphism in rocks of the Inner Piedmont belt increased in grade toward the core of the belt. Rocks along the flanks are typically at the albite-epidote amphibolite facies and at the lower subfacies of the amphibolite facies. In the core of the belt, the rocks are at the sillimanite-almandine subfacies of the amphibolite facies. Areas where the upper subfacies of the amphibolite facies was attained are outlined on plate 2*F* by the 1-percent isogram for sillimanite.

The area of metamorphic climax defined by the distribution of sillimanite is strongly asymmetric and is toward the southeast side of the Inner Piedmont belt.

The trend of the zone of rocks at the sillimanite-almandine subfacies is athwart the trends of the stratigraphic units in the Inner Piedmont belt (Overstreet and Bell, 1965a, p. 57). Where the continuity of the 1-percent isogram for sillimanite is interrupted between the North and South Tyger Rivers in Spartanburg County, S.C., the rocks decrease in metamorphic grade to the lower subfacies of the amphibolite facies. From a point just north of Paris Mountain in Greenville County, S.C., to a point a few miles west of the confluence of the North and South Tyger Rivers, a distance of 20 miles, the metamorphic isograds cut across the trend of foliation and the probable trends of bedding. The metamorphic isograds also cross regional planar structures in northeastern Anderson County, S.C., where the 1-percent isogram for sillimanite swings west at the Saluda River.

The metamorphic climax in the Inner Piedmont belt is interpreted as having occurred in Ordovician time and as having affected all earlier sequences of sedimentary and pyroclastic rocks (Overstreet and Bell, 1965a). A subsequent regional metamorphic event in late Carboniferous or Permian time is recorded in the Inner Piedmont by the retrogressive effects that it produced.

Cycles of intrusive activity are represented in the Inner Piedmont by plutons of granite and granodiorite and by dikes of pegmatite and gabbro that were emplaced at different times. Felsic plutonic igneous rocks of possible Cambrian, Ordovician to Devonian, and Carboniferous to Permian ages have been recognized. Mafic intrusive rocks are of Cambrian or Ordovician and Permian age. Diabase dikes of Late Triassic(?) age intrude the other igneous rocks. The plutonic igneous rocks of each cycle apparently were emplaced during or after the successive metamorphic episodes.

The rocks of the area have been continuously weathered and eroded since Cretaceous time. The crystalline rocks are now rather thoroughly weathered and are mantled by saprolite. At most places in the report area, the saprolite is 20–50 feet thick; in a few places it is as much as 180 feet thick; and even in the valleys where erosion has been deepest, at least 85 percent of the rocks have been converted to saprolite to depths of more than 5 feet.

The heavy minerals in the streams are derived almost entirely from saprolite, so the magnetite used for the analyses reported herein was weathered for a long time before entering the streams.

COLLECTION OF MAGNETITE

Magnetite used in this study is from detrital heavy-mineral concentrates collected in 1951–52 by personnel of the U.S. Geological Survey, supported by the Division of Raw Materials of the U.S. Atomic Energy Commission, during a study of fluvial monazite placers. D. W. Caldwell, N. P. Cuppels, A. M. White, and J. W. Whitlow prepared many of the concentrates.

The heavy-mineral concentrates were prepared by panning samples of gravel or sand dug from riffles in the present channels of small streams. Each sample weighed about 40 pounds. The samples were wet-sieved through a screen made of steel punch plate with ⅛-inch holes, the oversize discarded, and the minus ⅛-inch fraction washed free of clay. Sieved and washed sand was then panned in 16-inch stainless steel pans for 20–30 minutes to provide a concentrate containing as much as 95 percent magnetite and other minerals, of which ilmenite, garnet, monazite, and epidote were the most common. Most of the concentrates contained 1–40 percent magnetite. Between 5 and 20 percent quartz was left in the concentrate to avoid loss of heavy minerals sought in the final stage of panning. The procedure was described by Theobald (1957, p. 3–6). The magnetite used in the present investigation was separated with a hand magnet from the other minerals in the concentrate.

ANALYTICAL PROCEDURES

The magnetite samples were analyzed by field methods described by Ward, Lakin, Canney, and others (1963). Dithizone was the colorimetric reagent used for lead and zinc determinations, and 2,2′-biquinoline was the reagent used for copper determinations. The spectrographic determinations were made by a semiquantitative visual comparison method on the 1.5-meter mobile spectrograph of the U.S. Geological Survey. Because these methods were developed for the analysis of soils and rocks, they had to be modified to prevent interference from the large amount of iron in the magnetite. In the chemical procedure, the samples were fused with an excess of potassium pyrosulfate for at least 5 minutes. Iron interference was then controlled by adding two or three times the specified volume of the buffered complexing agent. In the spectographic procedure, a series of standards was prepared, using as a base magnetite nearly free of the metals sought.

RELIABILITY OF THE DATA

Variations among analytical results for a suite of magnetite separates may result from variations in (1) metal content of the magnetite, (2) amount of another mineral included in the magnetite, (3) amount of an artificial contaminant in the separates, or (4) the analytical method. The consistency of the distribution patterns for each of the elements across the report area seems to limit the possibility of artificial contamination of the separates. Artificial contamination is more apparent in smaller separates than in larger separates, and there appears to be more metal, particularly tin, in samples containing smaller amounts of magnetite.

The tin distribution in the magnetite concentrates is bimodal, indicating that the samples may represent two populations. For those samples where the heavy-mineral concentrate contains less than 1 percent magnetite,[1] there is a well-defined break between the two populations at about 10 ppm (parts per million) tin. About 20 percent of these magnetite separates contain 10 ppm tin or less; the remainder contain about 30 ppm (fig. 1). To assess the possibility that the higher mode for tin results from artificial contamination, a curve relating the tin content of the magnetite to the magnetite content of the heavy-mineral concentrate is compared in figure 2 with a similar curve calculated from the distribution in figure 1 by successive additions of tin-free magnetite. The actual decrease in the proportion of magnetite separates containing detectable tin as the amount of magnetite in the heavy-mineral concentrates increases is much greater than the calculated change. Artificial contamination may exist, but there is no evidence for it in the distribution pattern for these samples.

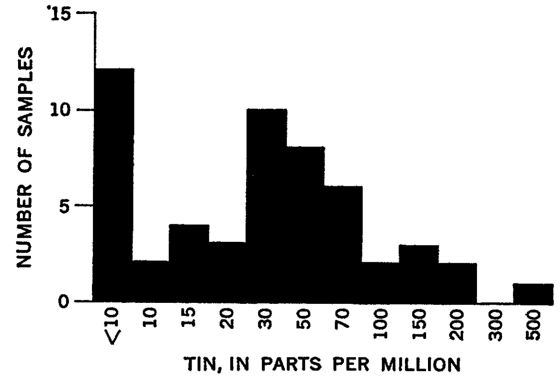

FIGURE 1.—Tin content of magnetite separates from heavy-mineral concentrates containing less than 1 percent magnetite.

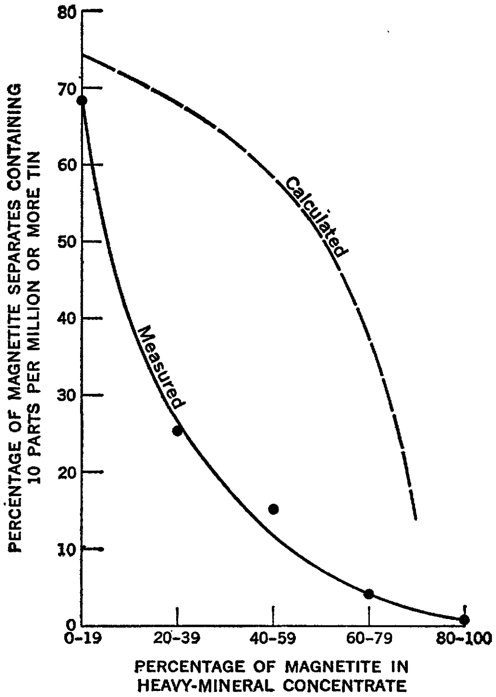

FIGURE 2.—Relation of the percentage of magnetite in heavy-mineral concentrates to the proportion of the samples containing more than 10 ppm tin. The calculated curve is controlled by the distribution of tin in samples containing less than 1 percent magnetite, and is projected on a basis of dilution by tin-free magnetite.

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[1] Percent is used for convenience. In these concentrates percent and weight of magnetite correlate so closely that both give virtually identical results.

Natural contamination of the separates by the inclusion of another mineral in magnetite or the intergrowth of magnetite with other minerals does occur. The unusually metal-rich separates were examined chemically, mechanically, and microscopically in search of a separate phase. The following, for example, were found in the residue from 0.5 g (gram) magnetite from sample 52–WE–109 dissolved in two successive 5-ml (milliliter) portions of hydrochloric acid:

> 15 mg (milligrams) leucoxene, mostly as boxworks resembling exsolution laminae visible in the original magnetite, 10 mg quartz with minor feldspar, 9 grains staurolite, 3 grains ilmenite, 1 grain zircon, and 1 grain magnetite (protected by a frosted coating of leucoxene).

The separates appear to contain about 99 percent magnetite, some of which has oxidized to maghemite(?) or hematite (martite).

Virtually all gross errors were eliminated by repeating analyses that originally gave anomalous or unusual analytical results; the repeated analyses were usually made using an independent analytical procedure. One gross error, detected in the analyses of the first group of samples, provided a measure of the precision of the chromium determinations. A minor chromium line in the spectrograms was mistakenly read against the antimony standard and reported as antimony. In figure 3 the erroneous antimony results are compared with the results for chronium in the same samples. The circled anlayses have been checked chemically, and none show antimony in excess of 100 ppm. This comparison indicates the validity of the fourfold subdivision of the chromium results that is used in the following discussion. The product-moment-correlation coefficient for these paired data (even though one set was read against the antimony standard rather than the chrominum standard) is 0.93 for those samples reported to contain at least 100 ppm antimony. A correlation between chromium and some other element or feature would be extremely poor if it could be masked by analytical variation.

Lead and copper were determined both chemically and spectrographically (fig. 4). The two regression lines represent the best fit of the chemical analyses to the spectrographic analyses and the best fit of the spectrographic analyses to the chemical analyses. A slight bias is evident for both elements; the chemical analysis is relatively high for lead and relatively low for copper, compared with the spectrographic analysis. The

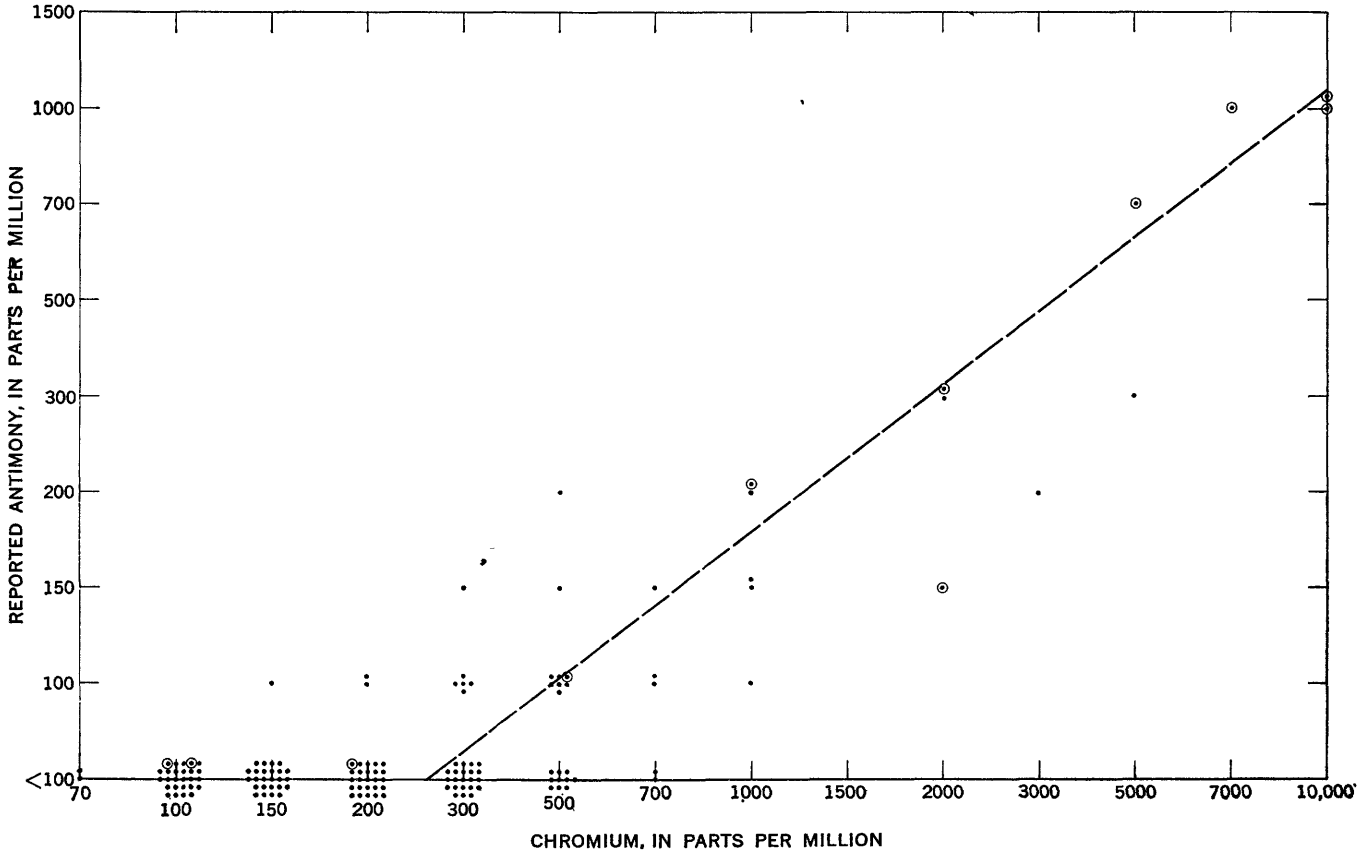


FIGURE 3.—Comparison of erroneously reported antimony with chromium reported for the same samples. Each original spectrographic analysis shown as a dot; those checked chemically are circled.

spread of the data in comparison with the analytical variation for both elements justified the subdivision of data used in the following discussion and shown in the illustrations of the geographic distribution of the elements (pls. 1, 2). The product-moment-correlation coefficients—0.86 for lead and 0.65 for copper—are such that only poor correlations among the elements will be missed because of analytical variation.

The methods of determining chromium, lead, and copper span the expected range of precision for the other elements. Several years' experience with these analytical procedures indicates that the method for spectrographic determination of copper is one of the least precise and that the method for chromium is one of the most precise. Because of their greater sensitivity and somewhat greater precision, chemical determinations were used wherever available. Where samples were too small for chemical analysis, spectrographic analyses were substituted. Bias between the two methods is insignificant in relation to the subdivisions of the data we have used.

DISTRIBUTION OF THE ELEMENTS

Fifteen elements were sought by chemical and spectrographic analyses. The results of analyses of the 291 magnetite separates are tabulated in table 4 at the end of the report. The spectrographic method was used to determine titanium, chromium, manganese, and tin contents of 284 separates and beryllium content of 282 separates. Zinc, because of the poor sensitivity of the spectrographic method, was sought by chemical analysis in 283 of the separates (the remaining 8 contain less than 200 ppm). Lead and copper were sought in all samples analyzed by either technique, although the chemical results have been given priority in the discussions. Spectrographic determinations of vanadium, sought in 53 separates, and barium, sought in 85 separates, are discussed only briefly, as the coverage is considered inadequate. Molybdenum was detected in eight samples, and silver was detected in two samples; data for these elements are insufficient. Arsenic, antimony, and tungsten were consistently less than the lower limits of spectrographic detection, 1,000, 200, and 100 ppm, respectively.

TABLE 1.—*Grouping of eight minor elements by valence, coordination, and ionic radii with respect to iron in magnetite*

[Radii from Green (1959, table 2). Most have been recalculated to four-coordinated value for bivalent state. Geochemical nature from Rankama and Sahama (1950, table 4.3): S, siderophile; C, chalcophile; L, lithophile; parentheses, subordinate association]

	Radius, for indicated valence and coordination		Geochemical nature
Valence Coordination	+2 4	+3 6	
Fe (magnetite)	0. 70	0. 64	S, C, (L)
Mn	. 76	. 66	L
Cr	----------	. 63	L
Ti	----------	. 76	L
Zn	. 71	----------	C, (L)
Cu	. 68	----------	C
Pb	1. 14	----------	C, (S), (L)
Sn	. 88	----------	S, (C)
Be	. 33	----------	L

The eight elements for which adequate data are available—zinc, copper, lead, titanium, chromium, manganese, tin, and beryllium—may be conveniently grouped according to their valence states, coordination, and ionic radii with respect to iron in magnetite (table 1). Magnetite, as a member of the spinel group, is composed of 8 atoms of bivalent four-coordinated iron, 16 atoms of trivalent six-coordinated iron, and 32 atoms of oxygen per unit cell (Palache and others, 1952, p. 688). To allow diadochic substitution, an element must have a size at the valence and coordination state similar to that of the element to be replaced. Rankama and Sahama (1950, p. 122) put an approximate size limitation on diadochic substitution of ± 15 percent of the size of the element being replaced. Table 1 is therefore based on four-coordinated bivalent and six-coordinated trivalent ionic radii. Manganese, chromium, and titanium, which can substitute for trivalent iron, make up the first group. The inclusion of titanium in this group requires a slight stretching of the 15-percent limit, but the presence of titanium as a trivalent ion in magnetite has been inferred by several authors, and the evidence was recently summarized by Basta (1959, p. 711–717). The size of manganese ions would allow substitution in the bivalent as well as trivalent positions, although the substitution would be more easily accomplished in the latter position. As will become evident, the pattern of distribution of manganese in these samples is more similar to those of chromium or titanium than to those of the other elements. Zinc and copper, which can easily substitute for bivalent iron, constitute the second group.

The remaining three elements—lead, tin, and beryllium—compose the third group. These elements do not have trivalent forms, and their bivalent four-coordinated sizes are not compatible with that of iron. This seemingly prohibits diadochic substitution, but it does not eliminate the possibility that these elements may occur in the framework of a magnetite lattice. Solid solution of other members of the spinel group with magnetite could easily allow for their introduction, either through the solid solution itself or by indirect diodochy of the trace elements with those of the solid solution. Although the extensive solid solution that occurs among the members of the magnetite series can be of little help, the limited solid solution that exists be-

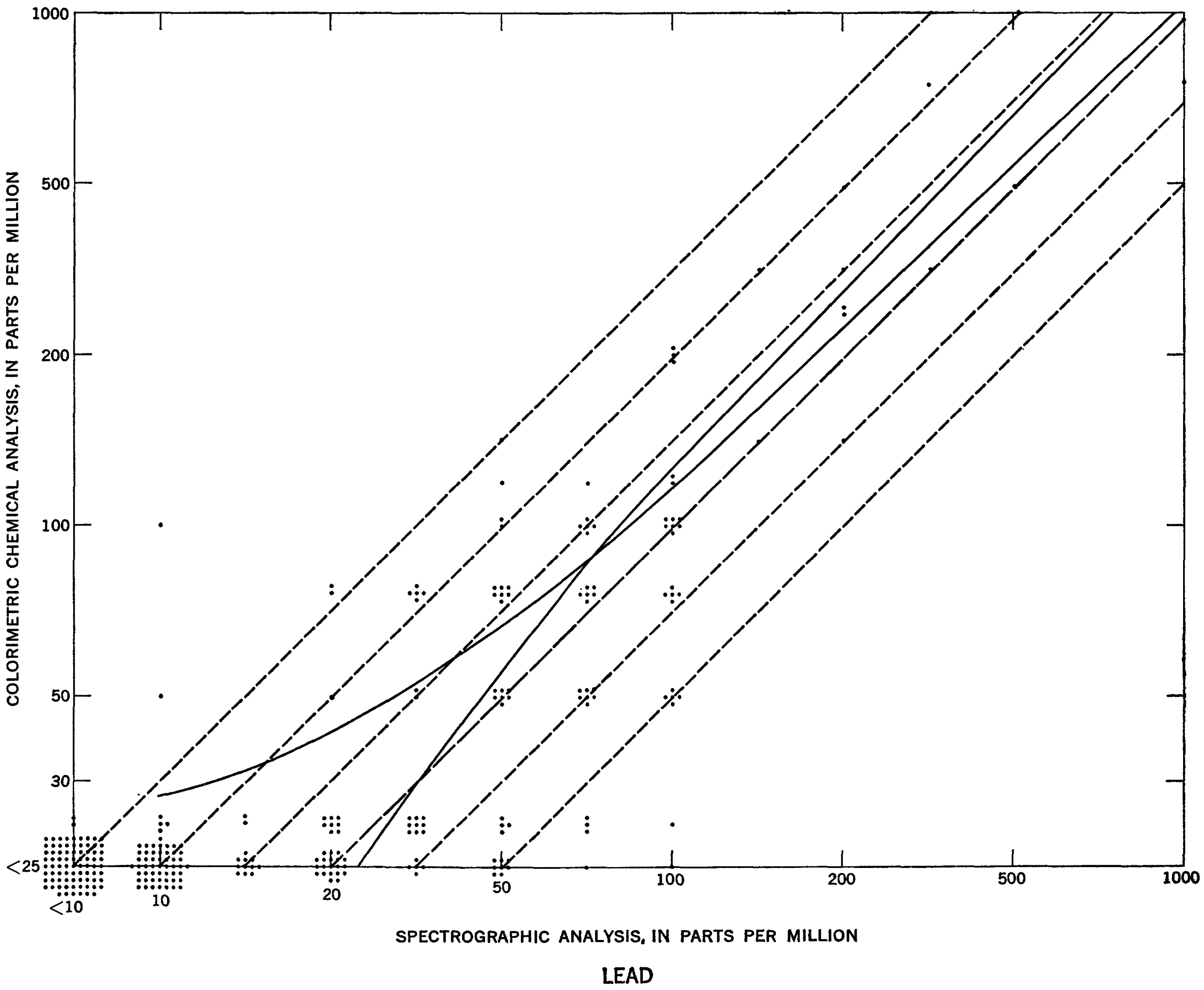
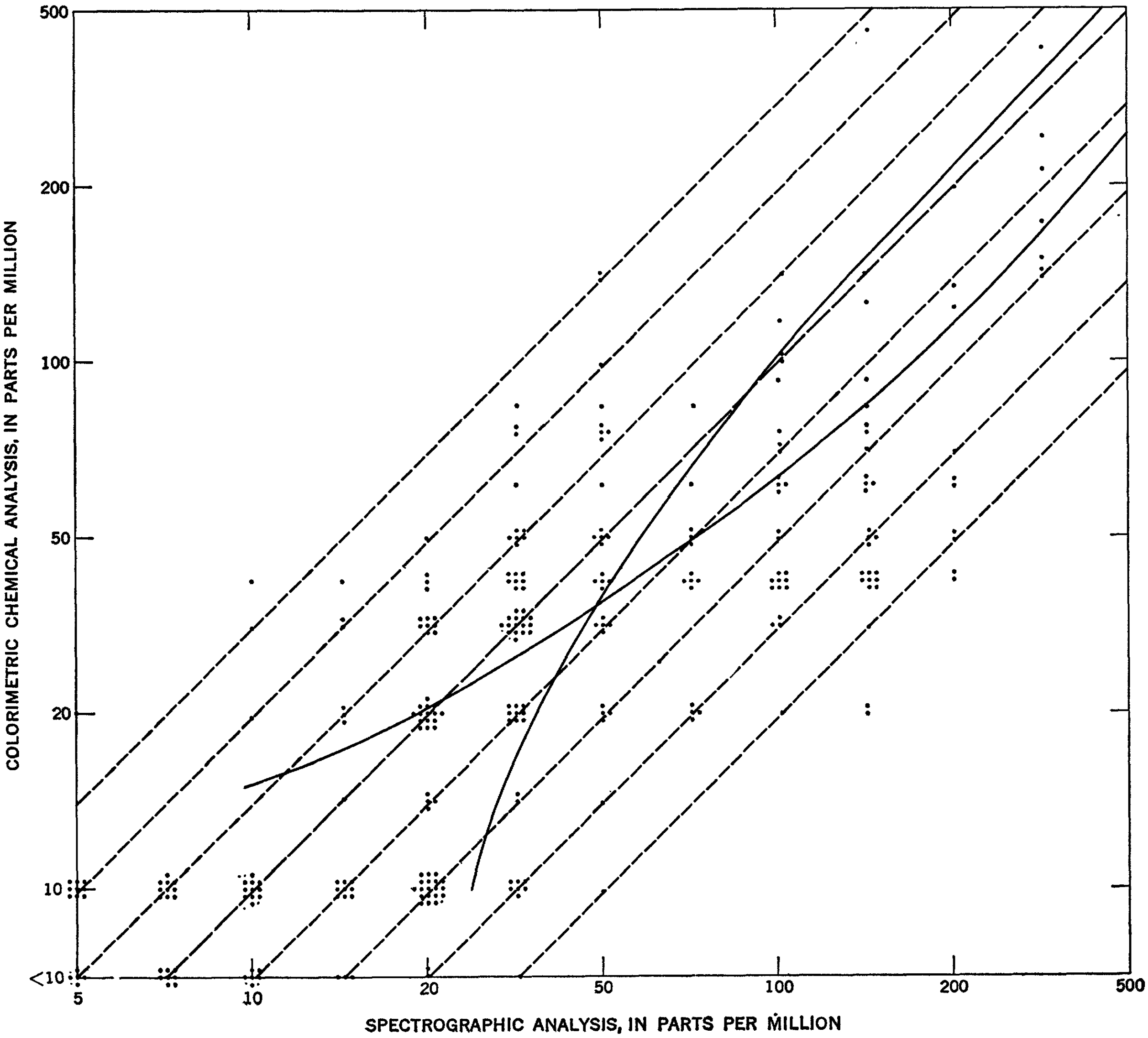


Figure 4.—Comparison of chemical and spectrographic analyses (290 duplicate determinations) for lead (above) and copper (on the facing page) in magnetite separates. Each pair of analyses denoted by a dot. Dashed line marks perfect correlation; short dashed lines denote spectrographic report intervals on either side of perfect correlation; solid lines are the linear regression curves (curved because of the logarithmic scales).

tween magnetite and the spinel or chromite series could be important in terms of trace elements. (For example, limited solid solution of magnetite and the spinel series with minor replacement of aluminum by beryllium could easily account for all the beryllium reported.) Artificial preparations of tin, lead, and beryllium spinels have been reported in both the magnetite and chromite series. (See Mellor, 1931, p. 201; 1934, p. 914.) The possibility that lead and tin are present in the quadrivalent form cannot be disregarded, particularly in view of possible compensating substitutions in the structural modification of the form $FeMgFeO_4$ as described by Barth and Posnjak (1931). This third group could be further subdivided into two subgroups, since lead and tin have radii considerably larger than that of iron whereas the radius of beryllium is considerably smaller.

The elements in each of these groups have in common many features of distribution; for this reason, they are considered by groups. Because manganese, chromium, and titanium can best be used to illustrate a major geographic subdivision of the data, they are considered first. The data for all the elements are summarized in table 2, which illustrates the similarity of elements within each group and the breaks between groups for each of the measures of central tendency. The comparison of mean, median, and mode provides a crude measure of the shape of the distribution for each ele-



COPPER

ment. Each distribution is skewed toward higher values.

Table 2.—*Summary of analyses of magnetite separates from the Inner Piedmont belt of North and South Carolina*

[In parts per million]

Element	Number of analyses	Mean	Median	Mode	Range
Mn	284	[1] 1,750	1,500	1,500	100->10,000
Cr	284	[1] 890	300	200	20->10,000
Ti	284	[1] 6,000	5,000	3,000	1,500->10,000
Zn	283	98	75	50	25- 1,000
Cu	291	40	30	10	<10- 450
Pb	291	[2] 50-64	<25	<25	<25- 1,000
Sn	284	[2] 32-37	10	<10	<10- 2,000
Be	282	<1	<1	<1	<1- 15

[1] Minimum value, values of >10,000 taken as 10,000.

[2] End points of range represent minimum (all values of less than the lower limit of sensitivity taken as zero) and maximum (all values of less than the lower limit of sensitivity taken as equal to the lower limit of sensitivity) possible values for the mean.

MANGANESE, CHROMIUM, AND TITANIUM

Manganese, chromium, and titanium are the most abundant of the trace elements. Distributions of all three are skewed toward high values and are truncated at the upper limit of spectrographic sensitivity (10,000 ppm in most analyses but 20,000 ppm for some titanium determinations). The distributions are not only skewed on an arithmetic scale but appear to retain a considerable amount of skewing on the logarithmic scale used in spectrographic reporting (fig. 5). There are marked differences in detail among the distributions.

The patterns formed by plotting and contouring the data on a planimetric base (pl. 1) exhibit a marked dichotomy. On the basis of this dichotomy, the report area was divided into a northern zone and a southern

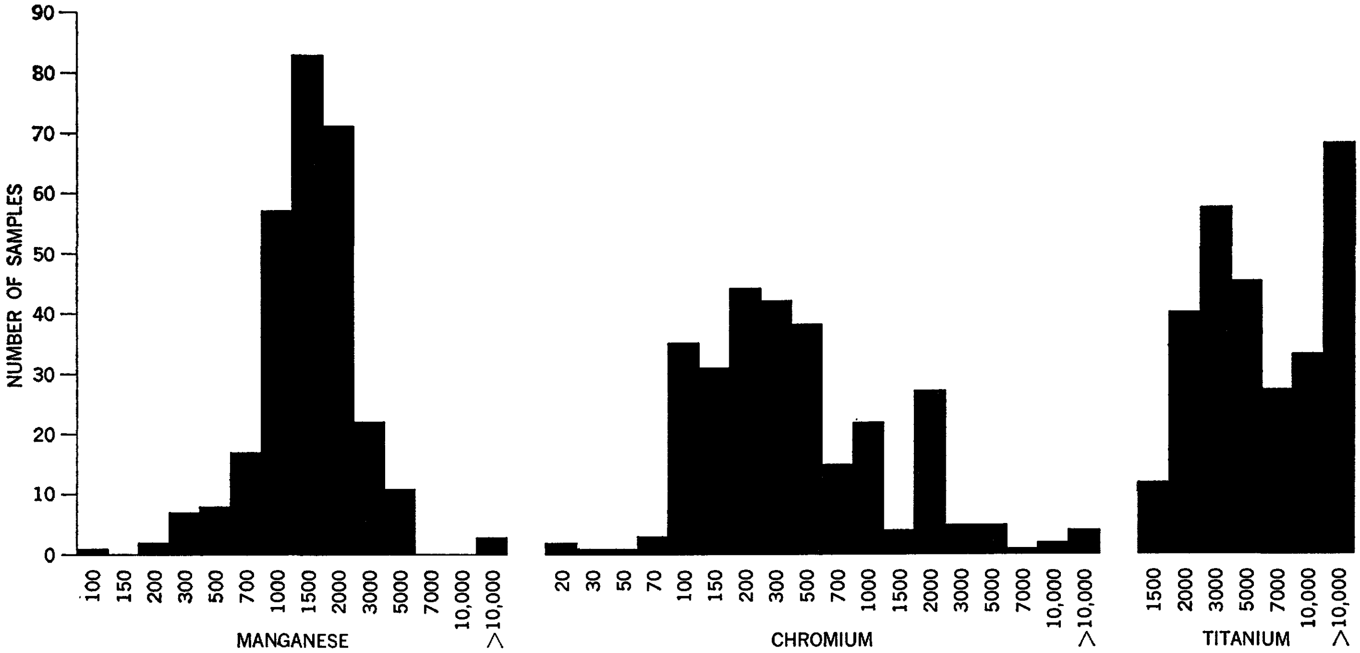


FIGURE 5.—Manganese, chromium, and titanium (in parts per million) in magnetite separates.

zone. In the northern zone the values for chromium are complex but are generally higher than in the southern zone, where values for manganese and titanium are relatively higher. The dividing line between the two apparent populations cannot be determined precisely (owing largely to the nature of the sampling and the data), but it is about along the course of the Tyger River. A third, composite zone, herein called the middle zone (pl. 1*A*), has been established to include the breaks in the distribution for these three elements as well as breaks in the distribution patterns of copper and zinc (pl. 2*A*, *C*) and a narrowing in the belts rich in lead, tin, and beryllium (pl. 2*B*, *D*, *E*). The southern boundary of the middle zone is defined by the locations of the breaks in data for manganese, chromium, and titanium, which are approximately coincident. The northern boundary of the middle zone is defined by the northernmost possible position for the break in the zinc data. The southernmost possible position for the break in the zinc data and the inferred position of the break for copper, lead, and beryllium are approximately coincident and lie near the middle of the zone.

Having thus bracketed the break, we can test the validity of the subdivision. Because the data are truncated, are measured by a logarithmic scale, and have a strongly skewed but unknown distribution, a nonparametric test was used here and for most like data throughout the report. The nonparametric tests are distribution free and usually do not require that the data be measured on an interval scale. These advantages eliminate the necessity for guessing at the form of the distribution and then projecting this form into the unknown realm above and below the sensitivity of the analytical procedures. There is the further advantage of speed gained by avoiding what would undoubtedly be a cumbersome transformation if the nature of the distribution could be unraveled. With the nonparametric tests there is a slightly greater chance of overlooking an existing correlation, but for the number of samples involved this additional risk is negligible. The chance of finding a false correlation is no greater with a nonparametric test than with the parametric test.

A median test (Siegel, 1956, p. 111–116) establishes the dichotomy in the distribution of manganese, chromium, and titanium. The hypothesis is that the chromium content of the magnetites is greater in the northern zone than in the southern, and that the reverse is true for manganese and titanium. The null hypothesis is that the manganese, chromium, and titanium contents in the northern and southern zones are approximately the same. The χ^2 test for two independent variables may be used. The two categories are discrete north and south of the middle zone. Rejecting the null hypothesis at 1 chance of error in 20 ($\alpha = 0.05$) is completely reasonable for these data, but, as will be seen, the chance of error is considerably less. A two-tailed test has been used, although a one-tailed test is permissible under the original hypothesis. A total of 256 samples was tested—93 from the southern zone and

163 from the northern, and the smallest entry in the contingency tables is 18. The critical values of χ^2 are:

α	χ^2
0.05	3.84
.01	6.64
.001	10.83

The results of the median test are:

Element	χ^2	$p(H_0)$
Manganese	14.54	<0.001
Chromium	33.78	$<.001$
Titanium	7.13	$<.01$

These results indicate that the original hypothesis may be accepted with a high degree of confidence; that is, we will consider the dichotomy to have been established.

Separating the data for the northern and the southern zones (fig. 6) provides a clearer picturer of the distribution. The possibility that the individual populations of manganese and chromium have logarithmic distributions must be strongly hedged because of the inherent logarithmic scale of spectrographic analysis and the irregular sample distribution for chromium.

The arcuate manganese-poor area is the most conspicuous feature of the northern zone. It generally follows the course of the First Broad River in North Carolina and swings westward in South Carolina to cross Cherokee County and the middle reaches of the Pacolet River in Spartanburg County. The area terminates against the middle zone on the south and against the south flank of the South Mountains on the north. The northern and southern parts of the manganese low coincide with titanium lows, and the prominent titanium-rich area in Cleveland County, N.C., is broken along the First Broad River. The titanium- and chromium-rich area that includes most of Cleveland County dominates the pattern for these elements in the northern zone. A discontinuous area of low values for both elements lies to the west of the high along the western limit of the report area.

An area lean in all three metals occupies a large part of Anderson County in the southern zone. A second area that is low in manganese and titanium trends eastward from the western limit of the report area south of Greenville. A titanium-rich area surrounds the low in Anderson County, which is flanked by manganese-rich areas on the north, east, and south.

COPPER AND ZINC

Average zinc values in the magnetite separates are intermediate between those of manganese, chromium, and titanium and those of lead, tin, and beryllium. Average copper values are similar to those of lead. The range for both elements is about one and a half orders of magnitude. The general distribution for both is strongly skewed toward high values, even when plotted on the geometric reporting scale (fig. 7). Weak bimodal, or possibly trimodal, distributions are evident for both; the second mode is near 150 ppm for copper and 700 ppm for zinc. The skewing is due at least partly to this bimodal character.

Geographic distributions of copper and zinc are shown on plate 2*A*, *C*. There is a strong pattern of elongate north-trending areas of above- or below-average zinc content. The same pattern is evident for copper, though the pattern is less distinctive and seems to break down in the northern zone where the prominent highs trend more eastward This pattern is distinctly broken along a line across central Spartanburg and northern Greenville Counties, S.C., in the middle zone as defined in the preceding section on "Manganese, Chromium, and Titanium." The pronounced dichotomy noted for manganese, chromium, and titanium is not evident for copper and zinc. The medians of copper and zinc are the same in the northern zone as they are in the southern zone, and they coincide with the median for the combined data—30 ppm for copper and 75 ppm for zinc. Instead of the dichotomy, there is a break in the data and an apparent offset of about 15 miles in the patterns.

In the southern zone both the copper-rich area and the elongate low-zinc area extending southward from Greenville follow approximately along the Saluda River. The high-copper area along the middle reaches of the Enoree River is poor in zinc. At no place in the southern zone does a zinc value in excess of 300 ppm coincide with a copper value in excess of 75 ppm; that is, the second modes described for the overall distribution of these two elements are not geographically coincident in this zone. Despite this apparent reversal of highs and lows, the two elements are not negatively correlated. Kendall's correlation coefficient τ (for discussion of τ see p. A15) is negative but unusually small (-0.009)—only 6 of 112 correlations of various combinations of the 8 elements are smaller. We can say with considerable confidence that in the southern zone the two elements do not correlate, and the only similarities between them are the type of pattern, their concentration range, and their expected geochemical behavior.

In the northern zone the copper- and zinc-rich areas appear to coincide fairly well. The zinc-rich area extending irregularly northward from the vicinity of Spartanburg overlaps the copper-rich area north of Spartanburg and a large part of the copper-rich area along the Cleveland–Rutherford County line in North Carolina. The principal area of copper-rich magnetite is along the lower reaches of Buffalo Creek near the

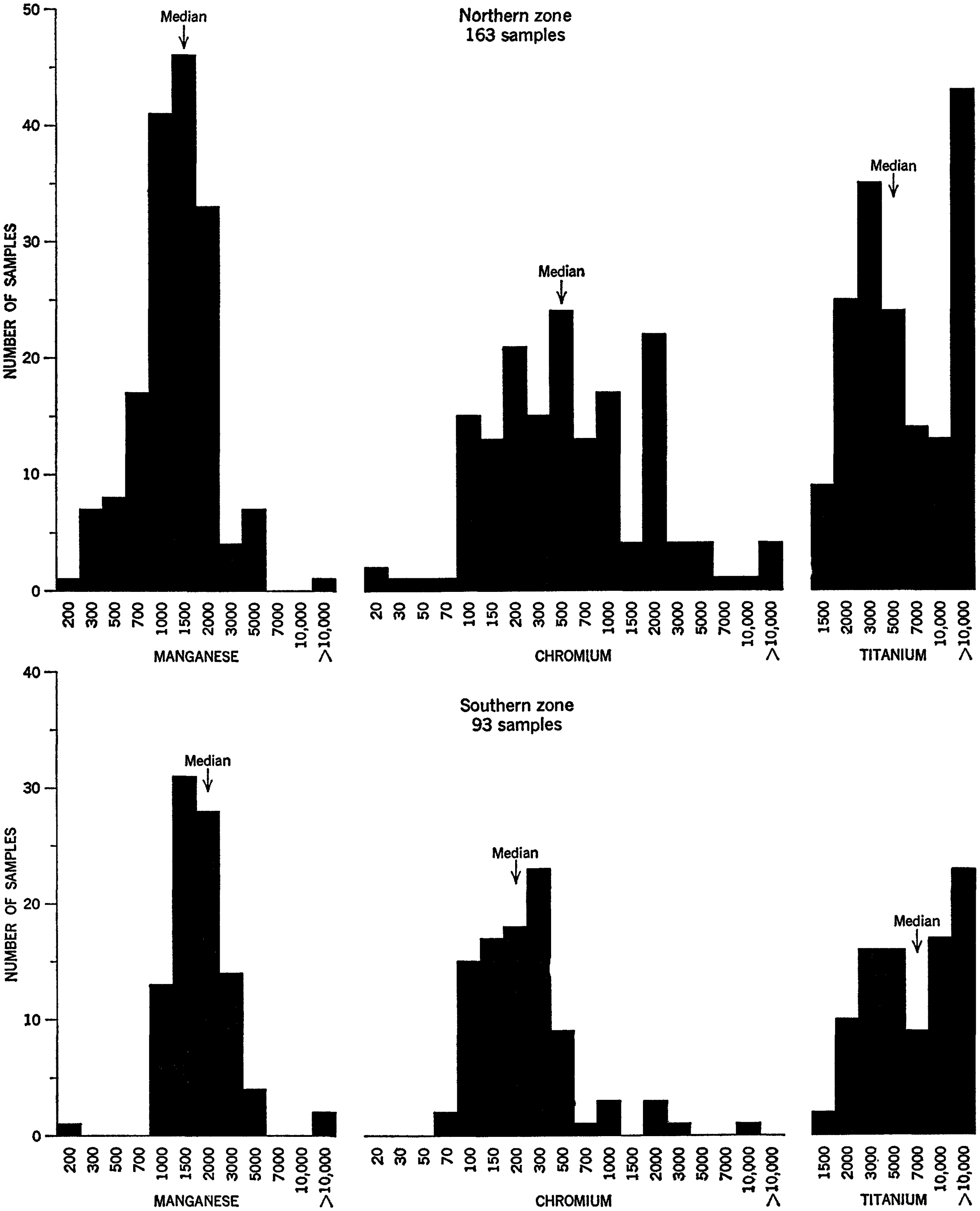


Figure 6.—Manganese, chromium, and titanium (in parts per million) in magnetite separates from the northern and southern zones of the Inner Piedmont belt.

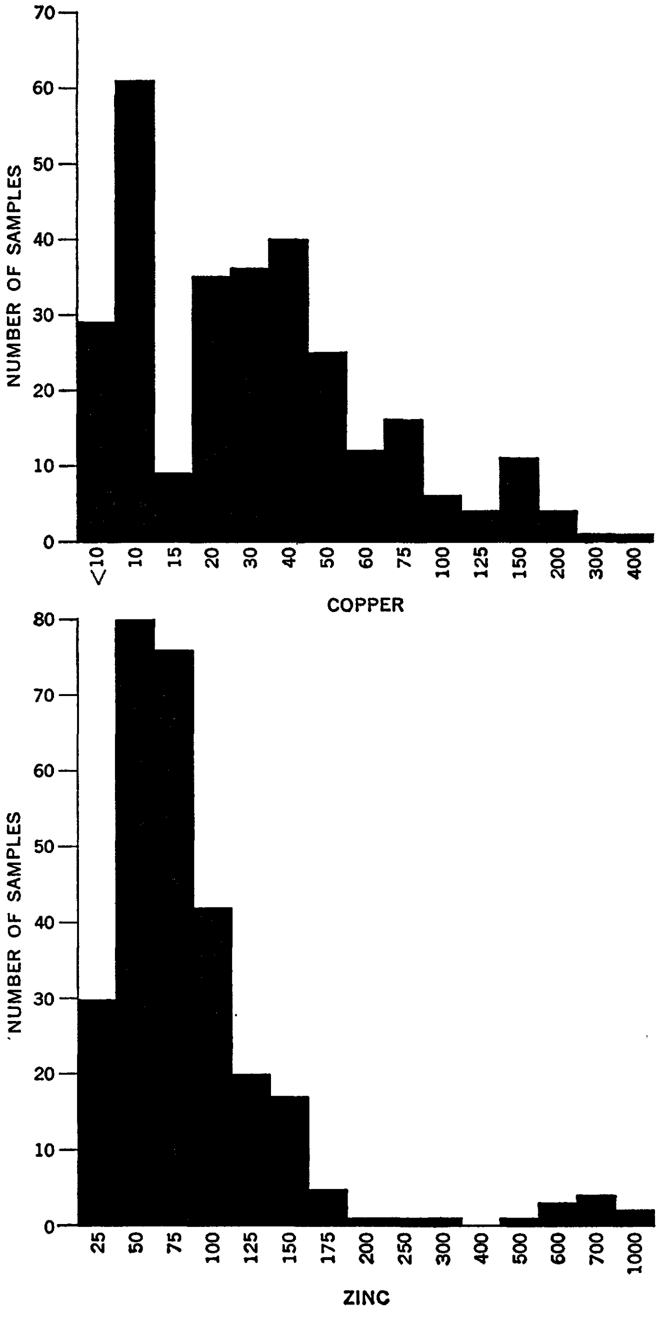


FIGURE 7.—Copper and zinc (in parts per million) in magnetite separates.

North Carolina–South Carolina line. This area is also rich in zinc. Kendall's correlation coefficient τ for copper and zinc in the northern zone (+0.15) is significant at $\alpha=0.01$.

A pronounced difference occurs in the interrelations between the two elements across the hiatus marked by the middle zone. This difference refutes simple fault displacement, as might be inferred from the uniform displacement of the north-trending elongate patterns. Some change in process must have been involved. The patterns are generally parallel to zones of regional metamorphism, and the areas of high concentration, particularly for zinc, appear to flank the zones of maximum metamorphism.

The copper-rich area along Buffalo Creek at the North Carolina–South Carolina line is the principal feature of the distributions. Included in this area are 8 nearby samples of the 27 that constitute the higher mode for copper; four of the six highest values occur in this group. Two of the samples from the second mode of zinc occur in this same area; this is the only place where samples from the second mode for zinc coincide with those from the second mode for copper.

More information is available on the zinc content than on the contents of other minor elements in magnetites. In the two areas from which a considerable amount of data has been accumulated—the Front Range of Colorado and the Concord quadrangle, North Carolina—values are similarly distributed. The general background level seems to be below 100 ppm; locally higher levels of concentration generally range from 100 to 200 ppm; and the highest levels, not uncommonly in excess of 1,000 ppm, occur in alluvial magnetite separates adjacent to zinc-rich mining districts or in magnetites separated from igneous rocks inferred to be genetically related to zinc-rich ore deposits. The highest values usually occur in large areas in which the zinc content generally ranges from 100 to 200 ppm. This pattern is nearly identical with that in the Inner Piedmont belt. A cumulative frequency curve (fig. 8) shows that 65 percent of the samples contain 75 ppm zinc or less. The slope of the curve breaks at about 100 ppm to accommodate about 30 percent of the samples whose zinc contents are in the range 100 to 200 ppm. Above 200 ppm the slope of the curve is exceedingly low until the second mode is reached above 500 ppm. The nature of the distribution and the analogy between the Front Range and the Concord quadrangle suggest at least two populations. The concentration of values in the range 100 to 200 ppm could be due to either a third population or a mixture of the two populations. By analogy it can be inferred that magnetite separates containing more than 400 ppm zinc are derived from a rock type that had the potential of genetic association with zinc-rich deposits. This rock must be a minor type occurring in isolated rather small areas scattered along the margins of the high-rank metamorphic rocks.

A similar interpretation may apply to the copper distribution. The probability of two populations again seems high. If the copper highs can be assigned to a rock type, the distribution of this rock with respect to

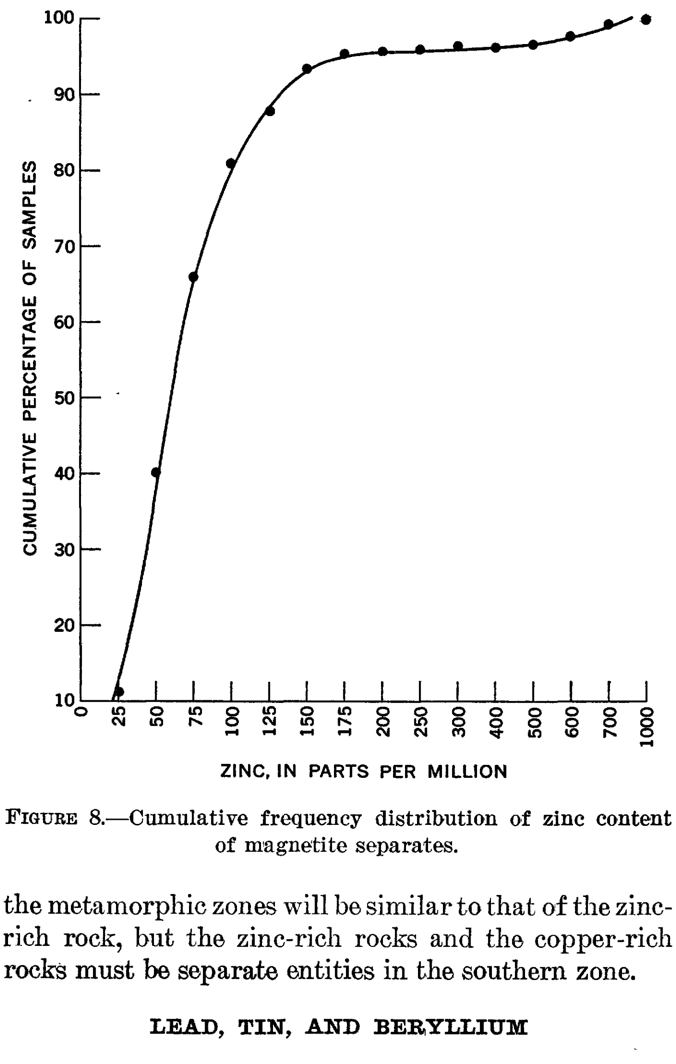


FIGURE 8.—Cumulative frequency distribution of zinc content of magnetite separates.

the metamorphic zones will be similar to that of the zinc-rich rock, but the zinc-rich rocks and the copper-rich rocks must be separate entities in the southern zone.

LEAD, TIN, AND BERYLLIUM

The average amounts of lead, tin, and beryllium found in the magnetite separates are the lowest values obtained for the three groups of elements. The average for beryllium seems to be considerably below the averages for tin and lead. The total range for each is more than an order of magnitude. As less than half the separates contain detectable quantities of these three elements (fig. 9), evaluating the nature of the overall distribution is difficult. Nevertheless, it is clear for at least lead and tin that even on the geometric and logarithmic reporting scales the distributions are strongly skewed toward high values. It seems likely that at least two populations are represented, one including the samples with detectable metal and the other including samples with average metal content below the limit of sensitivity. Two populations can be demonstrated for a part of the tin distribution when the effect of variation in the quantity of magnetite in the concentrate is removed. (See fig. 1.)

The geographic distribution of these minor elements is shown on plate 2*B*, *D*, *E*. The patterns shown on these maps are markedly similar. High values are clustered in a relatively narrow belt extending northeastward from the Saluda River to the North Carolina–South Carolina line. The pattern for beryllium loses coherency in North Carolina, and only a series of isolated spots remains. The patterns for lead and tin generally expand into North Carolina and continue to the northern and eastern limits of the report area. In South Carolina the patterns terminate abruptly against the Saluda River, but there is a slight indication of a trend change southward toward an area of high concentration along the general course of the Saluda River; this trend change is particularly evident in the pattern for tin. Scattered along the northeast-trending belt are areas of higher concentrations that are generally coincident for all three elements. The largest and most metal-rich of these, not reflected in the beryllium data, is along Buffalo Creek in southeastern Cleveland County, N.C. Other metal-rich areas are in South Carolina along the western tributaries to the Pacolet River, along the South Tyger River, and near Greenville.

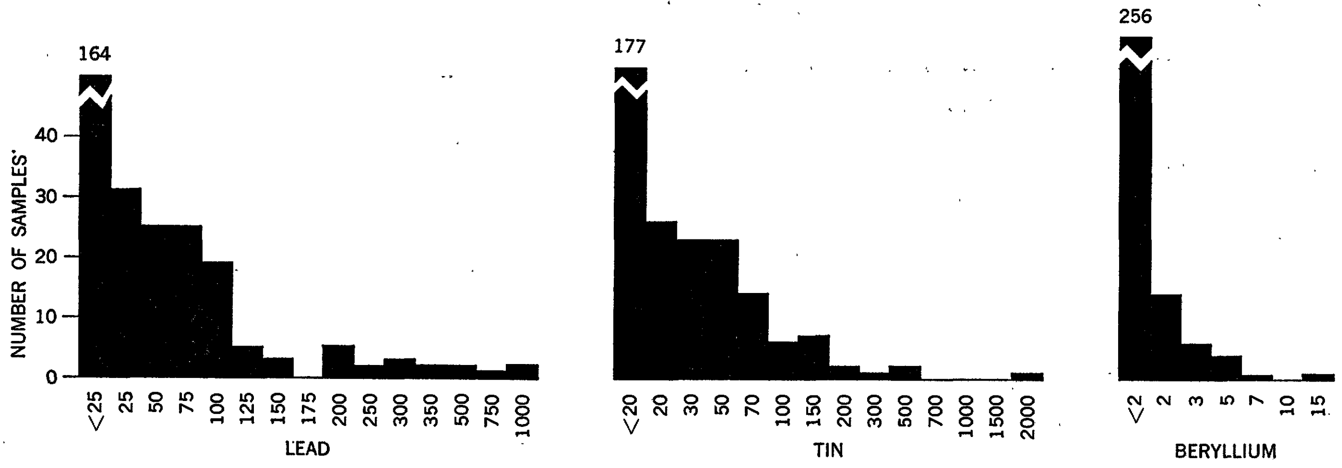


FIGURE 9.—Lead, tin, and beryllium (in parts per million) in magnetite separates.

The break in data, so conspicuous for the other elements, is obscure for lead, tin, and beryllium. A general narrowing of the belts rich in all three elements near Spartanburg coincides with the break in the patterns of distribution of zinc and copper. This narrowing indicates a slight discontinuity in the data for lead, tin, and beryllium, but the most conspicuous feature of the distribution of these three elements is the continuity of the patterns across the middle zone.

VANADIUM AND BARIUM

Vanadium and barium were determined in a small number of samples collected from unevenly distributed localities, so interpretation of the data is less reliable than it is for the eight elements already discussed. Data are sufficient, however, to allow certain generalizations to be made concerning the usefulness of these elements for future investigations. The geochemical nature of both elements is lithophile, according to Rankama and Sahama (1950, table 4.3, p. 88). Vanadium occurs in both the bivalent and the trivalent states in nature, but ionic radii of both are large enough to inhibit diadochy with iron in the magnetite lattice (0.84 A (angstrom) for the bivalent form in four-coordination and 0.74 A for the trivalent form in six-coordination). The most reasonable substitution would be trivalent vanadium in the bivalent iron position, as suggested by the data of Barth and Posnjak (1931, p. 255). If this were possible, vanadium could be grouped with copper and zinc; otherwise it could not be assigned to a group. Barium can be bivalent but not trivalent. The bivalent four-coordinated form has an ionic radius of 1.28 A, which places barium with the group of elements (tin and lead) that are too large for diadochic substitution in magnetite.

The median and modal concentrations for vanadium are coincident at 1,500 ppm, and the mean concentration is 1,400 ppm. These values are high, suggesting that entry of vanadium into the magnetite lattice is fairly easy. The range of concentrations is 100 to 2,000 ppm, somewhat greater than an order of magnitude and comparable to the range for the other bivalent elements. The distribution of vanadium may be skewed toward low values on the logarithmic reporting scale (fig. 10). Vanadium is the only element for which negative skewing is evident.

The median and modal concentrations for barium are coincident at 20 ppm, and the mean concentration is between 32 and 33 ppm. These values are low and are similar to those obtained for lead and tin. The concentrations generally range from 10 to 300 ppm. There is slight evidence, both from the comparison of the median and mean and from the histogram (fig. 10), that the distribution is skewed toward high values.

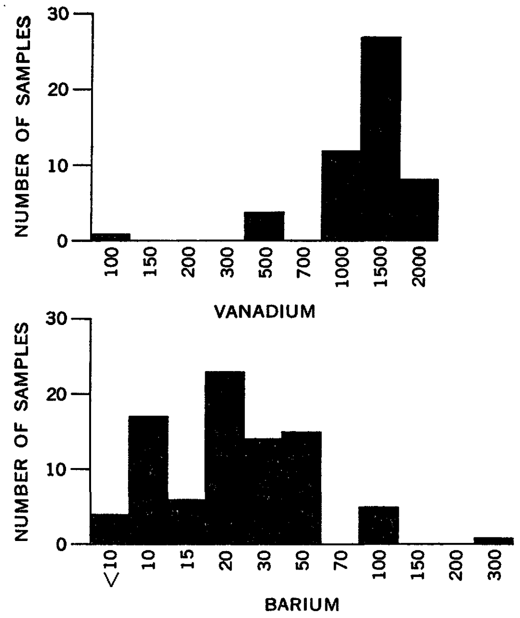


FIGURE 10.—Vanadium and barium (in parts per million) in magnetite separates.

RELATIONS AMONG THE ELEMENTS

The relative concentrations of several of the elements vary either directly or inversely with each other. Many of these relations may be seen by comparing the geographic distributions of the several elements. Because few of the correlations among the elements are perfect, it is often difficult to decide whether they are real features of the distribution or result largely from chance and the desire to find correlations. There are several statistical methods for evaluating the degree of relation between two characteristics of a population; one of these, Kendall's correlation coefficient (τ), was used to evaluate possible combinations of pairs of elements determined in the magnetite separates. Like the median test used in the discussion of the distribution of manganese, chromium, and titanium, Kendall's τ is a nonparametric test. It is distribution free, and for these data it requires only that the data may be ordered according to the concentration of the elements to be compared. The Stuart modification (T. G. Lovering, written commun., 1958) allows easy and rapid handling of large numbers of samples. Kendall's τ for combinations of the eight principal elements is given in figure 11. Ideally, values of $+1$ or -1 indicate perfect correlation, whereas 0 indicates complete absence of correlation.

ALL SAMPLES

Cr	Ti	Mn	Cu	Zn	Pb	Sn	Be	
−0.33*	−0.29*	—	−0.35*	−0.11	−0.39*	−0.31*	−0.09	Percent of magnetite
	0.26*	—	0.27*	—	0.20*	0.36*	—	Cr
		0.42*	0.23*	0.16*	0.14*	0.12*	—	Ti
			—	0.19*	—	—	—	Mn
				0.12*	0.39*	0.30*	—	Cu
					—	0.09	—	Zn
						0.28*	—	Pb
							—	Sn

SOUTHERN

Ti	Mn	Cu	Zn	Pb	Sn	Be	
0.31*	0.16	0.17	—	—	0.19*	—	Cr
	0.47*	0.20*	—	—	—	—	Ti
		—	—	—	—	—	Mn
			—	0.25*	0.25*	0.18	Cu
				—	—	—	Zn
					0.22*	—	Pb
						0.14	Sn

MIDDLE

Ti	Mn	Cu	Zn	Pb	Sn	Be	
0.33	—	0.30	—	0.34	0.47*	—	Cr
	—	0.42*	—	—	—	—	Ti
		—	—	—	—	—	Mn
			—	0.36*	0.30	—	Cu
				—	—	—	Zn
					0.42*	—	Pb
						—	Sn

NORTHERN

Ti	Mn	Cu	Zn	Pb	Sn	Be	
0.33*	—	0.28*	0.10	0.23*	0.39*	—	Cr
	0.38*	0.26*	0.25*	0.22*	0.16*	−0.11	Ti
		—	0.31*	—	—	—	Mn
			0.15*	0.45*	0.29*	—	Cu
				0.12	0.18*	—	Zn
					0.25*	—	Pb
						—	Sn

FIGURE 11.—Correlation coefficients (Stuart modification of Kendall's τ) among the minor elements in magnetite separates. All numbers shown are significant at $\alpha=0.05$; those marked by an asterisk are significant at $\alpha=0.01$. Correlation not significant at $\alpha=0.05$ where no entry shown.

NORTH-SOUTH DICHOTOMY

The prominent break in the data in central Spartanburg and northern Greenville Counties, S.C., was established in the discussion of manganese, chromium, and titanium (p. A9–A11). This break is evident in the patterns of the other elements also, though its nature changes from group to group, and profoundly affects the correlations among them.

In the southern zone the three possible combinations of pairs of manganese, chromium, and titanium all have significant correlation coefficients. The correlation between manganese and titanium is the strongest measured. That between manganese and chromium is significant at $\alpha=0.05$ but is the weakest of the three and may result largely from the close association of titanium with both chromium and manganese. In the northern zone the correlations of titanium with both chromium and manganese are highly significant, but the correlation between manganese and chromium is exceedingly weak ($\tau=+0.005$). In the middle zone, presumed to contain a mixture of rocks from both the northern and southern zones, only the correlation between titanium and chromium is significant. The prominent positive correlation of manganese with titanium in the northern and southern zones is not only absent from the middle zone but is replaced by a moderate negative correlation coefficient (-0.13). The coefficient for manganese and chromium is also negative (-0.17). This pronounced reversal in the nature of the association between manganese and the other members of the trivalent group also suggests that more than mixing of two populations is involved in the middle zone.

The dichotomy is further indicated by a comparison of manganese, chromium, and titanium with the other elements. In the southern zone there are significant correlations of copper with chromium and titanium and of tin with chromium, but these are not exceptional. None of the other correlations are significant. In the northern zone the only correlations that are not significant are those of manganese with copper, lead, tin, and beryllium, and of chromium with beryllium. Titanium correlates with all the other elements, and chromium correlates with all but beryllium. The absence of correlation with beryllium is not surprising in view of the small number of samples in which it was detected; it should be noted, however, that beryllium has negative correlation coefficients with all three of these elements in the northern zone and positive correlation coefficients with all three in the southern zone. In the middle zone the only significant correlation coefficients are those of chromium with copper, lead, and tin, and of titanium with copper. All four significant coefficients in the middle zone are larger than their equivalents in either the northern or southern zone.

The relations between copper and zinc have been noted, and the relations of these two elements to the other elements follow a similar pattern. Copper correlates with lead, tin, chromium, and titanium in both the northern and southern zones, and there is little evidence of any differences in correlation between the zones. In sharp contrast, zinc correlates with all the elements but beryllium in the northern zone but with none of the elements in the southern zone.

Tin and lead correlate with each other and with copper and chromium regardless of zonal location. These are the most significant correlations involving tin and lead, and they emphasize the general continuity of the distribution patterns for the two elements across the dichotomy. They suggest an association based on the ionic radii and the charge of these four elements across the group boundaries. Somewhat weaker correlations of tin and lead with zinc and titanium in the northern zone are absent from the southern zone, indicating the dichotomy in data for zinc and titanium.

The small range of values and the limited number of concentrates containing detectable beryllium preclude strong correlations of this element with the others. In general, the value of τ obtained for beryllium correlations with copper, lead, and tin is positive and within the range 0.1–0.2 in the southern and middle zones. In the northern zone, the correlation coefficients are 0.05 or less, and correlations with the other elements are all negative. The limited data for beryllium seem to reflect the dichotomy.

The differences in associations between elements across the dichotomy are pronounced. They are large enough to suggest that different processes or conditions controlled the accumulation of minor elements in the magnetites on the two sides of the break. Further, there is some evidence that a third set of conditions controlled the distribution of manganese, chromium, titanium, and copper in the middle zone. The relations among lead, tin, and copper are generally continuous across, and unaffected by, the dichotomy.

IONIC-RADIUS GROUPING OF ELEMENTS

The grouping of elements previously established (p. A7) was based on the hypothetical assumption of diadochic substitution for iron in the magnetite lattice. This grouping has been convenient in discussing the elements and may be, at least in part, a real feature of the distribution. It seems worthwhile to consider next the features of the measured distributions that tend to support or deny the hypothetical grouping.

The manganese-chromium-titanium grouping is based on the possible diadochy with trivalent iron. The three elements have in common many features of distribution, particularly the sharp north-south dichotomy. Close geochemical affinity is shown by the highly significant correlations of titanium with both chromium and manganese in both the northern and the southern zones. Correlation of manganese with the bivalent groups, the other possible substitution for this element, is nonexistent in the southern zone and less common in the northern zone than is correlation of the bivalent elements with chromium or titanium. The highly significant correlation of manganese with titanium and the weaker or nonexistent correlation of manganese with chromium suggest some undetermined feature common to manganese and titanium but not shared by chromium. This suggestion is supported by the reversal of medians across the dichotomy: chromium has a significantly higher median in the northern zone than in the southern zone, whereas manganese and titanium have significantly higher medians in the southern zone than in the northern zone. The most obvious feature common to manganese and titanium but not shared by chromium is a stable quadrivalent form.

Copper and zinc can substitute diadochically for bivalent iron. The patterns for the two elements have the same general trend, and the elements have similar median values. As has been noted, they are, however, not consistently related. The correlation coefficient is highly significant in the northern zone but insignificant in the southern zone. Despite their geochemical similarity, copper and zinc behaved differently and independently in different parts of the area.

Lead and tin ions are too large for direct substitution in the magnetite lattice. Both have remarkably similar patterns of distribution, both have similar median values, and neither is markedly affected by the dichotomy. The correlation coefficient of tin with lead is highly significant in each of the zones. A strong association seems evident. However, both lead and tin correlate even more strongly with copper than with each other.

Beryllium is too small for direct substitution in the magnetite lattice. Its pattern and low median value suggest a weak association with lead and tin, but this association is largely confined to the middle and southern zones. There is a significant correlation between beryllium and tin in the southern zone, but in the northern zone beryllium does not seem to be directly related to the other elements. The only significant correlation is negative and relates beryllium with the trivalent group through titanium. Beryllium's only other coefficients that approach significance are also in the trivalent group and are negative: −0.09 with manganese and −0.07 with chromium.

Correlations of elements across the group boundaries are common and, in general, seem to follow a distinctive pattern. The strongest and most consistent of these correlations are those of copper with lead and tin. Less strong but consistent are those of copper with chromium and titanium, and of tin with chromium. With the exception of the copper-lead-tin association, these correlations between groups are subordinate to those within a group.

There is little doubt that the grouping of elements based on ionic radii in coordination states acceptable to the spinel lattice is a real grouping. It provides a practical basis for evaluating the data and indicates associations that can be expected in further studies of the minor-element content of magnetite. The presence of this grouping does not, however, validate the theoretical base on which the grouping was established. The geochemical similarities of the elements in each group are such that the association could be expected from several combinations of events other than diadochic substitution in, or solid solution with, magnetite. The strong association of copper, lead, tin, and chromium that crosses group boundaries should be further investigated, as these elements are commonly associated in base-metal deposits.

The possibility that these elements are present in a discrete mineral phase included in, intergrown with, or exsolved from the magnetite cannot be eliminated; nevertheless, polished-section studies of several concentrates did not reveal such a phase. Tin- and lead-rich concentrates were dissolved in hydrochloric acid in an attempt to chemically isolate a metal-rich phase, but both metals were found in the acid-soluble fraction rather than in the residue. The residue from the acid leach was mostly an open latticework of clean white titanium oxide mimicking exsolved ilmenite that could be seen in polished sections of the magnetite. This residue can account for a large part of the titanium but not for tin and lead. The tin and lead are not present as any of the common oxides or silicates of these elements; these compounds are insoluble in hydrochloric acid. Some of the metals, however, could be present as finely divided sulfides that could be overlooked in polished section and are commonly soluble in acids.

The variation in metal content of the magnetite concentrates undoubtedly results from variation in concentration of metal in the environment of crystallization. The observed grouping, regardless of whether direct substitution in a spinel lattice is involved, could result from the association of the metals in the environment.

PROMINENT HIGHS

The metal content of the magnetite separates varies with the concentration of metal in the environment of original crystallization, regardless of the nature of incorporation of the metal in the magnetite. This variation suggests that areas rich in metals may be sought indirectly by investigating areas containing metal-rich magnetites. Areas rich in one element have been discussed, but several of these warrant emphasis because they contain high concentrations of several minor elements.

A major copper and tin high along the lower reaches of Buffalo Creek is in the southeast corner of Cleveland County, N.C., and adjacent parts of Cherokee County, S.C. A major lead high lies a short distance to the northwest, and a zinc high lies along the State line. The eastern limit of these highs is not defined by these data. The highest values obtained for copper, tin, lead, and zinc are in this general area.

A second copper and tin high occurs along the western tributaries of the Pacolet River north of Spartanburg, S.C. There is a small lead high in the same area, and the general levels of zinc and beryllium are above average.

A lead and beryllium high extends north from the Enoree River through Greenville, S.C. Highs for tin, zinc, and copper have the same trend and overlap those for lead and beryllium.

A weak high extends generally eastward from the Second Broad River into the western tributaries of the First Broad River northeast of Rutherfordton, N.C.; it is best defined by zinc but is shown also by tin and copper.

VANADIUM AND BARIUM

The abundance of vanadium and barium, determined in 53 and 85 of the magnetite separates, respectively, is not adequately known for direct evaluation of their geographic distribution. Comparison of the limited data for these elements with those for the other elements allows some insight into expected distributions. Correlation coefficients of vanadium and barium with seven of the other elements are given in table 3.

TABLE 3.—*Correlation coefficients (Stuart modification of Kendall's τ) for vanadium and barium in comparison with seven other minor elements in magnetite separates from the Inner Piedmont belt, North and South Carolina*

[All numbers shown are significant at $\alpha=0.05$; those marked by asterisk are significant at $\alpha=0.01$. Correlation not significant at $\alpha=0.05$ where no entry shown]

	Cr	Ti	Mn	Cu	Zn	Pb	Sn
V				*−0.39	−0.34	*−0.35	
Ba	*+0.32		−0.14	*+.46	−.18	*+.30	*+0.27

Vanadium has marked negative correlations with all the other bivalent elements. Though not significant, even the value of τ for vanadium and tin is large and negative (−0.22) in contrast to that for the trivalent elements, all of which have an absolute value of τ less than 0.1. The consistent values of the correlations of vanadium with copper, lead, and zinc in contrast to the weak or insignificant correlations of zinc with copper and lead suggest that vanadium can be used as a general indicator element. A separate containing an unusually low vanadium concentration should at least be checked for unusually high copper, lead, or zinc concentrations. This relationship further suggests that vanadium can be expected to be scarce in the central part of the area, where copper, lead, and zinc are abundant, and abundant along the flanks of the area, where copper, lead, and zinc are scarce.

Barium has an exceedingly strong positive correlation with copper and generally parallels copper in association with the other elements. Surprisingly, barium correlates less strongly with lead and tin than does copper. (Compare fig. 10 with table 3.) The positive correlations of barium with copper, chromium, lead, and tin are all strong, however, and together with the significant negative correlations with zinc and manganese indicate fairly well the expectable distribution of barium: there should be general north-trending highs in the middle part of the area flanked by general lows.

RELATION OF TRACE ELEMENTS IN MAGNETITE TO THE DISTRIBUTION OF MAGNETITE

The distribution of magnetite, expressed as percentage of the quartz-free heavy-mineral concentrate, is shown on plate 2*F*. In general, a large area lean in magnetite occupies the central part of the report area. Nearly all samples from this central area contain less than 10 percent magnetite, and most contain less than 5 percent. Nearly all samples collected just west of the central, lean area contain more than 10 percent magnetite, and most contain more than 20 percent. To the east in South Carolina, a similar area of magnetite-rich samples occurs, but the transition is less abrupt than the one to the west. In North Carolina the east boundary of the magnetite-poor area is at best poorly defined. A sharp constriction in the magnetite-lean area generally follows the course of the South Tyger River in western Spartanburg and Greenville Counties; it lies in the middle zone as previously defined (p. A10). The magnetite-lean area is displaced along this constriction; the area to the south is offset to the west, much as are the patterns for copper and zinc content of the magnetite. Where the magnetite-lean area is much narrowed in the middle zone, the patterns for lead and tin content of the magnetite are also narrowed.

The pattern of distribution of magnetite rather strongly resembles the patterns of distribution for the minor constituents of the magnetite. Most of the features or contrasts in the minor-element patterns that we have considered significant are in the zone lean in magnetite. For most of the elements the higher values are in the central part of the area and the lower values are on the flanks. Some trace elements (notably copper, lead, and tin) are most abundant along the east edge of the report area and near the North Carolina–South Carolina boundary, where control for the east limit of the magnetite-poor area is lacking. To illustrate these general relations, the 10-percent isogram on plate 2*F* has been superimposed on each map of trace-element distribution (pls. 1, 2).

The relation of trace elements to distribution of magnetite is further defined by the statistical comparison in the top chart in figure 11. The correlation of seven of the eight elements with the percentage of magnetite in the concentrate is negative and significant at $\alpha=0.05$. For five of the elements the correlation is highly significant at $\alpha=0.01$ ($\tau_{\alpha=0.01}=0.10$). Manganese is the only element not having the general inverse relation of metal content of the magnetite to the percentage of magnetite in the original heavy-mineral concentrates; for manganese this relation is nearly random ($\tau_c=+0.003$).

This strong consistent relation of the metal content to the amount of magnetite could be expected to lead to consistent positive correlations among the various element pairs. Indeed, virtually all the significant correlations among these pairs (fig. 11) are positive. However, two lines of evidence suggest that independent control, rather than cause and effect, produces this relation of the positive correlations among element pairs to the negative correlations of the elements with the proportion of magnetite in the original concentrate: First, the strongest and most consistent correlation among the element pairs is that between manganese (which has no relation to the magnetite distribution) and titanium (which has a strong relation to the magnetite distribution). Both titanium and chromium are strongly correlated with the magnetite distribution, but the correlation of the two as an element pair is consistently poorer than that of manganese and titanium.

The second line of evidence is provided by the correlation of copper and lead, the elements most closely related to magnetite distribution. Plate 2 shows that areas where the original concentrates contain more than 10 percent magnetite generally coincide with areas where the contents of copper and lead are low. In the magnetite-poor zone, the average metal content of the magnetite is higher, but there is considerable consistent variation in the metal content of the magnetite; that is, the patterns of high copper and lead content are within the magnetite-poor areas, and these patterns are truncated by the magnetite-rich areas. As a test of the effect of the magnetite distribution on the association of these two elements, the variation in magnetite content of the original concentrates may be removed by considering only those magnetite concentrates from original heavy-mineral concentrates containing 1 percent magnetite or less. (Using concentrates with more magnetite is impractical, because these magnetites generally contain less than detectable amounts of lead, and the critical patterns for copper and lead are chiefly confined to the magnetite-poor area.) From the northern zone there are 74 concentrates containing 1 percent magnetite or less. The lead and copper contents of these magnetites are <25–1,000 ppm and 10–250 ppm, respectively. The Stuart modification of Kendall's τ for the association of the two elements gives $\tau_c = +0.36$. This result is highly significant ($\tau_{\alpha=0.01} = 0.20$), even though only 43 percent of the samples from the northern group can be used. The value at constant magnetite content, $\tau_c = +0.36$, is, however, considerably less than that for the northern group as a whole, $\tau_c = +0.45$. The associations of the pairs of elements are apparently independent of, but enhanced by, the association of the elements with the distribution of magnetite.

The most obvious cause for the observed variation of the elements with the amount of magnetite would be a contaminant in the magnetite concentrates that provides most or all of the trace constituents and dilution of the contaminant by addition of barren magnetite. This possibility is discussed, and for practical purposes eliminated, in the section "Reliability of the Data." The data presented tend to substantiate the previous conclusion that contamination, either natural or artificial, is negligible. The major features attributable to the trace-element distributions are either evident in the distribution of magnetite (the north-south dichotomy) or are extant in a given part of the magnetite distribution and absent from the rest of that distribution (the principal metal highs and the trends they define are in magnetite-poor areas).

The more reasonable cause for the observed associations seems to be the basic geochemistry of magnetite and its interrelations with the regional geology.

GEOLOGIC INTERPRETATION

The source rocks for the magnetite are mostly paragneiss and paraschist and minor bodies of orthogneiss and nongneissic granitic, gabbroic, and syenitic rocks, in the following approximate abundances:

	Percent
Biotitic paraschist and paragneiss	65
Sillimanitic paraschist and paragneiss	20
Amphibolite	1
Granitic orthogneiss	10
Nongneissic granite	4
Gabbro and syenite	Trace

The magnetite in at least 85 percent of the rocks crystallized when the schists and gneisses formed. The minor-element composition of this magnetite presumably reflects the bulk composition of the rocks under conditions of the regional metamorphic maximum, possibly somewhat modified by a later metamorphic episode. Large local variations in the composition of the magnetite must have been caused by large additions of anomalous magnetite in order to overcome the spatially dominant regional trends. The principal geologic factors controlling the distribution of minor elements in the magnetite were either the bulk composition of the metamorphic rocks or the grade of regional metamorphism, locally modified for some elements, notably zinc, beryllium, and tin, by additions from the igneous rocks. Interpretation is generally limited by the inadequacy of present knowledge of the regional geology.

NORTH-SOUTH DICHOTOMY

Division of the report area into northern, middle, and southern zones appears to reflect the intensity of regional metamorphism. The broadest expanse of rocks at the sillimanite-almandine subfacies, approximately defined by the 1-percent isogram for sillimanite, is in the northern zone. The belt of high-grade metamorphic rocks narrows greatly and swings westward for about 20 miles in the middle zone. The intensity of metamorphism apparently decreased southward in the southern zone where the amount of sillimanite decreases and the belt of sillimanite-bearing rocks narrows. Garnet, rutile, and tourmaline, which accompany magnetite in the concentrates derived from the highest grade metamorphic rocks, are most abundant in the northern zone, much less abundant in the middle zone, and least abundant in the southern zone.

The middle zone marks a change in direction and in intensity of geotherms. There is no structural evidence that these changes are accompanied by faults approaching the apparent displacement in the middle zone, as neither the amphibolites nor the Kings Mountain belt on the east side of the high-grade metamorphic rocks is offset.

Lithologic changes superimposed on the metamorphic zonation probably enhance the north-south dichotomy, as the middle zone lies immediately south of pronounced changes in the abundance of mafic components in the metamorphosed sedimentary rocks flanking the belt. The composition of the plutonic igneous rocks changes from granite and quartz monzonite in the central and northern parts of the area to granodiorite in the southern part. However, the compositional change of the igneous rocks is slight, gradual, and lies to the south of the middle zone. Zircon, a common accessory mineral in the plutonic rocks, is the only heavy mineral accompanying magnetite in the concentrates that persists continuously across the middle zone.

DISTRIBUTION OF THE ELEMENTS

MANGANESE, CHROMIUM, AND TITANIUM

The distribution patterns for manganese, chromium, and titanium in magnetite seem to result from the original composition of the sedimentary and pyroclastic rocks and from the energy input during metamorphism. The patterns reflect in a minor way the intrusion of granitic rocks, particularly postkinematic rocks.

Analyses of slate, phyllite, schist, gneiss, granite, diorite, amphibolite, and gabbro in the Kings Mountain and Inner Piedmont belts, available for South Carolina (Sloan, 1908, p. 250–264) and Georgia (Crickmay, 1952), show a narrow range in abundance of manganese and titanium in bulk samples of the rocks (no data are available for chromium).

Bulk samples of granite, syenite, and pegmatite from Cabarrus County, N.C., 60 miles east of the Inner Piedmont belt, contain less manganese, titanium, and chromium than do samples of mafic rocks from the same area (Henry Bell 3d, oral commun., 1962).

Rock	Number of analyses in average	Average, in percent	
		MnO	TiO_2
Slate and phyllite	7	0.09 (0.32 for 2)[1]	0.76
Biotite schist and gneiss	8	.32	.68
Felsic volcanic rocks	5	.26	.54
Granite	5	Trace (0.11 for 1)[1]	.59
Diorite and gabbro	6	.25	.53
Amphibolite	8	.17	.85

[1] Average of entries given as more than trace.

Analyses of rocks in the vicinity of Shelby in the northern zone of the Inner Piedmont belt indicate the distribution of manganese, titanium, and chromium (Overstreet and others, 1963):

[Chemical analyses by Lois Trumbull, Faye Neuerberg, L. C. Peck, and W. J. Blake, Jr.; spectrographic analyses by J. D. Fletcher and P. R. Barnett]

Rock	Average, in percent		
	Chemical		Spectrographic
	MnO	TiO_2	Cr
Biotite schist	0.07	0.40	0.000x+
Sillimanite schist	.08	1.07	.01
Hornblende-biotite-oligoclase gneiss	.12	.69	.002
Diopside-biotite gneiss [1]	.09	.71	.01
Toluca Quartz Monzonite [1]	.03	.22	.0002
Pegmatite	.01	.15	.0001

[1] Average of two determinations.

NOTE.—The concentrations of the elements determined by semiquantitative spectrographic analysis are bracketed into groups each of approximately one-third of an order of magnitude, x+ indicating the higher portion (10–15 percent); x, the middle portion (5–2 percent); and x−, the lower portion (2–1 percent). Comparisons of this type of semiquantitative results with those obtained by quantitative methods, either chemical or spectrographic, show that the assigned group includes the quantitative value in about 60 percent of the analyses.

Partition of the minor elements in the rocks is less pronounced than in the accessory magnetite, but their distribution in the rocks somewhat resembles that in the magnetite. Manganese may be more abundant in the schist and gneiss in the southern zone than in the northern zone, and titanium may be somewhat more abundant in biotite schist and gneiss than in other rock types. There may be less manganese, chromium, and titanium in the granites and more titanium in the sillimanite schist than in the other rocks. The sillimanite schist in the northern zone is considerably richer in chromium than are the biotite schist and hornblende-biotite-oligoclase gneiss. The southward-broadening series of manganese-high areas along the core of the belt are interpreted as being remnants of a formerly more extensive pattern derived from sedimentary and pyroclastic rocks that are richer in manganese in the southern zone than in the northern zone. Perhaps the sedimentary rocks immediately overlying the ancient Precambrian basement are most common in the southern zone, whereas the overlying sequence is most abundant in the northern zone. The older sequence, derived from weathered rocks, contains a more abundant pelitic fraction and is richer in aluminum and titanium than the overlying sequence (Overstreet and Bell, 1965a; Overstreet and others, 1963); it is therefore reasonable to expect more manganese in the older sequence.

The effects of the metamorphic climax in Ordovician time are evident in the original stratigraphic sequence. Pelites at the staurolite-kyanite subfacies appear to have been the preferred hosts of manganese-rich magnetite, and at higher metamorphic grade the manganese content of the magnetite tended to decrease. Thus, a notable manganese low was formed in the southern zone in the area bounded by the 1-percent isogram for sillimanite, at the sillimanite-almandine subfacies, whereas the largest area of manganese-rich magnetite, in Greenville, Laurens, and Abbeville Counties, is at the kyanite-staurolite subfacies. Staurolite is abundant in the northern zone near the manganese high along the Cleveland–Lincoln County line. The absence of a persistent manganese high between Gaffney and the big bend in the Catawba River, coextensive with the area in which staurolite is most abundant, apparently resulted from the composition of the sediments overlying the lower sequence. The most intense metamorphism, and the least manganese in the magnetite, is in the northern zone, particularly in the arcuate area of manganese lows extending from the Pacolet River through Gaffney and Shelby to the South Mountains. The manganese low in this area is probably superimposed on an original general manganese high. Perhaps, as metamorphism increased above the kyanite-staurolite subfacies, manganese changed from the trivalent to the quadrivalent state, thereby facilitating volume reduction and making manganese less acceptable in the magnetite lattice. Such behavior is evident for titanium, which, as the quadrivalent form rutile, is rather abundant in areas outlined by the 1-percent isogram for sillimanite.

Magnetite is abundant in postkinematic intrusive rocks and is probably low in manganese, as observed by Henry Bell 3d (oral commun., 1962), for Cabarrus County, N.C. The large manganese low centered at Anderson probably resulted from a flood of manganese-poor magnetite from many small bodies of postkinematic quartz monzonite and granodiorite.

The interpretation of the distribution of titanium in magnetite is similar to that for the distribution of manganese. In the southern zone biotite schist and gneiss are apparently somewhat richer in titanium than in the northern zone, probably because of a regional lithologic change. High contents of titanium in detrital magnetite occur in a broader area in the southern zone than in the northern zone, a distribution considered to reflect lithologic units. The two prominent titanium highs in the northern zone, the high on the Enoree River, and the three peripheral highs around Anderson are probably residual from a former broad zone of highs. In the northern zone the highs are separated by an arcuate low along the First Broad River. This low closely resembles the manganese low and is attributable to the same factor: intense regional metamorphism that reduced the amount of titanium in the magnetite from maximum amounts incorporated at lower metamorphic facies. The low at Greenville is attributable to this factor. Low-titanium magnetite from magnetite-rich postkinematic granitic rocks flooded the concentrates in Anderson County and produced the low in that area.

The same geologic processes that governed the distribution of manganese and titanium presumably governed the distribution of chromium. In rocks of the northern zone, chromium is most abundant in sillimanite schist and is scarce in biotite schist, quartz monzonite, and pegmatite. Spectrographic analyses of 124 heavy-mineral concentrates in the belt show that in most the chromium content is within the range 100 to 1,000 ppm. The chromium content of the heavy minerals shows no apparent systematic variation.

The difference in abundances of chromium in magnetite in the northern and southern zones is too great to be explained by differences in metamorphic intensity. Chromium presumably was more abundant in the original rocks of the northern zone. The most significant high for chromium in the magnetite is along the First Broad River north of Shelby, in the area of maximum regional metamorphism; magnetite presumably was still accumulating chromium at the maximum temperatures and pressures reached. The chromium low in Anderson County can be attributed to a flood of chromium-poor magnetite from postkinematic granitic rocks.

COPPER AND ZINC

The abundance of copper in rocks in the Shelby area and in the adjacent Lincolnton and Kings Mountain area is known from quantitative and semiquantitative spectrographic analyses of bulk samples of the rocks (Overstreet and others, 1963; W. R. Griffitts, written commun., 1958):

[Analyses by J. D. Fletcher, P. R. Barnett, A. A. Chodos, R. G. Havens, A. T. Myers, and P. J. Dunton. For explanation of symbols see table, p. A21]

	Number of samples	Copper content (percent)	
		Quantitative	Semiquantitative
Biotite schist	1	------	$0.000x^{-}$
Biotite schist and gneiss	10	------	.00x
Biotite-oligoclase gneiss	5	------	$.00x^{-}$
Hornblende-biotite-oligoclase gneiss	1	0.0006	------
Sillimanite schist	1; 4	.006	$.00x^{+}$
Diopside-biotite gneiss	2	.002	------
Granite gneiss	1	------	$.00x^{-}$
Toluca Quartz Monzonite (Ordovician)	2; 7	.0006	$.00x^{-}$
Pegmatite related to Toluca Quartz Monzonite	1	.0003	------
Yorkville Quartz Monzonite (Permian)	4	------	.00x
Cherryville Quartz Monzonite (Mississippian(?) to Permian(?))	8	------	$.00x^{-}$
Pegmatite related to Cherryville Quartz Monzonite	2	------	.00x

The zinc content was below the limit of detection in all bulk samples of rock analyzed. In 124 spectrographic analyses of heavy-mineral concentrates, copper is uniformly 0.00x percent and zinc is less than 0.01

percent. The average values for copper in the rocks are of the same order of magnitude as those for copper in the magnetite. The average values for zinc in the magnetite are considerably greater than those for zinc in the rocks.

For copper in the magnetite, lows of 40 ppm or less coincide with low-rank metamorphic rocks along the flanks of the belt, and highs of 50–80 ppm copper or more in broad centrally located areas coincide with higher rank metamorphic rocks. The copper high along the Saluda River and most of the copper highs in the northern zone are within the sillimanite isograd. Seemingly, the magnetite was still taking on copper at the peak metamorphism. The large copper low in Anderson County and the small lows around Lincolnton and Newton appear to reflect a superimposed flood of copper-poor magnetite from postkinematic granite and granodiorite.

There is little evidence to relate the copper distribution to copper-bearing deposits. The Graham gold mine, reported by Pardee and Park (1948, p. 76) to contain copper, is in an unsampled basin between the drainage basins numbered 262 and 264. The Cameron lead mine, reported by Keith and Sterrett (1931, p. 12) to have been worked for copper, is 2¾ miles southeast of Gaffney, 8 miles along strike from the principal copper high. Copper was not reported by Sloan (1908, p. 81–83) in his description of mineral deposits in the southern zone. There is no unusual amount of copper in magnetite from the vicinity of the several gossanlike deposits of limonite in South Carolina (Keith and Sterrett, 1931, map; Sloan, 1908, p. 102, 106).

The general pattern of distribution of zinc in magnetite is defined by zones of 100–200 ppm content that parallel the zones of regional metamorphism, but the relatively higher zinc content is marginal to the metamorphic maximum. Thus, the areas of both maximum and minimum metamorphism are relatively lean in zinc.

Interruptions in the general pattern as well as in most zinc maximums apparently result from adulteration of the metamorphic magnetite population by zinc-poor magnetite from granite or by zinc-rich magnetite from syenite. Both granite and syenite are rich in zircon and contain the indicated zinc-rich or zinc-poor magnetite in the Concord area, North Carolina (Henry Bell 3d, oral commun., 1962). Distribution of zircon in the heavy-mineral concentrates favors this explanation for most of the zinc lows shown on plate 2*C*. Magnetite from the syenite in Cabarrus County, N.C., is both rich in zinc and lean in copper (Henry Bell 3d, oral commun., 1962), and the syenite in the Inner Piedmont belt in South Carolina probably correlates with syenite in Cabarrus County (Overstreet and Bell, 1965a). The zinc highs above 250 ppm in the southern zone do not correlate with copper highs. Several of these highs are in areas where syenite or syenite pegmatite have been reported (Overstreet and Bell, 1965b; Leiber, 1860, p. 29). Similar relations probably exist for the zinc-rich and copper-poor areas in the northern zone, though only the zinc high southeast of Newton can be correlated with a zircon-rich pegmatite of probable syenitic character located across the Catawba River in Iredell County, N.C. (Pratt and Lewis, 1905, pl. 2).

The east-northeast-elongated area of zinc-rich magnetite between the First and Second Broad Rivers northeast of Rutherfordton is parallel to, and possibly, a continuation of, a strongly developed system of faults that crosses the northwest quarter of the Shelby quadrangle from the east end of the high (Overstreet and others, 1963). Neither the faults nor the sillimanite schists in which they occur are known to be mineralized in the quadrangle, and syenite was not observed there.

The northeast-trending area of zinc-rich magnetite at the State line northeast of Gaffney is associated with copper in abundances greater than 180 ppm. In this respect, the zinc high is unique. The streams from which the magnetite was taken head in staurolite schist and Cherryville Quartz Monzonite along the west side of the Ordovician to Mississippian Blacksburg and Battleground Schists (Keith and Sterrett, 1931, maps), where northeast-trending high-angle faults separate the staurolite schist and quartz monzonite on the west from the sericite schist of the Kings Mountain belt on the east. Neither zinc nor copper has previously been reported from near this zinc- and copper-rich area, but the Cameron lead mine, reported to have been originally opened for copper (Keith and Sterrett, 1931, p. 12) is 8 miles to the southwest and nearly on strike with the high. The site of the Cameron mine, 2¾ miles southeast of Gaffney, is not a zinc high, and zinc sulfides have not been observed at the mine, which is in a quartz vein containing siderite, galena, and chalcopyrite.

LEAD, TIN, AND BERYLLIUM

Contents of lead, tin, and beryllium are known for rocks in the Shelby area and adjacent parts of the Kings Mountain, Gaffney, and Lincolnton quadrangles (Overstreet and others, 1963; W. R. Griffitts, written commun., 1958). The analyses are given in the following table.

[--------, looked for but not found; n.d., not determined. Spectrographic analyses by J. D. Fletcher, P. R. Barnett, A. A. Chodos, R. G. Havens, A. T. Myers, and P. J. Dunton. For further explanation of symbols see table, p. A21]

Rock	Number of samples	Percent					
		Quantitative			Semiquantitative		
		Pb	Sn	Be	Pb	Sn	Be
Biotite schist	1	n.d.	n.d.	n.d.	0.00x	--------	0.000x
Biotite schist and gneiss	10	n.d.	n.d.	0.0001	.00x-	--------	n.d.
Biotite-oligoclase gneiss	5	n.d.	n.d.	.0002	.00x	--------	n.d.
Hornblende-biotite-oligoclase gneiss	1	0.003	--------	.0001	n.d.	n.d.	n.d.
Sillimanite schist	1 and 4	.01	--------	.0003 and .0001	Trace	--------	n.d.
Diopside-biotite gneiss	2	.002	--------	n.d.	n.d.	n.d.	n.d.
Granite gneiss	1	n.d.	n.d.	n.d.	.00x	--------	--------
Toluca Quartz Monzonite	2 and 7	.006	--------	n.d.	.00x	--------	n.d.
				.0001±	.00x	--------	n.d.
Pegmatite related to Toluca Quartz Monzonite	1	.008	--------	n.d.	n.d.	n.d.	n.d.
Yorkville Quartz Monzonite	4	n.d.	n.d.	.003	.00x+	--------	n.d.
Cherryville Quartz Monzonite	7	n.d.	n.d.	.0005±	.00x	0.00x	n.d.
Pegmatite related to Cherryville Quartz Monzonite	2	n.d.	n.d.	.005±	.00x	.00x	n.d.

The contents of lead in the rocks and in the magnetite (table 3) are of about the same order of magnitude, but contents are locally as much as an order of magnitude greater in the magnetite than in the rocks. The lead-rich sillimanite schist shown in the quantitative analyses is anomalously pyritiferous. Possibly the presence of the sulfide accounts for the unusual abundance of lead, because four samples of sillimanite schist for which there are semiquantitative analyses contain less than 100 ppm lead. Lead is slightly more abundant in the Toluca Quartz Monzonite and related pegmatites. The possible relation of the Toluca to the lead content of magnetite is discussed on page A26.

Tin is consistently less abundant in the rocks than in the magnetite. The low beryllium contents of the rocks are paralleled by low beryllium contents of the magnetite. The close correlation between the distribution of tin- and beryllium-rich magnetite and the geographic distribution of the tin- and beryllium-rich Cherryville Quartz Monzonite and related pegmatites indicates that the Cherryville is the specific source for this magnetite.

Semiquantitative spectrographic analyses of 124 heavy-mineral concentrates from the report area show a distribution of lead, tin, and beryllium that is in remarkably close agreement with the distributions shown by the analyses of the magnetite separates.

The lead contents of 71 concentrates ranged from 100 to 1,000 ppm; these concentrates came from the core of the belt, where magnetite contains at least 50 ppm lead. Concentrates along the flanks of the belt contain less than 100 ppm lead, and magnetite separates from the same area contain less than 50 ppm lead. Concentrates from streams in the parts of Pickens, Oconee, and Abbeville Counties in the report area and in western, southern, and southeastern Anderson County also contained less than 100 ppm lead. The magnetite in this area is also low in lead. Two concentrates from northeastern Greenville County and one from southeastern Rutherford County contained 1,000–10,000 ppm lead. The abundance of lead in the concentrates from northeastern Greenville County was not duplicated in the magnetite, but the lead high in southeastern Rutherford County is about 4 miles southwest of the high for lead in magnetite east of Rutherfordton.

The tin contents of 39 of the 124 concentrates ranged from 10 to 1,000 ppm. The distribution of these tin-bearing concentrates follows and extends the pattern shown by tin in magnetite (pl. 2*B*). Tin in concentrates from the southern zone extends the pattern of tin in magnetite along the line between Pickens and Anderson Counties to Oconee County and thence southward to the Seneca River in Anderson County. Tin in the concentrates also makes a closure between the east fork of tin in magnetite at the Saluda River and the tin in magnetite at the Little River in Abbeville County. In the northern zone, tin in concentrates from Cherokee County northwest of Gaffney forms an extension of the high values of tin in magnetite at the State line on the west side of the Broad River and brings it to the river east of Gaffney. The great highs for tin in magnetite south of Morganton and in Catawba County are not matched by tin in the heavy-mineral concentrates.

The beryllium contents of 31 of the 124 heavy-mineral concentrates ranged from 1 to 10 ppm. The distribution pattern for the beryllium-bearing concentrates resembles that for beryllium in magnetite across Cherokee, Spartanburg, and Greenville Counties. Beryllium-bearing concentrates also form a strong trend from Gaffney northeastward through eastern Cleveland County into western Gaston and Lincoln Counties. North-central Lincoln County and east-central Catawba County have several large drainage basins from which beryllium-bearing concentrates were taken. In the northern zone, beryllium is much more common in the concentrates than in the magnetite. The concentrates probably contain other beryllium-bearing minerals, most likely beryl.

In the northern zone, the beryllium content of the concentrates has a decided trend along the west side of the pluton of Cherryville Quartz Monzonite and through the areas of beryl-bearing sheet-muscovite pegmatites in Cleveland, Gaston, Lincoln, and Catawba Counties (Griffitts and Overstreet, 1952, fig. 1; Griffitts and Olson, 1953, fig. 77; Griffitts, 1954, fig. 1).

In the middle zone, however, the distribution of beryllium-bearing concentrates and beryllium-bearing magnetite in western Cherokee and central Spartanburg Counties is not matched by the occurrence of numerous pegmatite dikes containing sheet muscovite (Griffitts, 1953, fig. 104).

In the southern zone an extensive area from which beryllium-bearing concentrates were taken extends southward on the east side of Greenville from the northern part of the county through the high for beryllium in magnetite nearly to the Saluda River. Beryllium in the concentrates also extends the trend of the beryllium in magnetite from Greenville southeastward along the divide between the Enoree and Reedy Rivers into northwestern Laurens County. As in the middle zone, the locations of beryllium-bearing concentrates and high values for beryllium in magnetite in the southern zone are not accompanied by numerous sheet-muscovite-bearing pegmatite dikes, though a few dikes occur in southern Greenville County (Griffitts, 1953, fig. 104). These dikes are far to the southwest of the southwest end of the pluton of Cherryville Quartz Monzonite (Griffitts and Overstreet, 1952, fig. 1).

Relations of the beryllium-bearing concentrates to beryllium-rich magnetite in the middle and southern zones seem to indicate that pegmatites related to the Cherryville Quartz Monzonite occur in these areas, but these pegmatites do not contain exploitable sheet muscovite. Hence, they have not been mined, and their distribution has not been mapped. Concentrations of beryllium and tin occur where magnetite from other sources is not so abundant that the values of beryllium or tin in the concentrate or in magnetite are depressed to background or undetectable levels. In the middle and southern zones, pressure and temperature during emplacement of these pegmatite dikes may have been generally too low for crystallization of sheet muscovite. Since the presence of sheet muscovite was previously the criterion for determining the distribution of pegmatites, the continuity of their zone of emplacement was assumed to be interrupted where the muscovite was not found. On the basis of new criteria, it can be inferred that the pegmatite dikes related to the Cherryville Quartz Monzonite form a zone 50 miles long that cuts across stratigraphic units and metamorphic facies from the southwest end of the pluton at Gaffney to the Saluda River south of Greenville.

Lead in magnetite apparently is remarkably sensitive to the abundance of magnetite in the concentrate; lead highs develop only where amounts of magnetite are small. Closure of the pattern of lead highs at the Saluda River closely parallels the flood of magnetite entering concentrates south of the river. The southeast and northwest edges of the pattern for lead closely conform to the place where the magnetite content rises above 10 percent of the weight of the concentrate. Tin is slightly less sensitive than beryllium to the total abundance of magnetite, particularly in the extreme northeastern and southwestern parts of the report area; nevertheless, tin clearly occurs in areas lean in magnetite. Beryllium in magnetite is very sensitive to the total amount of magnetite in the concentrate, and it declines abruptly in magnetite-rich areas like that south of the Saluda River, eastern Greenville County, northwestern Spartanburg County, east-central Cherokee County, and Lincoln and Catawba Counties. No unusual abundances of lead, tin, or beryllium occur in the great magnetite highs in Polk, Rutherford, McDowell, Pickens, Oconee, Abbeville, Greenwood, and Laurens Counties.

The shapes, trends, and sizes of the areas high in tin and beryllium, and the similar spatial relations of these areas to the areas containing sparse magnetite suggest that tin and beryllium are most abundant in magnetite from a single source poor in magnetite. Only small amounts of this magnetite are available for concentration in the streams; thus, its effect on the concentration of minor elements in the magnetite separate is negligible where magnetite from other sources is abundant. Trends of the tin-rich and beryllium-rich areas are across the metamorphic isograds and regional structure. Therefore, the source of the tin- and beryllium-rich magnetite must be younger than the metamorphic climax in which the isograds were formed.

The source of the tin- and beryllium-rich magnetite may confidently be ascribed to the Cherryville Quartz Monzonite and related pegmatite dikes, because (1) these rocks are uniquely rich in tin and beryllium; (2) they characteristically are lean in minor accessory minerals, including magnetite; (3) they are postkinematic intrusive rocks emplaced after the metamorphic climax; and (4) the pluton of Cherryville Quartz Monzonite is a crosscutting body on a regional scale, and the bodies of pegmatite are mostly dikes.

The lead distribution may not have resulted from the factors noted for tin and beryllium, despite their similar patterns. The available data do not clearly indicate whether the similarity in distribution arises from similar origins of the lead-rich magnetites or from similar conditions permitting detection of the minor amounts of lead, tin, and beryllium. Analyses of bulk samples of the rock show that the Cherryville Quartz

Monzonite and its pegmatites contain no more lead—possibly even less—than the Toluca Quartz Monzonite and its pegmatites, synkinematic intrusives that occur throughout the lead high from the Catawba River at least as far south as Spartanburg. Lead is absent from such typical areas of Cherryville Quartz Monzonite as near Lincolnton. However, lead is particularly abundant northeast of Gaffney in the part of the Buffalo Creek drainage basin that is dominantly underlain by Cherryville Quartz Monzonite. The area containing above-average amounts of lead is larger than that for tin or beryllium, but lead is more abundant in magnetite than is tin or beryllium. Perhaps both the Toluca and the Cherryville have contributed lead-rich magnetite to the streams, and the present broad lead pattern reflects two sources. Lead-rich magnetite has not come from the low-grade metamorphic rocks outside the core of the Inner Piedmont belt nor from the magnetite-rich post-kinematic granitic rocks and granodiorite in Anderson County.

Close correlation of lead and tin with chromium and copper appears to result from the mixing of chromium- and copper-rich magnetite of metamorphic origin with lead- and tin-bearing magnetite of igneous origin in the core of the Inner Piedmont belt, where only small amounts of magnetite occur.

Loss of above-average amounts of beryllium in the northern zone because of influx of beryllium-deficient magnetite of metamorphic origin may explain the dichotomy in the data for beryllium in magnetite. The amount of beryllium in the concentrates does not decrease along the southeast side of the northern zone.

VANADIUM AND BARIUM

Contents of vanadium and barium have been spectrographically determined for the crystalline rocks around Shelby, Lincolnton, Gaffney, and Kings Mountain (Overstreet and others, 1963; W. R. Griffitts, written commun., 1958):

Spectrographic analyses by J. D. Fletcher, P. R. Barnett, A. A. Chodos, R. G. Havens, A. T. Myers, and P. J. Dunton. For explanation of symbols see table, p. A21]

Rock	Number of samples	Percent			
		Quantitative		Semiquantitative	
		V	Ba	V	Ba
Biotite schist	1	--------	--------	0.00x	0.0x+
Biotite schist and gneiss	10	--------	--------	.00x+	.0x
Biotite-oligoclase gneiss	5	--------	--------	.0x-	.0x+
Hornblende-biotite-oligoclase gneiss	1	0.005	0.08	--------	--------
Sillimanite schist	1 and 4	.01	.08	.00x+	.0x-
Diopside-biotite gneiss	2	.006	.04	--------	--------
Granite gneiss	1	--------	--------	.00x-	.0x-
Toluca Quartz Monzonite	2 and 7	.002	.09	.00x-	.0x+
Pegmatite related to Toluca Quartz Monzonite	1	.001	.09	--------	--------
Yorkville Quartz Monzonite	4	--------	--------	.00x	.x-
Cherryville Quartz Monzonite	7	--------	--------	.00x-	.0x
Pegmatite related to Cherryville Quartz Monzonite	2	--------	--------	.00x-	.0x-

Vanadium and barium were spectrographically determined in 124 heavy-mineral concentrates from the Inner Piedmont belt. One concentrate from the flank of the belt in the northwestern part of the northern zone contained 1,000–10,000 ppm vanadium. The vanadium content ranged from 100 to 1,000 ppm in 63 concentrates, predominantly from the flanks of the belt, and from 10 to 100 ppm in 55 concentrates, mainly from the core of the belt. Three of the five concentrates that lacked vanadium are from Anderson County; the remaining two came from the core of the belt in the southern and northern zones. The highest value for barium in the concentrates was 1,000 ppm in a sample from the core of the belt in the northern zone, near the mutual corner of Cleveland, Gaston, and Lincoln Counties. The barium content ranged from 10 to 100 ppm in 87 concentrates, many of which came from the flanks of the belt. Two samples from the core and one from the northwest flank of the northern zone contained 1–10 ppm barium. Barium was absent from 33 concentrates, mostly from the middle zone and the core of the northern zone.

The distribution of vanadium in the concentrates accords with the postulated behavior of vanadium in magnetite. Vanadium is more abundant on the flanks of the belt than in the core. As currently understood, the main factor controlling the abundance of vanadium in magnetite is progressive regional metamorphism. As metamorphic grade increases, vanadium in magnetite decreases, whereas copper increases.

Barium in the heavy-mineral concentrates tends to behave conversely to its postulated behavior in magnetite. In the concentrates it tends to be most abundant along the flanks of the belt, whereas in magnetite it is most abundant in the core of the belt. Available data are inadequate to resolve these apparent conflicting observations, but the concentrates may contain another barium-bearing mineral, such as barite, which would reverse the postulated trend.

PROMINENT HIGHS

Anomalous abundances of the metals that may warrant detailed investigation occur at coincident or adjacent highs of several metals in magnetite. The most prominent of these highs are on lower Buffalo Creek, on the Pacolet River, at Greenville, and in the divide between the First Broad and Second Broad Rivers.

The prominent highs for lead, tin, copper, and zinc in the lower parts of the Buffalo Creek drainage basin in Cleveland County, N.C., and Cherokee County, S.C., are localized in a faulted area where Cherryville Quartz Monzonite intrudes rocks ranging in metamorphic grade from the greenschist facies to the staurolite-kyanite subfacies. Small amounts of copper and lead have been mined from a vein a few miles to the southwest, in an area that is not shown by these data to be anomalously metalliferous. The lower Buffalo Creek high is probably the best place in the sampled area for further work, particularly for a detailed geochemical survey.

The Greenville area, from Paris Mountain southward to the Enoree River, contains overlapping highs for lead, tin, beryllium, zinc, and copper. It is a very complex region of high-rank metamorphic rocks that are tightly folded, athwart the regional trend, widely intruded by granite and pegmatite, and doubtless much faulted. It is the second best place in the sampled area for further work, in particular for detailed geologic mapping and for geochemical survey.

A small area of high values for copper and tin in the western tributaries of the Pacolet River north of Spartanburg, S.C., generally also contains above-average amounts of zinc, lead, and beryllium. The area is north of a major synclinal crosswarp in a region of very high grade metamorphic rocks about which geologic details are unknown.

The weak high defined by zinc, copper, and tin that extends eastward from the Second Broad River to western tributaries of the First Broad River northeast of Rutherfordton, N.C., leads into a faulted zone at the west side of the Shelby quadrangle, North Carolina, and is a western projection of that zone. The faulted zone in the Shelby area is not a geochemical high, nor was base-metal mineralization evident in the mapped part of the zone. Therefore, whatever metallization occurs in this zone probably is greater west of the mapped area. Detailed geologic and geochemical mapping of this fault zone would further define patterns of mineralization in this part of the Piedmont.

Some of the tin- and beryllium-rich areas may contain spodumene-bearing pegmatite dikes, because cassiterite and beryl are common accessory minerals in the spodumene pegmatites of the tin-spodumene belt east of the report area (Griffitts, 1954, p. 3). On the basis of spectrographic analyses of heavy-mineral concentrates made in 1951–52, the occurrence of economic deposits of cassiterite is considered unlikely.

GEOCHEMICAL INTERPRETATIONS

A summary of the geochemical features and problems related to the study of the trace-element composition of the magnetite separates includes these pertinent features: (1) Some of the magnetite separates contain fairly large quantities of titanium, chromium, manganese, copper, zinc, lead, tin, beryllium, vanadium, and barium. For most of these elements and separates, the metal content of the magnetite is probably greater than that of the alluvium from which the separates were obtained. (2) The content of each metal varies rather widely among the analyzed separates. The range in values obtained for these elements in the magnetite separates probably greatly exceeds the range that could be obtained for the alluvium. (3) The elements are grouped according to the general level of concentration, the geographic pattern of distribution, and the associations among the elements. This grouping is compatible with the chemical properties of the elements, particularly with the four- and six-coordinated bivalent and trivalent ionic radii found in spinel structures.

The following conclusions seem warranted on the basis of these facts. A general partition of many of the trace elements favors magnetite over most other rock-forming minerals. The amount of metal attracted and retained by the magnetite will be strongly influenced by the amount of metal available. The availability of the metal is controlled by the absolute quantity of metal in the system, the nature of the system, and the nature of the individual elements. The first of these controls, in large part geologic, was considered under "Geologic Interpretation." The second cannot be evaluated from these data but seems to be of minor importance. The third results in the grouping of the elements by their chemical properties and involves the nature of incorporation of the metals in the concentrates.

The most likely location for the metal in the separates seems, from the limited data available, to be the magnetite lattice or another spinel in solid solution with the magnetite or an exsolved phase. Though largely speculative, this conclusion provides a basis for further work. The possibilities for variety in spinels, beyond those found in natural systems to date, deserve attention. The presence of such a variety of elements interacting in a single relatively simple structure should provide an unusual opportunity to study the vagaries not only of the structure itself but also of the various trace elements.

Magnetite, particularly separates from alluvium, is an almost ideal medium for the study of the distribution of some trace elements on a regional scale—a form of geochemical census. Sampling bedrock for such a program involves technical problems of selective outcrop, gross differences among rock types, and other problems that now seem insurmountable. Sampling of soils involves similar problems. For these spot samples, the basic problem is to collect average samples useful for regional comparisons. Therefore, the most successful minor-element-distribution maps produced have been based upon stream sediments. (See, for example, the excellent maps of northern Nova Scotia by Holman and Gilbert, 1959a, b, c, d.) Evidently, one of the most objective and readily obtainable average samples is that obtained from eroded and transported debris in streams. Stream sediments, however, vary in metal content not only with the metal content of bedrock in the drainage basin but also with the erosion, transportation, and sedimentary history of the sediment. The effects of this variation are minimized, however, because only a single component of the sediment, magnetite, is used. The use of magnetite has the further advantage of raising the general background of metal content to levels more easily reached by present analytical procedures.

There can be no doubt from the data presented that the regional distribution of some trace elements can be studied by the analysis of detrital magnetite. Before general studies of this type can be undertaken and interpreted, however, stated problems concerning the basic geochemistry of magnetite must be at least partly answered. In addition, it will be desirable to have some information on the transformations undergone by magnetite, and particularly its trace-element constitution, during weathering, erosion, and transportation. Fortunately, such information is becoming available through studies of the magnetite-maghemite-hematite series and of the solubility of trace elements in magnetite.

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TABLE 4.—*Analyses of alluvial magnetite concentrates from the Inner Piedmont belt of North and South Carolina*

[Leaders (-----) indicate not determined. Arsenic, antimony, and tungsten were consistently less than the lower limits of spectrographic detection, 1,00 0, 200, and 100 ppm., respectively]

Sample locality No. (pl. 1)	Field No.	Weight of concentrate (grams)	Magnetite																	
			Percent of concentrate		Weight (grams)	Colorimetric analyses (ppm)			Semiquantitative spectrographic analyses (ppm)											
			As counted	Quartz-free		Lead	Copper	Zinc	Lead	Copper	Zinc	Manganese	Tin	Titanium	Chromium	Beryllium	Barium	Vanadium	Silver	Molybdenum
Concentrates from tributaries to the Savannah River, S.C.																				
1	52-DC-184	60. 9	2	2	1. 2	<25	20	50	15	100	<200	1, 500	30	15, 000	3, 000	<1	-----	2, 000	<1	<10
2	71	34. 4	<1	<1	. 1	<25	<10	125	20	50	<200	2, 000	10	20, 000	200	<2	-----	-----	<1	<5
3	177	459. 4	78	83	358. 3	<25	<10	50	<10	7	<200	1, 000	<10	1, 500	150	<2	-----	-----	<1	<5
4	201	103. 8	16	16	16. 6	<25	<10	25	10	50	<200	1, 500	15	3, 000	300	<2	-----	-----	<1	<5
5	200	136. 5	72	75	98. 3	<25	10	50	10	15	<200	1, 000	<20	5, 000	200	<1	<10	-----	<1	-----
6	199	1, 998. 5	79	88	1, 578. 8	<25	10	25	<10	5	<200	1, 000	<20	5, 000	100	<1	-----	2, 000	<1	<10
7	85	283. 9	71	78	201. 6	25	30	50	<10	15	<200	1, 500	<10	1, 500	70	<2	-----	-----	<1	<5
8	207	87. 4	47	58	41. 1	<25	30	50	10	50	<200	1, 500	<20	5, 000	500	<1	20	-----	-----	-----
9	132	493. 5	61	67	301. 0	<25	10	50	<10	7	200	1, 500	<20	7, 000	150	<1	-----	1, 500	<1	<10
10	135	375. 5	33	38	123. 9	<25	40	175	<10	50	<200	1, 500	<10	10, 000	100	<2	-----	-----	<1	<5
11	129	182. 0	<1	<1	. 2	<25	<10	700	30	20	1, 000	3, 000	150	20, 000	10, 000	<2	-----	-----	-----	-----
12	144	1, 162. 2	22	24	255. 7	<25	30	75	<10	10	<200	1, 500	10	5, 000	200	<2	-----	-----	<1	<5
13	157	113. 4	16	17	18. 1	<25	40	50	10	100	<200	1, 500	<20	>10, 000	300	<1	100	-----	-----	-----
14	164	958. 5	27	31	258. 8	<25	20	75	<10	20	<200	2, 000	<20	>10, 000	200	<1	20	-----	-----	-----
15	166	160. 9	<1	<1	. 4	<25	40	50	10	100	200	1, 500	<20	20, 000	2, 000	<1	-----	1, 500	<1	<10
16	114	670. 8	51	57	342. 1	<25	<10	50	<10	10	<200	1, 500	<10	3, 000	150	<2	-----	-----	<1	<5
17	111	380. 7	59	66	224. 6	50	10	75	<10	10	200	1, 500	<20	5, 000	150	<1	-----	1, 500	<1	<5
18	100	291. 3	77	82	224. 3	<25	10	75	<10	10	<200	1, 000	<10	3, 000	150	<2	-----	-----	<1	<5
19	95	970. 1	4	4	38. 8	<25	<10	50	<10	50	<200	1, 500	15	20, 000	300	<2	-----	-----	<1	<5
20	47	283. 0	25	29	70. 8	<25	<10	150	<10	7	<200	2, 000	<10	3, 000	100	<2	-----	-----	<1	<5
21	39	134. 7	1	1	1. 3	<25	80	125	50	150	<200	1, 500	<20	>10, 000	1, 000	<1	100	-----	-----	-----
22	59	192. 1	33	41	63. 4	<25	10	125	<10	7	300	2, 000	<20	7, 000	200	<1	-----	1, 000	<1	<10
23	27	118. 0	33	42	36. 6	50	30	75	<10	15	<200	1, 500	<10	3, 000	100	<2	-----	-----	<1	<5
24	216	10. 5	7	16	. 7	<25	40	75	10	70	<200	2, 000	10	5, 000	100	<2	-----	-----	<1	<5
25	214	41. 0	5	5	2. 0	<25	75	50	<10	30	<200	2, 000	<10	5, 000	200	<2	-----	-----	<1	<5
26	257	823. 6	75	80	617. 7	<25	<10	150	<10	7	<200	1, 000	<10	3, 000	200	<2	-----	-----	<1	<5
27	288	102. 1	16	17	16. 3	<25	<10	50	<10	20	<200	1, 500	<10	2, 000	100	<2	-----	-----	<1	<5
28	301	105. 5	2	2	2. 1	<25	10	75	20	30	<100	1, 500	20	3, 000	150	<2	-----	-----	<1	<5
29	320	414. 8	29	31	120. 3	<25	40	75	<10	15	<200	1, 500	<10	3, 000	100	<2	-----	-----	<1	<5
30	238	268. 0	24	27	64. 3	<25	40	175	<10	10	<200	1, 500	10	3, 000	300	<2	-----	-----	<1	<5
31	330	163. 0	32	34	52. 2	<25	<10	100	<10	10	<200	1, 000	<10	3, 000	70	<2	-----	-----	<1	<5
32	367	96. 3	1	1	1. 0	25	20	50	20	20	200	1, 500	<20	10, 000	200	-----	-----	1, 000	<1	<10
33	704	8. 0	3	3	. 2	25	30	700	30	30	1, 500	3, 000	<10	10, 000	150	2	-----	-----	<1	<5
34	233	538. 1	40	46	215. 2	<25	10	250	10	20	<200	2, 000	<20	>10, 000	300	<1	20	-----	-----	-----
35	703	22. 7	28	33	6. 4	<25	10	125	10	20	<200	2, 000	10	7, 000	200	<2	-----	-----	<1	<5
36	691	12. 1	<1	<1	<. 1	-----	-----	-----	30	50	<200	2, 000	30	5, 000	200	<2	-----	-----	<1	<5
37	695	50. 5	3	3	1. 5	25	60	50	30	150	200	5, 000	20	15, 000	500	<1	-----	1, 000	<1	<10
38	690	232. 4	2	2	4. 6	25	10	125	20	50	<200	5, 000	15	>20, 000	300	<2	-----	-----	<1	<5
39	700	25. 3	3	3	. 8	<25	10	100	10	15	<200	2, 000	50	3, 000	2, 000	<2	-----	-----	<1	<5
40	702	63. 0	36	42	22. 7	25	20	25	20	20	200	3, 000	<20	10, 000	300	<1	-----	1, 500	<1	<10
41	688	49. 1	21	26	1. 0	<25	10	100	<10	20	<200	2, 000	<10	3, 000	150	<2	-----	-----	<1	<5
Concentrates from tributaries to the Saluda River, S.C.																				
42	52-CS-36	285. 5	33	38	94. 2	<25	10	125	<10	20	<200	2, 000	<20	5, 000	100	<1	<10	-----	-----	-----
43	37	59. 1	35	39	20. 7	25	20	150	25	20	<200	2, 000	<10	10, 000	200	<1	20	-----	-----	-----
44	38	60. 1	9	10	5. 4	<25	150	75	30	200	<200	2, 000	<20	10, 000	200	<1	20	-----	-----	-----
45	52-DC-444	82. 5	27	29	22. 3	50	20	50	30	50	200	3, 000	<20	15, 000	300	1	-----	1, 500	<1	<10
46	463	484. 0	48	55	232. 3	<25	<10	75	<10	10	<200	1, 500	<10	2, 000	150	<2	-----	-----	<1	<5
47	443	7. 5	<1	<1	<. 1	-----	-----	-----	20	50	<200	3, 000	70	15, 000	500	<2	-----	-----	<1	<5
48	435	186. 5	22	23	41. 0	<25	<10	75	<10	10	<200	1, 500	<10	7, 000	150	<2	-----	-----	<1	<5
49	482	178. 1	8	9	14. 2	100	150	75	70	50	<200	1, 500	50	3, 000	150	3	-----	-----	<1	<5
50	418	162. 2	17	20	27. 6	<25	10	75	<10	15	<200	1, 000	<10	2, 000	100	<2	-----	-----	<1	<5
51	483	150. 6	2	2	3. 0	<25	40	75	30	100	<200	2, 000	<20	>10, 000	500	<1	10	-----	-----	-----
52	407	96. 5	2	2	1. 9	500	220	125	500	300	200	5, 000	500	5, 000	300	<1	-----	1, 000	<1	<10
53	400	193. 9	<1	<1	. 3	<25	75	75	30	50	<200	1, 500	30	15, 000	500	<2	-----	-----	<1	<5
54	508	43. 3	6	6	2. 6	75	50	75	10	20	<200	1, 500	<10	7, 000	100	<2	-----	-----	<1	<5
55	383	47. 5	7	8	3. 3	<25	75	75	15	50	<200	3, 000	<10	10, 000	200	<2	-----	-----	<1	<5
56	396	109. 8	29	31	31. 8	<25	20	175	<10	10	<200	1, 000	<10	5, 000	100	<2	-----	-----	<1	<5
57	392	20. 2	4	5	. 8	<25	10	75	15	30	<200	1, 500	10	7, 000	300	<2	-----	-----	<1	<5
58	385	106. 5	2	2	2. 1	100	100	75	70	50	<200	200	20	2, 000	500	3	-----	-----	<1	<5
59	386	122 0	1	1	1. 2	75	40	50	50	100	<200	1, 500	100	10, 000	1, 000	<1	-----	1, 000	<1	<10

60	577	390.0	18	19	70.2	<25	20	150	<10	20	<200	2,000	<10	3,000	150	<2	----------	----------	<1	<5
61	372	132.8	7	7	9.2	<25	75	100	10	50	<200	1,000	20	2,000	300	<2	----------	----------	<1	<5
62	369	30.3	6	7	1.8	<25	40	125	10	100	<200	1,500	10	2,000	300	<2	----------	----------	<1	<5
63	709	101.5	49	55	49.7	<25	30	25	15	50	200	3,000	<20	10,000	300	<1	----------	1,500	<1	<10
64	683	53.7	2	2	1.1	<25	100	100	20	100	<200	3,000	10	>20,000	200	2	----------	----------	<1	<5
65	447	45.9	2	2	.9	<25	130	25	100	200	<200	1,500	<20	5,000	1,000	2	100	----------	----------	----------
66	461	104.4	4	4	4.2	300	150	75	200	50	<200	2,000	70	2,000	100	<2	----------	----------	<1	<5
67	471	47.2	3	3	1.4	300	80	75	150	30	<200	1,000	30	2,000	300	5	----------	----------	<1	<5
68	601	134.4	2	2	2.7	<25	10	100	20	15	<200	1,000	10	2,000	200	<2	----------	----------	<1	<5
69	543	19.9	<1	<1	<.2	200	40	75	100	200	<200	>10,000	<20	>10,000	200	<1	10	----------	----------	----------
70	566	543.2	<1	<1	2.4	<25	15	100	10	100	<200	>10,000	<10	>20,000	100	3	----------	----------	<1	<5
71	675	36.0	5	6	1.8	<25	30	100	<10	20	<200	1,000	10	3,000	300	<2	----------	----------	<1	<5
72	671	46.2	11	12	5.1	125	40	50	10	100	200	5,000	<20	20,000	200	<1	----------	1,500	<1	<10
73	620	133.2	50	53	66.6	<25	10	75	20	20	200	3,000	<20	10,000	500	<1	----------	1,500	<1	<10
74	629	42.3	18	19	7.6	<25	30	125	10	20	<200	1,500	<10	10,000	150	<2	----------	----------	<1	<5
75	651	7.8	15	16	1.2	<25	10	125	20	30	<200	2,000	<20	10,000	200	<1	10	----------	----------	----------
76	637	13.0	16	17	2.1	<25	30	100	<10	30	<200	2,000	<10	10,000	100	<2	----------	----------	<1	<5
77	646	137.6	61	65	119.6	<25	<10	100	<10	7	<200	2,000	<10	2,000	100	<2	----------	----------	<1	<5
78	647	58.6	37	43	21.7	<25	10	125	<10	10	<200	3,000	<10	5,000	100	<2	----------	----------	<1	<5
79	640	60.8	35	39	21.3	<25	10	50	15	7	200	3,000	<20	10,000	300	<1	----------	2,000	<1	<10

Concentrates from tributaries to the Enoree River, S.C.

80	52-CS-546	113.3	22	22	24.9	25	20	50	20	70	200	3,000	<20	7,000	300	<1	----------	2,000	<1	<10
81	549	107.0	65	74	69.5	<25	15	700	10	20	<200	2,000	<10	3,000	300	<2	----------	----------	<1	<5
82	553	39.9	13	15	5.2	25	50	125	15	50	<200	2,000	10	2,000	300	<2	----------	----------	<1	<5
83	573	113.5	1	1	1.1	<25	50	1,000	50	30	1,500	2,000	50	10,000	500	7	----------	----------	<1	<5
84	576	56.2	1	1	.6	<25	50	125	50	100	<200	1,500	70	5,000	500	15	----------	----------	<1	<5
85	616	147.6	2	2	2.9	50	60	150	100	150	200	2,000	30	15,000	2,000	<1	----------	1,000	<1	<10
86	596	49.8	1	1	.5	25	40	50	30	70	<200	1,500	30	5,000	150	2	----------	----------	<1	<5
87	606	146.0	<1	<1	.4	50	50	700	50	70	700	3,000	70	15,000	150	2	----------	----------	<1	<5
88	652	98.7	1	1	1.0	100	40	75	100	50	<200	2,000	50	10,000	500	2	----------	----------	<1	<5
89	632	63.9	2	2	1.3	50	20	50	50	20	<200	1,000	20	7,000	150	<2	----------	----------	<1	<5
90	700	125.3	6	7	7.5	25	75	50	20	100	<200	3,000	<10	20,000	150	<2	----------	----------	<1	<5
91	679	13.1	22	24	2.9	<25	60	50	20	150	200	3,000	20	15,000	300	<1	----------	1,500	<1	<10
92	696	104.6	27	29	28.2	<25	30	75	10	20	<200	2,000	<10	10,000	300	<2	----------	----------	<1	<5
93	713	67.5	16	67	41.2	25	10	75	10	20	<200	2,000	<20	3,000	300	<1	----------	1,500	<1	<10
94	721	143.7	87	90	125.0	<25	<10	125	10	5	<200	2,000	<20	5,000	200	<1	<10	----------	<1	<10
95	725	60.9	35	36	21.3	<25	10	50	10	5	200	2,000	<20	10,000	200	<1	----------	2,000	<1	<10
96	730	35.8	34	40	12.2	<25	20	100	10	30	<200	2,000	<20	7,000	500	<1	30	----------	<1	<10

Concentrates from tributaries to the Tyger River, S. C.

97	52-CS-475	12.9	2	4	.2	<25	90	75	20	150	<200	2,000	20	10,000	1,000	<1	100	----------	<1	<10
98	473	43.7	53	64	23.2	<25	10	100	10	7	<200	1,000	20	7,000	200	<1	10	----------	<1	10
99	476	60.6	11	15	6.7	75	60	75	20	50	200	2,000	<20	7,000	300	<1	----------	1,500	<1	<10
100	485	89.6	2	3	1.8	300	120	50	300	100	<200	3,000	150	5,000	300	3	----------	----------	<1	<5
101	516	103.4	2	2	2.1	200	60	50	70	100	<200	1,500	70	5,000	2,000	<1	----------	1,000	<1	<10
102	538	29.3	21	26	6.1	<25	50	100	15	150	<200	2,000	<20	>10,000	700	<1	50	----------	<1	10
103	736	238.0	65	70	154.7	<25	10	100	10	30	----------	2,000	<20	7,000	300	<1	20	----------	<1	10
104	39	804.7	79	91	635.7	<25	<10	75	10	10	<200	2,000	<20	3,000	100	<1	<10	----------	<1	<10
105	40	1,164.2	85	96	989.6	<25	10	75	<10	5	<200	2,000	<20	5,000	100	<1	10	----------	<1	<10
106	450	186.8	50	61	93.4	<25	<10	75	<10	5	<200	3,000	<10	2,000	100	<2	----------	----------	<1	<5
107	457	130.7	37	57	48.4	<25	20	75	10	20	<200	2,000	<10	2,000	150	<2	----------	----------	<1	<5
108	443	255.2	69	85	176.1	<25	10	50	10	5	<200	2,000	<20	2,000	100	<1	----------	1,500	<1	<10
109	428	169.3	47	60	79.6	<25	20	50	10	30	<200	2,000	10	3,000	100	<2	----------	----------	<1	<5
110	354	100.0	<1	<1	.2	50	20	100	70	30	<200	1,000	30	5,000	600	2	----------	----------	<1	<5
111	381	101.0	19	21	19.2	<25	<10	75	<10	20	<200	3,000	<10	2,000	300	<2	----------	----------	<1	<5
112	410	136.2	15	16	20.4	<25	<10	50	10	30	<200	2,000	15	5,000	500	<2	----------	----------	<1	<5
113	408	90.8	23	26	20.9	<25	20	50	<10	20	<200	3,000	10	5,000	500	<1	----------	1,500	<1	<5
114	402	159.8	36	44	57.5	<25	10	100	10	20	<200	1,500	<20	3,000	500	<1	10	----------	<1	10

TABLE 4.—*Analyses of alluvial magnetite concentrates from the Inner Piedmont belt of North and South Carolina*—Continued

Sample locality No. (pl. 1)	Field No.	Weight of concentrate (grams)	Magnetite																		
			Percent of concentrate		Weight (grams)	Colorimetric analyses (ppm)			Semiquantitative spectrographic analyses (ppm)												
			As counted	Quartz-free		Lead	Copper	Zinc	Lead	Copper	Zinc	Manganese	Tin	Titanium	Chromium	Beryllium	Barium	Vanadium	Silver	Molybdenum	
Concentrates from tributaries to the Pacolet River, S.C. and N.C.																					
115	52-CS-94	64.9	69	74	44.8	<25	<10	25	15	7	<200	1,000	<10	1,500	150	<2	---	---	<1	<5	
116	19	144.7	45	51	65.1	<25	10	25	15	20	<200	1,000	15	1,500	500	<2	---	---	<1	<5	
117	35	762.9	55	68	419.6	<25	150	25	50	300	<200	2,000	<20	>10,000	200	<1	10	---	<1	<10	
118	41	454.4	57	64	259.0	<25	<10	150	<10	5	<200	2,000	<20	10,000	100	<1	10	---	<1	<10	
119	43	178.3	32	39	57.1	<25	20	50	10	70	200	2,000	<20	10,000	150	<1	---	1,500	<1	<10	
120	44	150.8	67	79	101.0	<25	10	75	10	15	<200	1,000	<20	3,000	500	<1	10	---	<1	10	
121	47	106.4	73	84	77.7	<25	30	25	10	20	<200	1,000	<10	2,000	100	<2	---	---	<1	<5	
122	61	248.4	58	66	144.1	<25	30	25	15	20	<200	1,000	<10	1,500	100	<2	---	---	<1	<5	
123	71	261.0	64	78	167.0	<25	10	25	10	10	<200	700	<10	2,000	100	<2	---	---	<1	<5	
124	74	275.2	64	76	176.1	25	10	50	20	20	200	2,000	<20	5,000	300	<1	---	1,500	<1	<10	
125	114	71.5	<1	<1	<.7	50	150	100	100	100	200	1,500	50	7,000	---	<1	---	1,000	<1	<10	
126	126	62.7	<1	<1	<.6	100	150	150	---	---	---	---	---	---	1,000	---	---	---	---	---	
127	148	74.4	2	2	1.5	50	20	25	100	20	<200	500	70	1,500	300	3	---	---	<1	<5	
128	185	96.7	2	2	1.9	75	10	25	100	15	<200	200	<20	3,000	500	<1	30	---	<1	10	
129	164	339.7	10	12	33.9	100	20	25	100	15	<200	700	15	2,000	200	5	---	---	10	<5	
130	205	145.7	1	1	1.5	<25	40	50	20	100	<200	2,000	50	20,000	1,000	2	---	---	5	<5	
131	277	77.6	21	28	16.3	<25	10	50	10	30	<200	1,000	<10	3,000	200	<2	---	---	<1	<5	
132	289	162.7	2	2	3.2	<25	20	25	50	30	<200	1,000	20	3,000	500	<2	---	---	<1	<5	
133	306	109.7	1	1	1.1	25	30	25	50	100	<200	1,500	20	10,000	500	<2	---	---	<1	<5	
134	315	166.6	<1	<1	.1	350	150	150	30	150	<200	2,000	150	3,000	1,000	<1	---	500	<1	<10	
135	325	189.9	2	2	3.8	250	75	125	200	50	<200	700	100	2,000	500	2	---	---	<1	<5	
136	334	49.3	2	2	1.0	<25	30	50	20	30	<200	1,500	10	5,000	300	<2	---	---	<1	<5	
137	215	145.7	46	52	67.0	<25	10	75	10	15	<200	1,000	10	1,500	200	<2	---	---	<1	<5	
138	226	95.8	2	2	1.9	25	10	50	100	30	<200	1,500	50	7,000	2,000	<2	---	---	<1	<5	
139	257	126.3	1	1	1.3	75	60	75	50	200	200	1,500	30	20,000	1,000	---	---	---	---	---	
140	270	34.1	20	27	6.8	<25	15	50	20	30	<200	1,500	20	3,000	700	<2	---	---	<1	<5	
141	412	155.2	67	71	104.0	<25	20	50	<10	50	<200	1,000	<20	10,000	200	<1	10	---	<1	10	
Concentrates from southern tributaries to the Broad River, S.C. and N.C.																					
142	52-WE-159	222.8	7	7	15.6	<25	30	50	10	30	<200	2,000	<20	5,000	700	<1	---	2,000	<1	<10	
143	153	181.0	12	15	21.7	<25	50	50	<10	30	<200	1,500	20	3,000	700	<2	---	---	<1	<5	
144	150	39.5	20	23	7.9	<25	30	100	<10	30	<200	1,500	100	3,000	5,000	<2	---	---	<1	<5	
145	135	81.5	19	21	15.5	<25	20	50	<10	30	<200	1,000	<10	2,000	150	<2	---	---	<1	<5	
146	124	101.7	1	1	1.0	<25	15	50	20	15	<200	1,000	70	3,000	700	<2	---	---	<1	<5	
147	52-PK-17	309.7	<1	<1	1.1	75	30	100	70	30	200	1,000	15	3,000	200	2	---	---	<1	<5	
148	51-PK-69	63.0	<1	<1	<.6	50	40	75	70	150	<200	1,500	<20	<10,000	2,000	<1	50	---	<1	<10	
149	63	238.5	<1	<1	.7	100	60	100	100	100	<200	1,500	200	5,000	5,000	<1	---	1,000	<1	<10	
150	56	9.2	<1	<1	<.09	---	---	---	20	150	<200	5,000	30	<10,000	5,000	<1	20	---	<1	<10	
151	52-PK-27	59.2	1	1	.6	25	40	25	50	30	<200	1,000	20	5,000	500	<2	---	---	<1	<5	
152	52	161.8	1	1	1.6	50	20	25	70	20	<200	500	15	1,500	300	2	---	---	<1	<5	
153	165	27.4	23	31	6.3	25	70	100	70	100	---	1,000	150	7,000	1,000	<1	30	---	<1	<10	
154	166	69.6	1	2	.7	<25	40	50	10	50	<200	1,000	10	3,000	200	<2	---	---	<1	<5	
155	83	80.8	<1	<1	.3	50	75	100	---	---	---	---	---	---	---	---	---	---	---	---	
156	72	123.3	2	3	2.5	25	40	25	30	30	<200	700	10	3,000	200	<2	---	---	<1	<5	
157	68	22.1	3	5	.7	<25	40	25	50	30	<200	700	20	2,000	200	2	---	---	<1	<5	
158	160	85.1	19	30	16.2	---	---	---	20	30	<200	2,000	20	<20,000	500	<2	---	---	<1	<5	
159	157	77.0	14	28	10.8	<25	20	75	10	70	<200	1,000	70	>10,000	1,500	<1	20	---	<1	<10	
160	164	60.6	30	42	18.2	<25	20	50	<10	15	<200	2,000	<20	7,000	30	<1	---	2,000	<1	<10	

Concentrates from northern tributaries to the Broad River, S.C. and N.C.

161	52-WE-166	398.5	60	77	239.1	<25	10	100	10	7	<200	1,500	<20	5,000	100	<1	10	-----	<1	<10
162	101	34.4	3	5	1.0	250	150	75	250	150	<200	700	30	3,000	700	<1	30	-----	<1	<10
163	107	127.9	45	49	57.6	<25	10	100	<10	5	<200	1,000	<20	3,000	100	<1	10	-----	<1	<10
164	108	21.9	15	20	3.3	<25	20	125	20	30	<200	1,500	<20	10,000	300	<1	20	-----	<1	<10
165	109	51.6	8	13	4.1	30	90	75	30	90	<200	1,000	20	7,000	500	<1	20	-----	<1	<10
166	57	24.3	29	40	7.0	<25	40	50	<10	150	200	2,000	<20	20,000	3,000	<1	-----	1,500	<1	<10
167	52	220.3	68	78	149.8	<25	<10	50	<10	15	<200	1,500	10	2,000	200	<2	-----	-----	<1	<5
168	31	23.6	2	4	.5	<25	10	75	20	100	200	2,000	20	5,000	500	<1	-----	2,000	<1	<10
169	14	473.8	<1	<1	2.6	<25	30	50	50	30	<200	1,500	15	3,000	300	<2	-----	-----	<1	<5
170	8	278.0	2	3	5.6	25	10	75	30	15	<200	1,000	<10	3,000	200	<2	-----	-----	<1	<5
171	51-PK-238	48.6	6	10	2.9	50	50	50	100	70	<200	1,500	50	10,000	1,000	<1	50	-----	<1	<10
172	52-WE-175	215.4	51	67	109.8	<25	10	50	<10	5	<200	2,000	<20	3,000	70	<1	-----	1,500	<1	<10
173	51-PK-148	143.1	29	33	41.5	<25	10	50	10	5	<200	1,000	<20	5,000	100	<1	30	-----	<1	<10
174	151	175.2	19	21	33.3	<25	10	25	10	7	<200	1,500	<20	5,000	150	<1	-----	1,500	<1	<10
175	144	220.1	72	75	158.5	<25	20	75	<10	20	<200	1,500	<20	5,000	200	<1	15	-----	<1	<10
176	79	187.0	13	18	24.3	<25	30	50	10	50	<200	1,000	<20	5,000	2,000	<1	50	-----	<1	<10
177	201	80.7	14	67	33.1	<25	10	100	<10	5	<200	1,500	<20	3,000	50	<1	10	-----	<1	<10
178	196	288.4	62	72	178.8	<25	10	100	<10	20	<200	1,000	<20	3,000	100	<1	10	-----	<1	<10
179	99	160.0	2	2	3.2	<25	60	300	<10	150	<200	1,500	150	>10,000	>10,000	<1	30	-----	<1	<10
180	116	77.9	1	1	.8	<25	10	75	10	20	<200	1,000	<20	10,000	500	<1	20	-----	<1	<10
181	127	28.3	1	1	.3	75	50	100	70	150	<200	3,000	20	>10,000	2,000	<1	30	-----	<1	<10
182	132	137.9	<1	<1	<1.4	100	20	75	50	150	<200	5,000	20	>10,000	2,000	<1	20	-----	<1	<10
183	138	10.9	<1	<1	<.1	100	20	50	70	150	<200	2,000	50	>10,000	2,000	<1	20	-----	<1	<10
184	31	198.7	<1	<1	<1.9	<25	40	150	50	70	<200	1,000	150	>10,000	>10,000	<1	10	-----	<1	<10
185	15	55.6	<1	<1	<.5	50	40	150	10	150	<200	3,000	20	>10,000	700	<1	10	-----	<1	<10
186	14	55.7	<1	<1	<.5	75	40	100	50	200	<200	2,000	30	>10,000	1,500	<1	20	-----	<1	<10
187	33	37.7	<1	<1	<.4	150	50	100	200	200	<200	1,500	50	>10,000	2,000	<1	20	-----	<1	<10
188	29	47.1	<1	<1	<.5	75	40	125	30	150	<200	5,000	50	>10,000	2,000	1,000	15	-----	<1	<10
189	27	157.8	<1	<1	<1.6	125	30	75	70	150	<200	5,000	<20	>10,000	700	<1	15	-----	<1	<10
190	35	41.1	<1	<1	<.4	75	50	100	30	150	<200	1,500	50	>10,000	2,000	<1	20	-----	<1	<10
191	47	28.2	<1	<1	<.3	100	40	125	100	150	<200	2,000	20	>10,000	1,000	<1	20	-----	<1	<10
192	46	103.1	<1	<1	<1.0	500	50	100	200	150	<200	2,000	100	>10,000	1,500	<1	50	-----	<1	<10
193	51	20.5	<1	<1	<.2	75	70	150	30	150	<200	5,000	70	>10,000	500	<1	20	-----	<1	<10
194	51-JW-95	249.3	1	1	2.5	75	40	25	100	20	<200	300	<20	2,000	2,000	<1	50	-----	<1	<10
195	67	111.4	1	1	1.1	75	50	50	100	30	<200	300	<20	7,000	2,000	<1	15	-----	<1	<10
196	79	62.1	1	1	.6	75	40	25	100	30	<200	300	20	10,000	2,000	<1	20	-----	<1	<10
197	84	435.0	2	3	8.7	75	30	25	100	30	<200	300	<20	5,000	1,000	<1	30	-----	<1	<10
198	87	89.5	2	2	1.8	100	50	25	100	50	<200	300	<20	3,000	2,000	<1	30	-----	<1	<10
199	52-CS-840	440.0	4	6	17.6	<25	15	50	<10	20	<200	1,000	50	2,000	2,000	<2	-----	-----	<1	<5
200	838	57.0	<1	<1	<.5	100	40	50	50	30	<200	1,500	30	3,000	150	5	-----	-----	<1	<5
201	836	51.5	<1	<1	<.5	-----	-----	-----	30	100	<200	1,500	300	10,000	3,000	<1	-----	1,000	<1	<10
202	855	66.9	1	1	.7	25	40	100	20	30	<200	1,500	<10	3,000	200	<2	-----	-----	<1	<5
203	803	121.7	<1	<1	.6	75	30	25	30	30	<200	700	30	1,500	150	2	-----	-----	<1	<5
204	741	213.2	<1	<1	<2.1	50	40	100	50	50	<200	1,500	10	3,000	300	<2	-----	-----	<1	<5
205	753	60.3	1	1	.6	350	60	50	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
206	785	116.3	<1	<1	116.3	100	30	100	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
207	52-DC-13	82.0	<1	<1	82.0	25	100	1,000	50	100	1,500	1,500	<10	3,000	300	<2	-----	-----	<1	<5
208	51-KR-82	124.2	1	1	124.2	100	80	150	10	70	<200	1,500	<20	>10,000	2,000	<1	10	-----	<1	<10
209	51-JW-46	43.5	3	5	43.5	75	40	25	70	70	<200	300	50	5,000	3,000	1	20	-----	<1	<10
210	51-OT-138	57.8	<1	<1	57.8	50	40	150	50	150	<200	5,000	<20	>10,000	500	<1	20	-----	<1	<10
211	51-OT-88	55.5	<1	<1	<.5	100	60	50	100	100	<200	1,000	<20	>10,000	700	<1	300	-----	<1	<10
212	51-JW-64	20.9	1	1	.2	-----	-----	-----	100	200	<200	3,000	50	>10,000	2,000	<1	30	-----	<1	<10
213	56	60.4	1	1	.6	100	130	75	70	150	<200	1,000	50	>10,000	2,000	<1	30	-----	<1	<10
214	62	20.6	1	1	.2	100	50	75	70	70	<200	500	<20	<10,000	2,000	1	30	-----	<1	<10
215	51-OT-200	29.9	1	1	.3	125	40	75	100	150	<200	1,000	50	>10,000	700	1	100	-----	<1	<10
216	207	75.6	<1	<1	<.7	50	50	75	70	100	<200	700	70	7,000	1,000	<1	50	-----	<1	<10
217	51-KR-33	134.0	1	1	1.3	100	50	25	100	50	<200	500	<20	5,000	2,000	<1	20	-----	<1	<10
218	51	23.0	<1	<1	<.2	125	70	75	100	200	<200	1,000	50	>10,000	700	<1	50	-----	<1	<10
219	61	10.3	<1	<1	<.1	750	140	150	1,000	200	<200	2,000	70	>10,000	700	<1	50	-----	<1	<10
220	73	45.6	<1	<1	<.4	750	160	75	300	300	<200	1,500	100	>10,000	1,000	1	50	-----	<1	<10
221	77	15.7	<1	<1	<.2	50	250	150	100	300	<200	1,500	200	>10,000	1,500	<1	50	-----	<1	<10
222	99	28.8	<1	<1	<.3	200	90	50	100	150	<200	500	70	>10,000	2,000	<1	30	-----	<1	<10
223	104	78.4	3	4	2.4	75	40	25	70	50	<200	500	30	3,000	2,000	<1	50	-----	<1	<10
224	117	22.9	<1	<1	.1	100	120	150	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
225	116	40.8	<1	<1	<.4	150	180	100	150	300	<200	2,000	500	>10,000	500	1	50	-----	<1	<10
226	114	3.8	<1	<1	<.03	75	50	500	20	200	<200	>10,000	<20	>10,000	500	<1	20	-----	<1	<10
227	105	41.6	1	1	.4	*200	70	50	70	100	<200	500	2,000	5,000	1,000	<1	50	-----	<1	<10
228	113	9.0	3	4	.3	-----	-----	-----	70	300	<200	1,500	30	>10,000	1,000	1.5	50	-----	<1	<10
229	111	110.9	24	29	26.6	1,000	450	600	150	500	1,000	2,000	30	1,500	20	<1	-----	100	<1	<10
230	167	25.2	14	25	3.5	<25	30	25	10	30	<200	1,000	<10	3,000	150	<2	-----	-----	<1	<5
231	170	91.3	4	6	3.6	50	40	75	70	70	<200	700	<20	7,000	2,000	<1	30	-----	<1	<10

TABLE 4.—*Analyses of alluvial magnetite concentrates from the Inner Piedmont belt of North and South Carolina*—Continued

Sample locality No. (pl. 1)	Field No.	Weight of concentrate (grams)	Magnetite																	
			Percent of concentrate		Weight (grams)	Colorimetric analyses (ppm)			Semiquantitative spectrographic analyses (ppm)											
			As counted	Quartz-free		Lead	Copper	Zinc	Lead	Copper	Zinc	Manganese	Tin	Titanium	Chromium	Beryllium	Barium	Vanadium	Silver	Molybdenum
Concentrates from tributaries to the Catawba River, N.C.																				
232	52-WE-194	40.4	13	15	5.3	<25	10	50	<10	10	<200	1,500	<20	3,000	20	<1	---	500	<1	<10
233	195	65.5	7	8	4.6	<25	10	75	<10	15	<200	1,000	<10	3,000	100	<2	---	---	<1	<5
234	237	41.7	8	13	3.3	<25	20	75	<10	20	<200	1,000	15	2,000	300	<2	---	---	<1	<5
235	239	79.0	20	23	15.8	<25	<10	75	<10	15	<200	1,000	<10	2,000	150	<2	---	---	<1	<5
236	243	313.5	32	35	100.3	<25	<10	75	<10	7	<200	1,500	50	2,000	1,000	<2	---	---	<1	<5
237	220	73.5	1	1	.7	<25	10	50	<10	20	<200	1,000	15	3,000	300	<2	---	---	<1	<5
238	213	172.9	70	81	121.0	<25	<10	75	<10	7	<200	1,500	<10	2,000	150	<2	---	---	<1	<5
239	207	32.4	30	37	9.7	<25	50	50	<10	30	<200	1,500	<10	5,000	100	<2	---	---	<1	<5
240	300	171.8	23	24	39.5	<25	<10	175	<10	10	<200	1,000	100	2,000	7,000	<2	---	---	<1	<5
241	294	102.5	17	25	17.4	<25	<10	75	<10	15	<200	1,500	10	2,000	300	<2	---	---	<1	<5
242	265	238.6	24	26	57.3	<25	10	50	<10	10	<200	2,000	<20	3,000	1,000	<1	---	1,500	<1	<10
243	289	21.2	30	36	6.4	<25	15	75	<10	20	<200	1,500	<10	2,000	200	<2	---	---	<1	<5
244	303	44.1	15	17	6.6	<25	15	75	10	30	<200	1,500	10	2,000	300	<2	---	---	<1	<5
245	336	115.3	18	20	20.7	<25	10	100	<10	10	<200	1,000	50	2,000	3,000	<2	---	---	<1	<5
246	322	66.8	14	18	9.3	<25	40	100	10	30	<200	1,000	70	2,000	5,000	<2	---	---	<1	<5
247	314	60.8	21	26	12.8	25	10	50	10	10	200	1,500	20	3,000	5,000	<1	---	1,500	<1	<10
248	52-WE-350	46.2	1	1	.5	25	15	600	15	50	300	5,000	15	>20,000	500	<2	---	---	<1	<5
249	360	39.5	1	1	.4	50	40	125												
250	380	67.4	<1	<1	.4	75	30	50	50	20	<200	700	15	2,000	200	<2	---	---	<1	<5
251	619	87.8	1	1	.9	200	30	200												
252	623	252.8	1	1	2.5	<25	30	50	10	100	<200	2,000	20	15,000	3,000	<1	---	1,500	<1	<10
253	814	453.2	4	4	18.1	<25	30	75	20	50	<200	700	20	10,000	2,000	<1	15	---	<1	<10
254	831	277.2	19	20	52.7	<25	<10	75	<10	10	<200	1,000	15	3,000	150	<2	---	---	<1	<5
255	787	118.6	10	10	11.9	<25	20	75	<10	20	<200	1,000	30	5,000	500	<2	---	---	<1	<5
256	775	82.2	<1	<1	.1	25	10	50	30	10	<200	700	30	3,000	700	3	---	---	<1	<5
257	839	564.8	24	25	135.5	<25	<10	75	<10	5	<200	1,000	<10	3,000	100	<2	---	---	<1	<5
258	740	566.4	2	3	11.3	<25	40	50	30	20	<200	2,000	<20	5,000	700	<1	---	1,000	<1	<10
259	847	60.1	6	6	3.6	<25	20	75	15	50	200	1,500	<20	10,000	500	<1	---	1,500	<1	<10
260	52-CS-872	74.5	25	30	18.6	<25	30	50	10	30	<200	1,500	<10	3,000	100	<2	---	---	<1	<5
261	874	206.8	4	5	8.3	<25	30	50	20	30	<200	700	<10	1,500	200	<2	---	---	<1	<5
262	875	45.2	23	25	10.4	<25	10	50	<7	7	200	1,500	<20	5,000	150	<1	---	1,500	<1	<10
263	867	99.1	<1	<1	<1.0	25	30	75	20	30	<200	1,000	<10	2,000	150	<2	---	---	<1	<5
264	873	93.5	32	39	29.9	<25	10	50	<10	20	<200	2,000	<20	5,000	200	<1	---	1,500	<1	<10
265	52-WE-443	68.2	<1	<1	.1	50	50	75	20	30	<200	2,000	<10	10,000	100	<2	---	---	<1	<5
266	441	36.7	<1	<1	.1	75	50	50	30	30	<200	1,500	30	3,000	100	<2	---	---	<1	<5
267	435	34.5	1	1	.3	25	60	50	30	200	1,000	2,000	300	5,000	>10,000	<1	---	1,500	<1	<10
268	404	88.3	1	2	.9	75	30	50	50	20	<200	500	15	2,000	300	<2	---	---	<1	<5
269	401	58.0	3	4	1.7	150	20	50	50	20	<200	700	30	5,000	300	<2	---	---	<1	<5
270	600	79.4	<1	<1	.2	125	75	100	50	30	<200	1,500	50	5,000	200	<2	---	---	<1	<5
271	604	155.6	18	20	28.0	<25	10	75	10	20	<200	700	<10	3,000	200	<2	---	---	<1	<5
272	638	16.9	<1	<1	<.2				30	200	<200	2,000	200	7,000	300		---	300	<1	<10
273	658	45.1	1	1	.4	<25	10	150	<10	20	200	2,000	15	15,000	300	<2	---	---	<1	<5
274	634	99.4	<1	<1	.4	50	15	75	50	20	<200	1,500	15	7,000	200	<2	---	---	<1	<5
275	673	79.2	<1	<1	.3	75	75	75	50	150	<200	1,500	<20	7,000	1,000	<1	---	500	<1	<10
276	721	204.4	<1	<1	.4	50	40	100	70	30	<200	1,000	50	7,000	700	<2	---	---	<1	<5
277	52-DC-842	388.8	7	8	27.2	<25	30	100	10	30	<200	1,500	30	5,000	1,000	<2	---	---	<1	<5
278	837	50.8	3	4	1.5	<25	30	50	70	30	<200	300	20	2,000	500	2	---	---	<1	<5
279	824	231.6	4	4	9.3	<25	20	75	10	20	<200	1,000	15	7,000	500	<2	---	---	<1	<5
280	819	408.8	7	7	28.6	<25	10	125	<10	20	500	2,000	<20	10,000	200		---	500	<1	<10
281	52-WE-744	228.0	52	57	118.6	<25	10	50	10	7	200	1,500	70	7,000	>10,000	<1	---	1,500	<1	<10
282	755	126.7	43	44	54.5	<25	10	50	<10	20	<200	700	<20	10,000	300	<1	15	---	<1	<10
283	761	141.0	20	21	28.2	<25	20	600	<10	20	300	1,500	150	7,000	>10,000	<1	---	---	<1	<5
284	765	61.8	4	4	2.5	<25	60	75	<10	30	<200	700	<10	1,500	200	<2	---	---	<1	7
285	52-DC-849	205.6	21	23	43.2	<25	10	75	<10	30	<200	1,500	<10	>20,000	150	<2	---	---	<1	<5
286	848	867.2	20	25	173.4	<25	20	50	<10	15	200	2,000	<20	20,000	500	<1	---	1,000	<1	<10
287	52-WE-873	188.0	1	1	1.9	75	30	75	50	30	<200	1,500	50	7,000	1,000	<2	---	---	<1	<5
288	857	88.9	12	12	10.7	<25	10	75	10	10	200	3,000	<20	15,000	500	<1	---	1,500	<1	<10
289	882	80.6	<1	<1	.2	50	20	100	30	30	<200	2,000	30	20,000	1,000	<2	---	---	<1	<5
290	52-CS-897	10.1	1	2	.1	50	50	100	50	50	200	1,500	30	2,000	200	5	---	---	<1	<5
291	52-DC-858	102.2	17	30	17.4	25	50	75	70	50	<200	1,500	15	2,000	500	<2	---	---	<1	<5