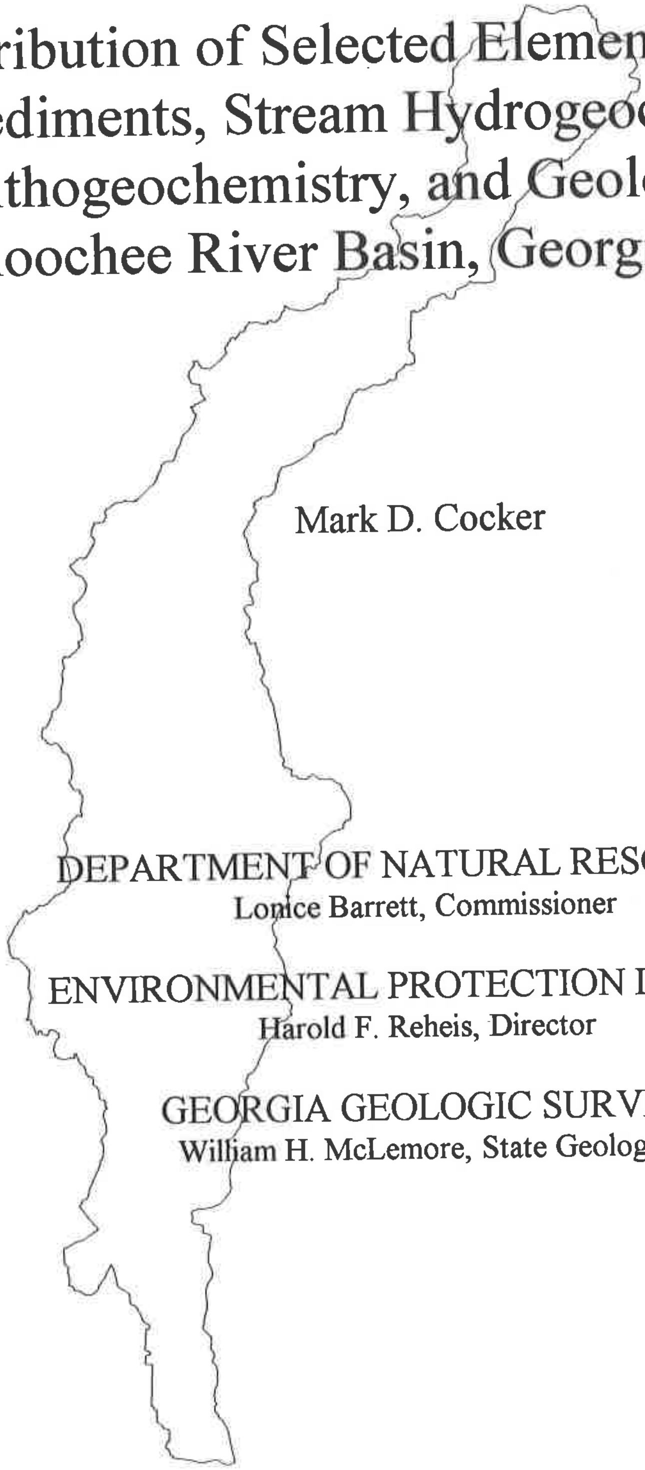

Distribution of Selected Elements in Stream Sediments, Stream Hydrogeochemistry, Lithogeochemistry, and Geology of the Chattahoochee River Basin, Georgia and Alabama

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ABSTRACT

The Georgia Environmental Protection Division is developing water quality management plans for the 16 major river basins within Georgia. These plans will evaluate the hydrogeochemistry of surface water and provide for maintenance of water quality within the river basins. This report documents natural background geochemistry and hydrogeochemistry of the Chattahoochee River Basin. Primary databases used in this study are the stream sediment and stream hydrogeochemical data generated by the U.S. Department of Energy's National Uranium Resource Evaluation (NURE) program, which was conducted in the late 1970's. These databases provide the most extensive geochemical sample coverage for the state. The NURE data, however, do not cover the entire Chattahoochee River Basin; generally the coverage extends to the south end of Stewart County.

Because NURE data are from stream sediments and water, those data may be directly related to the water quality of streams. NURE data are also an important geochemical baseline with which to evaluate environmental changes that may have occurred since the NURE program. The present study involves extensive use of a computer-based Geographical Information System (GIS) to map, analyze, and relate the geochemical data to other geographical and geological databases.

The Chattahoochee River Basin is the longest and economically the most important river system within Georgia. This basin is also important to parts of Alabama and Florida. The Chattahoochee River Basin extends from the Blue Ridge Mountains near the North Carolina border through the Atlanta metropolitan area, across the Piedmont and through the Coastal Plain to Jim Woodruff Dam for a distance of 430 miles. It joins the Flint River to form the Appalachicola River in Florida. For much of its course in the northern part of the basin, the Chattahoochee River follows or flows southwest parallel to a major fault system (i.e., the Brevard fault zone). The Chattahoochee River then flows south and crosscuts crystalline rocks of the Piedmont and sedimentary rocks of the Coastal Plain.

Differences in regional geology from the northern to the southern end of the Chattahoochee River Basin are reflected in the stream sediment geochemistry and stream hydrogeochemistry. Approximately 70 percent of the basin in Georgia is underlain by Precambrian and Paleozoic age crystalline rocks of the Blue Ridge and Piedmont provinces. The remaining 30 percent is underlain by sedimentary strata of the Coastal Plain province. Crystalline rocks in the northern part of the basin are predominantly gneiss (39 percent), schists (19 percent), and metaquartzites and metagraywackes (13 percent), with lesser amounts of amphibolitic rocks (9 percent), and granites (4 percent). Coastal Plain sediments in the southern half of the basin range in age from Cretaceous to Oligocene. Older sediments in the northern part of the Coastal Plain are dominantly sand- and clay-rich formations. Younger sediments in the southern part of the Coastal Plain are dominantly calcareous.

Regional differences in pH, conductivity, and alkalinity of stream waters are spatially related to regional geology and reflect a fundamental geological influence on the hydrogeochemistry. These geological effects may be due to differences in rock geochemistry, porosity, and permeability. Stream hydrogeochemistry may affect dissolution or precipitation of metals. Rocks and stream sediments may serve as important buffering agents on natural and anthropogenic contamination, and this will be reflected in stream hydrogeochemistry.

This study examined the spatial relations of the following metals in stream sediments: aluminum, arsenic, barium, beryllium, chromium, cobalt, copper, lead, nickel, zinc, iron, magnesium, manganese, titanium and vanadium. Iron, magnesium, manganese, titanium and vanadium are included because of their influence on the availability of heavy metals to stream water and their use in interpreting the distribution of heavy metals. Most metal concentrations can be related to either the regional geology, structural trends or the local effects of individual rock units as documented in the section on the Chattahoochee River Basin's geology.

The effects of contamination that were noted during the NURE sampling period may be present in a small portion of that study's stream sediment and stream samples. Studies of specific watersheds, conducted in 1975 and 1976, show that streams in urban areas contribute a large amount of suspended sediment to streams. Those sediments contain a large amount of heavy metals.

INTRODUCTION

The Georgia Environmental Protection Division is developing water quality management plans for the 16 major river basins within Georgia. These plans will evaluate the hydrogeochemistry of surface water and provide for maintenance of water quality within the river basins. Documentation of a river basin's background geochemistry provides an important platform with which to evaluate surface water hydrogeochemistry and from that, the maintenance of water quality. Documentation of the Oconee River Basin and the Flint River Basin geology and geochemistry was completed previously (Cocker, 1996b, 1998b).

The Chattahoochee River Basin extends from northeastern Georgia to eastern Alabama and south to the Appalachicola River in Florida (Fig. 1). That area includes parts or all of 36 counties in Georgia. Counties within the Chattahoochee River Basin include Banks, Carroll, Chattahoochee, Cherokee, Clay, Clayton, Cobb, Coweta, Towns, Dawson, Decatur, DeKalb, Douglas, Early, Forsyth, Fulton, Gwinnett, Habersham, Hall, Harris, Heard, Lumpkin, Marion, Meriwether, Muscogee, Paulding, Rabun, Randolph, Seminole, Stewart, Talbot, Taylor, Troup, Union, Webster, and White Counties (Fig. 2). The largest cities within the Chattahoochee River Basin in Georgia are Alpharetta, Atlanta, Buford, Columbus, Gainesville, LaGrange, Marietta, Smyrna, Newnan, Norcross, and Roswell. The Flint, Ocmulgee, Oconee and Savannah river basins border the Chattahoochee River Basin to the east. On the west side of the Chattahoochee River Basin are the Tennessee, Coosa and Tallapoosa river basins.

Geochemistry and geology of a river basin provide an important and relatively stable framework with which to evaluate the hydrogeochemistry of that river basin. Stream sediment geochemistry represents the average composition of rocks within each drainage from which the sediments are derived. Stream sediment geochemistry is a more consistent database than stream hydrogeochemistry because of temporal changes in Eh-pH conditions of a stream that are related to variations in landscape type and precipitation. Temporal variations in precipitation and runoff affect concentrations of metals in stream water, also. The natural hydrogeochemistry of streams and rivers is principally affected by rocks and sediments through which the water flows. Stream sediment geochemistry can be used to quantify natural geochemical baselines and anthropogenic effects. Natural element enrichments caused by mineralization, host-rock sources and landscape type can be distinguished from anthropogenic effects in stream sediments (Birke and Rauch, 1993; Cocker, 1996b; Simpson and others, 1993; and Xie and Ren, 1993). Soil contamination related to atmospheric deposition may also be reflected in the stream's drainage. Contaminants temporarily stored in flood plain sediments may be continuously released to streams by erosion of those stream's flood plain sediments (Leigh, 1995; Cocker, 1995a, 1996b).

Stream sediments within the Chattahoochee River Basin are affected, in part, by erosion and sedimentation caused by land clearing and agricultural practices of the 1800's and early 1900's. Rapid urban growth during the second half of the 20th century has also contributed to the sediment load of streams. Water movement through these sediments increases the availability of metals to the streams. Also, as streams began to reestablish grade and cut into the thick accumulations of sediments (Trimble, 1969), sediments were remobilized into major rivers and reservoirs. Because more than 90 percent of the transport of most primary pollutant metals in river systems is as a solid phase (Horowitz, 1991), concentration of these metals into primary water supplies is of concern.

Mapping of surficial geochemical data over large areas during the past decade has provided an overview of relative geochemical abundances, regional geochemical trends and anomalous distribution patterns (Birke and Rauch, 1993; Bolviken and others, 1990; Cocker, 1995a, 1996a, and 1996b; Darnley, 1990; Davenport and others, 1993; Kerr and Davenport, 1990; Koch and others, 1979; Koch, 1988; McMillan and others, 1990; Reid, 1993; Simpson and others, 1993; and Xie and Ren, 1993). Surficial geochemical data are important for solving problems in mineral resources, geology, agriculture, forestry, waste disposal, and environmental health.

Since production of the Geochemical Atlas of Georgia (Koch, 1988), significant advances in computer technology and software permit a more sophisticated spatial analysis of data collected within and adjacent to Georgia (Cocker and Dyer, 1993). This report emphasizes databases produced by the U.S. Department of Energy's National Uranium Resource Evaluation (NURE) Program in the late 1970's that were also used by Koch (1988). The NURE Program was designed to assess the uranium potential of the United States. These databases are the largest and most extensive geochemical and hydrogeochemical databases for Georgia. Data are mainly from stream sediments, streams and ground water. This report expands on the maps produced by Koch (1988) and continues the work begun by Cocker (1996a and b) by examining, in detail, the stream sediment and stream geochemistry of the Chattahoochee River Basin in Georgia. This investigation focused on those trace elements which are regarded as primary pollutants in Water Quality Standards or Drinking Water Standards. These elements include: antimony, arsenic, beryllium, cadmium, chromium, copper, lead, mercury, nickel, selenium, silver, thallium, and zinc. Data are presently lacking however, for antimony, cadmium, mercury, selenium, and thallium. Most of the data used in this study are from stream sediment and stream samples. Additional data are from river sediment and river samples, and from rock, saprolite and soil samples.

This report may serve as a guide for other government agencies as the reports for the United Kingdom (Simpson and others, 1993) and for the Oconee River Basin in Georgia (Cocker, 1996a and b). Systematic geochemical mapping of the United Kingdom has confirmed relationships between regional geochemical data and the known distribution of agricultural disorders (Simpson and others, 1993). That geochemical mapping highlighted the principal mineralized areas, disclosed areas with contaminated agricultural soils, and indicated further suspect areas requiring detailed investigations. These geochemical maps provide a unique source of multi-element data for detailed agricultural and health studies. They have been used to site water monitoring stations and have indicated suspect elements for inclusion in water quality monitoring programs (Simpson and others, 1993). Regional geochemical data have been used to define metal-rich drainage inputs to estuaries used for shellfish culture and to guide area selection for many aspects of ecological and environmental research (Simpson and others, 1993). Cocker (1996a and b) described the initial use of the NURE data and GIS to document background geochemistry and hydrogeochemistry of the Oconee River Basin in Georgia. Regional tectonostratigraphic terranes that differed in origin and composition strongly affected the observed geochemistry and hydrogeochemistry of the streams. That geochemical mapping highlighted known mineralized areas and suggested additional "unprospected" areas as potential sources of high heavy mineral concentrations. That study also indicated suspected point sources of anthropogenic contamination that may require further detailed investigations.

GEOGRAPHICAL INFORMATION SYSTEMS AND MAPS

A Geographical Information System (GIS) was used in this study to perform spatial operations on the geochemical and geological data and to link data from various databases using location as a common linkage. A GIS identified and extracted from those databases specific items such as drainage basin boundaries, rock units, different types of samples, and unique geochemical values or ranges of geochemical values. The GIS was used to select single or multi-element data for a river basin and display that data with geographical or geologic information. The GIS was also used to contour the geochemistry and hydrogeochemistry.

Geographical, geochemical, and geological databases used in this project are derived from a variety of sources, have different geographical extent, are at different scales and projections, and contain different types of data such as points, arcs, and polygons. Examples of point data include stream sediment sample points, wells, rock samples, water samples, and mines. Arcs include stream segments and roads. Polygons include such data as: geologic units, hydrologic units, soil types, and political units.

Databases from the Georgia Geologic Survey's GIS that were used in this project include hydrography, hydrounits, county boundaries, geology, major lakes, major roads, soils, physiography, and land use data. Hydrography databases include streams and rivers. Hydrounit databases are drainage basins and smaller divisions within those drainage basins defined by the U.S. Geological Survey. Additional databases used for this project for the GIS include NURE (National Uranium Resource Evaluation) geochemical and hydrogeochemical data, Georgia Environmental Protection Division hydrogeochemical data, mines and prospects, and various databases based on published and unpublished Georgia Geologic Survey geochemical data, published U.S. Geological Survey geochemical data, and geochemical data from student theses.

Contoured geochemical maps contained in this report are sized to fit the pages of the report and are at a scale of 1:1,712,636. Geochemical data were interpreted from 1:500,000 scale versions of the maps. These maps are at the same scale as other statewide maps of Georgia published by the Georgia Geologic Survey. Copies of 1:500,000 scale maps used in this study are in open-files of the Georgia Geologic Survey.

Geochemical maps were developed through a series of steps using a GIS. Sample point coverages were created from latitude and longitude data in the NURE databases. NURE databases were joined to the sample point coverages. Contoured geochemical maps were developed by using Environmental Systems Research Institute's (ESRI) Arc/Info version 7.02. A triangular integrated network (TIN) was generated from sample points within the NURE geochemical coverages. From that TIN, a lattice was created in which each cell was assigned a geochemical value relative to that of two or more nearby sample points. Contours were then created by linking lattice cells with equal geochemical values. Because the Chattahoochee River Basin is located within five 1° x 2° National Topographic Map Series (NTMS) quadrangles, these databases were contoured as a single coverage. This contoured coverage was clipped with the outline of the Chattahoochee River Basin to include only those contours within the Chattahoochee River Basin. This method was used to eliminate or reduce edge effects created by the contouring software. Edge effects are created where data points are absent, and the software creates contours relative to nonexistent data. Unavoidable edge effects appear as elongated contours on some geochemical maps, particularly along the southern edge of the data coverage.

Maps depicting various types of rock units in the Chattahoochee River Basin were created by selecting a particular rock type or groups of rock types (Table 1) from the

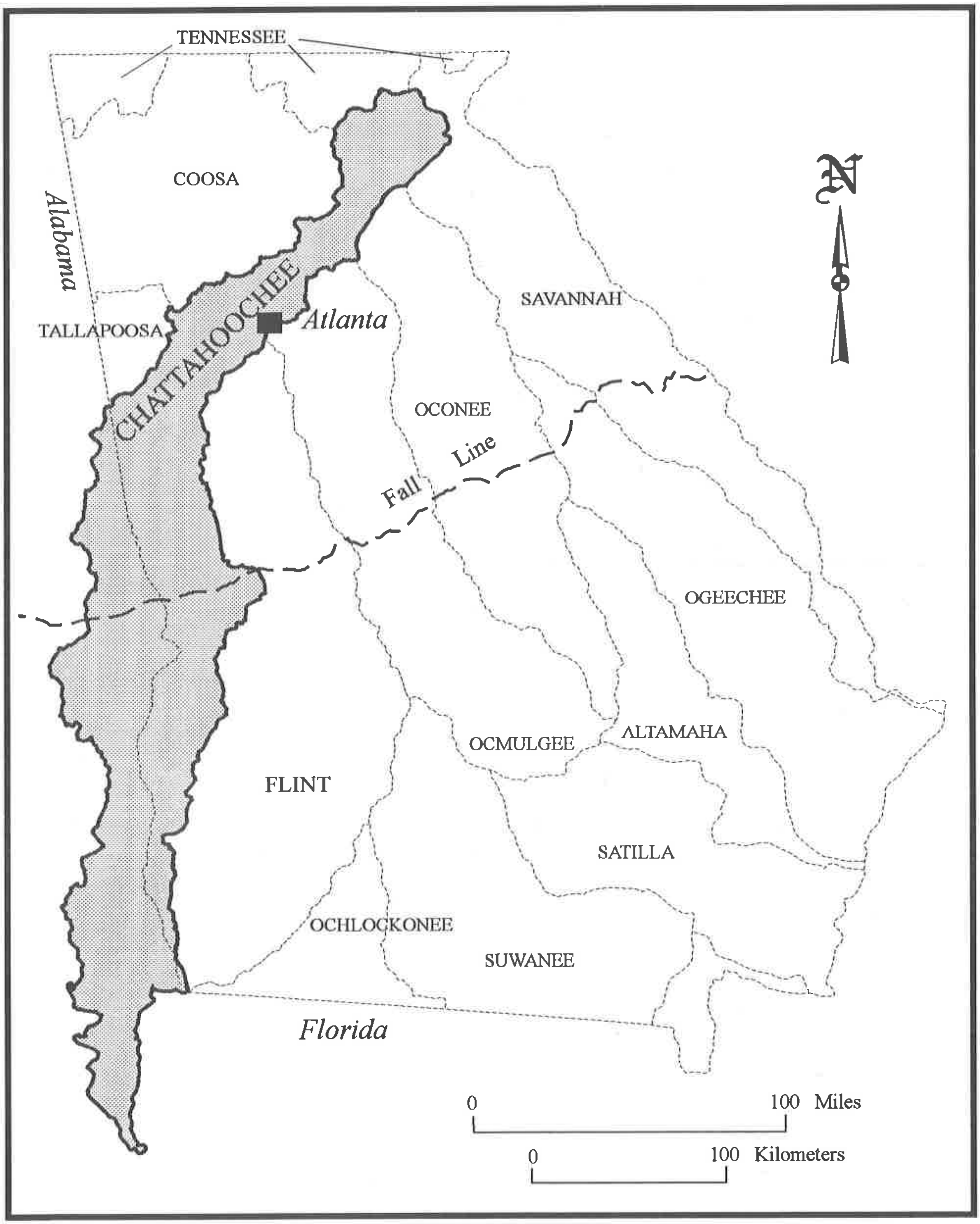

Figure 1. Location of the Chattahoochee River Basin.

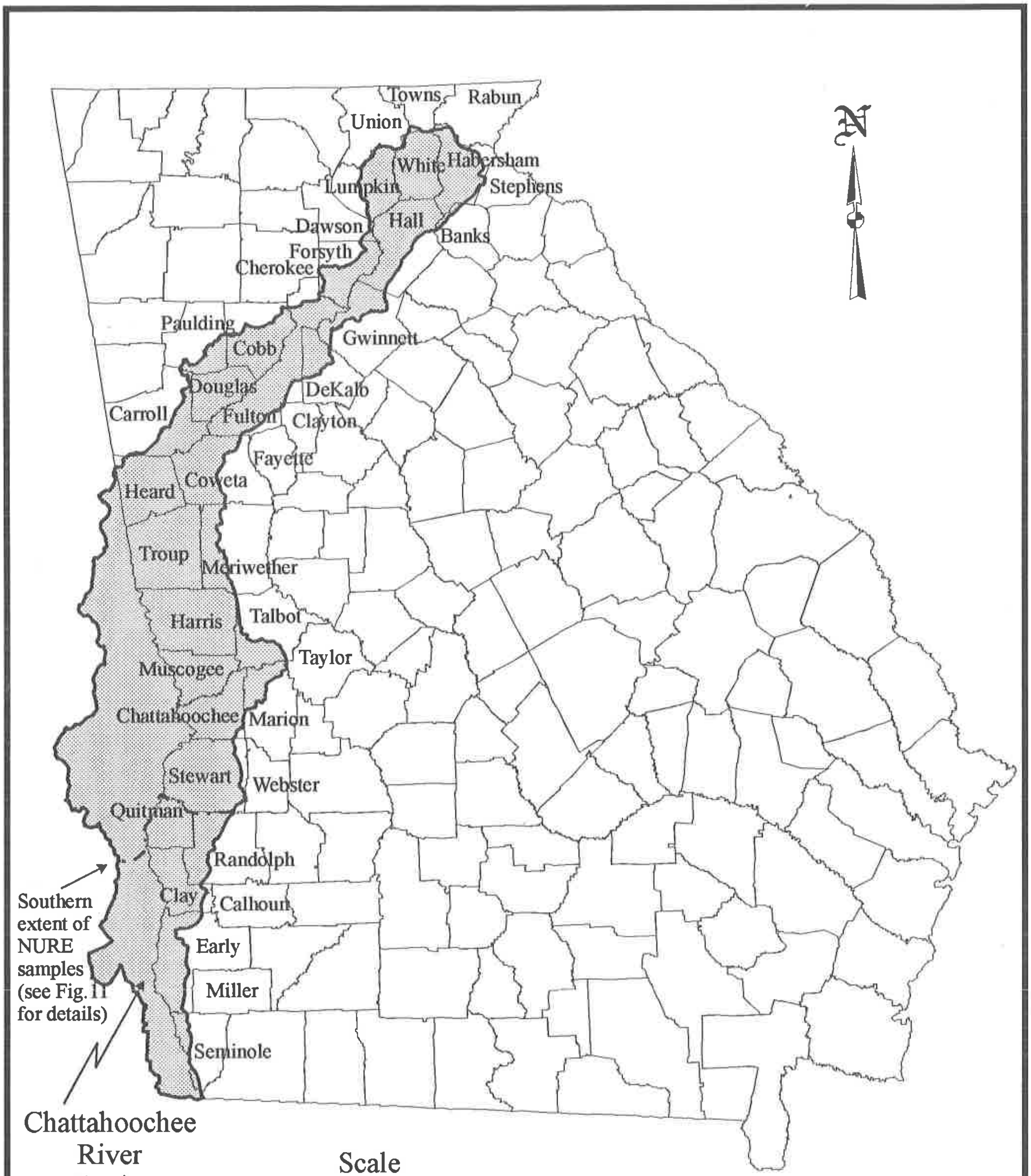

Figure 2. Chattahoochee River Basin and county location map.

Table 1. Area and relative size of rock units in the Chattahoochee River Basin within Georgia arranged alphabetically. (Source: Geologic Map of Georgia (Georgia Geologic Survey, 1976).

Map Symbol	Map Unit	Area (miles^2)	Percentage of basin
Kt	Cretaceous - Tuscaloosa Formation	6.82	0.11
Kr	Cretaceous - Ripley Formation	39.40	0.66
Kb	Cretaceous - Blufftown Formation	208.40	3.48
Kc	Cretaceous - Cusseta Sand	137.19	2.29
Ke	Cretaceous - Eutaw Formation	4.39	0.07
Kp	Cretaceous - Providence Sand	176.00	3.52
Ptu	Paleocene - Tuscahoma Sand	133.64	2.23
Pcn	Paleocene - Nanafalia, Porters Creek and Clayton Formations - undifferentiated	73.71	1.23
Pc	Paleocene - Clayton Formation	208.97	3.49
Pnf	Paleocene - Nanafalia Formation	122.49	2.05
Ec	Eocene - Claiborne Formation	134.48	2.25
Eli	Eocene - Lisbon Formation	133.31	2.23
Eo	Eocene - Ocala Limestone	11.78	0.20
Eta	Eocene - Tallahatta Formation	22.44	0.37
Eo-Os	Eocene and Oligocene residuum - undifferentiated	181.96	3.04
Qal	Quaternary - stream alluvium and stream terrace deposits	106.64	1.78
bg1	biotite gneiss	523.76	8.75
bg2	biotite gneiss/ amphibolite	34.73	0.58
c1	mylonite and ultramylonite	52.23	0.87
c2	flinty crush rock	1.03	0.02
fg1	biotite gneiss/ feldspathic biotite gneiss	11.92	0.20
fg2	biotite gneiss - undifferentiated	0.62	0.01
fg3	biotitic gneiss/ mica schist/ amphibolite	813.52	13.59
fg4	biotitic gneiss/ amphibolite	39.17	0.65
gg1	granite gneiss - undifferentiated	145.15	2.43
gg2	granite gneiss/ gneissic granite (augen or porphyritic)	104.91	1.75
gg3	muscovite granite gneiss	11.96	0.20
gg4	granite gneiss/ amphibolite	7.13	0.12
gg5	calc-silicate granite gneiss	41.39	0.69
gg6	granite gneiss/ granite	79.27	1.32
gr1	granite undifferentiated	101.27	1.69
gr1b	porphyritic granite	157.32	2.63
gr4	charnockite	0.27	0.00
m2	amphibolitic schist/ amphibolite	0.43	0.01
ms1	amphibolitic schist	1.13	0.02
ms3	amphibolite schist/ amphibolite - metagraywacke/ mica schist	8.55	0.14
mm1	amphibolite	61.22	1.02
mm2	hornblende gneiss	18.05	0.30

Table 1. (Continued)

mm2	hornblende gneiss	18.05	0.30
mm3	hornblende gneiss/ amphibolite	320.43	5.35
mm4	hornblende gneiss/ amphibolite/ granite gneiss	74.03	1.24
mm9	amphibolite/ mica schist/ biotitic gneiss	30.53	0.51
pa1	aluminous schist	71.68	1.20
pa2	sillimanite schist	46.12	0.77
pg1	garnet mica schist	26.34	0.44
pg2	garnet mica schist/ gneiss	52.68	0.88
pg3	garnet mica schist/ amphibolite	0.24	0.00
pm2	metagraywacke/ mica schist	237.38	3.97
pm3a	mica schist/ gneiss/ amphibolite	35.37	0.59
pms1	mica schist	49.61	0.83
pms2	mica schist/ amphibolite	20.94	0.35
pms3	mica schist/ gneiss	225.83	3.77
pms3a	metagraywacke/ mica schist-quartzite/ amphibolite	465.60	7.78
pms4	mica schist/ quartzite/ gneiss/ amphibolite	29.84	0.50
pms5	graphite schist	51.44	0.86
pms6a	sericite gneiss/ amphibolite	6.85	0.11
pms7	button mica schist	41.40	0.69
q1	quartzite	79.91	1.34
q1a	quartzite/ mica schist	17.31	0.29
q1b	quartzite/ mica schist/ amphibolite	1.58	0.03
q1c	quartzite/metagraywacke	1.57	0.03
um	ultramafic rocks - undifferentiated	6.61	0.05
Water	lakes, ponds, etc.	141.39	2.36
Total		5984.98	100.00

GIS coverage developed from the Geologic Map of Georgia (Georgia Geological Survey, 1976). Additional ultramafic occurrences documented by Prowell (1972) were used to create an additional coverage to augment the Geologic Map of Georgia GIS coverage. Other more recent maps that have not been digitized into coverages were scanned, traced and edited in CorelDraw version 7.0 - image editing software.

Maps showing the metal and pegmatite mines are derived from several coverages. The metal deposits coverage was developed from mine locations determined for the Greater Atlanta Region (McConnell and Abrams, 1984) and plotted on 1:100,000 scale topographic maps. Location data in Lesure (1992a and b) and Lesure and others (1991 and 1992) were also used for the metal deposits coverage. Locations of pegmatites and pegmatite mines were derived from field studies on pegmatites in the Georgia Piedmont (Cocker, 1992a, 1992b, 1995b, and unpublished data).

GENERAL GEOLOGY

The following discussion is a generalized summary of the geology of the Chattahoochee River Basin. A more detailed description is presented in the Appendix. Maps showing the distribution of the rocks discussed below and in the following sections are included in the Appendix (Figs. A-1 through A-21).

Geology strongly influences the physiography, geochemistry, soils, surface and ground water resources of the Chattahoochee River Basin. The Chattahoochee River Basin in Georgia is underlain by older (Precambrian and Paleozoic) crystalline rocks in the northern 70 percent of the basin and by younger (Cretaceous and Tertiary) sedimentary rocks in the southern 30 percent of the basin. Crystalline rocks are predominantly gneiss (39 percent), schists (19 percent), and metamorphosed sedimentary rocks (13 percent) with lesser amounts of metamorphosed volcanic rocks (9 percent),and granites (4 percent). In the northern half of the basin, the course of Chattahoochee River is principally guided by a zone of intensely sheared and less resistant rocks created by movement along the Brevard fault zone, a major structure that extends from Alabama to Virginia (Fig. A-20). The Brevard fault zone marks the boundary between the Blue Ridge geologic terrane to the northwest and the Inner Piedmont geologic terrane to the southeast. Rock units are generally aligned to the northeast, parallel to regional structures that include the Brevard Fault zone. In the southern part of the basin, the Chattahoochee River cuts across both resistant and less resistant rock units of the Piedmont and the Coastal Plain.

The Blue Ridge terrane (Figs. A-20 and A-21) contains several groups of rocks that contain predominantly metamorphosed volcanic rocks or metamorphosed sedimentary rocks. Rocks are mainly gneisses, schists, quartzites, and amphibolites. Types of rocks influence the stream drainage patterns, the type and geochemistry of the soils and sediments that are derived from those rocks, and the chemistry of the water that flows through and reacts with the rocks, soils and sediments. Metamorphosed volcanic rocks contain high concentrations of metals and host the Dahlonega gold belt and the Carroll County gold belt (Fig. 4). Metals with higher concentrations include copper, zinc, arsenic, mercury, lead, nickel, molybdenum, and iron. Many of the metal ores are massive sulfides, and weathering of these sulfides may increase stream acidity. Numerous small ultramafic rocks bodies in the northernmost part of the basin contain high concentrations of chromium, nickel, and asbestos. Metamorphosed sedimentary rocks generally contain lower concentrations of metals with the exception of the relatively small Hall County gold belt. Individual rock units are summarized in Table 1.

The Inner Piedmont terrane (Figs. A-20 and A-21) generally contains metamorphosed sedimentary rocks such as gneisses, schists and quartzites. Small granitic intrusions are found in the Atlanta area and are important sources of crushed stone for aggregate. Amphibolitic rocks, resulting from metamorphic processes acting on older volcanic rocks, are found in the southwestern part of the basin in Troup and adjacent counties. Higher concentrations of metals such as copper, zinc, lead and iron are associated with these amphibolites. Chromium-bearing ultramafic rocks are associated with the amphibolite. Beryllium-bearing pegmatites are also found in Troup County. Individual rock units are summarized in Table 1.

The southern third of the basin is underlain by Cretaceous and Tertiary sedimentary rocks of the Coastal Plain. These rocks are predominantly older sands and clays near the Fall Line and younger carbonate rocks in the southernmost part of the basin. Dips are gentle to the southeast at a few tens of feet per mile. Several important aquifers are associated with the more permeable rock units. Recharge areas for these aquifers are generally located where these rock units crop out in the northern part of the Coastal Plain. Rock composition and permeability have a strong influence on water that flows through them. Iron ores, kaolin, and bauxite are found and have been mined from the upper or northern part of the Coastal Plain. Quaternary alluvium deposits are found in stream and river valleys, with the larger and thicker deposits in the major river valleys. Commonly, these deposits underlie the flood plains of the river systems. Individual rock units of the Coastal Plain are summarized in Table 1.

MINERAL DEPOSITS AND THEIR GEOCHEMISTRY

Mineral deposits may have an effect on water quality because of abnormally high concentrations of heavy metals, effects of weathering on sulfides, and anthropogenic contamination related to mining and processing of the mineral deposits. Several geochemical studies that include mineral deposits within the Chattahoochee River Basin are discussed in the section on lithogeochemistry.

Mineral deposits that have been developed within crystalline rocks of the Chattahoochee River Basin include: crushed stone, sand and gravel, gold, pyrite, beryl, and mica. Olivine, asbestos, corundum, talc, vermiculite, kyanite, sillimanite, and various heavy minerals have been prospected or have undergone minor production. Kaolin, bauxite, iron ore, and sand and gravel have been mined from or prospected for in Coastal Plain sediments of the Chattahoochee River Basin.

Mineral deposits are commonly concentrated in elongate bands or "belts," which, in general, extend through the Chattahoochee River Basin and adjacent areas from southwest to northeast. Concentrations of mineral deposits within a belt may be referred to as mineral districts.

Piedmont and Blue Ridge

Gold and Sulfides

Three main gold belts extend through the Chattahoochee River Basin (Fig. 3): the Dahlonega gold belt, the Hall County gold belt, and Carroll County gold belt. These belts are generally associated with specific lithologies or groups of rock units. The Dahlonega belt is located principally within rocks of the New Georgia Group. Mineralization in the Hall County and Carroll County districts is found within the metasedimentary rocks of the Sandy Springs Group.

The Dahlonega gold belt is the largest producer of gold in Georgia with an estimated production of 400,000 to 500,000 ounces of gold (Pardee and Park, 1948). This belt contains three types of gold-bearing deposits: 1) alluvial placer deposits, 2) saprolite deposits, and 3) primary veins or lodes. Much of the gold was recovered by hydraulic mining of saprolites developed on mica schist and gneiss overlying amphibole gneiss. Placer ore was recovered by sluice boxes and amalgamation with mercury. Lode ore from underground mines was processed by stamp mill crushing followed by amalgamation or wet chlorination processes (Gillon, 1982). Locally anomalous concentrations of arsenic, antimony, mercury, molybdenum, silver and tungsten are associated with the gold deposits (Albino, 1990).

Mineralization in the Hall County gold belt consists of quartz veins that appear to occupy dilatant fractures in metasedimentary rocks within the Brevard fault zone. Fractures are believed to be associated with post-metamorphic movement along the Brevard zone (Allen, 1986).

The Carroll County gold belt in the Blue Ridge terrane contains numerous gold and sulfide deposits that are believed to be of volcanogenic origin and subsequently modified by metamorphic and tectonic processes. Ore deposits are principally strata-bound and lie within a sequence of metamorphosed mafic to felsic volcanic rocks interlayered with subordinate meta-sediments (McConnell and Abrams, 1984).

Chromite

Chromite deposits in Troup County were investigated by the U.S. Bureau of Mines (Ballard, 1948). These deposits are approximately 8 miles northeast of La Grange and 0.75 miles south of Louise. Chromite occurs as lenses in generally small peridotite or dunite masses. Analyses of the chromite ores generally contained 30 to 50 weight percent Cr_2O_3, 10 to 16 weight percent iron, and 0.1 to 0.4 weight percent nickel. Lateritic garnierite contained 2.08 percent nickel. Although prospected during the early 1900's, no economic production is reported for these deposits. Chrysotile asbestos is also reported from the perioditic rocks.

Heavy Minerals

The Blue Ridge and Piedmont monazite belts (Fig. 4) contain phosphates, oxides and silicates of thorium, uranium, cerium, dysprosium, europium, hafnium, lanthanum, lutetium, samarium, titanium, ytterbium, and zirconium. Principal minerals include monazite, xenotime, and zircon. Monazite, xenotime, zircon, and titanium oxides such as rutile, ilmenite and leucoxene form the bulk of economically important heavy mineral deposits (Mertie, 1979; Overstreet and others, 1968).

In the Piedmont monazite belt, these minerals occur principally within granitic and intermediate/biotitic gneisses and migmatitic rocks north of the Towaliga fault zone. In Georgia, the Blue Ridge monazite belt is principally located within Forsyth, Hall, White and Habersham Counties. Heavy minerals are effectively concentrated by sedimentary processes and may be found in higher concentrations in stream sediments and paleo-beach deposits. An investigation of the heavy mineral composition of Chattahoochee River sediments (in an unpublished study by Cocker) indicates higher concentrations of these economic heavy minerals near their source areas in the Blue Ridge and Piedmont and with increasing distance down river in the Coastal Plain.

Asbestos

Asbestos deposits were mined in the northern part of the Chattahoochee River Basin near Helen during the early 1900's and 1950's (Hopkins, 1914; Gillon, 1982). The Sal Mountain and Powhatan mines were the principal producers of short fiber anthophyllite asbestos. Approximately 15,000 tons of asbestos was produced from the Sal Mountain deposit (Gillon, 1982). These deposits are associated with some of the small ultramafic bodies shown in Fig. A-10. Hurst and Crawford (1964) noted 32 asbestos occurrences in Habersham County that were associated with either ultramafic or amphibolitic rocks. The ultramafic rocks associated chromite deposits in Troup County may also contain asbestos.

Pegmatites - Mica and Beryl

Pegmatite deposits in Georgia are located in the southern Appalachian pegmatite province. This province is divided into two pegmatite belts, the Blue Ridge and Piedmont belts (Fig. 5), which are both intersected by the Chattahoochee River Basin. Investigations in the early part of the 1900's focused on the mineralogy, internal zoning, production and locations of pegmatites within Georgia (Beck, 1948; Furcron and Teague, 1943; Galpin, 1915; Heinrich and others, 1953; and Jahns and others, 1952). More recent studies examined the geochemistry of trace metals in muscovite, potassium feldspar, and tourmaline from pegmatites in the Cherokee-Pickens district in the Blue Ridge belt (Gunow and Bonn, 1989) and the Troup County district in the Piedmont belt (Cocker, 1994). Both of these districts have had production of mica and beryl.

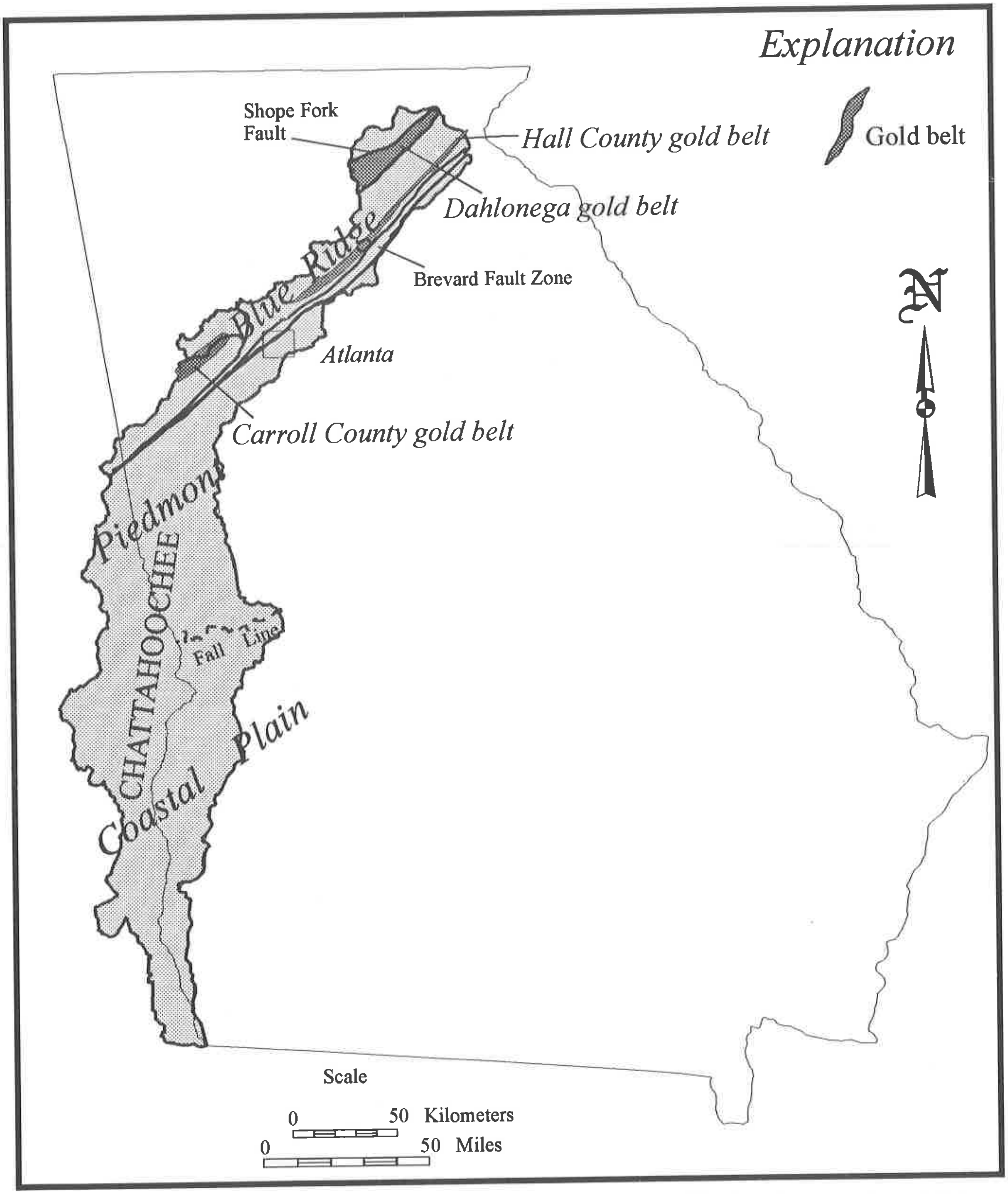

Figure 3. Gold belts in northern Georgia and adjacent parts of Alabama. (Modified from Pardee and Park, 1948.)

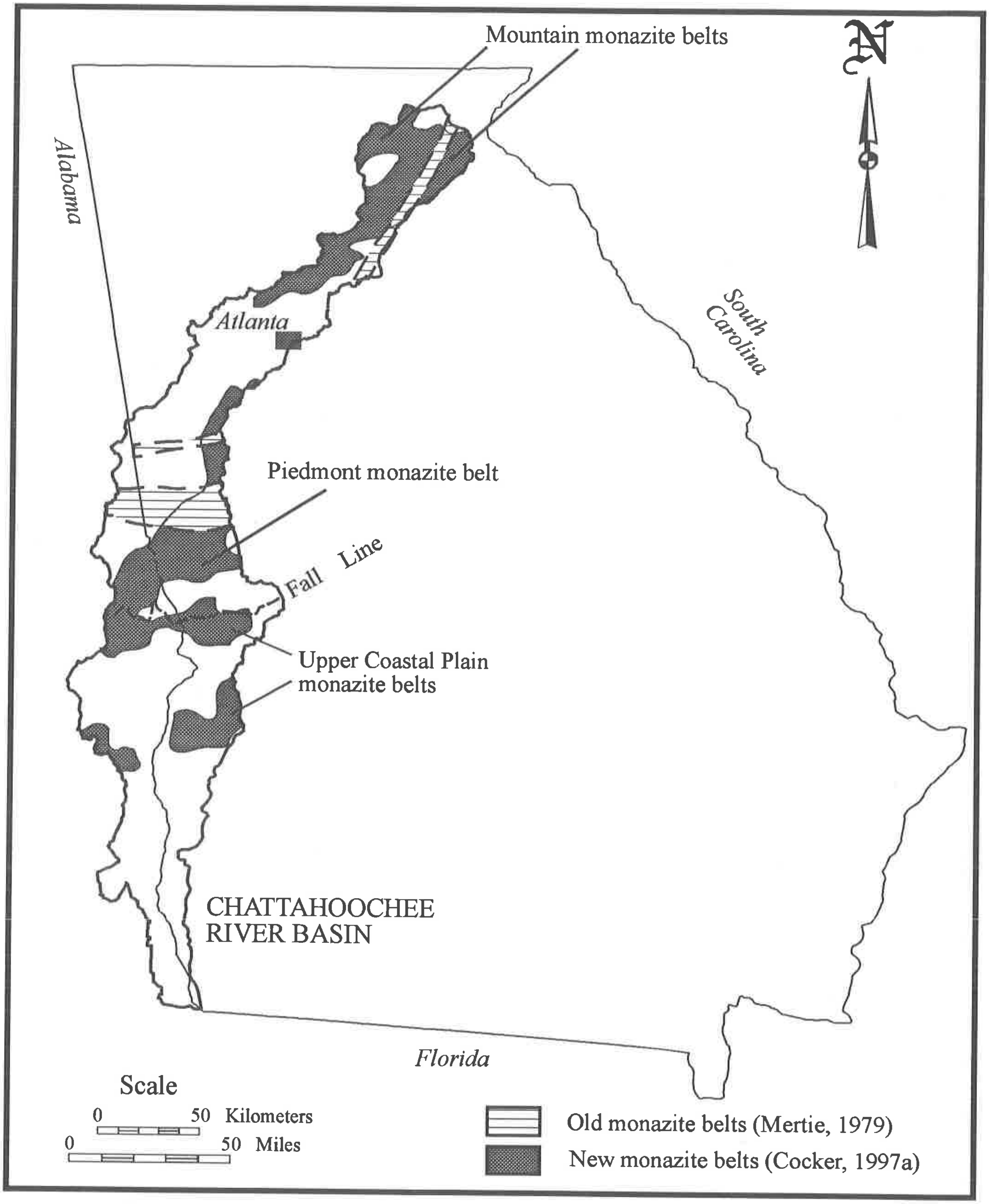

Figure 4. Monazite belts in Georgia and Alabama. Modified from Mertie (1979) and Cocker (1997a).

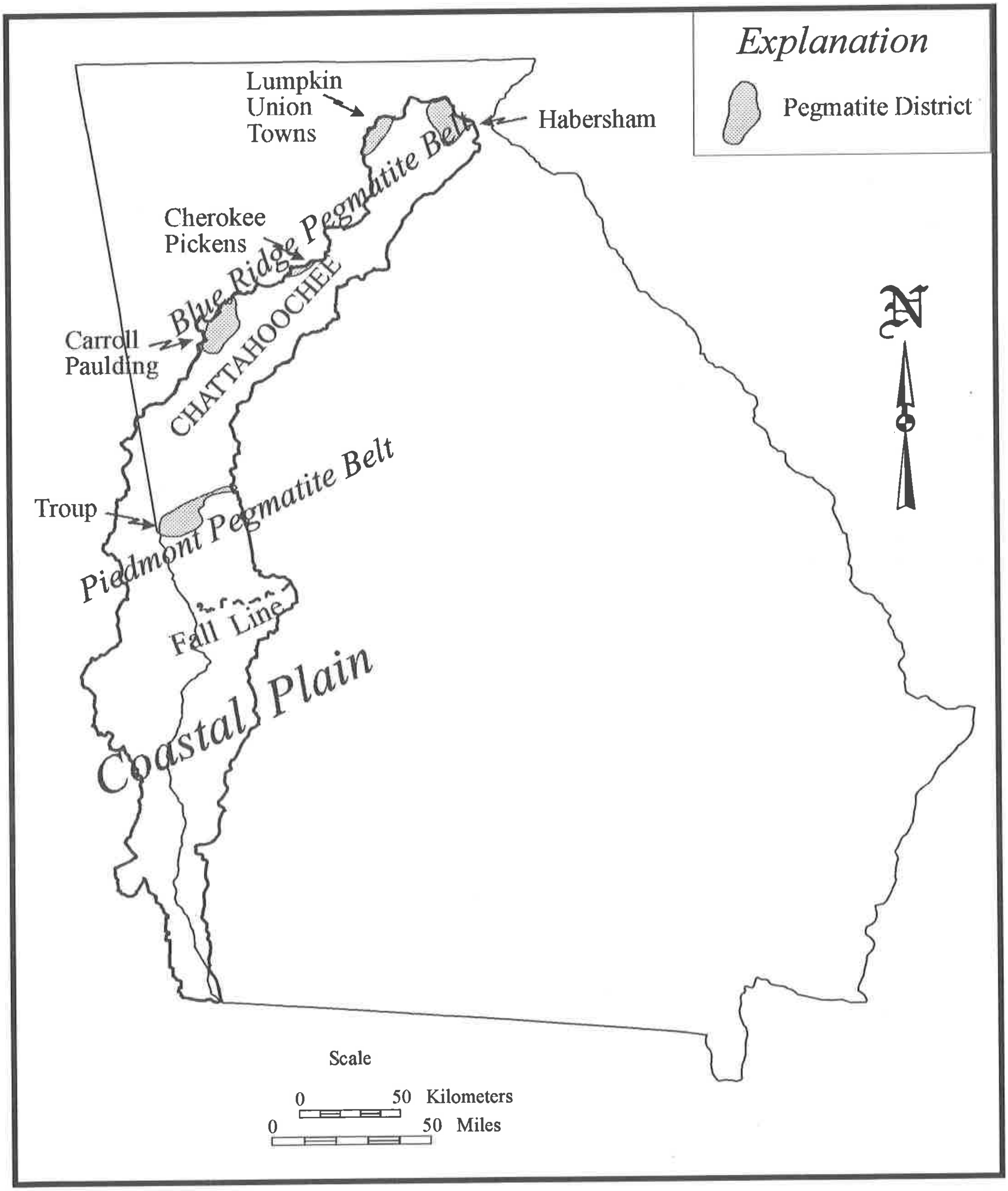

Figure 5. Pegmatite Districts in Georgia.

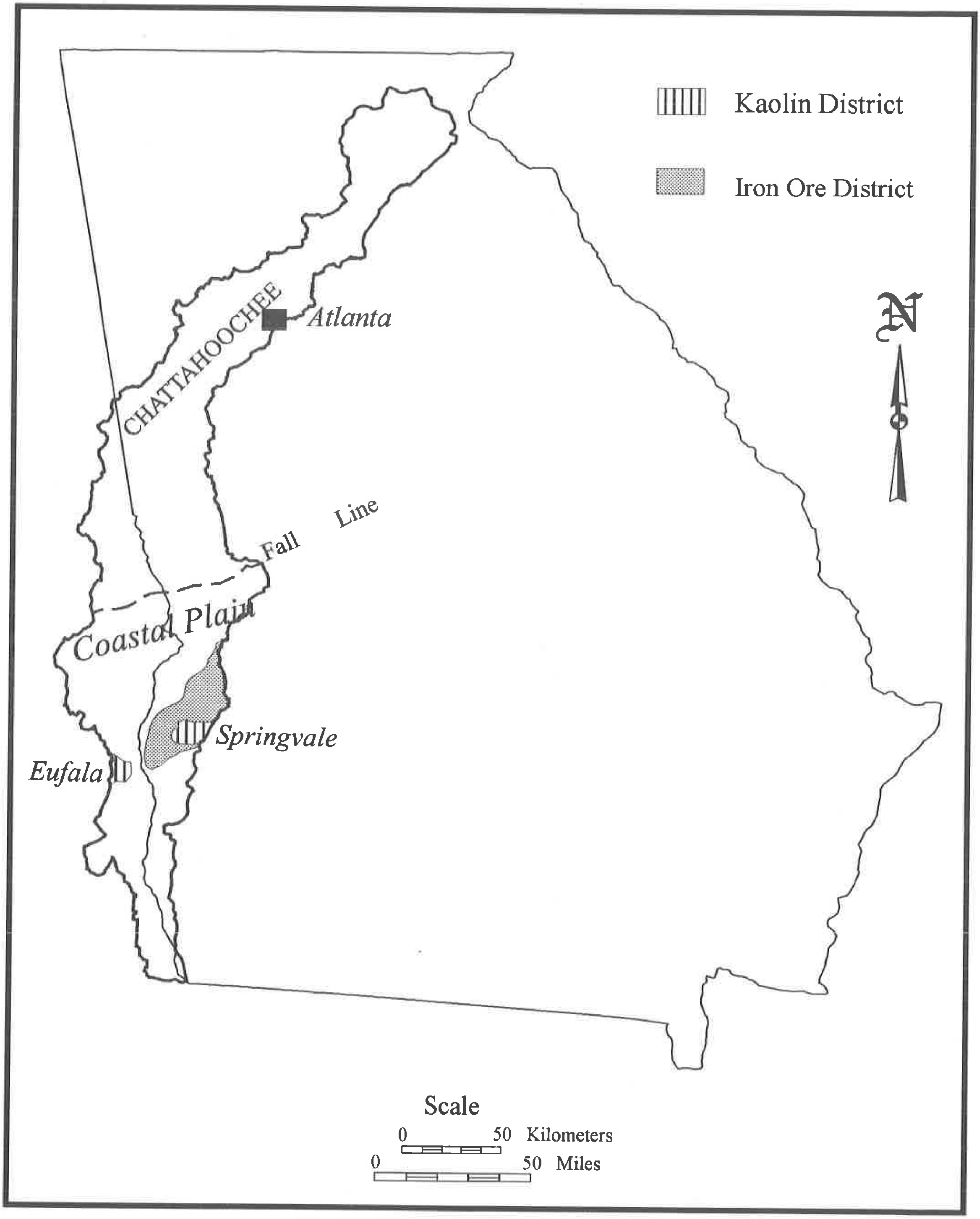

Figure 6. Mineral districts in the Coastal Plain.

Coastal Plain

Iron Ore

Within the Coastal Plain, large quantities of "brown iron ore" were mined from the Paleocene Clayton Formation (Fig. 6). One to two zones of iron ore are located near the base of the Clayton Formation. These zones are 3 to 10 feet thick and are 3 to 6 feet apart (Kirkpatrick, 1959). The ore is an intimate mixture of limonite and goethite. The presence of trace or heavy metals in these iron ores is undocumented, but could be present because of the scavenging effects of iron oxides. Mining operations within the Chattahoochee River Basin were located about 5 miles west of Lumpkin and about two miles northeast of Lumpkin in Stewart County. Ore outcrops have been noted in a number of localities in Stewart and Quitman Counties (Furcron, 1956).

Kaolin and Bauxite

In Georgia, kaolin and bauxite deposits are found within Cretaceous to Eocene age strata near the Fall Line (Fig. 6). Small amounts of kaolin and bauxite were produced from Paleocene age sediments in the Chattahoochee River Basin . Minor amounts of generally impure kaolin, which is usually in small lenses, occur also in Cretaceous sediments within the Chattahoochee River Basin (Smith, 1929). Bauxites have an alumina content of 52 to 61 percent. Primary minerals of bauxite are diaspore and gibbsite. Bauxitic clays have an alumina content of 40 to 52 percent and are a mixture of bauxite and kaolin (Smith, 1929). Bauxite deposits are apparently derived by weathering of kaolin deposits. Generally, silica is the primary component of the kaolin that is leached from the deposits. Trace metal contents are unknown but may be essentially nonexistent because of the extreme leaching necessary to produce these deposits.

SURFICIAL GEOLOGY

Precipitation

Precipitation affects surficial geology through weathering and erosion of rocks and soils, and it affects the volume of stream discharge. Annual precipitation can vary significantly in different parts of the Chattahoochee River Basin (Fig. 7) and from year to year. Average annual precipitation in the Chattahoochee River Basin south of Hall County is generally 50 to 53 inches and increases to 64 inches north of Gwinnett County. Precipitation is lowest in the Atlanta area with an average of 49 inches (Carter and Stiles, 1983; Hodler and Schretter, 1986). Precipitation is greatest in the northern part of the basin because the Blue Ridge Mountains act as a barrier to the north-flowing, moisture laden air from the Gulf of Mexico. Precipitation ranges from 30 to 70 inches per year within the Chattahoochee River Basin. The average pH of precipitation in Georgia has declined from 5.6 in 1955 to 4.5 in 1980 (Hodler and Schretter, 1986).

Geomorphology

River basin geomorphology affects the residence time of water in the ground, the rate at which water moves through the basin, and the type of geological material through which water may acquire its chemical characteristics. Geomorphology of the Chattahoochee River Basin is controlled by rock composition, structural development, precipitation, weathering, and erosional history.

Chattahoochee River

The size of the Chattahoochee River Basin is 8,707 square miles with 5,984 square miles in Georgia and 2,723 square miles in Alabama. It is approximately 360 miles long, and averages 28 miles wide (range of width is 10 to 56 miles). The Chattahoochee River has a total length of 434 miles (U.S. Army Corps of Engineers, 1985) and joins the Flint River at the Georgia-Florida State line to form the Apalachicola River. A graph of cumulative length versus cumulative drainage area for the Chattahoochee River indicates that each mile of the river drains an average area of about 1.4 square miles. Faye and others (1980) calculated that one mile of the Big Creek and Soque Rivers drains an area of about 0.7 square miles. Principal tributaries of the Chattahoochee include the Soque River, Chestatee River, Big Hog Wallow Creek, Peachtree Creek, Sweetwater Creek, New River, Yellowjacket Creek, Flat Shoal Creek, Upatoi Creek, Uchee Creek, Cowikee Creek, Pataula Creek, Hannahatchee Creek, Hatachahubbee Creek, Abbie Creek, Barbour Creek, Cemuchechubee Creek, and Omusee Creek.

A profile of the Chattahoochee River from Leaf to Steam Mill (Fig. 8) was derived from data published by the U.S. Army Corps of Engineers (1985) and Hess and Stamey (1993). This profile shows three concave segments separated by two nickpoints. The southernmost nickpoint (02339500) is the Fall Line, and the northernmost nickpoint (02335500) lies along the stretch of river from Roswell to Vinings. The gradient of the Chattahoochee River is steepest (11 to 22 feet per mile) from Helen to Cornelia and decreases to 5 to 2 feet per mile from Cornelia to Roswell (Fig. 9). Gradients of 3 to 6 feet per mile are present from Roswell through the Atlanta area. Gradients decrease to 1 to 2 feet per mile from Atlanta to Franklin and are relatively constant from the Cornelia-Gainesville area to the West Point-Columbus area. A higher gradient of 9 feet per mile is developed at the Fall Line between the West Point (02339500) and Columbus (02341500) gage stations. The gradient of the Chattahoochee River is lower (0.7 to 1 foot per mile) from the Columbus gage to its mouth. The Chattahoochee River has incised either into its flood plain or into rock where the flood plain is nonexistent.

Land Surfaces

The Chattahoochee River Basin extends from the Blue Ridge physiographic province through the Piedmont and nearly across the Coastal Plain physiographic province (Fig. 10). The headwaters of the Chattahoochee River and several of its major tributaries, the Chestatee and Soque rivers, lie within the Blue Ridge province. Terrain is steep and rugged, and stream valleys are steep and narrow. Runoff is rapid because of the steep terrain and steep stream gradients. The steepest gradient of the Chattahoochee River is within the Blue Ridge province (Fig. 10). Altitudes range from 1,600 feet to nearly 4,400 feet (LaForge and others, 1925).

The major portion of the Chattahoochee River Basin lies within the Piedmont physiographic province. The Piedmont is characterized by broadly undulating topography. This surface is broken by low knobs or ridges and by valleys 100 to 330 feet deep (Thornbury, 1965). Much of the topography of the Piedmont has resulted from prolonged exposure to deep weathering, and Piedmont geomorphology may be locally controlled by lithology and structure. Structural and lithologic control of river and stream patterns is especially evident in the upper half of the Chattahoochee River Basin where trellis patterns are dominant. Dominantly dendritic patterns are prominent in the Piedmont near the Fall Line and in much of the Coastal Plain.

Within the Chattahoochee River Basin, the Coastal Plain is characterized by deeply dissected hilly terrain near the Fall Line in Muscogee, Chattahoochee and Marion Counties in Georgia. The terrain becomes more gentle in the southern end of the Chattahoochee River Basin.

Surficial Deposits

Saprolite

Saprolite is weathered bedrock formed by intense chemical weathering that has removed as much as 60 percent of the rock mass with essentially no loss in volume (Soller and Mills, 1991), original textures or structures. Average saprolite thickness in the Piedmont rarely exceeds 70 feet, but the thickness can vary widely within a short distance. Considerable volumes of ground water flow through the saprolite and recharge streams in the Piedmont. Saprolite may increase the storage and residence time of water in a drainage basin. Ground water in saprolite may transport large amounts of dissolved metals. Saprolite is easily eroded when covering vegetation and soil are removed, particularly during land clearing operations.

Transported Regolith

Colluvium deposits, perhaps of Pleistocene age, are best developed in the Inner Piedmont along valley sides and heads. Colluvium, which developed as a result of downslope mass transport of saprolite and overlying soils, generally consists of massive, poorly sorted, firm sandy clay or clayey sand (Soller and Mills, 1991).

High-level alluvial terrace deposits are scattered along the sides of the principal Piedmont drainages. These terraces may be pre-Quaternary in age. Terrace deposits that are found along the Coastal Plain drainages apparently were developed contemporaneously with the Quaternary barrier island complexes (Soller and Mills, 1991). Within the Coastal Plain, alluvial deposits *Qal* (Table 1 and the Geologic Map of Georgia, Georgia Geological Survey, 1976) associated with rivers draining the Piedmont are more voluminous and contain a less mature mineral suite than alluvial deposits associated with streams and rivers that drain the Coastal Plain (Soller and Mills, 1991). Heavy minerals in Chattahoochee River sediments, which are discussed later, are less mature, particularly in the upper parts of the basin. Some heavy minerals, particularly in the lower part of the basin, are more mature, and may be derived from older sediments that have undergone more weathering.

Soils

Prolonged, intense weathering in Georgia forms clayey to sandy soils. The contact with the underlying saprolite generally is gradational. Predominant soil types in the Piedmont and Blue Ridge provinces are sandy loam clay to fine sandy loam. When covering vegetation is removed, soils are easily eroded and no longer protect the underlying saprolite from erosion. Directly south of the Fall Line, soils are loamy sand, sandy loam and sand. Sandy loam and clay to sand soils cover the rest of the Coastal Plain sediments within the Chattahoochee River Basin (Kennedy, 1964). Erosion of these soils produces sediment carried by streams and rivers. Clay and silt-sized particles are generally carried as suspended load. Sand-sized particles generally move as bedload, except during periods of high stream bedload capacity.

Recent Stream Erosion and Sedimentation

Human-related, recent erosion and sedimentation are important factors that affect water quality within the Chattahoochee River Basin. Land-use, soil-type, topography and climate contribute to erosion and transport of sediment in the upper part of the Chattahoochee River Basin. Sheet erosion is considered to be the dominant type of erosion in the upper part of the Chattahoochee River Basin (Faye and others, 1980). In the Oconee River Basin, severe erosion of agricultural land that occurred prior to the 1940's caused rapid deposition of sediments in headwater streams (Cocker, 1996b). It is likely that similar conditions existed in other parts of the southeastern Piedmont and in the Coastal Plain.

In the Chattahoochee River Basin, spectacular erosion related to human cultivation is found in Providence Canyon State Park and the area around Lumpkin in Stewart County. The average rate of down cutting for the years 1820-1930 was calculated to be approximately 8 inches per year. Headward erosion was estimated to be about 6 feet per year from 1955-1968. Lateral erosion was 2 feet per year during that same period (Joyce, 1985). This recent erosion began because of land clearing and poor farming practices during the 1800's and early 1900's. Erosion accelerated when the gullies cut through overlying harder sediments of the Clayton Formation and penetrated softer sediments of the Providence Formation (Joyce, 1985).

Kennedy's (1964) data suggest that streams below dams carry less sediment because of deposition of that sediment in ponds or reservoirs behind the dams. More suspended sediment is carried in Piedmont streams than in Coastal Plain streams because of factors that may include: more land development in the Piedmont; higher energy streams in the Piedmont; and deposition of sediment behind dams in the Piedmont. Kennedy (1964) found that discharge does not appear to affect the amount of suspended sediment in Coastal Plain streams.

During a period from September 1975 to June 1977, Faye and others (1980) examined erosion, sediment discharge, and channel morphology within the Upper Chattahoochee River Basin from the headwaters to West Point Dam. Nine watersheds that were examined include the Chattahoochee River above Leaf, the Soque River above Clarkesville, the Chestatee River above Dahlonega, Big Creek above Alpharetta, North Fork Peachtree Creek, South Fork Peachtree Creek, Peachtree Creek, Nancy Creek, and Snake Creek. Average annual erosion yields from these watersheds ranged from 860 to 6,390 tons per year per square mile (Table 2).

Faye and others (1980) found that the suspended concentration of nutrients and trace metals increased with increasing concentration of suspended silt plus clay. Turbidity increased with higher suspended sediment concentrations. Suspended sediment yields were greatest in urban areas and least in forested watersheds (Table 3). Comparison of calculated concentrations of suspended sediment to total chemical concentrations will help assess the impact of both point and non-point sources.

GEOCHEMISTRY

Metals In Stream Sediments

Natural Sources

Metals in stream sediments may be derived from a variety of sources and along a variety of paths. Erosion and transportation of metal-rich soils, gossans or other metal-bearing weathering products associated with ore deposits may account for some metals in stream sediments. Weathering of rocks that are not associated with ore deposits may contain concentrations of metals in greater amounts than normal mean crustal abundances (Table 4). Other metals may be derived from mobilization of clastic sediments in hydromorphic anomalies associated with springs or seeps. Metals may also be directly deposited from solution onto the stream sediments.

Arsenic is found in a wide variety of minerals, including arsenates, arsenides, arsenites, sulfides, sulfosalts, oxides, and native arsenic. The most common sources of arsenic are the minerals arsenopyrite and arsenic-bearing pyrite. The greatest concentrations of these minerals is in or near sulfide deposits and in argillaceous rock units (i.e., shales and schists). Arsenic-bearing minerals are generally unstable in a humid weathering environment, although arsenic-bearing pyrite and arsenopyrite in shales and schists may persist in a strong weathering environment. Arsenic may be found in lesser concentrations in sandy soils and in higher concentrations in silty soils (O'Neill, 1995).

Mafic and ultramafic rocks contain the highest concentrations of chromium with up to 3,400 ppm in an average ultramafic rock (McGrath, 1995). The primary ore and source of most of the chromium is the mineral chromite. High amounts of chromium may also be found in mica (Cocker, 1992a, b and c), garnet, chlorite, and tourmaline. Chromite is relatively resistant to weathering and may persist in stream sediments. Chromium is found in smaller concentrations than the median amount in coarse loamy, sandy and peaty soils, and in greater concentrations in clay-rich soils (McGrath, 1995).

Principal sources of cobalt are the sulfosalt minerals, cobaltite and skutterudite, that are generally found in ultramafic and mafic igneous rocks. Less important hosts for cobalt are the minerals olivine, pyroxene, amphiboles and biotite that are most abundant in mafic and ultramafic igneous

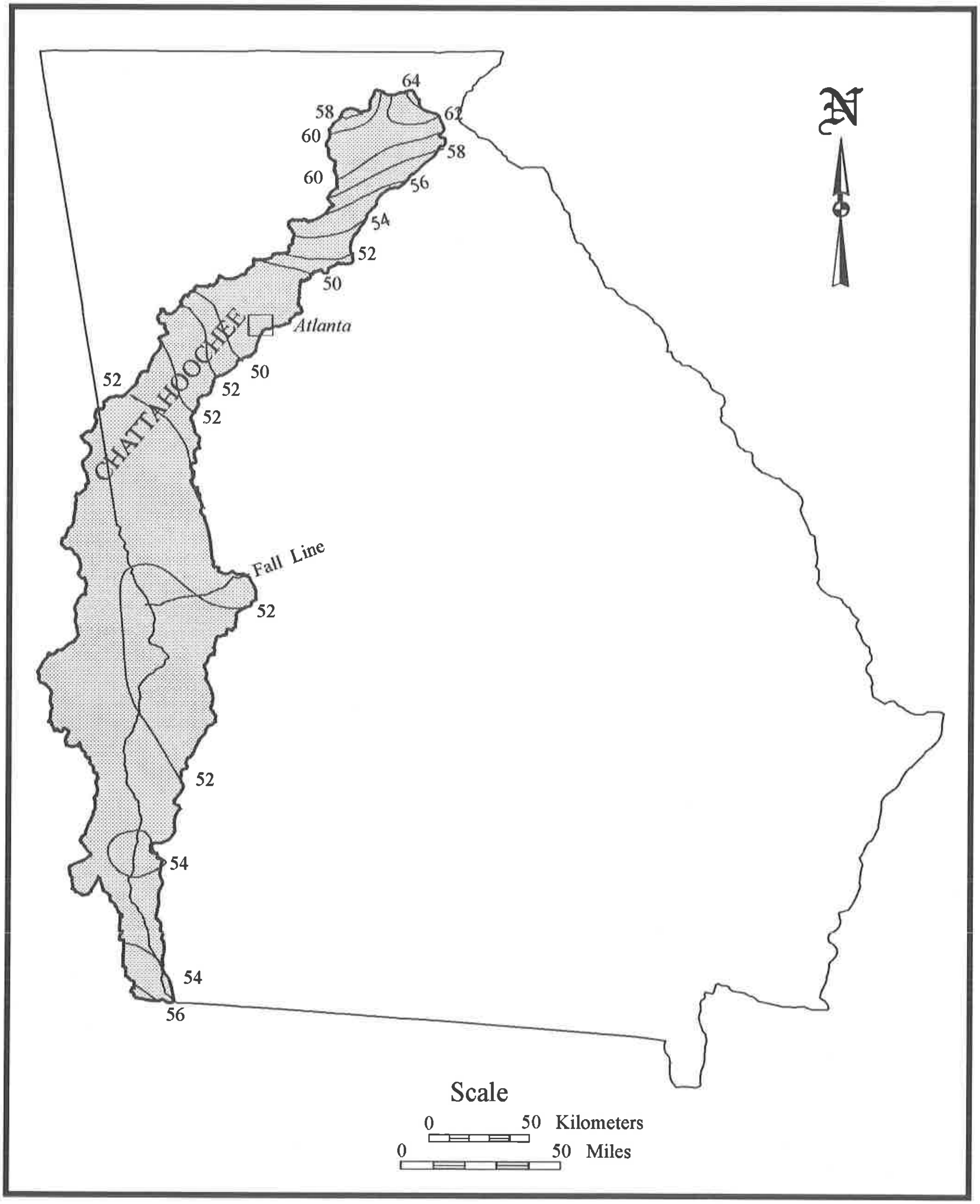

Figure 7. Average annual rainfall in the Chattahoochee River Basin. Lines are isopleths that indicate equal annual rainfall. Isopleths are in inches. (Modified from Carter and Stiles, 1983).

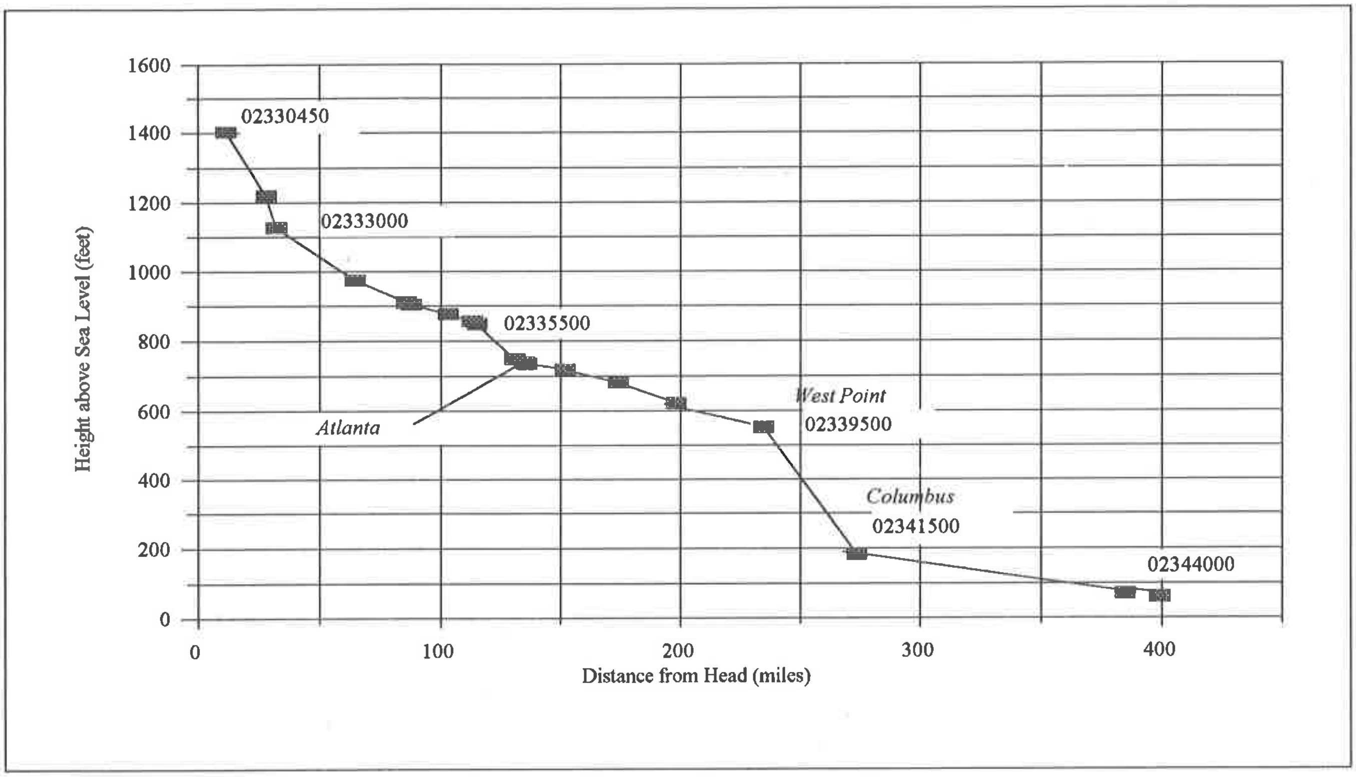

Figure 8. Profile of the Chattahoochee River.

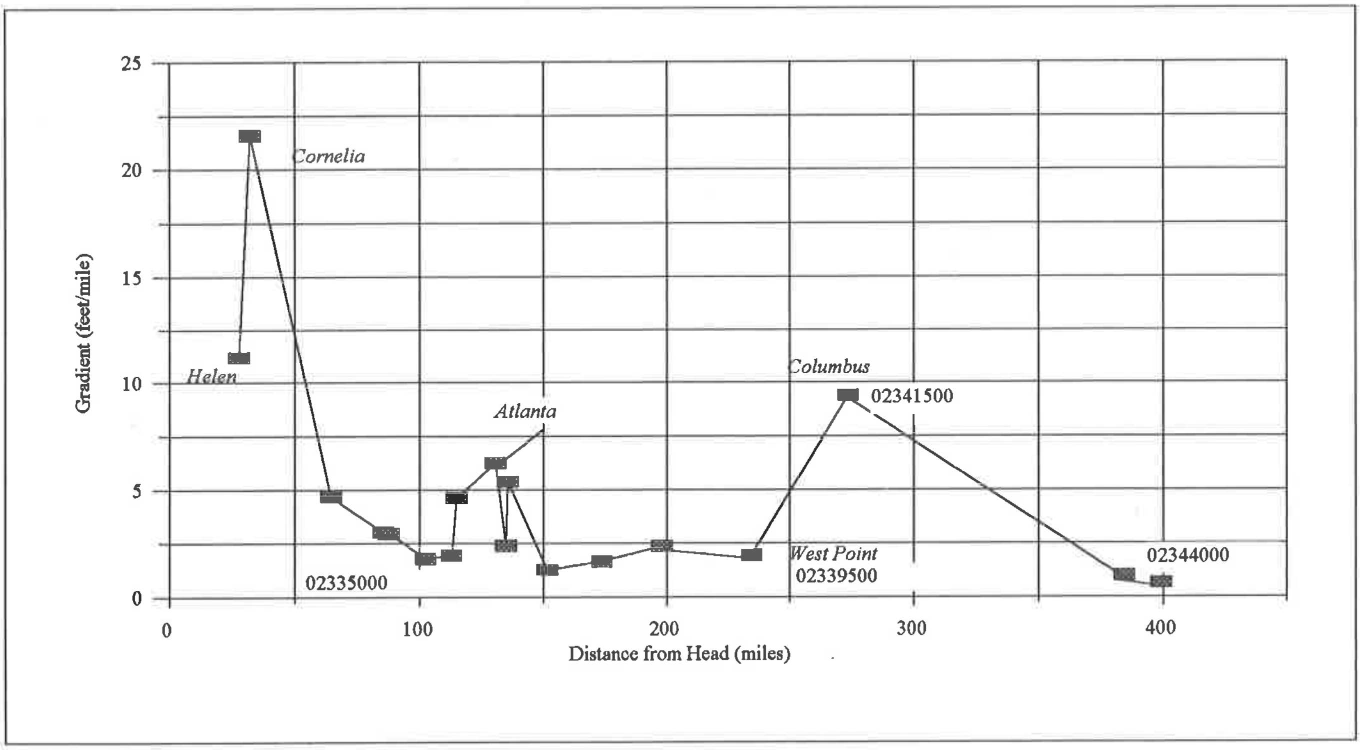

Figure 9. River gradient of the Chattahoochee River.

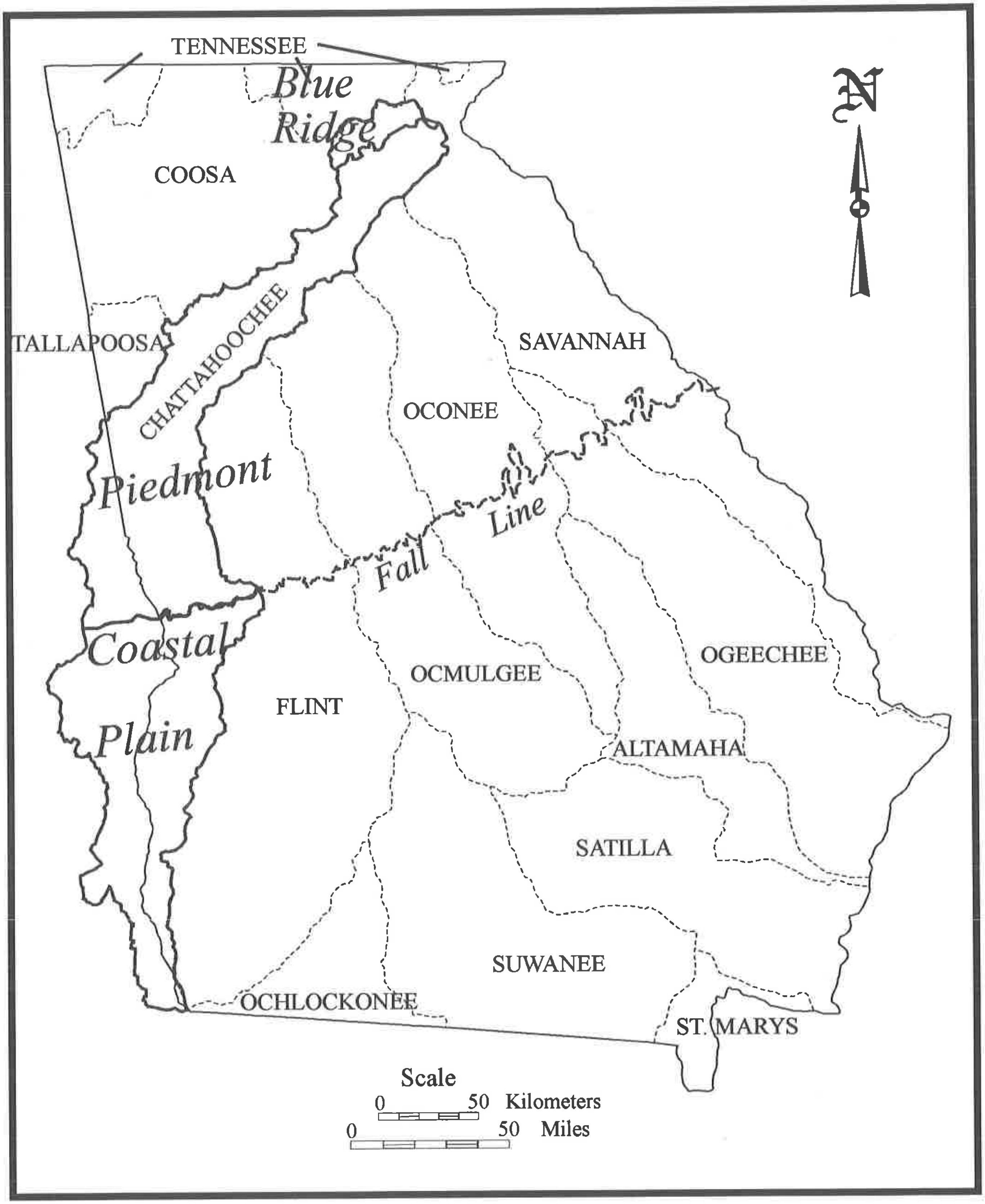

Figure 10. Physiographic provinces.

Table 2. Average annual sheet erosion, erosion yield, suspended-sediment discharge, suspended-sediment yield in the upper Chattahoochee River Basin (Data from Faye and others., 1980).

U.S. Geological survey station number[1]	Average annual sheet erosion (tons/year)	Erosion yield (tons/year/ mi^2)	Suspended sediment (tons/year)	Suspended discharge (tons/year/ mi^2)	Suspended silt plus sediment yield (tons/year)	Suspended silt plus clay discharge clay yield (tons/year/ mi^2)
02331000	305,000	2,030	43,000	287	18,800	125
02331250	613,000	6,390	43,200	450	17,900	186
02333500	482,000	3,150	52,300	342	24,700	161
02335700	199,000	2,760	24,000	333	17,800	247
02336120	41,800	1,230	15,100	443	8,820	259
02336250	25,600	860	25,400	858	12,200	412
02336300	80,500	930	65,500	755	32,500	374
02336380	30,500	880	19,800	569	16,000	460
02337500	70,300	1,900	13,300	359	10,000	270

[1]U.S.Geological Survey station number	Station name
02331000	Chattahoochee River near Leaf
02331250	Soque River near Clarkesville
02333500	Chestatee River near Dahlonega
02335700	Big Creek near Alpharetta
02336120	North Fork Peachtree Creek at Buford Highway near Atlanta
02336250	South Fork Peachtree Creek at Atlanta
02336300	Peachtree Creek at Atlanta
02336380	Nancy Creek at Randall Mill Road at Atlanta
02337500	Snake Creek near Whitesburg

Table 3. Annual yields of suspended chemical constituents from representative land-use watersheds. Values are in tons per year per square mile (Faye and others, 1980).

Land-use	P	N	C	Pb	Zn	Cu	Cr	As
Forest	0.15	0.36	7.4	0.033	0.048	0.034	0.027	0.0011
Rural	0.19	0.43	6.9	0.028		0.0028		
Urban	0.33	0.71	8.1	0.16	0.13	0.050	0.023	0.0038

rocks and biotite gneisses. Cobalt is commonly adsorbed on manganese oxides and may attain high concentrations in association with manganese-bearing rocks or sediments. The primary mineral hosts of cobalt are generally unstable in a humid weathering environment. In an acidic environment cobalt is easily dissolved and leached from the rock and soil. Formation of cobalt-bearing oxides, hydroxides and carbonates under alkaline conditions renders cobalt immobile under those conditions (Smith and Paterson, 1995).

Copper is most abundant as sulfides, but is locally abundant as sulfosalts, oxides, carbonates, native copper, and a silicate. Oxides, carbonates and the silicate chrysocolla are generally the weathering by-products of sulfides and sulfosalts. Chalcopyrite, the most abundant source of copper, may occur as a primary massive ore, disseminations in rock, or intimately intergrown with other ore-minerals. Trace amounts of copper may also be found in other silicates such as micas and amphiboles. Rocks with the highest average copper concentrations are generally mafic volcanic rocks and mafic intrusive rocks. Significantly higher than average concentrations of copper may also occur in shales and sandstones with many of the world's largest ore deposits in these rock types (e.g. Kupferschiefer in Germany and Poland; Zambian copper belt in Africa). The primary ores of copper are strongly susceptible to weathering in a humid environment. Fixation of copper in soils commonly reduces its mobility in the weathering environment. The abundance of copper in soils appears to be mainly a function of source materials rather than the type of soil (Baker and Senft, 1995).

Primary hosts for lead are generally sulfide and sulfosalt minerals, with lesser amounts of lead in carbonate and sulfate minerals. Lead may also substitute for large cations and be present in silicate minerals such as potassium feldspar and micas. Because of this tendency for substitution, lead is more abundant in felsic igneous rocks than in more mafic igneous rocks. Lead is also more concentrated in shales and sandstones, in part, because of substitution for potassium in clays and feldspars, and also because of abundant sulfides in shales. As with copper, many of the world's largest ore deposits of lead are in shales and sandstones or their metamorphic equivalents (e.g., Kupferschiefer in Germany; Zambian copper belt in Africa). Lead is apparently relatively immobile in a humid weathering environment; it is commonly fixed by organic material and adsorbed by silts and clays (Davies, 1995). The most important ores of manganese resulted either from in-situ weathering of manganese-rich rocks, or the dissolution of manganese and redeposition of manganese in sedimentary basins. Manganese oxides readily adsorb other trace metals that could be released to the environment by a change in oxidation or alkalinity. The availability of manganese to plants is an important problem especially in alkaline and oxidizing soils (Smith and Paterson, 1995).

Primary hosts of manganese are ferromagnesian silicates because of substitution of manganese for iron. Highest concentrations are thus in basic igneous rocks. Oxidation and alkalinity strongly affect the stability of manganese in the weathering environment. Manganese is soluble under acidic and generally reducing conditions (Garrels and Christ, 1965; Krauskopf, 1967). Manganese readily forms manganese oxides in a humid weathering.

Mafic and ultramafic rocks contain the highest concentrations of nickel with up to 3,600 ppm in an average ultramafic rock (McGrath, 1995). Nickel ores include primarily pentlandite and, to a lesser extent, garnierite. Pentlandite is a nickel -iron sulfide that usually is found as a magmatic segregation in ultramafic and mafic rocks, but may also occur in hydrothermal deposits in felsic environments. Nickel may also substitute for iron and magnesium in silicates such as pyroxenes, olivine, biotite and chlorite. Garnierite is a hydrous nickel-magnesium silicate formed by extreme weathering of nickel-bearing silicates in a humid climate. Garnierite has been reported in Troup County associated with ultramafic bodies (Cook, 1979) and probably should be found associated with other ultramafic rocks in the Blue Ridge and Piedmont provinces (Fig. A-10). High concentrations of nickel in soils overlying ultramafic rocks and perhaps the high magnesium:calcium ratio may account for poor plant growth on these rocks. Nickel is found in smaller concentrations than the median amount in coarse loamy, sandy and peaty soils, and in greater concentrations in clay-rich soils (McGrath, 1995).

Primary mineral hosts of zinc are sulfide and to a lesser extent oxide and phosphate minerals (Kiekens, 1995). Zinc is also found in trace amounts in silicate minerals such as micas and amphiboles. Zinc is generally more abundant in mafic rocks and shales. Many of the world's largest zinc deposits are in shales (e.g., Broken Hill, Australia). Large deposits of zinc are also of importance in carbonate rocks (e.g., Mississippi Valley-type deposits). Zinc is generally soluble under humid weathering conditions, but may be adsorbed on manganese or iron oxides and clays or organic matter. Concentrations of zinc in soils is mainly governed by the source rocks.

Mafic and ultramafic rocks generally contain disseminated metallic sulfides and oxides and may contain massive metallic sulfide and oxide deposits. Mineralization may contain copper, lead, zinc, nickel, iron, manganese, chromium, and cobalt, as well as sulfur, antimony, and arsenic. These rocks may be an important source of metals to local stream sediments, and they may also be natural sources of asbestos or asbestos-like materials. Chemical weathering may concentrate copper, chromium, nickel, titanium, lead, zinc, iron, magnesium and manganese in soils developed on these rocks. These metals generally occur in greater concentrations in silicate minerals in the ultramafic and mafic rock types than in more felsic rock types.

Table 4. Median concentrations of elements in average crustal rocks (values in ppm).

Element	Ultramafic Rocks	Mafic Rocks	Granitic Rocks	Limestones	Sandstones	Shales	Average Crustal
Al[3]	21,100	76,300	73,300	6,800	22,200	41,300	
As[1]	1.0	1.5	2.1	1.1	1.2	12	2
Ba[1]	0.4	330	840	92	170	550	580
Be[1,3]	0.x	0.x	3	0.x	0.x	3	2
Cr[1]	2,980	170	4.1	11	35	90	100
Co[1]	110	48	1	0.1	0.33	19	25
Cu[1]	42	72	12	5	10	42	50
Fe[1]	94,300	86,500	14,200	3,800	9,800	47,000	46,500
Pb[1]	1	4	18	5	10	25	10
Mg[3]	34,200	63,400	5,200	20,000	7,000	15,000	17,000
Mn[1,3]	1,040	1,500	390	1,100	170	850	1,000
Ni[1]	2,000	130	4.5	20	2	68	75
Na[1,3]	0.x	8,300	42,000	2,700	10,700	26,600	25,000
K[1]	34	8,300	42,000	2,700	10,700	26,600	25,000
Zn[1]	58	94	51	21	40	100	80
Ti[2,3]	3,000	9,000	2,300	400	0.x	4,600	4,400
V[1]	40	250	44	20	20	130	150
Sc[3]	5	35	2.8	1.5	1	14	

Sources:

1	(Rose and others, 1979)
2	(Levinson, 1974)
3	(Wedepohl, 1978)

Average crustal rocks are averages of granite and mafic rocks (Rose and others, 1979).
0.x represents a range of values from 0.1 to 0.9 ppm.

Geochemically, the Uchee belt (Fig. A-20) appears to be a narrow westward extension of the Carolina terrane through middle and western Georgia. Base- and precious-metal sulfide mineralization in the metavolcanic rocks of the Carolina slate belt within the Carolina terrane contains gold, copper, lead, zinc, iron, manganese, and barium. Other metals that are generally associated with the type of mineralization in the Carolina slate belt include: antimony, arsenic, bismuth, cadmium, chromium, mercury, molybdenum, silver, thallium, tellurium, and vanadium (Clark and others, 1993; Maddry and others, 1993; Tockman and Cherrywell, 1993). Base- or precious-metal mineralization has not been documented for the Uchee belt, and NURE geochemical data are limited for the Uchee belt in the Chattahoochee River Basin.

Other mafic igneous rocks that cut through or extend into the Chattahoochee River Basin include the Dadesville Complex, the New Georgia Group, and the Laura Lake Mafic Complex (Figs. A-3 and A-21). The New Georgia Group hosts a variety of volcanogenic mineral deposits that contain mineralization similar, in many respects, to that of the Carolina terrane. Mineralization in the Dadesville Complex is not as well known, but high background values of heavy metals may be expected to be associated with the mafic and ultramafic rocks in this complex. Mineralization in the Laura Lake Mafic Complex is also poorly known, but high background values of heavy metals may be expected to be associated with this rock unit.

During their formation, some sedimentary lithologies may become enriched in metals. Examples of metal enrichment found in the Chattahoochee River Basin include heavy minerals. Heavy minerals that may contain thorium, uranium, cerium, dysprosium, europium, hafnium, lanthanum, lutetium, samarium, titanium, ytterbium, and zirconium are concentrated in apparent metasedimentary units in the Blue Ridge and Inner Piedmont. Remobilization and redeposition of rare-earth element bearing heavy minerals resulted in their concentration in Cretaceous, Paleocene and Eocene sandy sediments south of the Fall Line (Fig. 4). Potential remobilization of heavy minerals may be occurring in present-day river systems as suggested by heavy mineral data discussed later. Although undocumented, other heavy minerals such as barite (a primary source of barium) could also be concentrated in heavy mineral deposits and result in anomalous barium in those sediments. Weathering of calcareous and kaolin-bearing strata in the Coastal Plain has concentrated iron and aluminum to form limonite and bauxite deposits (Fig. 6). Trace-metal content of these deposits is unknown, but iron-rich sediments are likely to absorb or adsorb trace-metals from solution.

Modes of Occurrence

Naturally derived metals may occur in stream sediments in the following forms (Rose and others, 1979):

1) Primary ore minerals that are generally resistant to weathering and are dense enough to occur within the heavy mineral fraction of the stream sediment.
2) Eroded secondary minerals such as oxides and carbonates of heavy metals. Most of these are friable and become dispersed as suspended load.
3) Precipitated minerals such as iron and manganese oxides, carbonates and silica that contain heavy metals incorporated into their structures.
4) Heavy metals that may be adsorbed onto iron and manganese oxides, clay minerals, or organic matter.
5) Organic matter that incorporated the metals during growth.

Anthropogenic Sources

Human activity within the Chattahoochee River Basin has introduced metals into the waters and stream sediments of the Chattahoochee River Basin. Generally, the major sources of metals introduced into the environment by man include metalliferous mining and smelting, agriculture, sewage sludge, fossil fuel combustion, metallurgical industries, electronics, chemical and other manufacturing industries, waste disposal, sports shooting and fishing, warfare and military training (Alloway, 1995). Most of these activities occur within the Chattahoochee River Basin.

The principal metalliferous mining activity in the Chattahoochee River Basin was gold mining. Gold mining has the potential to introduce metals such as tellurium, silver, arsenic, antimony mercury, and selenium (Alloway, 1995). Mercury is of particular concern within the Chattahoochee River Basin, because mercury was used in the amalgamation of gold.

Agricultural activity provides several pathways for metals to enter the environment. These pathways include impurities in fertilizers, sewage sludge, manures from intensive animal production, pesticides, refuse derived composts, desiccants, wood preservatives, and corrosion of metal objects (Alloway, 1995). Not all of these potential pathways are important in the Chattahoochee River Basin. Metals potentially introduced through agricultural activities include arsenic, cadmium, chromium, lead, manganese, mercury, molybdenum, nickel, uranium, vanadium, and zinc (Alloway, 1995). Within the Chattahoochee River Basin, during the first part of the twentieth century, arsenic was used extensively as a pesticide against the boll weevil.

Fossil fuel combustion has the potential to introduce such metals as lead, cadmium, chromium, zinc, arsenic, antimony, selenium, barium, copper, manganese, uranium, and vanadium into the environment (Alloway, 1995). Within the Chattahoochee River Basin, a significant concern is the potential widespread introduction of lead into the environment through the previous use of gasoline containing lead additives.

Household, municipal and industrial waste may introduce several metals into the environment including cadmium, copper, lead, tin, and zinc (Alloway, 1995). Within the Chattahoochee River Basin, improper disposal of batteries may introduce lead and other metals into the environment.

Geochemical Databases for Georgia

Geochemical databases that exist for the Chattahoochee River Basin are quite varied in their scope, quality, size, and type of sample. Stream sediments, stream water, spring water, ground water, soils, saprolite and rocks within the Chattahoochee River Basin have been analyzed within the last 40 years. Various types of state and federal geochemical surveys are best in overall quality, inclusiveness and size. Other studies, including those associated with student theses and contract studies performed by universities or "independent" individuals, are generally focused on "academic" or economic geology problems. These studies are generally limited in scope and of variable quality. The data cannot be directly compared with each other because of differing types of samples, sampling techniques, samplers, analytical techniques and analysts.

A number of these other geochemical and mineralogical data bases were examined during the course of this investigation. Although these studies are more limited in number of sample sites, size of areas sampled, and number of elements analyzed, they do provide some additional information that may be lacking in the NURE data bases. Some of the data may be used to confirm some of the relations observed in the NURE data. Within the Chattahoochee River Basin other chemical data include:

* 1,667 rock, soil and saprolite samples collected within and adjacent to the Dahlonega and Carroll County gold belts by the U.S. Geological Survey (Lesure, 1992a and b; Lesure and others, 1991 and 1992) with 396 sample points located within the Chattahoochee River Basin. Results are reported for silver, gold, arsenic, boron, barium, beryllium, calcium, cerium, cobalt, chromium, copper, iron, lanthanum, lead, magnesium, manganese, mercury, molybdenum, nickel, niobium, rubidium, scandium, strontium, tin, titanium, vanadium, tungsten, yttrium, zinc and zircon.

* 303 rock chip samples collected from the Dahlonega district with summary results reported for silver, arsenic, antimony, copper, lead and zinc (Cook and Burnell, 1985).

* 18 rock chip samples collected from the Hall County gold belt with results reported for silver, gold, arsenic, antimony, copper, lead and zinc (Allen, 1986).

* 33 surficial materials collected by the U.S. Geological Survey between 1961 and 1975 (Boerngen and Shacklette, 1981) with samples located within the Chattahoochee River Basin. Data include analyses for 46 elements. Analytical techniques are semiquantitative for some elements and quantitative for other elements in that survey.

* 43 rock samples collected by the U.S. Geological Survey and analyzed for whole rock and trace elements (Higgins and others, 1992).

* 1,968 stream sediment samples collected from nine counties that cover part of the Chattahoochee and Flint River Basins. Counties include Carroll, Heard, Coweta, Troup, Meriwether, Pike, Harris, Talbot, and Upson. Samples were analyzed for copper, lead and zinc by atomic-absorption spectroscopy at Rocky Mountain Geochemical Corporation, Salt Lake City, Utah. Results are plotted on county-scale maps, and distribution of anomalies are discussed (Hurst and Long, 1971).

* 24 stream sediment samples collected and analyzed for heavy minerals along the length of the Chattahoochee River (Cazeau, 1955).

* 10 rock samples collected from the Dahlonega district and analyzed for chromium, nickel and vanadium (German, 1985).

* 17 soil samples, with 10 collected by the Environmental Protection Division and the remainder in a study of old gold mines (J.German, 1995, personal communication).

* Water samples from 15 water quality monitoring stations along the length of the Chattahoochee River during 1957 and 1958 by the U.S. Geological Survey (Cherry, 1961). Two nearly complete surveys were conducted during several closely spaced days in April and May of 1958. Data include discharge, silica, iron, calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chlorine, fluorine, nitrate, dissolved solids, hardness, specific conductivity, pH and water color. Samples were also collected from tributaries of the Chattahoochee River.

* Water samples from 14 water quality monitoring stations of which 10 have some chemical data, and one has heavy metal analysis (Arnsdorff and others, 1991);

* Water samples collected from 9 water quality monitoring stations collected in the upper half of the Chattahoochee River Basin over a one-year period from Sept. 1975 to September 1976 by the U.S. Geological Survey. Data collected were for phosphorous, nitrogen, organic carbon, arsenic, chromium, copper, lead, and zinc (Faye and others, 1980).

By far the most inclusive, largest, and best in quality of the geochemical databases for Georgia are those generated by the U.S. Department of Energy's National Uranium Resource Evaluation (NURE) Program. Stream sediments, water wells, and streams were sampled for an area that includes approximately the northern two-thirds of the Chattahoochee River Basin. An important aspect of the NURE databases is that the samples were collected within a short period (1976 to 1978), and thus provides a critical baseline for comparative studies during subsequent times. In addition, samples were analyzed by the same laboratory, and by the same analytical procedures.

NURE Databases for Georgia

The NURE Program was established to evaluate domestic uranium resources in the continental United States and to identify areas favorable for uranium exploration. A nearly complete set of NURE geochemical data for the conterminous United States is presently available on CD-ROM from the U.S. Geological Survey (Hoffman and Buttleman, 1994). Files on that CD-ROM contain technical information concerning types of data collected in the field and obtained by laboratory analysis.

The program for 30 eastern states that included Georgia was directed by the U.S. Department of Energy's Savannah

River Laboratory (SRL). The SRL contracted sample collection and trained the samplers in sample collection and field analytical procedures. The SRL had the responsibility for the actual laboratory chemical analyses. Information regarding sample collection, preparation and analysis is briefly summarized in the following sections.

The NURE program consisted of five parts:

1)Hydrogeochemical and stream sediment reconnaissance survey,
2) Aerial radiometric survey,
3) Surface geologic investigations,
4) Drilling for geologic information,
5) Geophysical technology.

NURE data are organized by individual 1° x 2° National Topographic Map Series (NTMS) quadrangles. The Chattahoochee River Basin includes parts of the Greenville, Athens, Rome, Phenix City, and Dothan NTMS quadrangles.

Sample Collection and Field Measurements

Stream sediment and ground water samples were collected within Georgia during the period 1976 to 1978. Most samples were collected during July, August, and September of 1976. The next highest number of samples was collected during April 1978. The fewest number of samples was collected during April 1977.

A minimum of five sediment sub-samples was composited from each stream site. Approximately 400 grams of sediment passing a 420 micrometer (U.S. Std. 40-mesh) screen were collected. A sample of approximately (one liter) of filtered water was usually collected at each ground-water site. Dissolved ions in individual water samples were concentrated on ion exchange resin for analysis (Ferguson, 1978).

Sample locations were marked on compilation maps, which were returned to SRL for calculation of geographic coordinates. An electronic digitizer was used to measure, verify, and enter latitude and longitude data for each site into the SRL-NURE data base. These data were recorded to four decimal places, but are considered reliable to only three decimal places. Two to five percent of the sampled sites were routinely checked by SRL personnel or by a subcontractor to assure that reported field locations were accurate. More than 98 percent of the sampled sites were judged to be located as accurately as they could be plotted on county road maps. Most sites that were mapped incorrectly were within 1000 feet of their correct locations (Ferguson, 1978).

Location data in the computerized NURE databases were used to generate point coverages of stream sediment sample sites and ground water sample sites for each NTMS quadrangle. Correlation of the locations of most stream sediment sample locations with streams in the hydrography database shows that locations have been reasonably calculated. Samples that do not correspond with a stream segment on the hydrography database may be on a stream segment that is not included on that database.

Nominal stream sediment sampling density in rural areas was one site per 5 square miles, for a total of 1,413 sites per NTMS quadrangle. Sample sites cover most of the Chattahoochee River Basin from the northern headwaters to Stewart County, Georgia in the southern part of the basin. The area sampled, including both Georgia and Alabama, included approximately 74 percent of the Chattahoochee River Basin representing a total area of 8,707 square miles. Of 1,133 NURE stream sediment sample sites within the Chattahoochee River Basin, 1,008 are located in Georgia, and the remaining 125 are in Alabama. With a sample area of 7,605 square miles, this number of samples represents a ratio of one stream sediment sample site per 6.7 square miles. Distribution of stream sediment and stream samples (Fig. 11) should provide representative geochemical and hydrogeochemical images of the sampled portion of the Chattahoochee River Basin.

Analytical Methods

All analyses in the NURE study were done by automated neutron activation techniques (NAA). Sediment samples were dried at 105° C, sieved to less than 149 micrometers, blended, coned, and quartered. Half gram aliquots of the less than 149 micrometer material were packed in ultrapure polyethylene capsules for NAA analysis. The encapsulated samples were loaded into the NAA pneumatic system in batches of 25 that included one standard and one blank (Ferguson, 1978).

Each ground-water sample was treated with a 10-gram) portion of ultrapure mixed cation-anion exchange resin that collected all dissolved ions from the water. The quantity of water ranged from 50 to 1000 milliliters) depending upon sample conductivity. Resin samples were dried at 105°C and packed in ultrapure polyethylene capsules for analysis. Encapsulated samples, including one blank, were loaded in batches of 25 into the NAA pneumatic system. Standards were included in every fifth batch (Ferguson, 1978).

Analytical values were calculated using measured neutron fluxes, irradiation times, decay times, counting times, published values for activation cross-section, decay constants and spectra for each element. Spectral lines that were least likely to interfere with each other were used to determine elemental concentrations. Internal calibration was based on strong gamma-ray peaks for key elements that were present in all the stream sediments. Standard reference materials and blanks were included in the analyses for periodic checks on the analyses. Standards included blanks, a Savannah River Laboratory sediment standard, Department of Energy intersite

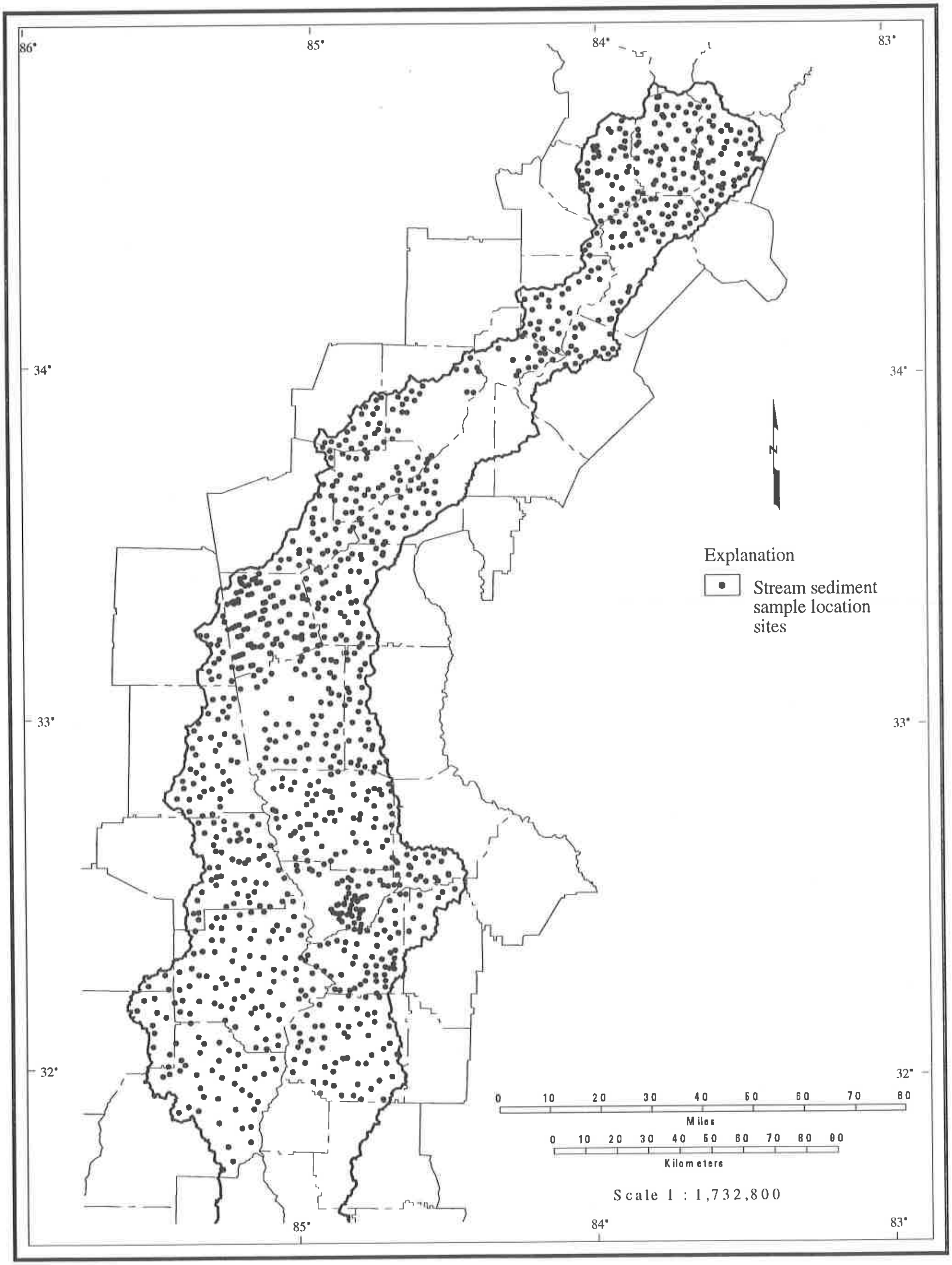

Figure 11. Stream sediment sample locations

comparison materials, and external reference materials such as U.S. Geological Survey and Spectroscopy Society of Canada standard rocks, and National Bureau of Standards (Ferguson, 1978).

Uranium was determined by counting neutrons emitted by induced fission products of ^{235}U in the sample. Other elements were determined by computer reduction of gamma-ray spectra collected at intervals from a few seconds to about 10 days after irradiation (Ferguson, 1978).

Initial analyses of stream sediment samples included a suite of elements (Table 5) for all the sample sites for which there was a sample. Conductivity, pH, alkalinity and temperature were measured from water samples collected at each site. Analyses of samples from many sample sites were conducted for a second suite of elements. For the Chattahoochee River Basin, this resulted in a "complete" set of stream sediment data for the Greenville and quadrangles and "incomplete" data sets for the Phenix City and Dothan quadrangles (Table 5). Stream and ground-water hydrogeochemistry is "complete" for all four quadrangles. The term complete is relative, because some sample sites have no analyses or measurements, and a few elements are not included in any of the NURE data sets for Georgia.

Some element concentrations in the NURE data sets (Hoffman and Buttleman, 1994) are reported as below a particular detection limit. The detection limit is defined as the concentration at which precision becomes +/- 100% (Fletcher, 1986). Analytical precision is defined as the percent relative variation at the 95% confidence level. Thus, "below detection limit" concentrations may range from zero to some level above that detection limit. In the case that an element has a detection limit of 5 ppm, its actual concentration may lie between 0 and 10 ppm. Detection limits may depend on factors such as analytical procedure, type of material, grain size of material, randomness of distribution of a particular element (nugget effect), and amount of sample analyzed. Documented sampling procedures of the NURE stream sediments (Ferguson, 1978; Hoffman and Buttleman, 1994) suggest that an attempt was made to minimize the effects of most of these factors and insure the best possible detection limits.

In order to incorporate the below detection limit data in statistical analyses, map-plots and other graphic displays in this investigation, the mid-point concentration between zero and the detection limit was used in the treatment of the NURE data. The mid-point concentration between zero and the detection limit was used, because it avoided the biases in data analysis that would result from using zero, the detection limit, or ignoring all "below detection limit"concentrations. This procedure is commonly used by exploration geochemists and the U.S. Geological Survey (A. Grosz and J. McNeal, 1997, personal communications).

In the present study, the GIS was used to identify each sample point that was geographically within each rock unit in Table 1. The number and percentage of sample sites within each rock unit are included in Table 6. Because a GIS coverage of Alabama's geology is not currently available, these calculations pertain only to those sample sites within Georgia. Summary statistics were calculated for each element for the entire Chattahoochee River Basin (Table 7). Summary statistics were also calculated for each element per rock unit (Table 8). Samples which were not analyzed for a particular element (e.g. Cu) were not included in the statistics for that element.

Identification of Data Gaps

Analysis of the background geochemistry of the Chattahoochee River Basin is incomplete because of significant gaps in sample coverage. Data gaps in the NURE stream sediment data base include: lack of analyses for some primary pollutant metals in all samples; lack of a complete suite of metal analyses for certain quadrangles; lack of background geochemical analyses for rocks within the basin; no distinction between total metal versus extractable metals in the analyses; no data on sediment grain-size distributions; and no data on size-fraction chemical analysis.

Analyses for several primary pollutant metals are lacking for all the NURE stream sediment samples. Databases for the Greenville, Atlanta, Rome, Dothan and Phoenix City 1° x 2° quadrangles do not include antimony, thallium, and mercury. Databases of the NURE stream sediment samples for the Dothan and Phoenix City 1° x 2° quadrangles do not include silver, beryllium, cobalt, chromium, copper, lithium, molybdenum, nickel, phosphorous, lead, and zinc. Because these elements are only included in the Greenville and parts of the Atlanta, Rome, Dothan and Phoenix City databases, a complete basin analysis is not possible for these metals.

Metal content of most rocks within the Chattahoochee River Basin is undocumented. High metal concentrations in some stream sediment analyses suggest that unknown sources for these metals exist within the Chattahoochee River Basin. The sources of these metals should be identified.

Stream sediments were only analyzed for total metal content. No distinction between immobile elements versus mobile and semi-mobile elements was made during analysis by the SRL or other laboratories. Cold extraction analytical techniques used with total metal analyses may indicate the potential mobility of the metals.

The NURE databases do not contain information regarding grain-size distributions, nor do they contain size-fraction chemical analyses. Differences in these factors between samples may strongly influence chemical analysis (Horowitz, 1991). This information was beyond the scope of the NURE program, but should be a consideration for further

Table 5. Elements analyzed in NURE stream sediment samples.

	Analyzed in all	Not Analyzed in				
Element	Databases	Dothan	Phenix City	Rome	Atlanta	Greenville
Ag		Ag		Ag		
Al	Al					
As		As	As*	As	As*	As
Ba		Ba	Ba*	Ba		
Be		Be	Be*	Be		
Ce	Ce					
Co		Co	Co*	Co	Co*	
Cr		Cr	Cr*	Cr	Cr*	
Cu		Cu	Cu*	Cu		
Dy	Dy					
Eu	Eu					
Fe	Fe					
Hf	Hf					
K		K	K*	K	K*	
La	La					
Li		Li	Li*	Li		
Lu	Lu					
Mg		Mg	Mg*	Mg		
Mn	Mn					
Mo		Mo	Mo*	Mo		
Na	Na					
Nb		Nb	Nb*	Nb		
Ni		Ni	Ni*	Ni		
P		P	P*	P		
Pb		Pb	Pb*	Pb		
Sc	Sc					
Sn		Sn	Sn*	Sn		
Sr		Sr	Sr	Sr	Sr	
Th	Th					
Ti	Ti					
U	U					
V	V					
W		W	W*			
Y		Y	Y*	Y		
Yb	Yb					
Zn		Zn	Zn*	Zn		

* Indicates that some analyses are available; commonly samples analyzed were from certain counties and not from others.

Table 6. Number and percentage of stream sediment sample sites per rock unit.

Map Symbol	Map Unit	Sample Sites	Percentage
Kt	Cretaceous - Tuscaloosa Formation	41	4.62
Kr	Cretaceous - Ripley Formation	11	1.24
Kb	Cretaceous - Blufftown Formation	36	4.06
Kc	Cretaceous - Cusseta Sand	23	2.59
Ke	Cretaceous - Eutaw Formation	20	2.25
Kp	Cretaceous - Providence Sand	19	2.14
Ptu	Paleocene - Tuscahoma Sand	8	0.90
Pcn	Paleocene - Nanafalia, Porters Creek and Clayton Formations - undifferentiated	0	0
Pc	Paleocene - Clayton Formation	0	0
Pnf	Paleocene - Nanafalia Formation	0	0
Ec	Eocene - Claiborne Formation	1	0.11
Eli	Eocene - Lisbon Formation	0	0
Eo	Eocene - Ocala Limestone	0	0
Eta	Eocene - Tallahatta Formation	0	0
Eo-Os	Eocene and Oligocene residuum - undifferentiated	1	0.11
Qal	Quaternary - stream alluvium and stream terrace deposits	1	0.11
bg1	biotite gneiss	104	11.72
bg2	biotite gneiss/ amphibolite	4	0.45
c1	mylonite and ultramylonite	11	1.24
c2	flinty crush rock	0	0
fg1	biotite gneiss/ feldspathic biotite gneiss	1	0.11
fg2	biotite gneiss - undifferentiated	1	0.11
fg3	biotitic gneiss/ mica schist/ amphibolite	148	16.69
fg4	biotitic gneiss/ amphibolite	6	0.68
gg1	granite gneiss - undifferentiated	32	3.61
gg2	granite gneiss/ gneissic granite (augen or porphyritic)	17	1.92
gg3	muscovite granite gneiss	1	0.11
gg4	granite gneiss/ amphibolite	0	0
gg5	calc-silicate granite gneiss	6	0.68
gg6	granite gneiss/ granite	9	1.01
gr1	granite undifferentiated	17	1.92
gr1b	porphyritic granite	8	0.90
gr4	charnockite	0	0
m2	amphibolitic schist/ amphibolite	0	0
ms1	amphibolitic schist	0	0
ms3	amphibolite schist/ amphibolite - metagraywacke/ mica schist	2	0.23
mm1	amphibolite	17	1.92
mm2	hornblende gneiss	5	0.56

Table 6. (Continued)

Map Symbol	Map Unit	Sample Sites	Percentage
mm2	hornblende gneiss	5	0.56
mm3	hornblende gneiss/ amphibolite	51	5.75
mm4	hornblende gneiss/ amphibolite/ granite gneiss	13	1.47
mm9	amphibolite/ mica schist/ biotitic gneiss	8	0.90
pa1	aluminous schist	14	1.58
pa2	sillimanite schist	7	0.79
pg1	garnet mica schist	3	0.34
pg2	garnet mica schist/ gneiss	10	1.13
pg3	garnet mica schist/ amphibolite	0	0
pm2	metagraywacke/ mica schist	41	4.62
pm3a	metagraywacke/ mica schist-quartzite/ amphibolite	10	1.13
pms1	mica schist	8	0.90
pms2	mica schist/ amphibolite	2	0.23
pms3	mica schist/ gneiss	49	5.52
pms3a	mica schist/ gneiss/ amphibolite	74	8.34
pms4	mica schist/ quartzite/ gneiss/ amphibolite	12	1.35
pms5	graphite schist	10	1.13
pms6a	sericite gneiss/ amphibolite	4	0.45
pms7	button mica schist	0	0
q1	quartzite	8	0.90
q1a	quartzite/ mica schist	1	0.11
q1b	quartzite/ mica schist/ amphibolite	0	0
q1c	quartzite/metagraywacke	0	0
um	ultramafic rocks - undifferentiated	1	0.11
Water		12	1.35

stream sediment geochemical programs.

Stream Hydrogeochemistry

Field analyses of stream water in the NURE database provide measurements of pH, conductivity, alkalinity and water temperature. A knowledge of the basic parameters of stream hydrogeochemistry is important to understanding the results and effectiveness of a water sampling program.

Within the Chattahoochee River Basin, regional trends in relief, stream pH, stream sediment iron and manganese, as well as organic-rich environments are important factors that will affect water chemistry. Along with its generally humid climate, regions in the Chattahoochee River Basin with moderate to strong relief and low pH will provide the most favorable conditions for water sampling (Rose and others, 1979). Streams in regions with alkaline, calcareous, ferruginous, and organic-rich environments reduce the effectiveness of water sampling (Rose and others, 1979).

Acidity (pH)

NURE hydrogeochemical data provide detailed information of stream pH in the upper 75 percent of the Chattahoochee River Basin. Although the average pH (6.9) of the 1,133 stream samples in the Chattahoochee River Basin is essentially neutral (Table 7), pH varies considerably within different areas of the Piedmont and within the Coastal Plain (Fig. 12). These differences can generally be directly attributed to the principal type of host rock in which the stream pH was measured. The Chattahoochee River Basin cuts across five zones in which the pH changes from acidic to alkaline. Two of these zones that are located within the Piedmont are similar to those described in the Oconee River

Table 7. Summary statistics of Chattahoochee River Basin geochemistry (1,133 samples). Temperature is in °C; alkalinity is in meq/L; conductivity is in micromhos/cm; metals are in ppm.

	Average	Mean	Standard Deviation	Maximum	Minimum
Water Temperature	22	22	3	34	17
pH	6.9	6.8	0.4	8.4	4.4
Alkalinity	0.28	0.28	0.20	2.80	0.02
Conductivity	46	45	29	360	1
Ag	0.2	0.14	0.14	1.10	0.05
Al	32,289	30,636	19,572	138,000	2,400
As	2	0	2	13	1
Ba	24.7	13.3	22.7	98.0	2.5
Be	1.0	0.7	0.5	3.0	0.3
Co	5.7	3.2	3.6	23.0	2.5
Cr	4.3	2.3	3.2	37.0	3.0
Cu	6.6	4.5	5.5	46.0	1.0
Fe	34,482	33,082	27,605	229,000	2,300
K	10,871	6,102	9,880	46,000	1,000
Li	9.3	6.4	5.2	25.0	2.5
Mg	2,241	1,258	1,407	10,300	200
Mn	773	702	1,059	12,100	20
Mo	1.6	1.1	0.9	5.0	1.0
Na	3,088	2,703	3,831	30,900	100
Ni	6.5	4.4	5.5	55.0	2.5
Pb	7	5	5	58	1
Sc	7.6	7.3	5.5	44.9	0.5
Ti	9,550	7,830	8,247	43,900	200
V	72	67	62	480	10
Zn	21.5	15.0	16.9	140.0	3.0

River Basin (Cocker, 1996b) and may be related directly to differences in tectonostratigraphic/lithologic terranes. The other three zones may be related to stratigraphically younger sediments in the Coastal Plain.

Streams within the northern part of the Coastal Plain in Talbot, Marion, Chattahoochee and Muscogee Counties, Georgia (Fig. 12) have the lowest pH (4.4 to 6.8) in the basin. This area is underlain by sands, clays and gravels of Cretaceous to Eocene age rocks. Coastal Plain rock units in the GIS geology database (Table 1) include those with the lowest mean pH (Table 8). Rock units (Table 1) which contain streams with the lowest mean pH (Table 8) include: *Kt* - Tuscaloosa Formation (5.6), *Ke* - Eutaw Formation (5.6), *Kb* - Blufftown Formation (6.3), *Ptu* - Tuscahoma Sand (6.3), *Qal* - Quaternary Alluvium (6.4), *Kr* - Ripley Formation (6.5), and *Kc* - Cusseta Sand (6.5). Similar low pH values (6.0 to 6.8) were also described for Coastal Plain sediments in the Oconee River Basin (Cocker, 1996b).

South of the more acidic streams is a zone (Fig. 12) of more alkaline streams. Stream pH measurements range from 7.0 to 7.9 in a band approximately 16 miles wide which arcs across Stewart County, Georgia. Carbonate rocks may buffer the stream water in this area. In the southern part of Stewart County, the streams again become more acidic (down to a pH of 5.8).

A narrow zone of neutral to alkaline streams (pH of 7.0 to 7.7), found in Talbot, Muscogee, and Harris Counties, Georgia (Fig. 12), is underlain by metavolcanic and metavolcaniclastic rocks of the Uchee terrane (Fig. A-20). Neutral to alkaline water may result from weathering of carbonate minerals in the metamorphic rocks and by hydrolysis of iron-magnesium silicate minerals.

The northern portion of the Chattahoochee River Basin, north of mid-Harris County, Georgia (Fig. 12), is characterized by small clusters of slightly alkaline (pH of 7.1 to 8.0) streams within a broader area of slightly acidic (pH of 6.1 to 7.0) streams. These small groups of slightly alkaline streams may be the result of geochemically ill-defined rock units or terranes that extend northeasterly through the Piedmont and Blue Ridge of Georgia. These rocks may include lenses or stratigraphically narrow amphibolites or marbles.

Rock units that contain streams with the highest mean pH include: *gg3* - muscovite granite gneiss (7.4), *pm3a* - metagraywacke (7.4), and *pms6a* - sericite schist (7.2). These rock units contain muscovite granite gneiss, metagraywacke, mica schist, quartzite and amphibolite (Table 1).

Several water samples, collected near anthropogenic activities that might influence the NURE analyses, had low pH values (4.6 to 5.5). Because these sample sites are located within the Tuscaloosa Formation (*Kt*) with characteristically low pH (5.6), low pH values may be natural instead of anthropogenic.

Specific Conductivity

Conductivity is a measure of the ability of water to conduct an electrical current and is measured in micromhos/cm. Water will conduct more electricity if it contains more ions to carry an electrical charge. Concentration of dissolved ions in water controls the conductivity of water. Dissolved ion concentrations may be estimated by multiplying conductivity by a factor of 0.55 to 0.75 (Driscoll, 1986). Water with a high specific conductivity will have a high electrochemical activity. High electrochemical activity facilitates the dissolution of iron-bearing materials such as naturally occurring silicates, oxides, sulfides, and man-made metallic objects.

Average conductivity in the Chattahoochee River Basin is within a range of 1 to 360 micromhos/cm. Different portions of the Piedmont and the Coastal Plain of the Chattahoochee River Basin may be distinguished by conductivities that are either above or below 46 micromhos/cm (Fig. 13). Regional trends that were noted further to the east in the Oconee River Basin (Cocker, 1996b) are present within the Chattahoochee River Basin but are generally not as well defined. The Chattahoochee River Basin cuts across several regions that differ in conductivity and may be related directly to different tectonostratigraphic/lithologic terranes in the Blue Ridge and Piedmont and to sedimentary units in the Coastal Plain. These regions are generally similar in extent to the regions of different pH.

Within the upper part of the Chattahoochee River Basin and north of the Brevard Fault Zone (Fig. 13), conductivities are between 20 and 50 micromhos/cm. A few scattered streams within this region have higher conductivities of 100 to 300 micromhos/cm. South of the Brevard Fault Zone, higher conductivities were measured in streams within the *pms3a* unit in Troup, Coweta and Fulton counties. In addition, scattered high measurements of up to 485 micromhos/cm were recorded for streams within this unit. Streams located south of the Towaliga Fault Zone within the Pine Mountain terrane have low conductivities, generally in the 30 to 45 micromhos/cm range (Fig. 13). In the Uchee terrane, conductivities range from 50 to 135 micromhos/cm.

South of the Fall Line, conductivities drop to 1 to 45 micromhos/cm in Muscogee, Marion, Webster, Chattahoochee and Stewart Counties, Georgia (Fig. 13). Irregular areas in Chattahoochee and Stewart Counties with conductivities of 50 to 110 micromhos/cm may divide the northern and southern portions of the Coastal Plain within the Chattahoochee River Basin.

The region of high conductivity streams (greater than 50 micromhos/cm) in the Uchee terrane (Fig. 13) appears to be similar to that previously documented for the Carolina terrane in eastern and central Georgia (Cocker, 1996b). Rocks

Table 8. Average geochemical concentrations per rock unit. (Concentrations in ppm. Values less than detection limit are explained on page 26).

Rock	Temp	pH	Alkal	Conduct	Ag	Al	As	Ba	Be	Co	Cr	Cu	Fe	K	Mg	Mn	Na	Ni	Pb	Sc	Ti	V	Zn
Eo-Os	30	7.1	0.12	10.0		48,100							26,800			390	100			8.2	6,900	80	
Kb	26.4	6.3	0.28	35.4		9,739							10,806		127	264				2.4	5,891	28.8	
Kc	27.3	6.5	0.37	47.5		9,656							9,491			154	204			2.5	5,083	22.6	
Ke	24.6	5.6	0.09	18.2		10,944							9,150			138	282			3.1	8,372	40.6	
Kp	27.9	6.7	0.30	27.5		19,594							38,510			385	1,256			6.2	9,721	63.7	
Kr	28.6	6.5	0.18	18.9		18,690							31,900			348				4.5	6,136	62.7	
Kt	21.6	5.6	0.10	21.4		16,250							12,162			334				4.7	11,125	53.8	
Qal	22.4	6.4	0.31	41.1		9,538							7,681			200				3.4	7,288	30.0	
Ptu	26.0	6.3	0.04	10.0		8,500							12,400			160				4.1	9,500	30.0	
Water	22.3	7.0	0.22	55.6	0.28	51,058		18.0	1.07	5.8	11.3	11.1	42,964	10,546	2,832	888	12,767	7.6	8.9	8.6	13,067	130.0	
bg1	21.4	7.0	0.26	40.6	0.32	44,745		26.8	0.96	7.6	3.2	12.2	12,400	15,690	1,842	693	6,949	9.4	10.4	8.7	8,833	71.4	
bg2	24.5	6.8	0.46	67.8		39,150							40,900			1,490	8,000			10.0	7,600	102.5	
c1	21.6	6.8	0.32	53.0		29,888							29,082			766	4,389			5.7	8,012	70.0	
fg3	21.7	6.9	0.22	44.4	0.26	41,396	2.0	41.1	0.87	5.2	6.8	8.8	39,594	10,129	2,135	942	6,005	7.2	7.8	10.4	13,424	120.1	
fg4	21.0	7.0	0.55	98.0	0.18	49,633		29.8	0.80	7.3	4.0	8.2	41,867	5,000	1,040	1,338	1,217	5.6	9.6	11.7	8,783	90.0	
gg1	22.0	6.9	0.19	38.6	0.23	38,357	2.0	24.2	0.77	4.9	5.8	6.9	27,088	12,196	1,887	605	5,000	5.5	8.3	7.4	7,850	68.2	18.0
gg2	21.8	6.9	0.21	40.0	0.20	36,893		21.0	0.73	4.6	5.0	5.8	29,751	8,903	1,917	619	5,185	5.0	7.4	7.4	8,903	66.2	15.6
gg3	24.0	7.4	0.54	85.0	0.10	33,100			1.50	5.0	3.0	6.0	16,300	20,000	600	460	2,200	10.0	5.0	6.6	4,700	50.0	20.0
gg5	21.7	7.1	0.35	51.5	0.13	40,283		26.2	0.63	5.0	3.0	4.7	27,233	8,500	1,200	1,460	3,300	4.0	6.7	14.6	3,950	53.3	16.2
gg6	20.9	7.1	0.3	45.3	0.17	41,112		53.0	1.10	6.2	3.0	5.7	26,300	13,333	2,467	887	3,012	8.7	5.0	12.4	6,650	64.3	16.0
gr1	21.8	6.6	0.22	41.8	0.42	41,753	1.0	51.2	1.44	5.8	5.8	9.4	25,694	17,167	1,056	874	3,353	9.1	11.4	6.8	8,894	48.8	33.0
gr1b	23.1	7.1	0.38	55.4	0.25	42,225		66.5	0.64	5.1	3.9	5.9	26,462	25,000	2,238	887	3,275	9.1	6.9	5.9	7,783	40.0	29.5
mm1	21.2	7.0	0.25	42.6	0.14	29,741		31.1	0.78	4.7	3.4	6.1	23,553	6,273	2,077	598	5,176	5.7	7.1	8.4	6,875	74.1	28.5
mm2	22.2	7.1	0.19	34.8	0.10	18,940		4.0	1.00	3.8	4.0	5.0	24,680	5,500	2,200	310	2,960	5.5	5.0	6.6	5,280	40.0	13.0
mm3	20.3	7.0	0.31	54.8	0.24	38,871	1.0	27.7	0.80	6.6	4.9	6.9	48,056	8,305	2,316	1,453	3,704	5.3	5.8	10.3	16,578	139.2	21.0
mm4	23.0	7.0	0.52	76.0		53,467							18,933			550	9,333			8.9	2,750	60.0	
mm9	20.0	6.8	0.33	53.1	0.25	33,771		26.4	1.19	7.8	5.0	3.6	39,800	2,250	4,862	828	3,162	5.4	13.6	9.2	15,550	121.4	16.3
ms3	20.0	6.7	0.15	29.5	0.25	28,400			0.38	2.5	5.3	6.5	25,500	4,500	1,675	430	8,150	2.5	5.0	10.2	8,250	60.0	15.0
pa1	21.4	6.9	0.17	37.8	0.29	37,936		33.7	0.56	4.6	4.5	5.5	26,450	11,182	2,018	538	2,914	6.7	5.5	7.9	7,950	60.0	25.5
pa2	22.3	6.9	0.33	57.9	0.13	46,057		20.0	1.25	11.5	3.5	13.3	41,443	14,667	2,117	1,201	2,400	5.3	10.5	7.5	12,686	108.6	40.7
pg1	21.7	7.1	0.19	35.0	0.47	42,100	2.0	32.3	0.83	13.0	10.0	18.0	48,700	8,000	4,300	517	1,600	16.7	16.0	6.7	22,600	123.3	66.7
pg2	20.9	7.0	0.23	35.5	0.16	29,433	1.5	18.3	1.10	4.7	3.5	8.6	26,190	7,000	2,283	356	1,111	7.5	9.1	4.7	7,943	29.5	
pm2	20.1	6.6	0.17	38.5	0.26	37,188		28.3	0.80	4.5	5.8	7.0	32,946	9,895	1,985	822	7,278	4.9	7.2	7.2	14,156	22.4	
pm3a	19.5	7.4	0.13	24.6	0.41	54,764			0.71	6.9	4.8	16.3	51,546	6,500	2,217	1,004	16,100	7.8	11.5	13.8	16,636	140.0	40.0
pms1	23.5	6.8	0.31	42.6	0.27	41,550		35.5	0.77	6.8	3.0	8.9	29,314	18,857	2,871	1,009	5,138	7.4	5.0	6.4	13,088	82.5	24.7
pms2	21.5	6.8	0.20	37.8	0.18	29,699	2.1	24.2	0.95	4.9	4.2	6.3	39,515	9,593	1,865	733	2,174	5.9	6.7	6.1	12,084	70.1	21.2
pms3	21.7	6.7	0.13	30.9	0.17	25,060	2.5	14.7	1.02	4.1	4.9	5.8	55,463	9,429	2,014	485	2,310	5.9	6.2	4.9	12,780	82.6	20.3
pms3a	21.6	6.9	0.27	44.2	0.18	34,256		41.0	0.88	6.6	4.2	6.7	29,500	11,000	1,952	1,070	1,490	5.6	7.1	6.2	10,837	66.3	22.3
pms4	22.8	7.0	0.13	27.3	0.14	25,175		10.6	1.07	3.2	3.7	6.6	39,318	6,857	2,029	328	1,600	8.6	5.7	8.3	9,792	52.5	20.6
pms5	21.3	6.7	0.10	25.9	0.19	23,189		12.5	1.13	4.5	4.9	5.4	49,920	7,750	1,475	380	2,320	6.6	6.0	5.0	17,900	74.4	16.9
pms6a	20.8	7.2	0.41	76.0	0.18	33,800		24.0	0.83	3.1	3.0	6.0	16,950	14,000	1,575	563	1,550	6.3	5.0	8.5	7,067	50.0	20.0
q1	21.3	7.0	0.21	36.0	0.26	32,822	1.5	48.0	1.00	3.8	4.8	9.2	40,989	12,000	1,775	903	3,844	4.1	10.8	8.0	19,400	67.8	32.6
um	18.0	6.6	0.12	21.0	0.25	52,300			0.50	11.0	2.5	7.0	19,800	14,500	2,000	470	9,800	7.0	17	3.9	5,100	60.0	26.0

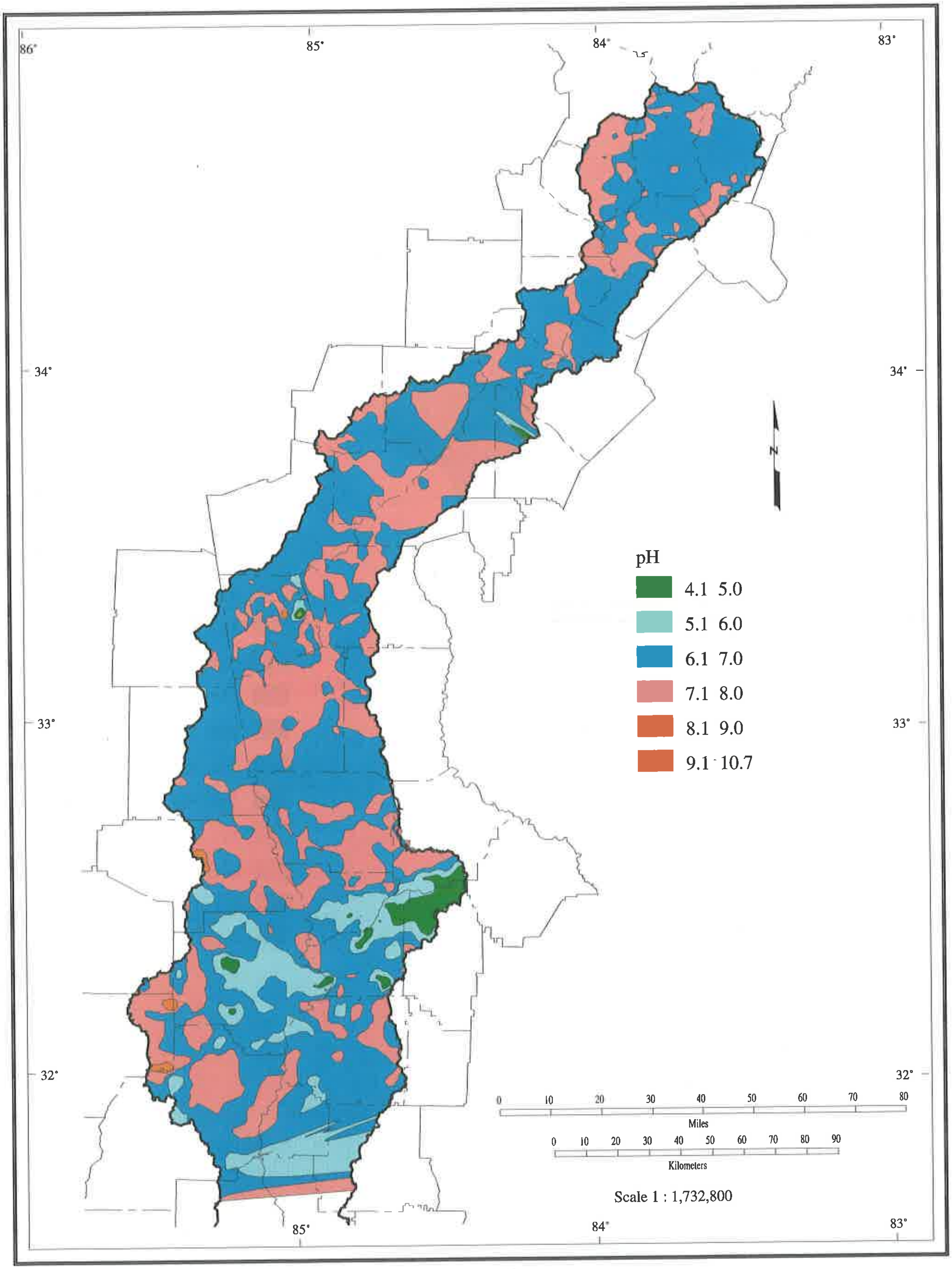

Figure 12. pH of stream water. Absence of data south of Stewart County and in parts of Cobb, Fulton and DeKalb Counties may cause contouring artifacts.

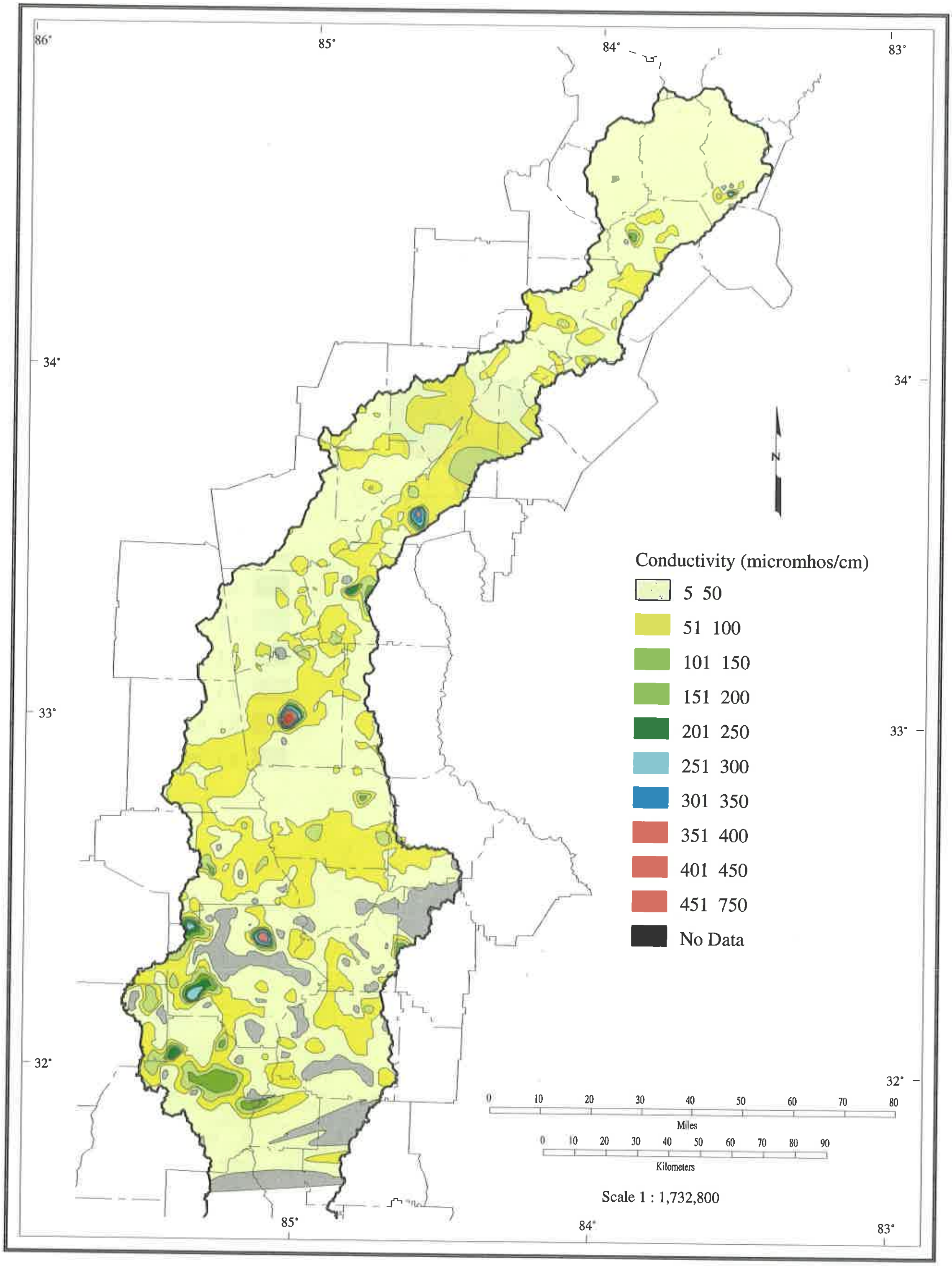

Figure 13. Conductivity of stream water. Absence of data south of Stewart County and in parts of Cobb, Fulton and DeKalb Counties may cause contouring artifacts.

within the Uchee terrane are not as well documented but may be geochemically similar to those of the Carolina terrane. Rocks within the Carolina terrane are generally less resistant to weathering because of their lower metamorphic grade and volcanic-derived composition than higher-grade, metasedimentary rocks within the Inner Piedmont. Streams within the Carolina and Uchee terranes will thus contain higher concentrations of dissolved material, and stream conductivities will be higher. This region of higher conductivity streams corresponds to a region containing stream sediments with high iron and sodium content. Elements such as sodium, calcium, magnesium and potassium often contribute to conductivity as discussed below. Stream conductivity correlates well with alkalinity as shown in Fig. 14.

Rock units (Table 1) which contain streams with the lowest mean conductivities (Table 8) include: *Eo-Os* - undifferentiated Eocene and Oligocene residuum (10 micromhos/cm), *Ptu* - Tuscahoma Sand (10 micromhos/cm), *Ke* - Eutaw Formation (18 micromhos/cm), *Kr* - Ripley Formation (19 micromhos/cm), *um* - ultramafic rocks (21 micromhos/cm), and *Kt* - Tuscaloosa Formation (21 micromhos/cm). The rock unit with the lowest conductivity is a Coastal Plain sandy sediment. Other rock units are high metamorphic grade sillimanite schists that may be relatively stable under chemical weathering conditions. Rock units that contain streams with the highest mean conductivity include: *fg4* - biotitic gneiss (98 micromhos/cm), *gg3* - muscovite granite gneiss (95 micromhos/cm), *pms6a* - sericite schist (76 micromhos/cm), and *mm4* - hornblende gneiss (76 micromhos/cm).

Conductivities of streams in the NURE study that were near anthropogenic activities do not appear to be affected by those activities. This is consistent with more recent, but spatially limited, data collected along the Chattahoochee River (Stokes and McFarlane, 1996; Stokes and McFarlane, 1997).

Alkalinity

Alkalinity is a measure of the acid neutralizing capacity of water; units are in terms of milliequivalents of acid per liter (meq/L). Average alkalinity in the Chattahoochee River Basin is 0.28 meq/L with a range of 0.02 to 2.80 meq/L. Alkalinities in the Chattahoochee River Basin show a strong positive correlation with conductivity and may be governed by the same factors that affect conductivity. Alkalinity of streams within the Chattahoochee River Basin may be divided into six principal zones: low alkalinity northwest of the Brevard Fault Zone, higher alkalinity southeast of the Brevard Fault Zone to the Pine Mountain terrane, low alkalinity in the Pine Mountain terrane, higher alkalinity in the Uchee terrane, low alkalinity in older sediments of the Coastal Plain, and higher alkalinity in younger sediments of the Coastal Plain (Fig. 15).

Alkalinity in the Brevard Fault Zone is generally less than 0.3 meq/L (Fig. 15). Very low alkalinities (less than 0.1 meq/L) are found in streams in the Blue Ridge physiographic province in the extreme northern part of the Chattahoochee River Basin (Fig. 15). Southeast of the Brevard Fault Zone, alkalinities are generally 0.3 to 0.5 meq/L (Fig. 15). Several streams had values of 1 to 1.3 meq/L in this zone. Streams within the Pine Mountain terrane, and over some granitic rocks north of the Towaliga Fault Zone in southeastern Troup County, are generally in the 0.1 to 0.2 meq/L range (Fig. 15). Streams in the Uchee terrane generally have higher alkalinities, in the 0.2 to 0.7 meq/L range, with a few streams up to 0.98 meq/L. Streams immediately south of the Fall Line have very low alkalinities, generally 0.02 to 0.14 meq/L (Fig. 15). In the southern part of Chattahoochee and Marion Counties through Stewart County, Georgia, alkalinities are quite variable - ranging from 0.08 to 0.9 meq/L. In adjacent parts of Alabama, alkalinities may be as high as 2.8 meq/L (Fig. 15).

Rock units (Table 1) which contain streams with the lowest mean alkalinity (Table 8) include: *Ptu* - Tuscahoma Sand (0.04 meq/L), *Ke* - Eutaw Formation (0.09 meq/L), *pms5* - graphite schist (0.10 meq/L), *Kt* - Tuscaloosa Formation (0.10 meq/L), *um* - ultramafic rocks (0.12 meq/L), *Eo-Os* - undifferentiated Eocene and Oligocene residuum (0.13 meq/L), *pm3a* - mica schist (0.13 meq/L). Except for *pms5* - graphite schist, these rock units are the same as those with the lowest conductivities. Several of these rock units (*Kt, Ke, Ptu*) are Coastal Plain sandy sediments. Rock units that contain streams with the highest mean alkalinity include: *fg4* - biotitic gneiss (0.55 meq/L), *gg3* - muscovite granite gneiss (0.54 meq/L), and *mm4* - hornblende gneiss (0.52 meq/L).

Water Temperature

Recorded temperatures of stream water during sample collection range from 17 to 34° C with an average temperature of 22°C. Water temperature did not display any correlation with alkalinity, conductivity or pH. It is not expected that water temperature affected those parameters. Water temperatures were generally higher, in the 26 to 35 °C range, in Coastal Plain streams.

Discussion of Stream and River Hydrogeochemistry

The Chattahoochee River Basin can be divided into several regions that differ in pH, conductivity and alkalinity. These regions are generally correlative with regional geologic and related geochemical trends. Regions of higher conductivity and higher alkalinity display a much closer relationship to regional geologic and geochemical trends than does pH.

Acidity of ground water and surface water, as measured by its pH, is strongly influenced by several factors including: composition of rocks and sediments with which the water is in contact, permeability of the rock or sediments, amount of organic activity, flow rate of ground water or surface water, temperature, and amount of precipitation. Weathering of sulfides causes a decrease in pH. Carbonates and silicates buffer the naturally weak acidity of rain water. Certain types of contamination may also influence pH.

Rocks and sediment compositions influence water pH during chemical weathering. Major factors that facilitate chemical weathering include: solution, hydration, oxidation, and hydrolysis. As in the Oconee River Basin (Cocker, 1996b) solution and hydrolysis of carbonates and hydrolysis of silicates may be the principal factors controlling pH of surface waters in the Chattahoochee River Basin. Reaction of carbonic acid (H_2CO_3) with carbonates produces bicarbonate (HCO_3^-). Hydrolysis of carbonates and silicates involves a reaction with water to form HCO_3^- or H_4SiO_4, which are weaker acids than water. Hydrolysis of silicates may involve carbonic acid in addition to water. Solution or hydrolysis of carbonates and hydrolysis of silicates produces a solution that is more basic than it was before these reactions. Continued reaction of the solution with silicates or carbonates eventually results in an alkaline solution.

Carbonate-bearing rocks such as limestones significantly reduce the acidity of water. Carbonates generally react with acidic solutions at a faster rate than silicates. Carbonate minerals may be abundant in silicate rocks because of low-grade metamorphism or hydrothermal alteration. Hydrolysis of mafic silicates such as olivine, amphiboles, pyroxenes, epidote, calcium-bearing feldspars, and biotite occurs at a faster rate than hydrolysis of felsic silicates such as quartz and sodium- or potassium-bearing feldspars. Water in contact with mafic silicates will become alkaline at a faster rate than water in contact with felsic silicates. Thus, silicate rocks that may be expected to increase the alkaline nature of water at the greatest rate include: amphibolites, metavolcanics, ultramafic rocks, gabbroic rocks, hornblende and biotite gneisses.

In an analogous study, LeGrand (1958) described two characteristic types of ground water in North Carolina that are derived from crystalline bedrock. One type is a soft, slightly acidic water that is low in dissolved mineral constituents. This soft ground water occurs with, and is derived from, granitic rock types. Median pH of this type of water is 6.5, and hardness, as $CaCO_3$, is 25 (LeGrand, 1958). Silica content in the granitic waters is as much as 30 to 50 percent of the total dissolved solids because of the lower amount of other dissolved constituents. Ground water from granitic rocks contains 5 ppm calcium, 35 ppm bicarbonate, 75 ppm dissolved solids and is classified as siliceous. Based on major element composition, granitic rocks include granite, granite gneiss, mica schist, slate and rhyolite volcanic and volcaniclastic rocks. The second type of ground water is a hard, slightly alkaline water that is relatively high in dissolved material. This hard ground water occurs in, and is derived from, dioritic type rocks. Median pH of this water is 7.1, and hardness, as $CaCO_3$, is 172. Ground water from dioritic rocks contains 49 ppm calcium, 137 ppm bicarbonate, and 269 ppm dissolved solids (LeGrand, 1958). Dioritic waters are classified as bicarbonate. Dioritic rocks generally resemble diorite in composition and include diorite, gabbro, hornblende gneiss and andesitic volcanic and volcaniclastic rocks. Because of their high levels of dissolved solids, ground water derived from dioritic rocks are expected to have high conductivities (LeGrand, 1958).

Within the Chattahoochee River Basin, carbonate-rich rocks occur in the southern part of the Coastal Plain and as small units within the Blue Ridge, Inner Piedmont and Pine Mountain terranes. Carbonate-rich rocks are located principally in the Paleocene and Eocene strata. Carbonate minerals may be present as bands or layers, or as disseminated secondary carbonate minerals in metavolcanic rocks, metavolcaniclastic rocks, ultramafic and mafic rocks (Cocker, 1996b). Within the Chattahoochee River Basin, carbonate-poor silicate rocks are prevalent in the Inner Piedmont, Blue Ridge, Pine Mountain and Uchee terranes and over much of the upper Coastal Plain.

Because of relatively slow reaction rates, water will become more alkaline or acidic the longer water is in contact with the rocks. Relatively impermeable rocks such as massive granites or gneisses or well cemented sedimentary or metasedimentary rocks will be the least likely to alter pH. Highly permeable rocks, such as poorly cemented quartzose sands in the Coastal Plain, allow a relatively rapid flow of water. Therefore, such rocks have little affect on pH. Rocks that are moderately permeable may retain water and are more likely to affect pH.

Slow-flowing streams that may be high in organic matter do not appear to have affected the acidity of streams in the Chattahoochee River Basin. Decaying organic matter tends to increase the acidity of the water. Carbonate and bicarbonate ions in ground water generally originate in soils from respiring organisms and decaying vegetation and from the dissolution of carbonate rocks (Driscoll, 1986). Higher organic activity will increase the amount of carbon available to form carbonic acid and increase the acidity of water. Rapidly decaying vegetation will also increase the acidity of water. Temperature affects pH by controlling the amount of CO_2 dissolved in water. At low temperatures, relatively large amounts of CO_2 are dissolved in water generating more carbonic acid and decreasing pH. Relatively small differences in water temperature that were recorded during sampling probably have not greatly affected pH in this Chattahoochee River Basin study. Low correlation coefficients suggest that temperature did not greatly affect pH

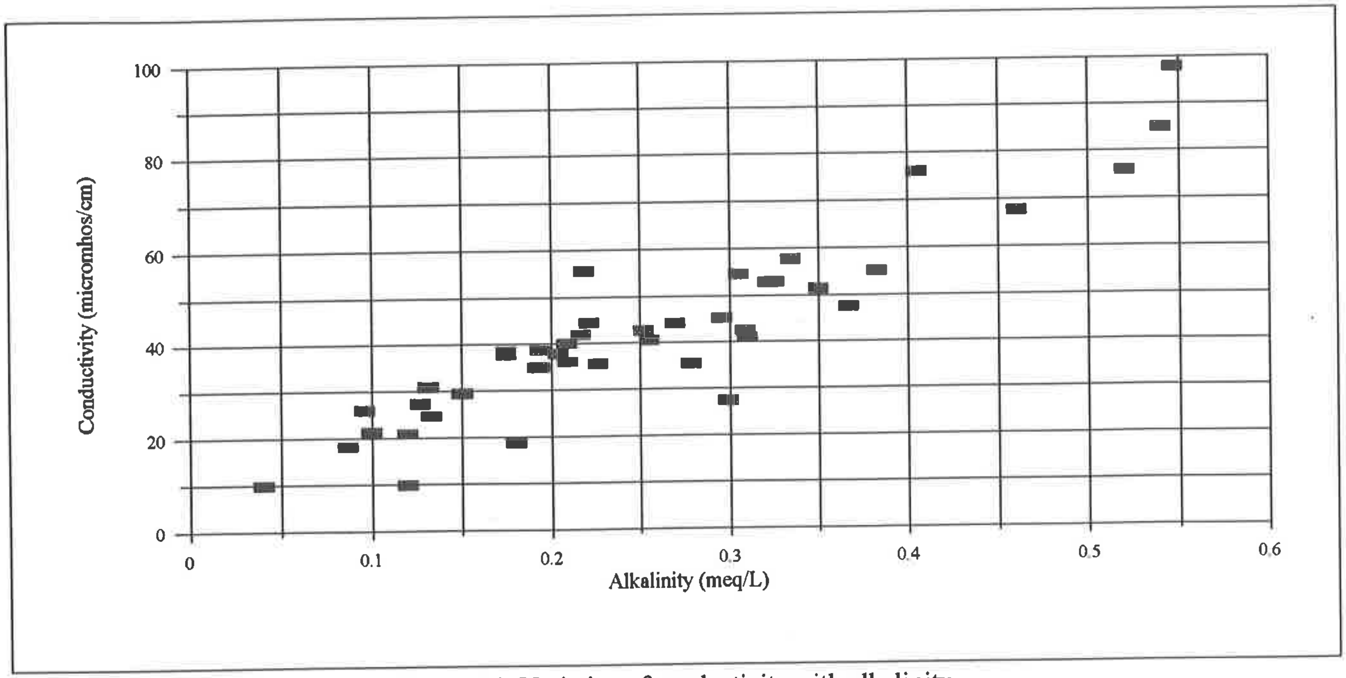

Figure 14. Variation of conductivity with alkalinity.

in the Chattahoochee River Basin. Acidity of water may increase near springs due to a higher content of CO_2 in ground water. In these instances, relatively lower temperature of ground water will tend to increase the amount of dissolved CO_2.

Precipitation's effect on pH depends on the rate of water flow. In areas with a high flow rate, an increase in precipitation will tend to shift the pH of the surface water toward the pH of the rainwater. In areas of low flow rates and high organic matter content, an increase in precipitation may raise pH. The effect of precipitation on pH in Chattahoochee River Basin streams could not be assessed with the available data.

Chemical weathering of various minerals will contribute dissolved solids to stream water and influence conductivity. Water from mafic rocks have a high content of dissolved solids due to greater solubility of iron-bearing mafic minerals (Price and Ragland, 1972). Water from quartzose and granitic rocks is lower in dissolved solids because of the lower susceptibility of felsic minerals to weathering.

Streams with high pH, conductivity and alkalinity (Figs. 12, 13 and 15) are primarily located in the Uchee terrane (Fig. A-20), between the Goat Rock Fault and the Fall Line. Such streams generally correlate with metavolcanic and metavolcaniclastic rocks. Streams within the predominantly metasedimentary rocks of the Inner Piedmont terrane have lower pH, conductivity and alkalinity. Streams within the Inner Piedmont (Fig. A-20) that have higher pH, conductivity and alkalinity may have some local lithologic (metavolcanic?) control. Correlation with particular rock units is more difficult because of ambiguities in the Geologic Map of Georgia (Georgia Geological Survey, 1976).

Higher stream pH in Stewart County may reflect the presence of carbonates. However, most of the carbonate-bearing rocks in the Coastal Plain are located to the south of the NURE stream sample coverage. Therefore, the major effects of carbonates on stream pH, conductivity and alkalinity are not shown in Figures 12, 13,and 15.

Stream Sediment Geochemistry

The following discussion focuses on heavy metals included in the NURE databases, several metals in which Georgia's Environmental Protection Division is interested (for example, aluminum), and several other metals (for example, iron, manganese) which are not defined as heavy metals. These other metals were included, because they may influence the distribution of heavy metals in sediments and water.

Aluminum (Al)

As in the Oconee River Basin (Cocker, 1996b), stream sediments in the Coastal Plain of the Chattahoochee River Basin are distinctly different in aluminum content from sediments in the Piedmont (Fig. 16). The concentration of aluminum in most Coastal Plain stream sediments is less than 20,000 ppm. In the Piedmont, aluminum is generally greater than 20,000 ppm. The Fall Line is marked by a sharp drop in aluminum from greater than 30,000 ppm to less than 20,000 ppm. This corresponds to the average concentration of aluminum in the Chattahoochee River Basin sediments of

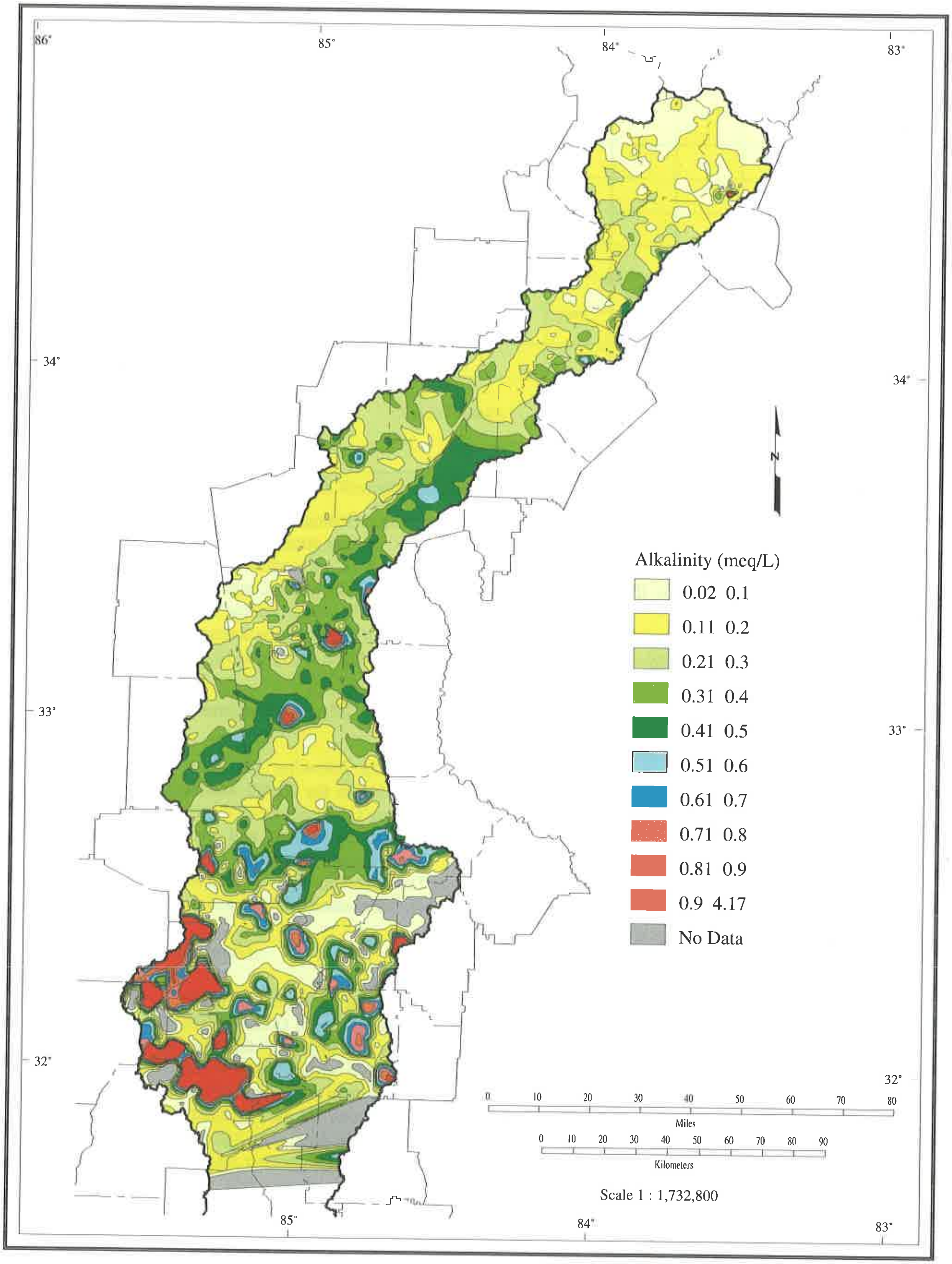

Figure 15. Alkalinity of stream water. Absence of data south of Stewart County and in parts of Cobb, Fulton and DeKalb Counties may cause contouring artifacts.

32,300 ppm (Table 7). Rock units (Table 1) with the lowest average aluminum (Table 8) include: *Ptu* (8,500 ppm), *Qal* (9,537 ppm), *Kc* (9,656 ppm), *Kb* (9,738 ppm), *Ke* (10,944 ppm), *Kt* (16,250 ppm), and *Kr* (18,690 ppm). These are all Coastal Plain sedimentary formations.

Anomalously high aluminum concentrations (65,000 to 124,000 ppm) occur in Coastal Plain stream sediments in Chattahoochee, Marion, and Stewart Counties (Fig. 16). Some of these high aluminum concentrations may be due to bauxite-bearing sediments.

Aluminum is high (50,000 to 96,000 ppm) in White and Lumpkin counties. A large aluminum anomaly is located in the northern parts of White and Lumpkin Counties and is associated with a biotite gneiss *bg1* (Fig. A-17) north of the Shope Fork Fault. This anomaly generally correlates with cobalt, copper, lead, nickel, silver, sodium, and zinc anomalies (Figs. 22, 23, 24, 25, 26, and unpublished Georgia Geologic Survey maps). Generally, aluminum is lower along the trace of the Brevard Fault Zone with values ranging from 14,000 to 48,000 ppm. Within the Piedmont, the highest concentration of aluminum in stream sediments is located south of the Brevard fault zone in Heard, Coweta and Troup Counties (Fig. 16). The highest concentration of aluminum (138,000 ppm) is found in Paulding County (Fig. 16). Aluminum is low (10,000 to 35,000 ppm) in the Pine Mountain terrane (Fig. 16). Rock units (Table 1) with the highest mean aluminum (Table 8) include: *pm3a* (54,764 ppm), *mm4* (53,467 ppm), and *um* (52,300 ppm).

Aluminum has correlations above the 0.5 level with manganese, scandium, sodium, cobalt, vanadium, copper, lead, and silver (Table 9). The association with sodium may indicate the presence of sodic plagioclase in the stream sediments.

Arsenic (As)

In the Chattahoochee River Basin of Georgia, only sediments from Douglas County were analyzed for arsenic. The highest arsenic value (9 ppm) is located in the northwestern part of the county (Fig. 17). Ten rock units contain sediments analyzed for arsenic (Table 8). Highest arsenic values were found in rock units *gg2* (3.6 ppm) and *pms3* (2.5 ppm). Rock units *gr1* and *mm3* had the lowest arsenic values (1.0 ppm).

The source of arsenic in these stream sediments has not been positively identified. Arsenic in the Chattahoochee River Basin may be related to the presence of base-metals in rock, soil and saprolite. Arsenic-bearing pyrite may occur in shales, schists or metallic vein deposits. High median concentration (Table 5) of arsenic (12 ppm) (Rose and others, 1979) in shales may be reflected in stream sediments derived from shales or their metamorphic-equivalent rock type. Metamorphosed shales include mica schists, garnet schists, or aluminous mica schists. Such schists are abundant in the Chattahoochee River Basin (Figs. A-5, A-6 and A-7). Weathering of arsenic-bearing pyrite may result in increased acidity and dissolution of arsenic into stream water rather than concentration in stream sediments. Arsenic in Chattahoochee River Basin stream sediments may be a residue from pesticides previously used on cotton crops.

Barium (Ba)

Barium analyses are limited to stream sediments in Gwinnett, Fulton, Cobb, Cobb, Paulding, Douglas, Carroll, Coweta, and Meriwether Counties in the Chattahoochee River Basin (Fig. 18). Average barium concentrations in Chattahoochee River Basin stream sediments is 24.7 ppm (Table 7). Highest barium values were found in granitic rock units: *gr1b* - porphyritic granite (65.5 ppm), *gg6* - granite gneiss (53.0 ppm), and *gr1* - granite (51.2 ppm) (Table 8). Barium in granitic rocks is likely to be contained in potassium-feldspar. Correlation coefficients for barium were highest with potassium (0.6263). Potassium is commonly concentrated in more fractionated rocks such as granites. The relation of barium to potassium is indicated in Fig. 19. Highest mean concentrations of barium (Table 5) are in granite (840 ppm), shale (550 ppm) and mafic rocks (330 ppm) (Rose and others, 1979). Higher barium concentrations are found in southern Meriwether County (up to 143 ppm), south Fulton County (up to 93 ppm), western Cobb County
up to 95 ppm), southeastern Carroll County (up to 98 ppm), and Gwinnett County (up to 210 ppm) (Fig. 61). Because of the rather limited coverage for barium, regional trends are not apparent.

The lowest barium concentrations (Table 8) were found in *mm2* - amphibolite (4.0 ppm), and *pms4* - mica schist (10.6 ppm), *pms5* - graphite schist (12.5 ppm), and *pms3* - mica schist (14.7 ppm).

Beryllium (Be)

Primary sources for beryllium in stream sediments in the Georgia Blue Ridge and Piedmont are probably granites (Table 5 and Fig. A-4) and pegmatites that contain the beryllium-bearing mineral beryl. The beryllium content of stream sediments in the Chattahoochee River Basin ranges from below the detection limit of 0.5 ppm up to 3.0 ppm. Areas within the Chattahoochee River Basin that contain greater than 2.0 ppm beryllium in stream sediments are found in Heard and Coweta Counties (Fig. 20). Regional trends in the contoured data are not immediately apparent on the map of the Chattahoochee River Basin. Spatial correlation with granitic rocks suggests that primary sources for beryllium are granitic rocks and pegmatites.

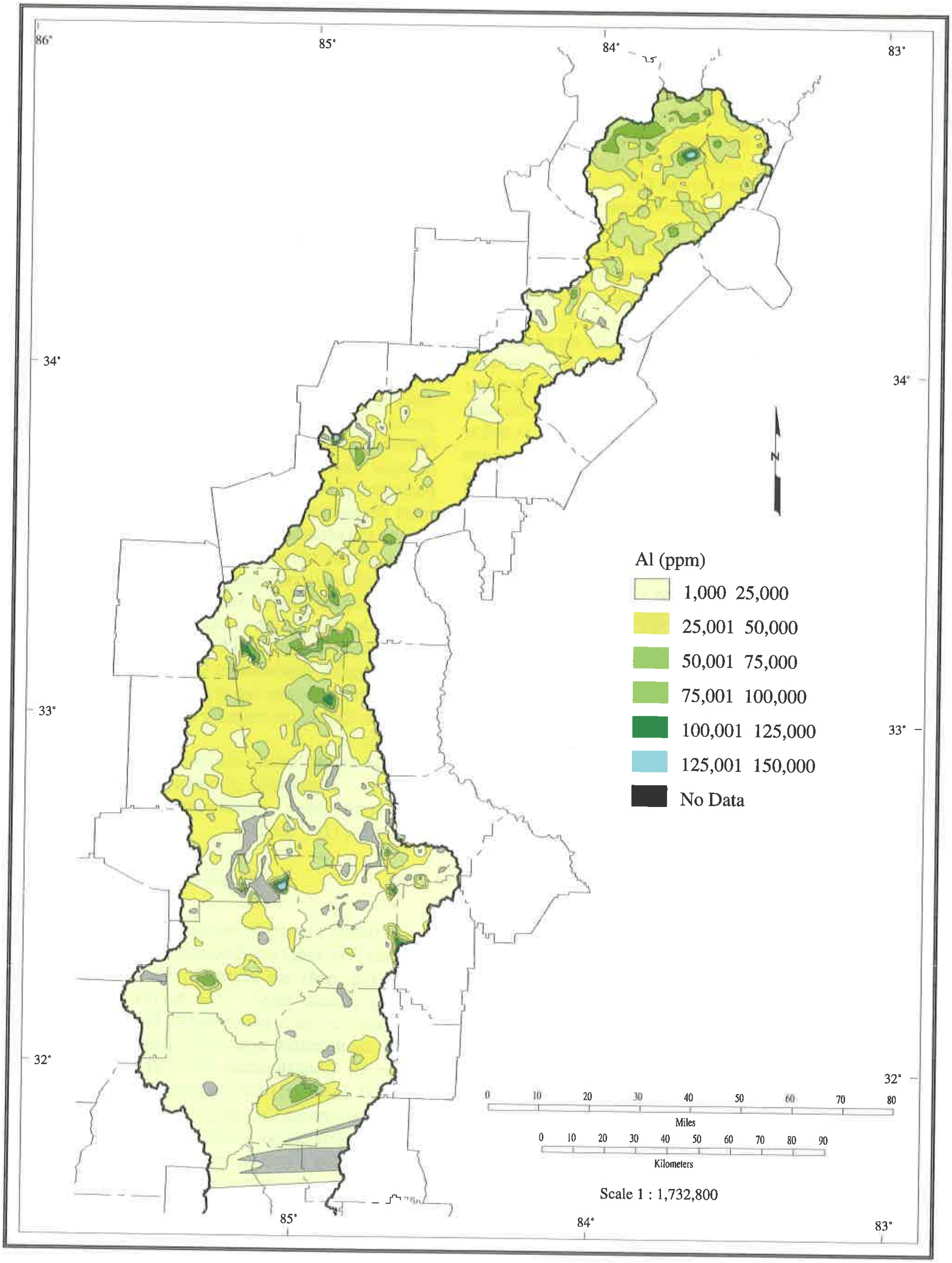

Figure 16. Aluminum in stream sediments. Absence of data south of Stewart County and in parts of Cobb, Fulton and DeKalb Counties may cause contouring artifacts.

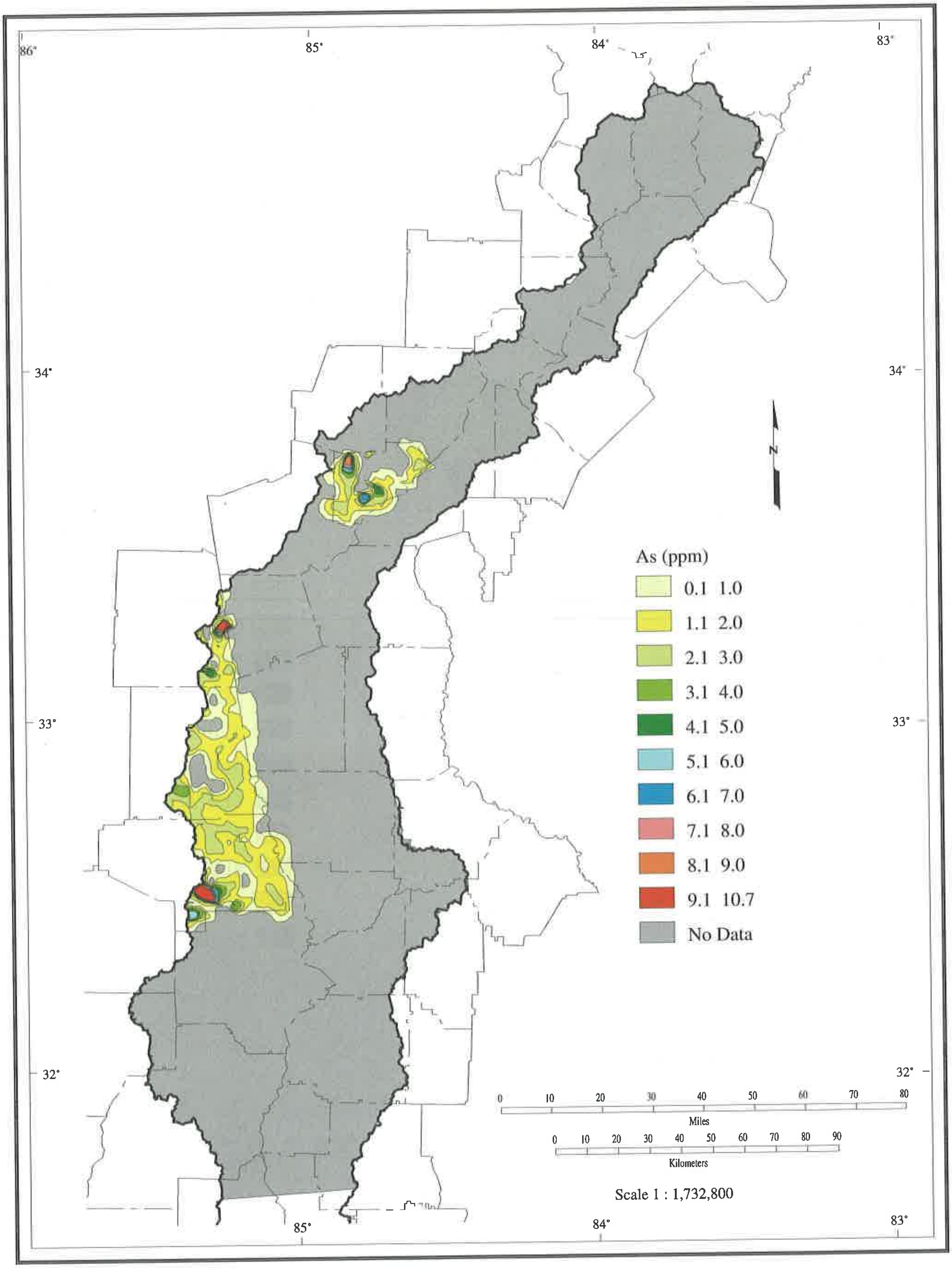

Figure 17. Arsenic in stream sediments. Absence of data south of Stewart County and in parts of Cobb, Fulton and DeKalb Counties may cause contouring artifacts.

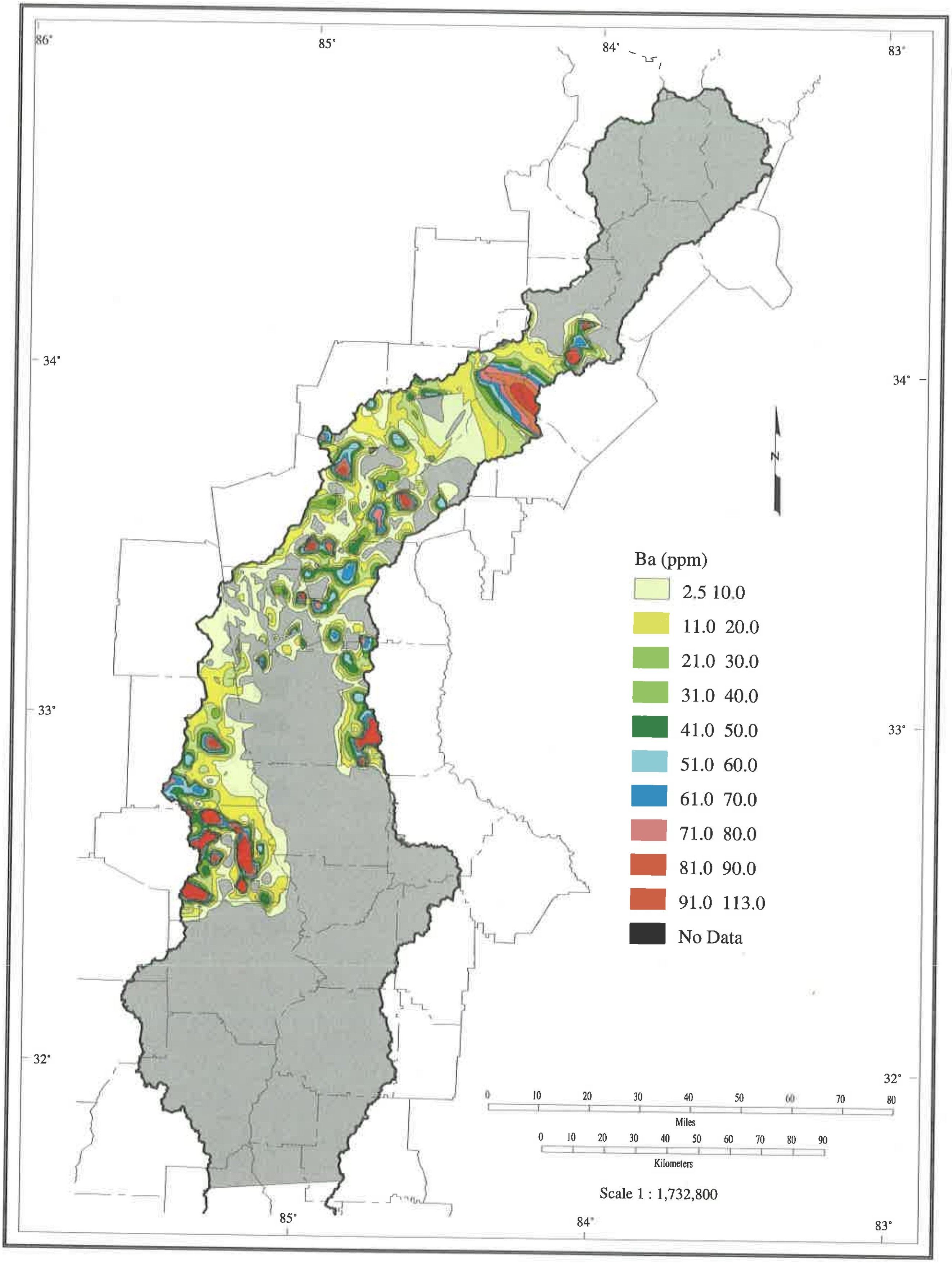

Figure 18. Barium in stream sediments. Absence of data south of Stewart County and in parts of Cobb, Fulton and DeKalb Counties may cause contouring artifacts.

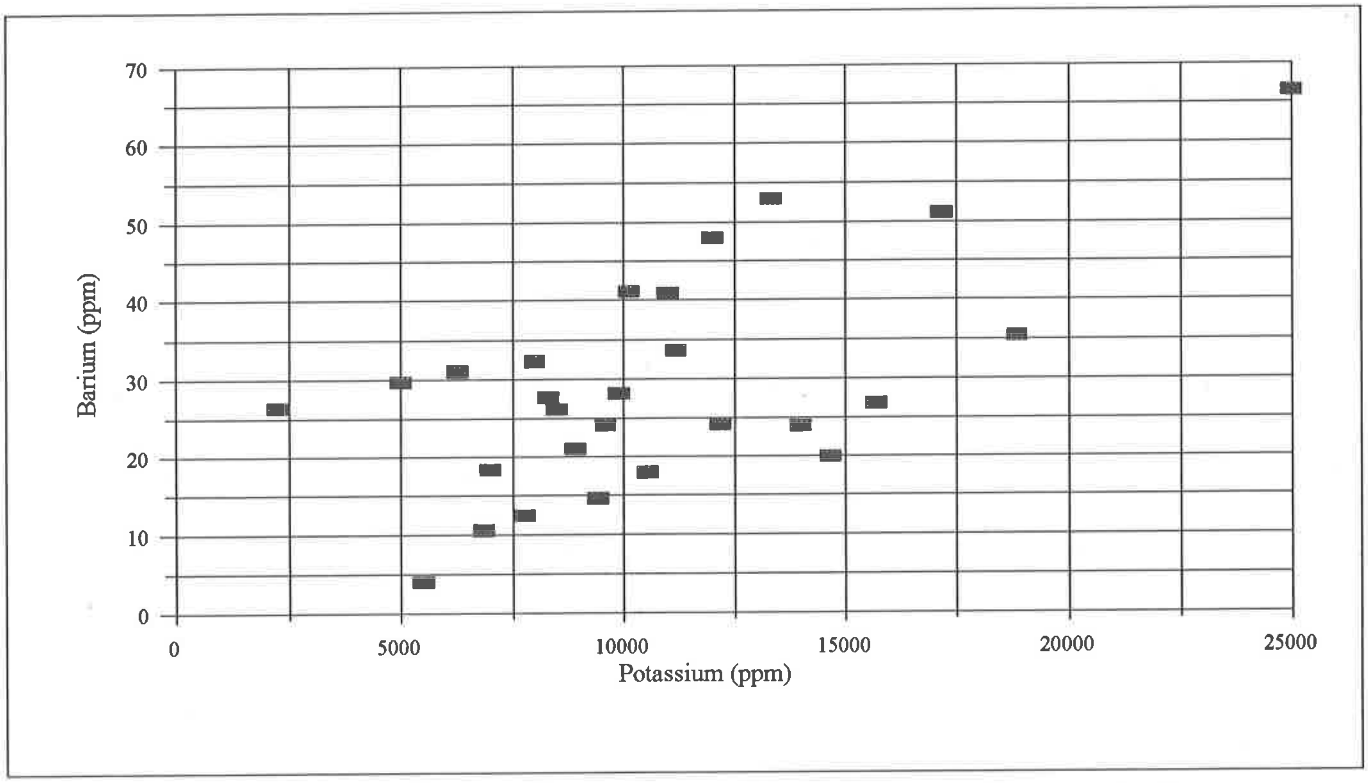

Figure 19. Variation of barium with potassium. A plot of average concentrations per rock unit.

Rock units (Table 1) with the lowest mean beryllium content (Table 8) include: *ms3* - amphibolite schist/ amphibolite-metagraywacke/mica schist (0.38 ppm), *um* - ultramafic rocks undifferentiated (0.50 ppm), and *pa1* - aluminous schist (0.56 ppm). Rock units (Table 1) with the highest mean beryllium (Table 8) include: *gg3*- muscovite granite gneiss (1.50 ppm), *gr1* -granite (1.44 ppm), and *pa2* - sillimanite schist (1.25 ppm). The concentration of beryllium in average crustal granitic rocks (3.0 ppm, Table 5) is consistent with the high beryllium values in stream sediments associated with Chattahoochee River Basin granites. High beryllium in gneisses and schists may be related to beryl-bearing pegmatites in or near those rock units.

Chromium (Cr)

Primary sources for chromium are ultramafic rocks and, to a lesser extent, amphibolites and shales. Median crustal concentrations for these rock types (Table 5) are 2,980 ppm, 170 ppm, and 90 ppm, respectively (Rose and others, 1979). The primary host for chromium is chromite, which is relatively stable and resistant to weathering. Other, chromium-bearing minerals include muscovite, diopside, and fuchsite, a chromium mica commonly associated with volcanogenic gold deposits. Average chromium concentration in the Chattahoochee River Basin is 4.3 ppm (Table 7).

Two large chromium anomalies are found in the northern part of the Chattahoochee River Basin - one in Habersham County and the other in Hall County (Fig. 21). They range from 6 to 30 ppm and 6 to 42 ppm respectively. These anomalous areas lie astride the Brevard fault zone (Fig. A-20) and do not appear related to any mapped rock unit (Fig. A-10). Scattered small anomalies west and southwest of Atlanta with up to 35 ppm chromium do not define any apparent trend (Fig. 21). Most chromium concentrations are 6 ppm or less in the Chattahoochee River Basin. Chromium analyses are lacking for Forsyth, Douglas, Troup, and Harris Counties and counties south of Harris County.

The chromium anomalies astride the Brevard fault zone (Fig. A-20) may be related to slices of ultramafic rock within the fault zone. Ultramafic rocks commonly occur in proximity to major crustal sutures or faults that join major crustal lithospheric plates. These intrusions or fault slices may be up to several tens of miles in length, but in Georgia they are generally small - approximately a few tens to hundreds of feet in length. Ultramafic lens-shaped masses are subject to low-grade metamorphism and are highly susceptible to weathering. Outcrops are rare, and direct evidence of their presence may be lacking. Rock units that cover larger areas than the ultramafic rocks may contribute a greater amount of chromium to the sediments than do the ultramafic rocks.

No chromium analyses are available for Coastal Plain stream sediments in the Chattahoochee River Basin. A comparison with Coastal Plain sediments in the Oconee River

Basin (Cocker, 1996c) and further to the east suggests that scattered anomalous chromium may be found perhaps related to heavy mineral deposits in Cretaceous to Eocene sedimentary formations.

Rock units (Table 1) with mean values below the detection limit of 5 ppm chromium (Table 8) include: *um* - ultramafic rocks, *pms6a* - sericite schist, *gg6* - granite gneiss, *pms1* - mica *schist, gg3* - muscovite granite gneiss, *gg5* - calc-silicate granite gneiss, *bg1* - biotite gneiss, *mm1* - amphibolite, *pa2* - sillimanite schist, *pg2* - garnet mica schist, *pms4* - mica schist, *gr1b* - porphyritic granite, *fg4* - biotitic gneiss, *mm2* - hornblende gneiss, *pms3a* - metagraywacke, *pms2* -mica schist, *pa1* - aluminous schist, *pm3a* - metagraywacke, *q1* - quartzite, *pms3* - mica schist, *pms5* - graphite schist, and *mm3* - hornblende gneiss. Rock units (Table 1) with the highest mean chromium (Table 8) include: *pg1* - garnet mica schist (10.0 ppm) and *fg3* - biotitic gneiss (6.8 ppm). The source of the chromium in these units may be nearby unidentified ultramafic rocks or chromium-rich mica in the schist.

Cobalt (Co)

Natural sources of cobalt include ultramafic rocks (110 ppm), amphibolites (48 ppm), and shales (19 ppm) (Table 5) (Rose and others, 1979). Within the Chattahoochee River Basin, a zone of high cobalt concentrations (10 to 15 ppm) extends northeasterly across the northwestern edge of White and Lumpkin Counties. This trend is spatially coincident with a biotite gneiss *bg1* mass (Fig. A-17) and with aluminum, copper, lead, nickel, zinc, silver, and sodium anomalies (Figs. 16, 23, 24, 25, 26, and unpublished Georgia Geologic Survey maps). In Cobb, Paulding, and Carroll Counties stream sediments may contain 10 to 13 ppm cobalt. Stream sediments within Coweta and adjacent parts of Fulton and Heard Counties contain 10 to 23 ppm cobalt. Natural rock unit sources for the cobalt south of Atlanta are not readily apparent from the state geologic map.

No cobalt analyses are available for Coastal Plain stream sediments in the Chattahoochee River Basin. A comparison with Coastal Plain sediments in the Oconee River Basin (Cocker, 1996c) and further to the east suggests that scattered anomalous cobalt may be occur related to heavy mineral deposits in Cretaceous to Eocene sedimentary formations.

Rock units (Table 1) with mean cobalt concentrations below the detection limit of 5 ppm (Table 8) include: *ms3* - amphibolite schist (2.5 ppm), *pms6a* - sericite schist (3.1 ppm), *pms4* - mica schist (3.2 ppm), *q1* - quartzite (3.8 ppm), *mm2* - hornblende gneiss (3.8 ppm), *pms3* - mica schist (4.1 ppm), *pms5* - graphite schist (4.5 ppm), *pm2*- mica schist (4.5 ppm), *gg2* - granite gneiss (4.6 ppm), *pa1* - aluminous schist (4.6 ppm), *pg2* - garnet mica schist (4.7 ppm), *mm1*- amphibolite (4.7 ppm), *pms2* - mica schist (4.9 ppm), and *gg1* - granite gneiss (4.9 ppm). The highest cobalt concentrations (Table 8) are in rock units: *pg1*- garnet mica schist (13.0 ppm), *pa2* - sillimanite schist (11.5 ppm) and *um* - ultramafic rocks (11.0 ppm). As noted above, high cobalt concentrations may be expected in ultramafic rocks and shales.

Cobalt shows a relatively good correlation with aluminum, zinc, copper, lead, magnesium, nickel, and vanadium (Table 9). The association of zinc, copper, lead, nickel and cobalt may indicate the presence of base metal sulfides in those stream sediments. The association with aluminum, vanadium, and magnesium suggests some lithologic controls on cobalt.

Copper (Cu)

High concentrations of copper (Table 5) in average crustal ultramafic rocks (42 ppm), mafic rocks (72 ppm), and shales (42 ppm) (Rose and others, 1979) indicate that these rock types or their metamorphic equivalents may be important sources of copper in stream sediments. Data for copper are lacking for Troup, Harris, Muscogee, Talbot and most of Forsyth Counties. No copper analyses are available for Coastal Plain rock units in the Chattahoochee River Basin. Low copper values in the Coastal Plain of other parts of Georgia suggest that Coastal Plain rock units in the Chattahoochee River Basin would also be low in copper. In part, this may be due to low pH in many Coastal Plain streams (Fig. 12).

Within the Chattahoochee River Basin, stream sediments generally contain less than 10 ppm copper (Fig. 23) with average copper content of 6.6 ppm (Table 7). Anomalously high copper values (10 to 52 ppm) found in the upper parts of White and Lumpkin Counties are spatially coincident with a biotite gneiss *bg1* mass (Fig. A-17) and with aluminum, cobalt, lead, nickel, zinc, silver, and sodium anomalies (Figs. 16, 22, 24, 25, 26 and unpublished Georgia Geologic Survey maps). A second anomaly of 10 to 25 ppm copper extends northeast from Forsyth through Hall and Habersham Counties. Anomalous copper (10 to 46 ppm) may be part of a northeast-trending zone in Coweta and south Fulton Counties. Copper anomalies in central and southern Coweta County are coincident with lead, nickel, and zinc anomalies discussed below. Stream sediments with a high copper content occur along the northeast trace of the Brevard fault zone within and beyond the Chattahoochee River Basin (Fig. 23 and unpublished Georgia Geologic Survey maps).

Rock units (Table 1) with the lowest copper content (Table 8) include: *mm9* - amphibolite (3.6 ppm), *gg5* - calc-silicate gneiss (4.7 ppm), *mm2* - hornblende gneiss (5.0 ppm), *pal* - aluminous schist (5.5 ppm), *gg6* - granite gneiss (5.7 ppm), *gg2* - granite gneiss (5.8 ppm), *pms3* - mica schist (5.8 ppm), *gr1b* - porphyritic granite (5.9 ppm), *gg3* - muscovite ppm), *gr1b* - porphyritic granite (5.9 ppm), *gg3* - muscovite granite gneiss (6.0 ppm), and *mm2* - hornblende gneiss (6.1 ppm). Most of these rock units are granitic and are not

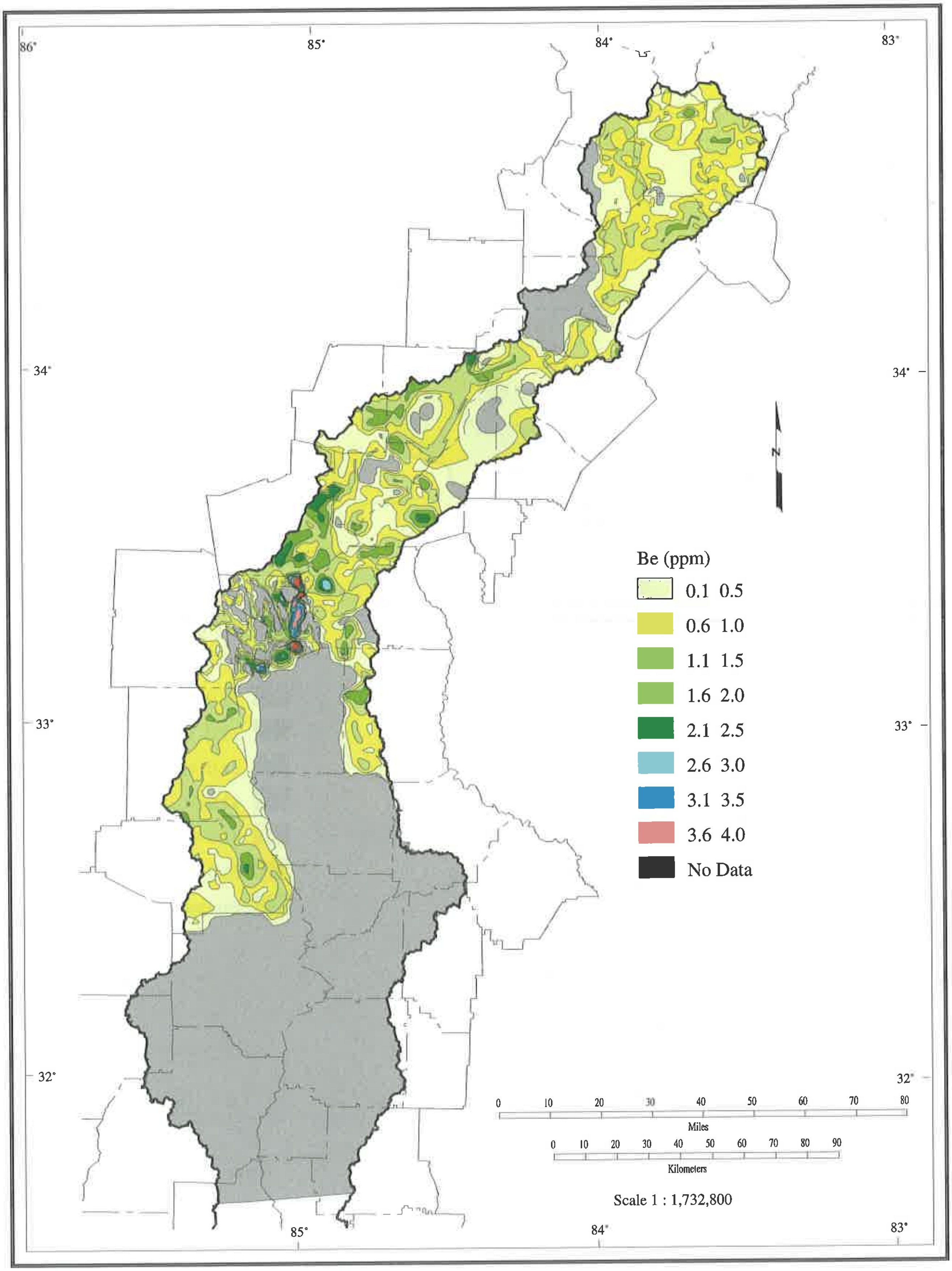

Figure 20. Beryllium in stream sediments. Absence of data south of Stewart County and in parts of Cobb, Fulton and DeKalb Counties may cause contouring artifacts.

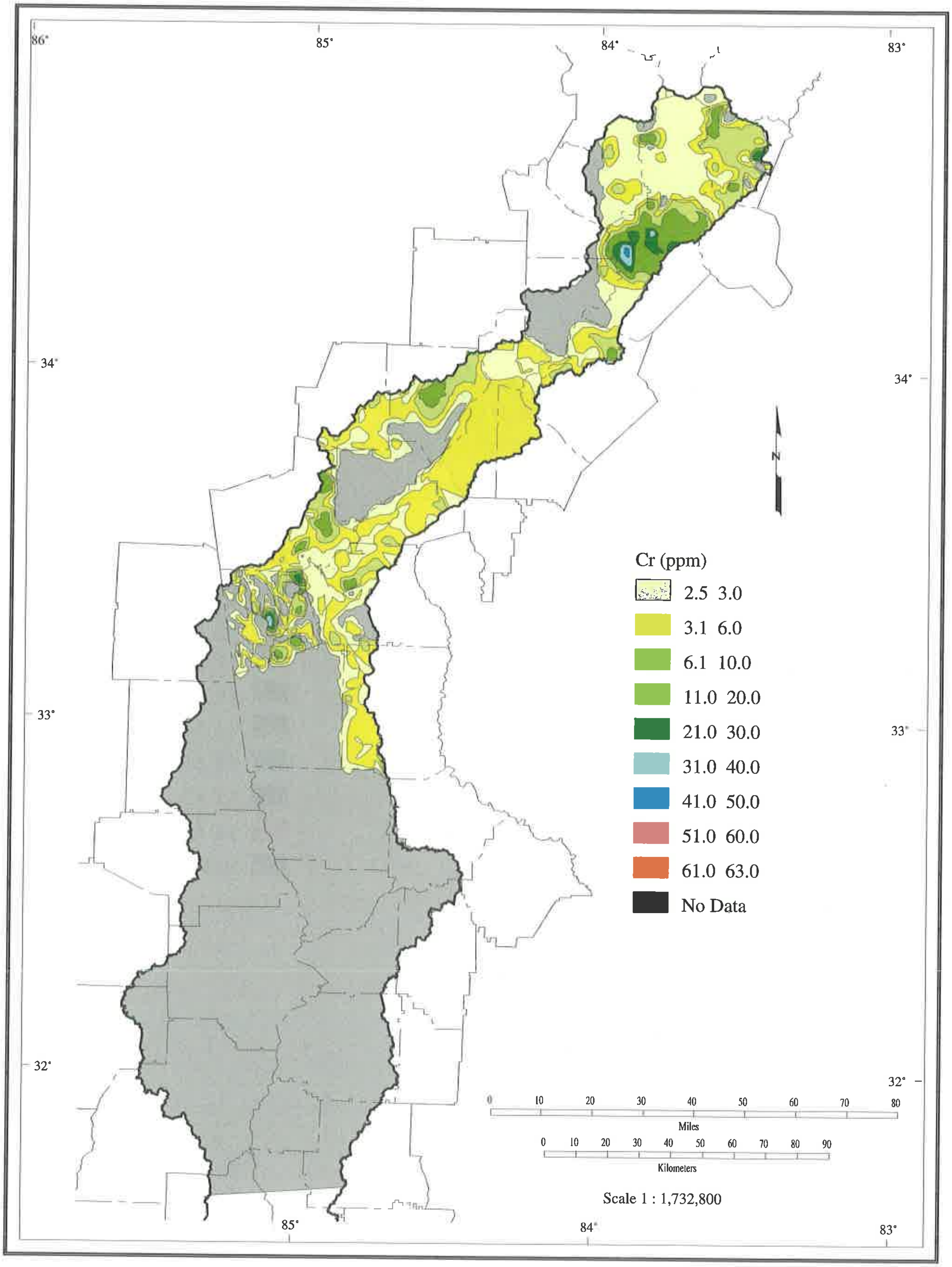

Figure 21. Chromium in stream sediments. Absence of data south of Stewart County and in parts of Cobb, Fulton and DeKalb Counties may cause contouring artifacts.

associated with base-metal mineralization. Rock units with the highest copper content (Table 8) include: *pg1* - garnet mica schist (18 ppm), *pm3a* - mica schist (16.3 ppm), *pa2* - sillimanite schist (13.3 ppm), and *bg1* - biotite gneiss (11.1 ppm). High copper was also noted in the *bg1* rock unit for Oconee River Basin sediments (Cocker, 1996b). Rocks with the highest copper content are mica schists, which may be due to naturally higher copper concentrations in the protolith (shale) for these rocks (Rose and others, 1979).

Copper shows a good correlation with zinc (Fig. 27), nickel, silver, lead, and cobalt (Table 9) which suggests the presence of base-metal sulfides in the stream sediments. The correlation with aluminum (Table 9) may be related to copper or base-metal mineralization in aluminous schists.

Lead (Pb)

Anomalous lead in stream sediments may be derived from granitic rocks, shales or sandstones that have median concentrations of 18 ppm, 25 ppm, and 10 ppm, respectively (Rose and others, 1979). Some anomalous lead in these rocks may be in potassium-feldspars. Within the Chattahoochee River Basin, lead in stream sediments ranges from below the detection limit of 10 ppm to a high of 58 ppm and average 7 ppm (Table 7).

High lead concentrations within the Chattahoochee River Basin (Fig. 24) occur along discontinuous northeast-trending zones approximately parallel to the orientation of the northern part of the basin and to the regional geology (Fig. A-20). One anomalous zone cuts through Habersham and White Counties, and along the border between Hall and Lumpkin Counties. This zone may be continuous with a trend further to the southwest in Cobb and Douglas Counties. A data gap in Cherokee, Douglas and Forsyth Counties interrupts the middle portion of this trend. Concentrations of up to 30 ppm lead are found in this zone. A second northeast-trending zone with up to 25 ppm lead appears to enter the extreme northwestern end of the Chattahoochee River Basin in White and Lumpkin Counties and is spatially coincident with a biotite gneiss mass (*bg1*) (Fig. A-17) and with aluminum, cobalt, copper, nickel, zinc, silver, and sodium anomalies (Figs. 16, 22, 23, 25, 26 and unpublished Georgia Geologic Survey maps). A third northeast-trending zone of high lead extends through Coweta, Heard and Troup Counties (Fig. 24). Up to 58 ppm lead is found in stream sediments along this trend. The highest lead concentration in the Chattahoochee River Basin is coincident with copper, cobalt and zinc anomalies in southern Coweta County near the border with Meriwether County. The present source of this anomaly is unknown. Slightly to the north of that anomaly is an elongate lead anomaly oriented to the northeast into the central part of Coweta County. This anomaly appears to be spatially coincident with a lead anomaly in alluvium noted by Hurst and Long (1971). This anomaly is also coincident with elongate copper, manganese, cobalt, and zinc anomalies in the NURE data. In the Hall County gold belt, high lead values are present in the rocks but are not found in the NURE stream sediments.

Of the 30 rock units that contain samples analyzed for lead, 22 had average lead below the detection limit of 10 ppm (Table 8). Rock units with the highest average lead include: *pg1* - garnet mica schist (16 ppm), *mm9* - amphibolite (13.6 ppm), *pm3a* - metagraywacke - (11.5 ppm), *gr1* - granite (11.4 ppm), *q1* - quartzite (10.8 ppm), *pa2* - sillimanite schist (10.5 ppm) and *bg1* - biotite gneiss (10.4 ppm). The presence of higher lead in quartzite within the Chattahoochee River Basin is interesting, because high lead was noted in quartzite in the Oconee River Basin (Cocker, 1996b). Rock units with the lowest lead (5 ppm) include: *gg3* - muscovite granite gneiss, *pms1* - mica schist, *mm2* - hornblende gneiss, *gg6* - granite gneiss, *ms3* - amphibolite schist, and *pms6a* - sericite schist. Samples from Coastal Plain sediments in the Chattahoochee River Basin were not analyzed for lead.

Nickel (Ni)

Natural sources of nickel are commonly ultramafic rocks, and, to a lesser extent amphibolites and shales with median concentrations of 2,000 ppm, 130 ppm, and 68 ppm, respectively (Table 5 and Rose and others, 1979). Concentrations of nickel in stream sediments within the Chattahoochee River Basin are generally less than 10 ppm, and most of those concentrations were below the detection limit of 5 ppm. Average nickel concentration is 6.5 ppm (Table 7). Distribution of nickel may be related to rock composition, with higher values correlative with the distribution of ultramafic and amphibolitic rock units (Figs. 6 and 13). Contouring of data for nickel generated a false anomaly covering a large part of central Fulton and northern DeKalb Counties (Fig. 25). No NURE data for nickel exist in this area.

In the extreme northern part of the Chattahoochee River Basin (Fig. 25), nickel (10 to 18 ppm) is concentrated in two zones approximately parallel to regional geology and structure (Fig. A-20). One zone cuts northeasterly across the Chattahoochee River Basin through White and Lumpkin Counties and is spatially coincident with a biotite gneiss (*bg1)* mass (Fig. A-17) and with anomalous aluminum, cobalt, copper, lead, zinc, silver, and sodium (Figs. 16, 22, 23, 24, 26, and unpublished Georgia Geologic Survey maps). A second zone extends through the southern end of Habersham and Hall Counties. This zone may continue into north Fulton and Cobb Counties. The presence of numerous ultramafic masses in the Blue Ridge terrane (Fig. 13) in the northern part of the basin may account for many of the anomalously high nickel concentrations in that area. Concentrations of 10 to 25 ppm nickel may form a third zone across Gwinnett, Fulton and

Cobb Counties. Scattered concentrations of nickel (10 to 56 ppm) are found in Piedmont streams south of Atlanta. Current distribution of data does not suggest a coherent pattern. A well-defined anomaly in Carroll County with up to 56 ppm nickel is not related to any specific mapped rock unit, although the anomaly trends parallel to regional geology.

Rock units (Table 1) with less than the detection limit of 5 ppm nickel (Table 8) include: *mm3* - hornblende gneiss (2.5 ppm), *gg5* - calc-silicate granite gneiss (4.0 ppm), *q1* - quartzite (4.1 ppm), *pm2* - metagraywacke (4.9 ppm). Rock units with the highest average nickel content include: *pg1* - garnet mica schist (16.7 ppm), *gg3* muscovite granite gneiss (10.0 ppm), *bg1* - biotite gneiss (9.4 ppm), *gr1 -granite* (9.1 ppm), *gr1b* - granite gneiss (9.1 ppm), *gg6* - granite gneiss (8.7 ppm), and *pms4* - mica schist (8.6 ppm). High nickel values were also noted in the Oconee River Basin for granite (*gr2a*) and biotite gneiss (*bg1*) are unusual and not yet explained (Cocker, 1996b). Samples from Coastal Plain sediments in the Chattahoochee River Basin were not analyzed for nickel. As discussed in the Oconee River Basin study (Cocker, 1996b), scattered and isolated nickel anomalies may be present, perhaps associated with concentrations of heavy minerals.

Strongest correlations for nickel are with copper, zinc, cobalt, and silver (Table 9). These correlations suggest the presence of base-metal sulfides.

Zinc (Zn)

Mafic rocks and shales may be important sources of zinc in stream sediments as suggested by concentrations of 94 ppm and 100 ppm, respectively (Rose and others, 1979). High zinc concentrations in White and Lumpkin Counties (up to 121 ppm) are spatially coincident with a biotite gneiss (*bg1)* mass (Fig. A-17) and anomalous aluminum, cobalt, copper, nickel, silver, sodium and lead (Figs. 16, 22, 23, 24, 25, and unpublished Georgia Geologic Survey maps). A northeast-trending zone through Habersham and Hall Counties that may extend through Fulton and Cobb Counties has concentrations of up to 55 ppm zinc (Fig. 26). A data gap is present in Forsyth County. A string of more northerly-trending anomalies is apparent in Hall and White counties with up to 75 ppm zinc. Concentrations of up to 130 ppm zinc are present in north Fulton and Cobb Counties. A northeast-trending anomaly in south Fulton and Coweta Counties contains up to 98 ppm zinc. A strong zinc anomaly (up to 140 ppm) is present in south Coweta and northern Meriwether Counties (Fig. 26). Scattered zinc anomalies (up to 70 ppm) in Heard, Carroll, and Douglas Counties display no apparent patterns.

Rock units (Table 1) with the lowest zinc content (Table 8) include: *mm2* - hornblende gneiss (13.0 ppm), *ms3* - amphibolite schist (15.0 ppm), *gg2* - granite gneiss (16 ppm), *gg6* - granite gneiss (16 ppm), *gg5* - calc-silicate granite gneiss (16.2 ppm), *mm9* - amphibolite (16 ppm), *pms5* - graphite schist (17 ppm), and *gg1* - granite gneiss (18 ppm). Low values of zinc in the granitic gneisses (*gg2, gg6, gg5,* and *gg1*) suggest that zinc mineralization is not associated with those rock types. Samples from Coastal Plain sediments in the Chattahoochee River Basin were not analyzed for zinc. Sedimentary rock units within the Coastal Plain of the Chattahoochee River Basin are most likely comparable to the low average zinc values (6.7 to 15.8) identified in the Oconee River Basin (Cocker, 1996b). Rock units with the highest zinc content (Table 8) include: *pg1* - garnet mica schist (67 ppm), *pa2*- sillimanite schist (41 ppm), and *pm3a* - metagraywacke (40 ppm).

Strongest correlations of zinc are with copper (Fig. 27), nickel, cobalt, silver, lead, chromium, and titanium (Table 9). The zinc-copper-nickel-cobalt-lead association suggests the presence of base-metal sulfides in those sediments.

Iron (Fe)

Iron has an important influence on water quality and provides important information regarding the effects of lithology on water quality. Iron is soluble under acidic and reducing conditions and insoluble under alkaline and oxidizing conditions. Increasing oxidation may change iron from a dissolved ferrous state to semisolid ferric state. This transformation commonly results in the precipitation of iron oxide or iron hydroxide coatings. Precipitation of iron causes the coprecipitation or absorption of other metals.

Iron bacteria such as Crenothrix, Gallionella, and Leptothrix may precipitate ferric iron or create gel-like slimes which may clog pipes and screens (Driscoll, 1986). Iron-bearing water encourages the growth of these bacteria.

Iron in stream sediments is an indication of the abundance of iron-bearing minerals. Iron compounds are probably the most important inorganic reducing agents. Waters without organic material lose their oxidizing character by reaction with silicates containing ferrous iron, such as biotite, chlorite, amphiboles, pyroxenes, or by contact with sulfides or ferrous iron-containing carbonates. As pH rises due to silicate hydrolysis, the environment becomes alkaline and reducing. In environments containing organic matter, biochemical reactions quickly remove oxygen, commonly with a marked increase in CO_2, and with production of hydrogen sulfide. Deoxygenation may be accompanied by a decrease in pH as CO_2 and H_2S are generated (Garrels and Christ, 1965).

Low iron content in stream sediments in the upper Coastal Plain (Fig. 28) correlates spatially with streams that have a very low pH (Fig. 12). Further south in the Coastal Plain, anomalous iron in stream sediments correlates spatially with the presence of residual iron, calcareous sedimentary units and higher stream pH. Correlation coefficients in Table

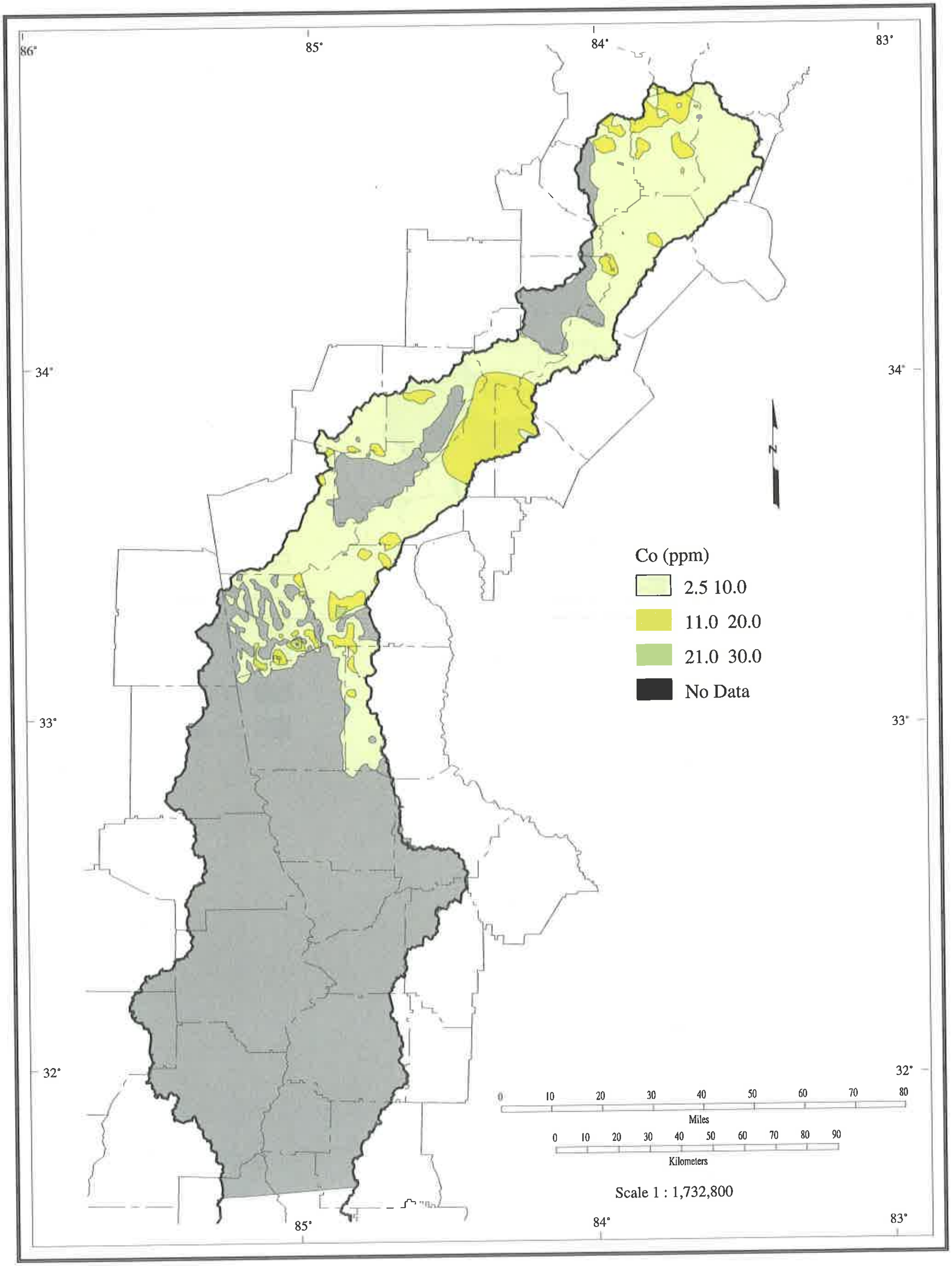

Figure 22. Cobalt in stream sediments. Absence of data south of Stewart County and in parts of Cobb, Fulton and DeKalb Counties may cause contouring artifacts.

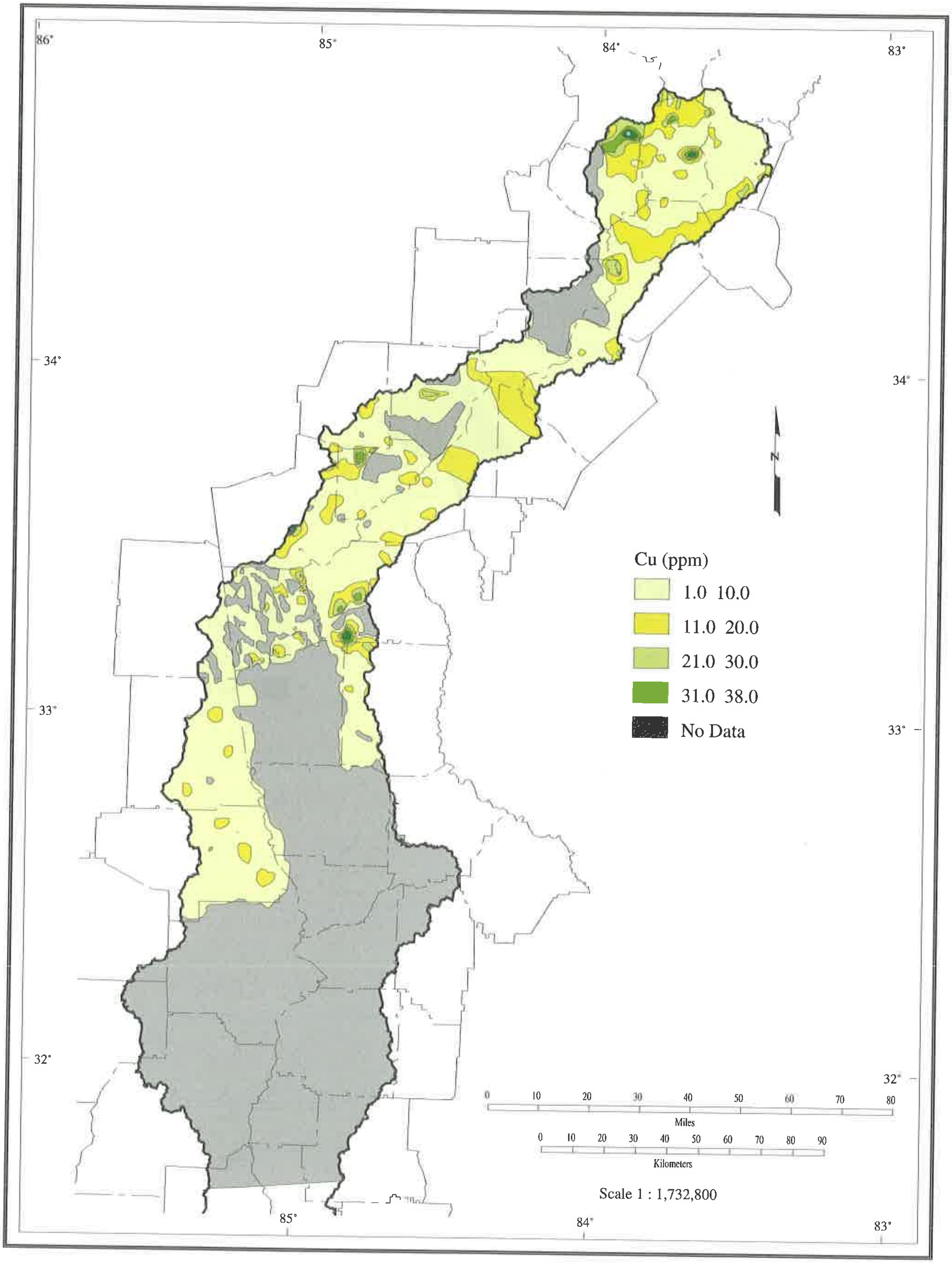

Figure 23. Copper in stream sediments. Absence of data south of Stewart County and in parts of Cobb, Fulton and DeKalb Counties may cause contouring artifacts.

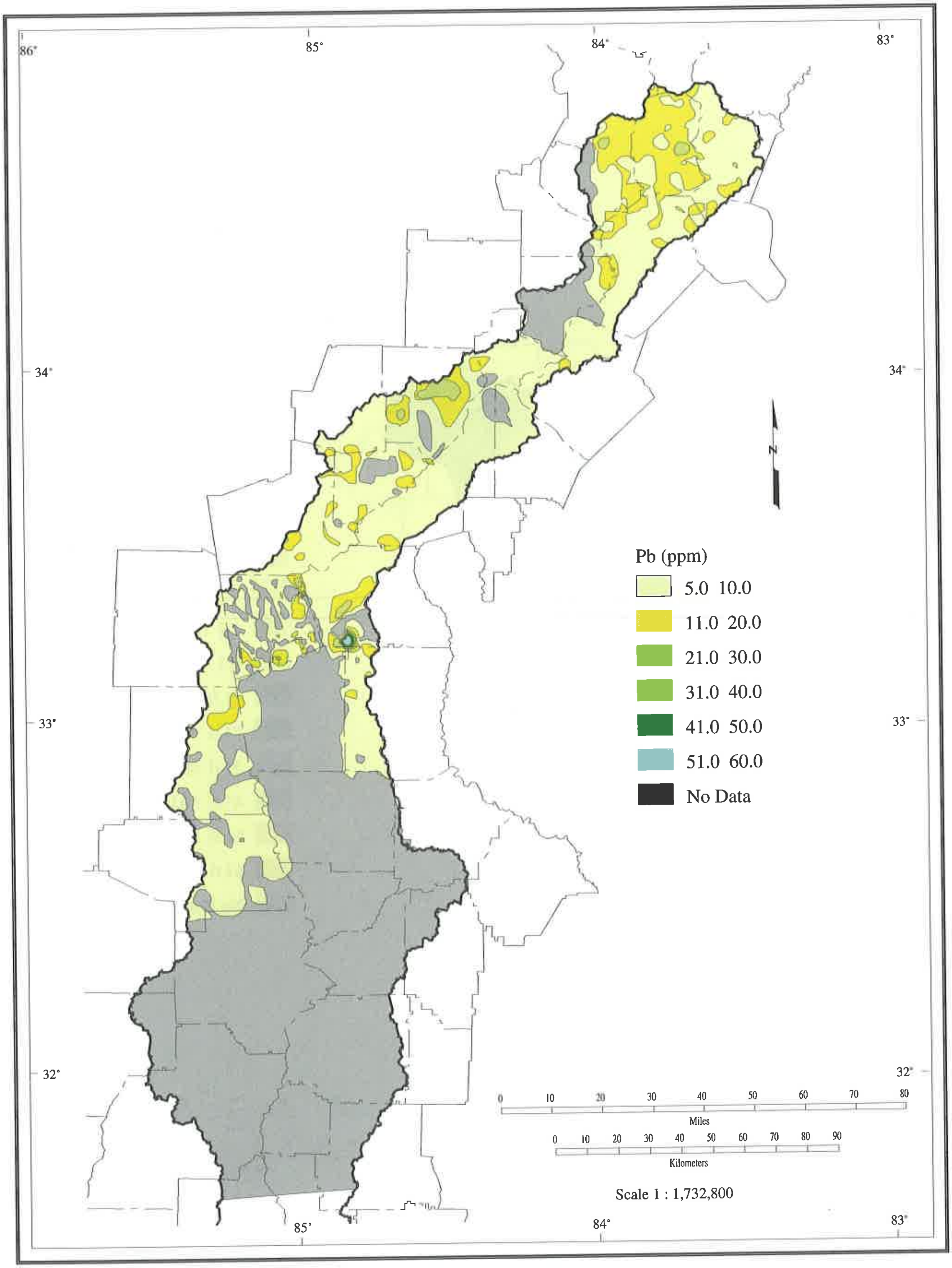

Figure 24. Lead in stream sediments. Absence of data south of Stewart County and in parts of Cobb, Fulton and DeKalb Counties may cause contouring artifacts.

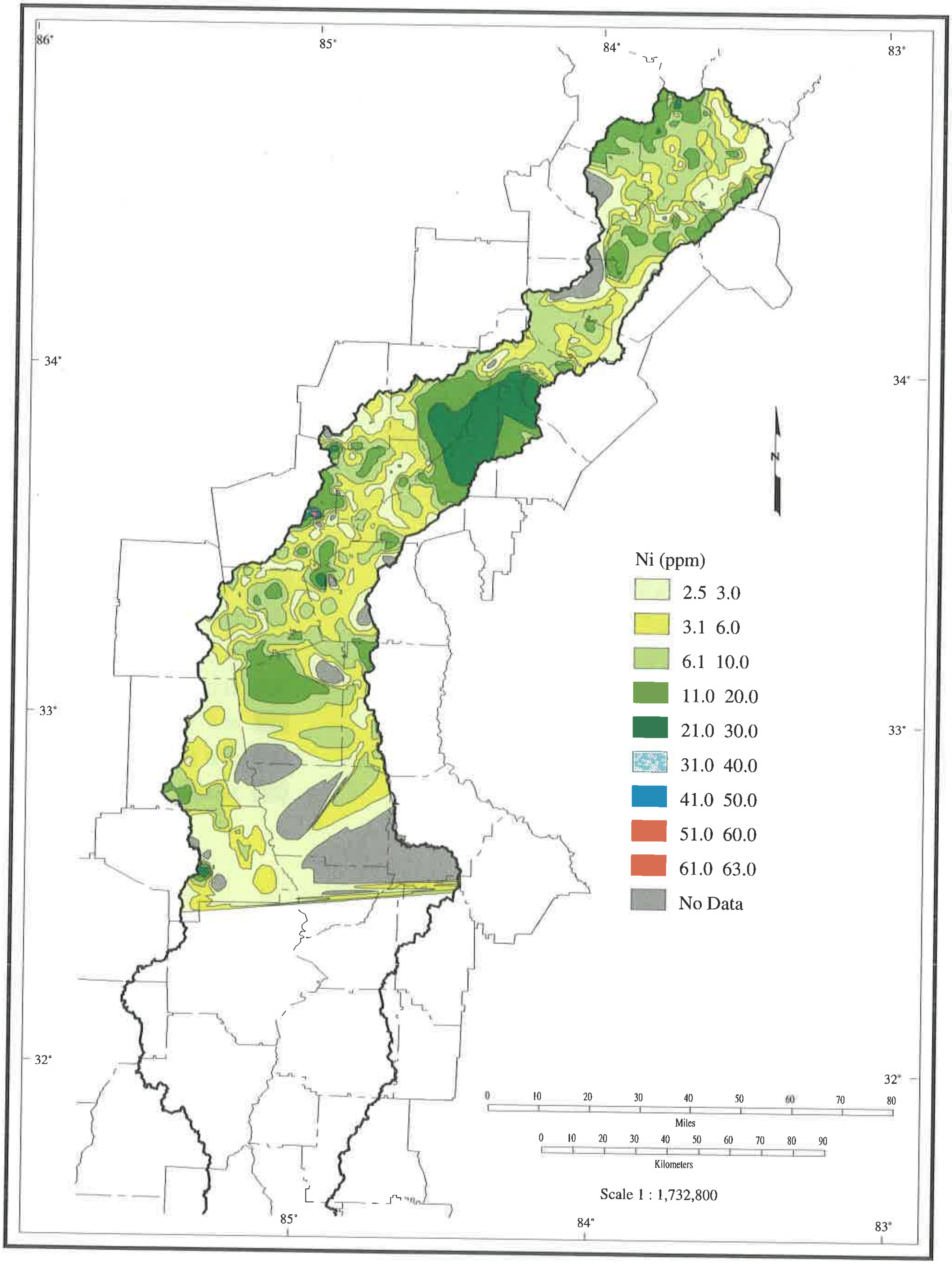

Figure 25. Nickel in stream sediments. Absence of data south of Stewart County and in parts of Cobb, Fulton and DeKalb Counties may cause contouring artifacts.

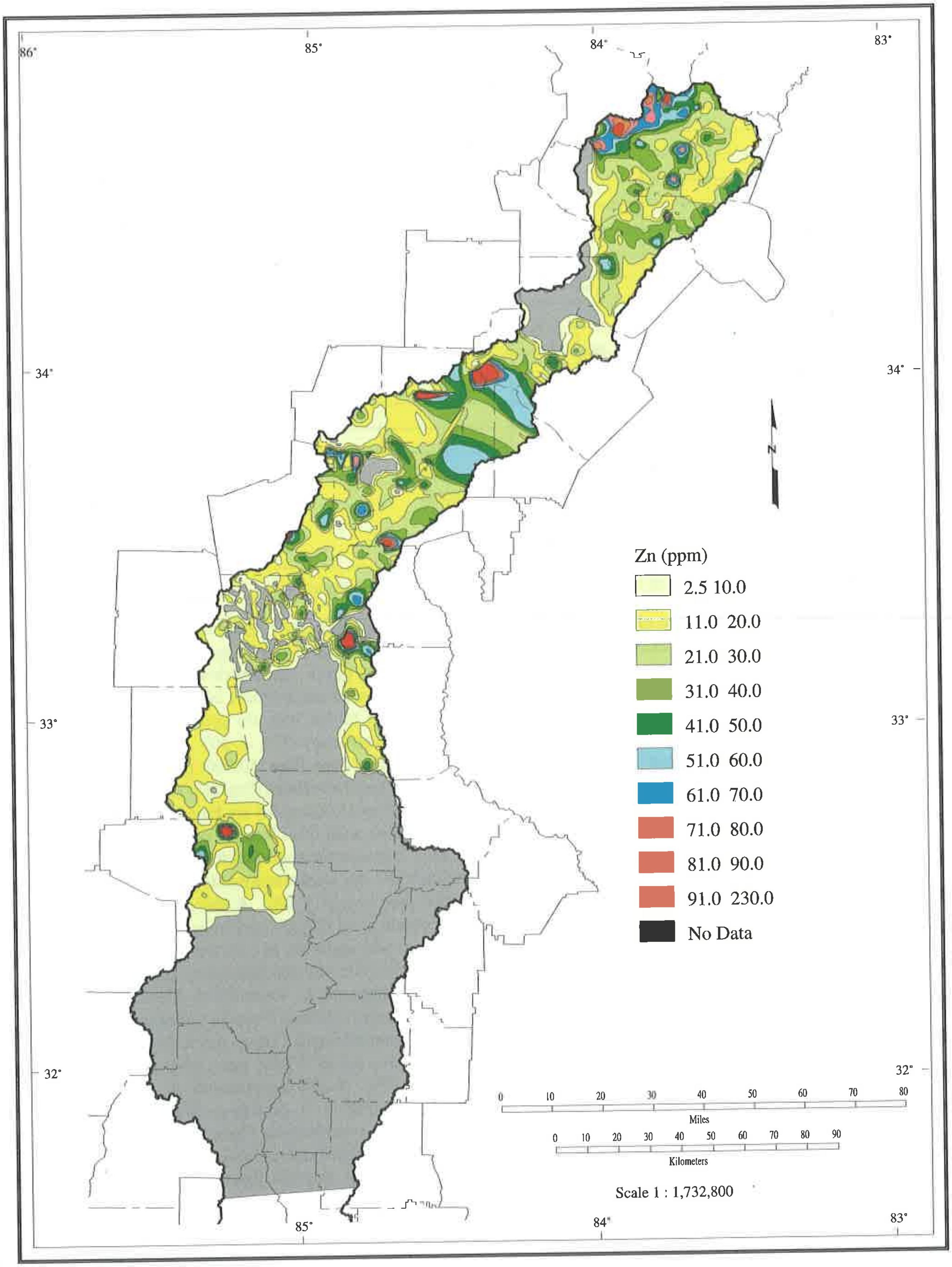

Figure 26. Zinc in stream sediments. Absence of data south of Stewart County and in parts of Cobb, Fulton and DeKalb Counties may cause contouring artifacts.

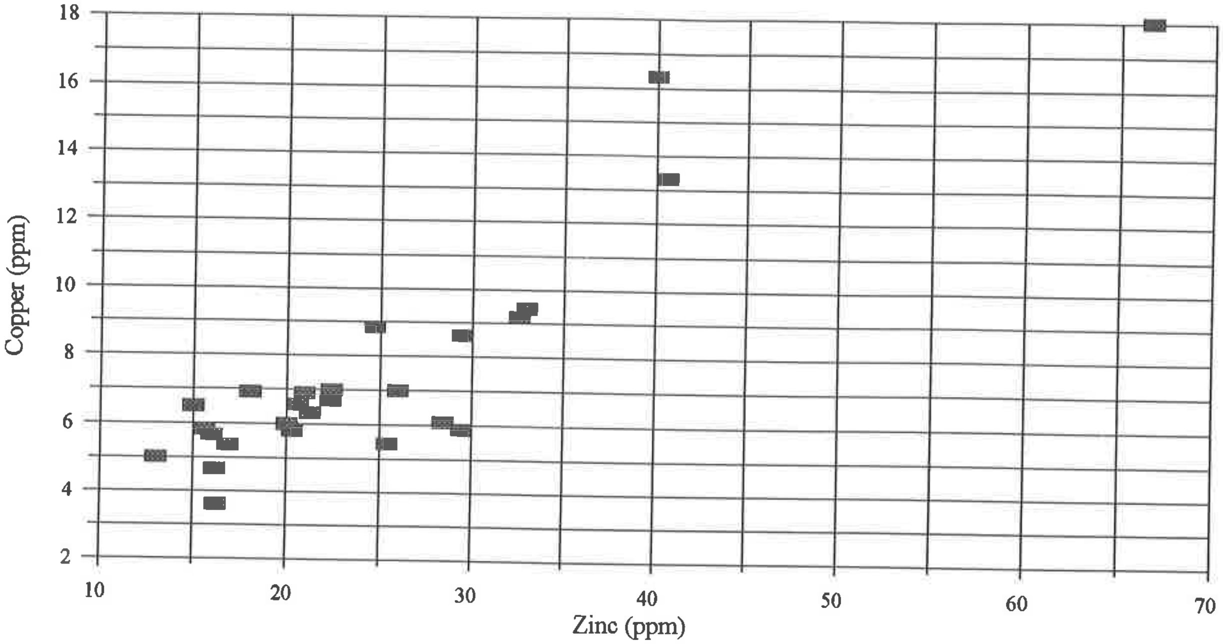

Figure 27. Variation of copper with zinc. A plot of average concentrations per rock unit.

9 suggest a moderately good correlation of iron with pH. At low stream pH (less than 6.5), iron in stream sediment samples is generally below 50,000 ppm (Fig. 29). With stream pH below 6.3, iron is less than 25,000 ppm. The highest iron in stream sediments occurs in streams with a pH of 6.5 to 7.5. Under low pH conditions, much of the iron may be in solution. These relationships may indicate leaching of iron from stream sediments and source materials by acidic waters, particularly in the Coastal Plain.

Rock units (Table 1) with the lowest iron content (Table 8) include: *Qal* - alluvium (7,681 ppm), *Ke* - Eutaw Formation (9,150 ppm), *Kc* - Cusseta Sand (9,491 ppm), *Kb* - Blufftown Formation (10,806 ppm), *Kt* - Tuscalossa Formation (12,163 ppm), *Ptu* - Tuscahoma Sand (12,400 ppm), *gg3* - muscovite granite gneiss (16,300 ppm), and *pms6a* - sericite schist (16,950 ppm). In the Coastal Plain of the Chattahoochee River Basin, sandy rock units, with a low stream pH, generally have the lowest iron values (Fig. 28). A similar relationship was noted in the Oconee River Basin (Cocker, 1996b). In contrast with the low iron values of most Coastal Plain sediments in the Chattahoochee River Basin, stream sediments in Stewart County contain up to 191,000 ppm iron. These values lie along a northeast-trending zone in Stewart County and probably are derived from the "brown iron ore" deposits in the Paleocene Clayton Formation.

Rock units (Table 1) with the highest iron content (Table 8) include: *pms3* - mica schist (55,463 ppm), *pm3a* - mica schist (51,546 ppm), *pms5* - graphite schist (49,920 ppm), *pg1* - garnet mica schist (48,700 ppm), and *mm3* - hornblende gneiss (48,056 ppm). Most of these rock units are schistose, and a few have an amphibolitic component.

Areas of higher iron are generally parallel to regional geology and structure (Fig. A-20). Iron concentrations are generally low (less than 50,000 ppm) over most of the Chattahoochee River Basin (Fig. 28). Lower concentrations of iron (6,900 to 25,000 ppm) are found along the trace of the Brevard fault zone from Heard County through Habersham County. Between the amphibolites of the Dadesville Complex and the Fall Line, stream sediments generally contain 2,500 to 50,000 ppm iron (Fig. 28). A few stream sediments in this area contain up to 122,000 ppm iron. Stream sediments to the northwest and southeast of the Brevard fault zone generally contain 25,000 to 100,000 ppm iron. Unusually high iron is found in sediments in southeastern Carroll County (up to 239,000 ppm), southern Paulding County (up to 134,200 ppm), southern Forsyth County (up to 145,300 ppm), and in White County (up to 127,000 ppm) (Fig. 28). The Dadesville complex (Fig. A-20), represented in part by the *mm3* amphibolite (Fig. A-3), probably accounts for the iron trend (Fig. 28) that extends from Alabama through Troup County and into Coweta County. Some of the scattered small anomalies in the northern part of the Chattahoochee River Basin (Fig. 28) may be related to the small bodies of ultramafic rocks (*um*) in that area (Fig. A-10).

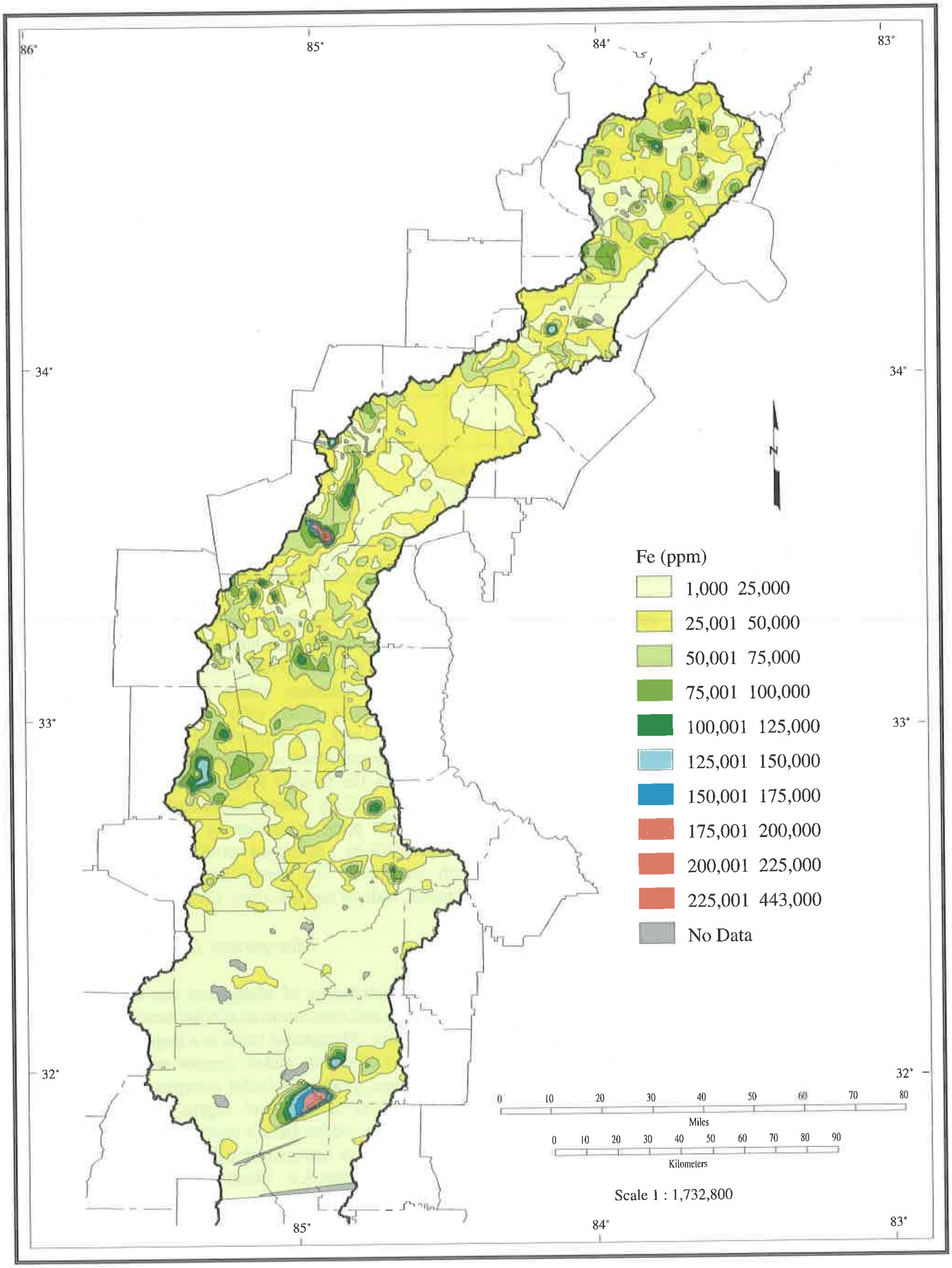

Figure 28. Iron in stream sediments. Absence of data south of Stewart County and in parts of Cobb, Fulton and DeKalb Counties may cause contouring artifacts.

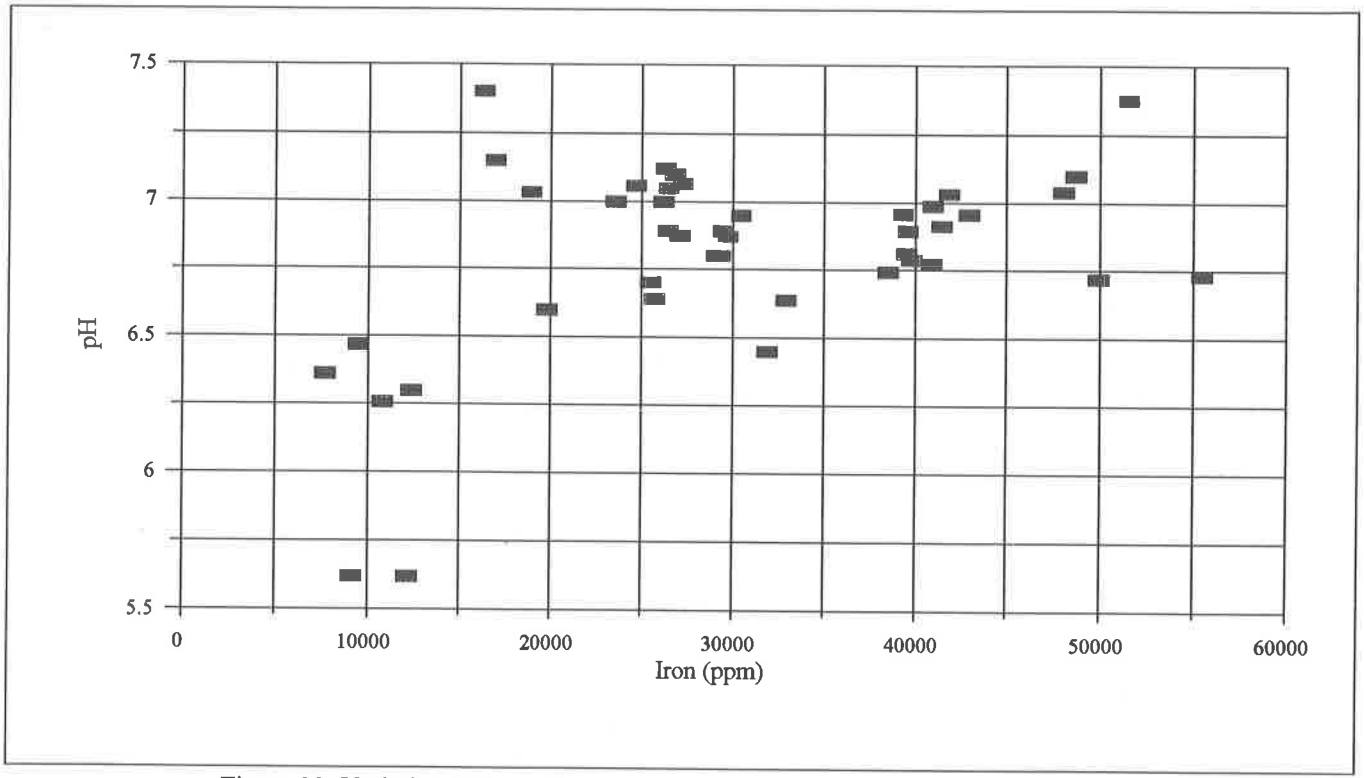

Figure 29. Variation of iron with pH. A plot of average concentrations per rock unit.

Strongest correlations for iron are with titanium, vanadium, and manganese (Table 9). These associations may indicate the presence of vanadium-bearing iron-titanium oxides such as magnetite, hematite and ilmenite. Moderately good correlations are with aluminum, pH, chromium, copper and scandium. In contrast to the Oconee River Basin with its abundance of Carolina terrane metavolcanic rocks, the association of sodium and magnesium with iron is not very important

Magnesium (Mg)

Primary sources of magnesium are ultramafic and mafic rocks and, to a lesser extent, carbonate rocks and shales (Table 5). These source rocks are present in the Chattahoochee River Basin and have a direct affect on the geochemistry of stream sediments. Average magnesium content of Chattahoochee River Basin stream sediments is 2,240 ppm (Table 7). Highest magnesium values in Chattahoochee River Basin stream sediments (Table 8) are related to rock units: *mm9* - amphibolite (4,862 ppm), *pg1* - garnet mica schist (4,300 ppm), and *pms1* - mica schist (2,871 ppm). High magnesium in amphibolites is attributed to abundant iron-magnesium silicates in those rock units. The strongest magnesium anomaly in the Chattahoochee River Basin is spatially coincident with rock unit *mm9* (Fig. A-3), which represents the Laura Lake Mafic Complex (Fig. A-21). Scattered small anomalies in the northern part of the Chattahoochee River Basin (Fig. 30) may be attributed to the many small ultramafic rocks (*um*) in this area (Fig. A-10). Rock units (Table 1) with the lowest magnesium values (Table 8) include: *gg3* - muscovite granite gneiss (600 ppm), *fg4* - biotitic gneiss (1,040 ppm), and *gr1* - granite (1,056 ppm). No samples from the Coastal Plain were analyzed, but sedimentary rock units within the Coastal Plain of the Chattahoochee River Basin are most likely comparable to the low magnesium values (630 to 970 ppm) identified in the Oconee River Basin (Cocker, 1996b). Strongest correlations for magnesium are with iron (Fig. 32), vanadium, aluminum, manganese, titanium, sodium and alkalinity (Table 9).

Manganese (Mn)

The distribution of manganese can strongly affect the distribution and concentration of other metals, particularly the heavy metals. Manganese oxide is a major factor controlling the content of cobalt, nickel, copper and zinc in soils and waters(Jenne, 1968). Colloidal manganese oxides generally adsorb cations to a greater degree than do iron oxides. Colloidal iron oxides have a positive charge up to a pH of about 8.5, while manganese oxides are negatively charged above a pH of about 3.0. Metal enrichment by adsorption is thus generally greater for manganese oxides than for iron oxides. Excess manganese in water can clog pipes and

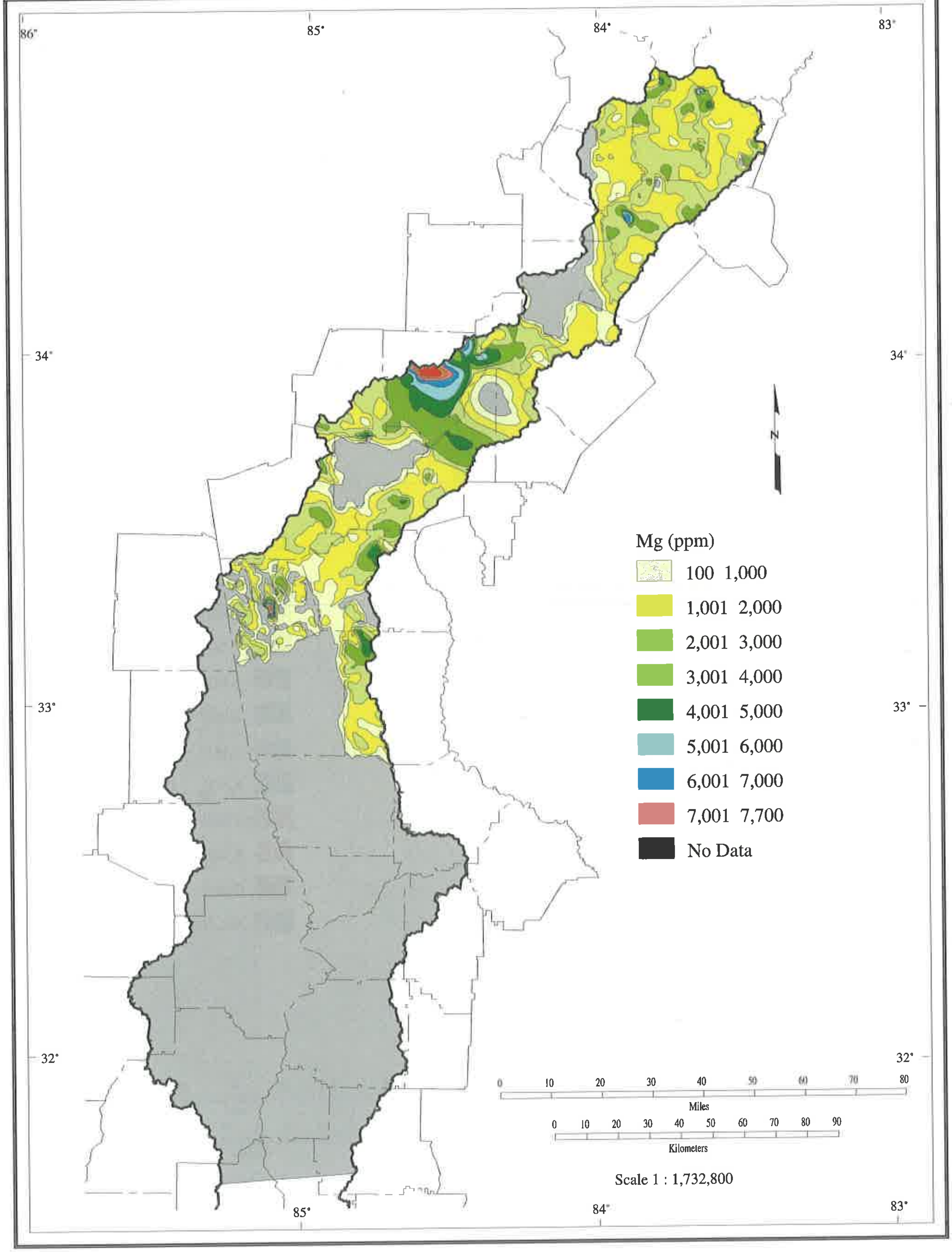

Figure 30. Magnesium in stream sediments. Absence of data south of Stewart County and in parts of Cobb, Fulton and DeKalb Counties may cause contouring artifacts.

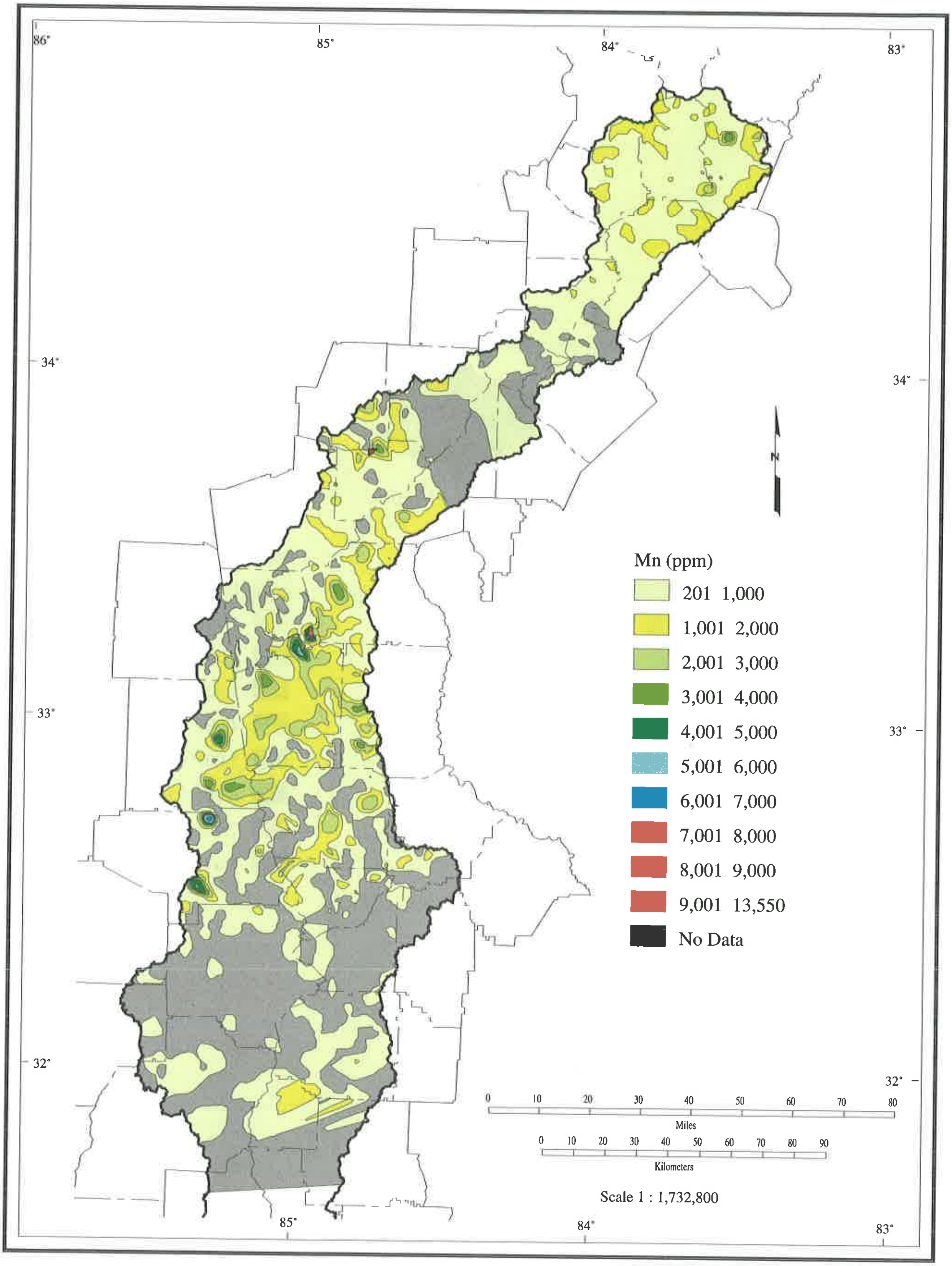

Figure 31. Manganese in stream sediments. Absence of data south of Stewart County and in parts of Cobb, Fulton and DeKalb Counties may cause contouring artifacts.

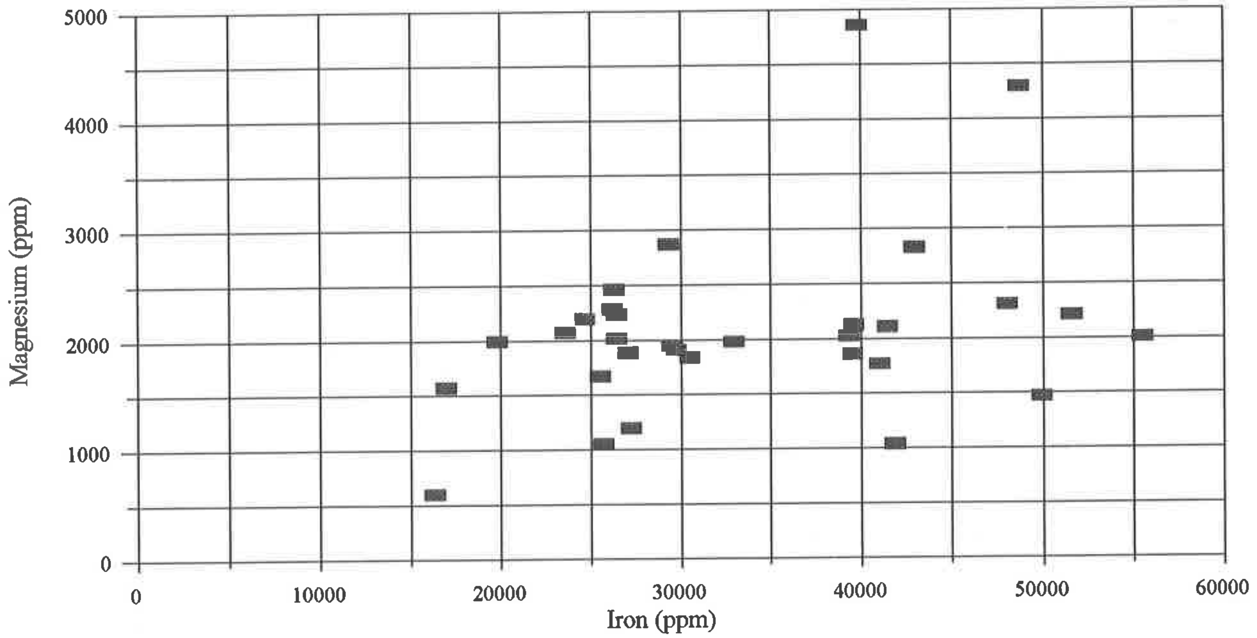

Figure 32. Variation of magnesium with iron. A plot of average concentrations per rock unit.

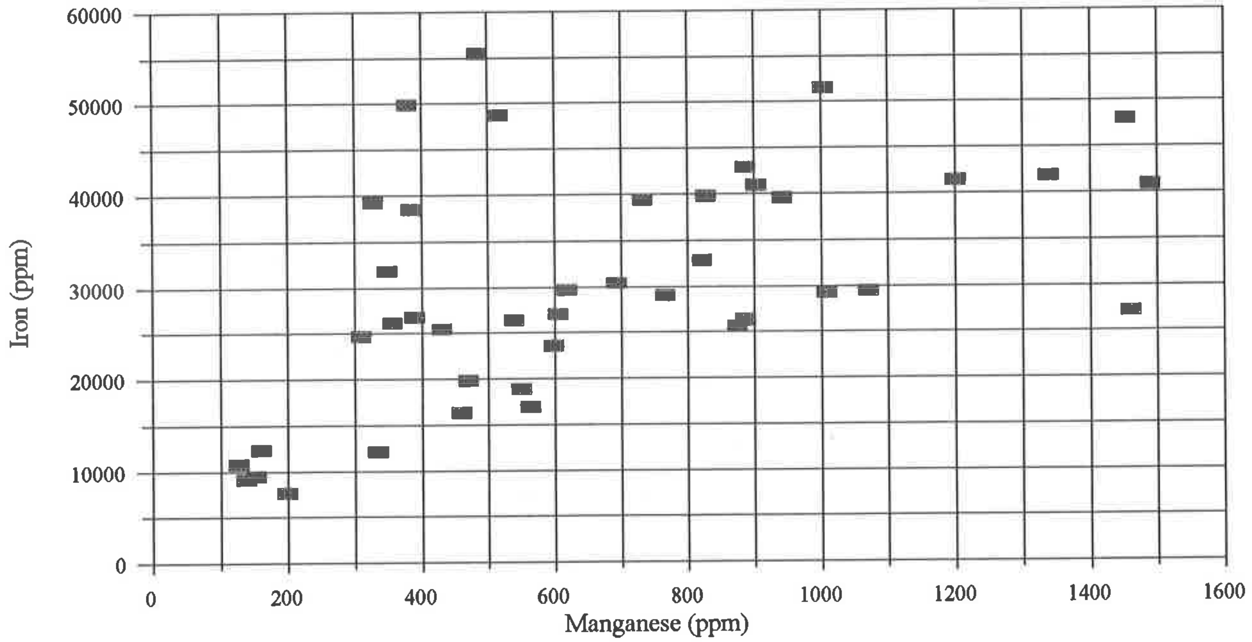

Figure 33. Variation of manganese with iron. A plot of average concentrations per rock unit.

screens, and stain clothes. Manganese is present as soluble manganese bicarbonate that will precipitate when carbon dioxide (CO_2) is liberated from solution. Manganese bicarbonate may change to manganese hydroxide with increased oxidation.

Correlation coefficients (Table 9) show a good correlation of manganese with conductivity, pH and alkalinity. A plot of manganese versus pH shows that the manganese content of stream sediments is generally less than 1,200 ppm where stream pH is less than 7.0. Manganese content is generally greater than 2,000 ppm, when stream pH is greater than or equal to 7.0. These relations suggest that manganese may be in solution under low pH conditions and as manganese oxides under high pH conditions.

High concentrations of manganese in stream sediments (Fig. 31) are located generally south of the Brevard Fault zone in the Inner Piedmont terrane (Fig. A-20). This is spatially correlative with higher concentrations of iron (Fig. 28), titanium, scandium, and vanadium (unpublished Georgia Geologic Survey maps). A narrow band of anomalous manganese, iron, vanadium, and scandium corresponds with the Uchee terrane (Fig. A-20). Slightly anomalous manganese concentrations are found in the lower part of the Chattahoochee River Basin where anomalous iron is related to the "brown iron ore" in the Paleocene Clayton Formation. Correlation coefficients also show a strong positive correlation with scandium, aluminum, vanadium, iron (Fig. 33), alkalinity, pH, and conductivity (Table 9).

Lowest manganese concentrations in the Chattahoochee River Basin (Table 8) are found in Coastal Plain stream sediments with average values that range from 127 to 390 ppm. Rock units with low manganese values include: *Kb* - Blufftown Formation (127 ppm), *Ke* - Eutaw Formation (138 ppm), *Kc* - Cusseta Sand (154 ppm), *Ptu* - Tuscahoma Sand (160 ppm), *Qal* - Alluvium (200 ppm), *mm2* -hornblende gneiss (310 ppm), *pms4* - mica schist (328 ppm), *Kt* - Tuscaloosa Formation (334 ppm), *Kr - Ripley Formation* (348 ppm), *pg2 - garnet mica schist* (356 ppm), *pms5*- graphite schist (380 ppm), *Kp* - Providence Sand (385 ppm), and *Eo-Os* Eocene-Oligocene residuum (390 ppm). Manganese was not retained in sediments derived from most Coastal Plain rock units, perhaps due to the low pH of most of these streams. Rock units with the highest manganese (Table 8) include: *bg2* - biotite gneiss (1,490 ppm), *gg5* - calc-silicate granite gneiss (1,460 ppm), *mm3* - hornblende gneiss (1,453 ppm), *fg4* - biotitic gneiss (1,338 ppm), *pa2* - sillimanite schist (1,201 ppm), *pms1* - mica schist (1,009 ppm), *pm3a* - metagraywacke (1,004 ppm), and *pms3a* - mica schist (1,070 ppm). Manganese concentrations are lower in the Chattahoochee River Basin than in the Oconee River Basin, which had values of 1,960 ppm to 3,300 ppm in amphibolitic and mafic rock units (Cocker, 1996b).

Titanium (Ti)

Median concentrations of titanium in average crustal rocks (Table 5) are 3,000 ppm in ultramafic rocks, 9,000 ppm in basalt, 8,000 ppm in granodiorite, and 2,300 ppm in granitic rocks. Median concentrations are 400 ppm in limestones and 4,600 ppm in shales (Levinson, 1974). Stream sediments within the Chattahoochee River Basin tend to equal or greatly exceed these crustal averages with average concentrations of 9,550 ppm (Table 7).

Highest concentrations of titanium occur in a belt extending from Habersham County into Forsyth County. High titanium values are also found in Harris County. These high titanium concentrations coincide with high concentrations of rare-earth metals and with heavy mineral/monazite belts (Fig. 4). As in the Oconee River Basin study (Cocker, 1996b), titanium shows a strong correlation with iron (Table 9 and Fig. 34). Titanium may be present as iron-titanium oxides such as ilmenite, hematite or magnetite.

Rock units with the lowest titanium content (Table 8) include: *mm4* - hornblende gneiss (2,750 ppm), *gg5* - calc-silicate granite gneiss (3,950 ppm), *gg3* - muscovite granite gneiss (4,700 ppm), *Kc* - Cusseta Sand (5,083 ppm), um - ultramafic rocks (5,100 ppm), and *Kb* - Blufftown Formation (5,891 ppm). Rock units with the highest titanium content (Table 8) include: *pg1* - garnet mica schist (22,600 ppm), *q1* - quartzite (19,400 ppm), *pms5* -graphite schist (17,900 ppm), *pm3a* - mica schist (16,636 ppm), *mm3* - hornblende gneiss (16,578 ppm), *mm9* - amphibolite (15,550 ppm), and *pm2* - metagraywacke (14,158 ppm).

Vanadium (V)

Studies indicate that excess vanadium may have adverse effects on plant growth; however, field data regarding vanadium pollution are rare (Edwards and others, 1995). The largest contributor of vanadium to the environment is the combustion of coal and oil, and the disposal of combustion wastes. Vanadium could be used as an indicator of contamination from such sources. Although vanadium is used in metallurgy, electronics, dyeing, and as a catalyst, the input into the environment from these sources is small (Edwards, and others, 1995).

In the Chattahoochee River Basin, the average vanadium concentration is 72 ppm (Table 8). Rock units with the lowest vanadium include: *Kc* - Cusseta Sand (23 ppm), *Kb* - Blufftown Formation (29 ppm), *Qal* - alluvium (30 ppm), *Ptu* -Tuscahoma Sand (30 ppm), *mm2* - hornblende gneiss (40ppm), *gr1b* - porphyritic granite (40 ppm), and *Ke* - Eutaw Formation (41 ppm). Rock units with the highest vanadium include: *pm3a* - mica schist (140 ppm), *mm3* - hornblende gneiss (139 ppm), *pg1* - garnet mica schist (123 ppm), *mm9*

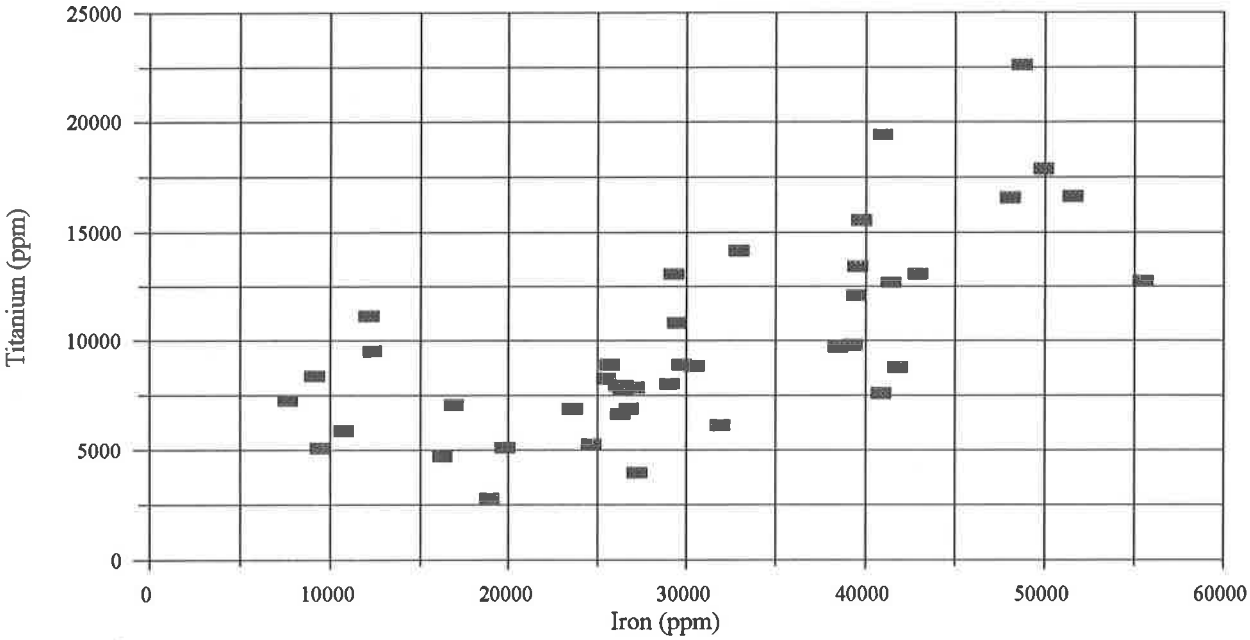

Figure 34. Variation of titanium with iron. A plot of average concentrations per rock unit.

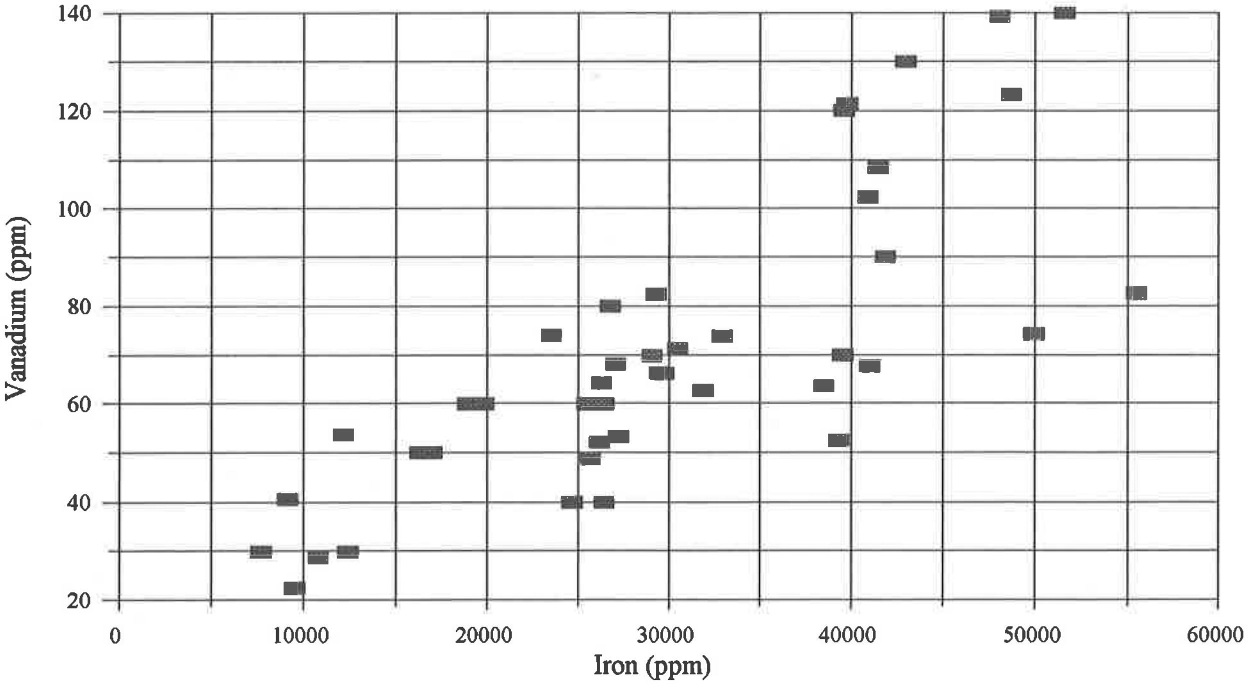

Figure 35. Variation of vanadium with iron. A plot of average concentrations per rock unit.

- amphibolite (121 ppm), and *fg3* - biotitic gneiss (120 ppm). The stronger vanadium anomalies are spatially associated with the *mm3* - hornblende gneiss unit in Troup County that constitutes the greater part of the Dadesville Complex (Figs. A-3 and A-20). A belt of high vanadium values, which extends from Habersham County into Forsyth County, coincides with high concentrations of titanium, rare-earth metals, and with heavy mineral/monazite belts. Lower vanadium concentrations in sandy units of the Coastal Plain are also coincident with a region with lower pH streams (Fig. 12). High vanadium in Quitman County may be associated with the "brown iron ore" deposits in the Paleocene Clayton Formation.

The vanadium-iron-titanium-manganese association (Table 9), which has been discussed earlier, is supported by a plot of vanadium versus iron (Fig. 35), and a similar distribution of titanium (unpublished Georgia Geologic Survey maps) and iron (Fig. 28).

The median concentration of vanadium in average crustal rocks (Table 5) is higher for mafic rocks (250 ppm) and shales (130 ppm) (Rose and others, 1979) than in other rock types. This relation is consistent with high vanadium in shales and amphibolitic rocks in the NURE sediment data.

Lithogeochemistry

Cook and Burnell (1985) mapped and sampled ten principal rock units within the Dahlonega district. A summary of their data provides documentation of the trace-metal content of major lithologic units in that district (Table 10). Gold and silver were analyzed by standard fire assay followed by atomic absorption spectrophotometry. Arsenic, antimony, copper, lead and zinc were analyzed by atomic absorption spectrophotometry (Cook and Burnell, 1985).

According to Cook and Burnell's data, the units *cp*, *igf-1* and *igf-2* have higher than average trace metals. These metals include arsenic, antimony, lead, and zinc. The amphibolite (*unu*) containing the Chestatee massive sulfide trend corresponds with the Univeter Formation of German (1985). That amphibolite contains the highest average silver and copper values in the Dahlonega district. Many Dahlonega district gold deposits are associated with the "Findley Ridge" amphibolite (equivalent to the Pumpkinvine Creek Formation in German, 1985). That amphibolite contains higher than average amounts of copper and arsenic. Cook and Burnell's data suggest that the chemical sediment (the iron formation within the Pumpkinvine Creek Formation in German, 1985), the metatuff (Barlow Gneiss in German, 1985), and the coarsely porphyritic facies of the garnet-biotite-quartz schist (Proctor Creek Member of the Canton Formation in German, 1985) may be the sources of metals for the Dahlonega district, and the Findley Ridge amphibolite may have served as the structurally permissive host for the sites of gold deposition.

The amphibolite and mica-quartz schist of German (1985) and the NW-area amphibolite-hornblende gneiss of Cook and Burnell (1985) correspond with the *bg1* unit (Fig. A-17) that is associated with stream sediments anomalous in aluminum, cobalt, copper, lead, nickel, silver, sodium, and zinc (Figs. 16, 22, 23, 24, 25, 26 and unpublished geochemical maps) that were discussed earlier. Cook and Burnell's (1985) data indicate that this unit contained relatively high zinc, silver and copper concentrations.

Lesure (1992a, 1992b) conducted a geochemical reconnaissance of the Dahlonega and Carroll County gold belts from 1966 to 1968. Lesure and others (1991 and 1992) report geochemical analyses from 1,667 rocks, saprolite and soil collected during that reconnaissance study. The data include multiple samples from many of the sample sites. Average geochemical concentrations were calculated for each sample point and a GIS coverage was created. A second coverage was derived by clipping the initial coverage with the borders of the Chattahoochee River Basin (Fig. 36). This derived coverage contains 396 sample points located within the Chattahoochee River Basin. This geochemistry is summarized in Table 11. Most samples were analyzed for iron, magnesium, titanium, antimony, arsenic, barium, beryllium, bismuth, cadmium, chromium, cobalt, copper, lead, manganese, nickel, scandium, silver, vanadium, and zinc. Semiquantitative analyses were done by optical-emission spectrography. Another set of samples was analyzed for copper, lead, and zinc by atomic-absorption techniques. A third set was analyzed for arsenic by colorimetric methods. These analyses were all performed in U.S. Geological Survey laboratories. A smaller set of samples was analyzed for copper, lead, zinc and arsenic by atomic-absorption techniques at Skyline Labs., Inc. (Lesure, 1992a and b).

Correlation coefficients (Table 12) indicate that duplicate analyses done by several methods and by the two labs are generally in agreement with each other. The correlation coefficients show strong associations between lead and zinc; copper and zinc; silver and zinc; silver and mercury; iron, vanadium, and scandium; and chromium and nickel (Table 12). Some of these associations (e.g. iron-vanadium-scandium) are evident in the NURE stream sediment samples. The more detailed sampling by Lesure and others (1991 and 1992) allows finer distinctions in the base- and precious-metal correlations.

Ten rock samples from the Pumpkinvine Creek Formation and the Univeter Formation were analyzed for vanadium, chromium and nickel (German, 1985). In the Pumpkinvine Creek Formation, concentrations for vanadium ranged from 45 to 100 ppm, chromium ranged from 50 to 350 ppm, and nickel from 60 to 110 ppm. In the Univeter Formation, concentrations for vanadium ranged from 50 to

240 ppm, chromium ranged from 5 to 310 ppm, and nickel from 15 to 250 ppm. Descriptions and locations of these samples and the method of chemical analysis for these samples are not provided (German, 1985).

Geochemical analyses for 15 samples collected from the Hall County gold district (Table 13) indicate that the Hall County veins are high in lead, zinc, silver, arsenic, antimony, gold, and copper (Allen, 1986). Correlation coefficients for the Hall County data (Allen, 1986) indicate two geochemical associations in samples from Hall County. These are copper-arsenic-gold and lead-zinc-silver-antimony (Table 14). The copper-arsenic-gold association may represent the presence of chalcopyrite inclusions in gold- and arsenic-bearing pyrite. The second association may represent the presence of silver-bearing sulfosalts.

GEOCHEMICAL STATISTICS

Basic statistics were computed for each element for all samples in the Chattahoochee River Basin, and all samples within various rock units within the Chattahoochee River Basin in Georgia. The previous study of the Oconee River Basin showed that stream sediment geochemistry and stream hydrogeochemistry are strongly influenced by the mineralogy of the rock units in contact with the water in a stream's basin (Cocker, 1996b).

Each sample site in the NURE database was assigned by the GIS to a geologic rock unit by overlaying the Geologic Map of Georgia coverage and the sample sites coverage. Some errors may result in assigning rock units to the sample sites because of differences in accuracy of the two coverages. Table 6 shows the number of sample sites that the GIS counted per rock unit. Because not all of the samples were analyzed for each metal, the number of samples per rock unit may be different for different metals. Rock units that had no sample sites are indicated as having zero sample sites. Table 6 also shows the percentage of sample sites that are found within each rock unit in the Chattahoochee River Basin. The percentage of total samples indicates the relative contribution of each rock unit to the overall geochemistry of the Chattahoochee River Basin. The number of sample sites indicates the reliability of the data assigned to each rock unit. Thus, a greater degree of confidence may be expected in the geochemistry for rock units *fg3, bg1, pms3a, mm3, pms3* than for rock units such as *Eo-Os, Qal, fg1, fg2, gg3, q1a, and um* (Table 1). Average values were calculated for all sample sites that are within each rock unit (Table 8).

Average concentrations of the various metals in the more common rock types in the earth's crust (Table 5) provide a standard for comparison with the NURE data. Table 5 shows that ultramafic and mafic rock units commonly contain higher concentrations of heavy metals than more felsic rocks such as granites. Shales also may be expected to be a source of heavy metals.

Correlation coefficients were calculated to provide a basin-wide picture of the more prominent geochemical relations (Table 15). Correlation coefficients were also calculated for samples grouped by rock unit (Table 9). Intragroup correlations aid in assessing effects of provenance versus other factors, such as anthropogenic sources (Cocker, 1996b). The great diversity of source materials, mixing of stream sediments and stream waters from different sources, and potentially different weathering environments may create considerable noise and reduce otherwise strong correlation coefficients. Variations in mineralogy may generate a low correlation coefficient between metals derived from the same source rock.

Strongest correlations (Table 9) are those in the iron-manganese-titanium-vanadium group and in the zinc-cobalt-copper-lead-nickel group. In the iron-manganese-titanium-vanadium group coefficients range from 0.5263 to 0.7882. This association suggests the presence of manganese- and vanadium-bearing iron-titanium oxides such as magnetite and ilmenite. Correlation coefficients of magnesium with these metals range from 0.3311 to 0.5339 in Table 9. An association of magnesium silicates with iron-titanium oxides is commonly found in mafic and ultramafic rock units.

In the zinc-cobalt-copper-lead-nickel group, coefficients that range from 0.3623 and 0.8988 suggest the presence of zinc-copper-cobalt-lead-nickel-bearing sulfides. Base-metal sulfide mineralization is locally abundant, particularly in the western and northern parts of the Chattahoochee River Basin. Relatively high silver correlations with this group (0.3976 to 0.6593) suggest that silver may be a previously unrecognized or unappreciated component of base-metal mineralization in Georgia. A weaker association of these metals with iron (0.2176 to 0.4157) may suggest the presence of iron-bearing sulfides or oxides with the other metals. The strongest correlation with iron is for copper, suggesting the presence of chalcopyrite in the sediments. Chalcopyrite is locally abundant in some rock units, particularly those in the western and northern parts of the Chattahoochee River Basin. A relatively high correlation of aluminum with most of these base-metals (except nickel), with coefficients between 0.4270 and 0.6126, may indicate a genetic relationship. Aluminum silicates are commonly formed in hydrothermal alteration zones associated with base- and precious-metal mineralization.

Alkalinity, pH and conductivity are regionally associated with tectonostratigraphic terranes and locally with individual rock units. However, this association is not as strong as that seen in the Oconee River Basin (Cocker, 1996b). Correlation coefficients of pH with alkalinity and conductivity are only 0.4025 and 0.4569, respectively. The stronger association in this group is between alkalinity and conductivity with a

Table 9. Correlation coefficients by rock unit.

	Temp	pH	Alkalinity	Conductivity	Ag	Al	As	Ba	Be	Co	Cr	Cu
Temperature	1.0000											
pH	-0.2554	1.0000										
Alkalinity	0.0339	0.4025	1.0000									
Conductivity	-0.2261	0.4569	0.9183	1.0000								
Ag	-0.2468	-0.1141	-0.3150	-0.2916	1.0000							
Al	-0.4110	0.6557	0.2732	0.3898	0.5229	1.0000						
As	0.5302	-0.1204	-0.5160	-0.3901	-0.3374	-0.2152	1.0000					
Ba	0.0707	0.0890	0.3346	0.1774	0.4215	0.4569	-0.5147	1.0000				
Be	0.4187	0.1400	0.2213	0.2494	-0.1654	-0.2037	-0.5300	-0.1465	1.0000			
Co	-0.1899	0.0057	0.1016	0.0438	0.3976	0.6126	-0.1118	0.1218	0.0426	1.0000		
Cr	0.0152	-0.0938	-0.2929	-0.1028	0.5480	0.1945	0.0327	-0.0499	0.0441	0.1693	1.0000	
Cu	-0.0277	0.2626	-0.1304	-0.1130	0.6593	0.5583	-0.2268	0.0709	0.0599	0.6082	0.4450	1.0000
Fe	-0.2827	0.4706	-0.0814	0.0564	0.2884	0.4458	0.0339	-0.2650	0.1140	0.2336	0.4678	0.4157
K	0.4609	0.0800	0.3281	0.2199	0.0907	0.3076	-0.3405	0.6263	0.1532	0.1129	-0.2217	0.0573
Mg	-0.1492	-0.0676	-0.1943	-0.2309	0.3659	0.0839	0.1001	-0.0126	-0.0345	0.4546	0.4210	0.2503
Mn	-0.3763	0.4598	0.4337	0.5279	0.0942	0.6570	-0.4866	0.3962	-0.0777	0.2780	-0.0074	0.1548
Na	-0.4457	0.3095	-0.0506	0.0691	0.4467	0.6174	0.2521	-0.0042	-0.3407	0.0847	0.2989	0.3806
Ni	0.2750	0.3257	0.0435	-0.0015	0.4888	0.2502	-0.1206	0.2268	0.2773	0.4948	0.3233	0.5570
P	-0.2475	-0.2626	-0.5212	-0.3614	0.4437	0.3716	0.0706	-0.0485	-0.1623	-0.0633	0.4772	0.3579
Pb	-0.4488	-0.1499	-0.1549	-0.1705	0.5697	0.5272	-0.2128	0.1412	0.0227	0.7495	0.2831	0.5556
Sc	-0.3769	0.6274	0.2719	0.3717	0.0767	0.6557	-0.2117	0.1638	-0.2109	-0.0630	-0.0014	0.1138
Ti	-0.3184	0.0898	-0.3260	-0.1758	0.5252	0.1496	-0.1969	0.0073	0.1103	0.3134	0.5529	0.5183
V	-0.3231	0.4030	0.0237	0.1698	0.4309	0.6052	-0.1236	-0.1032	0.0138	0.4895	0.5513	0.5468
Zn	0.0019	0.2089	-0.0788	-0.1104	0.6460	0.4720	-0.2478	0.2667	0.0403	0.6731	0.5520	0.8988

	Fe	K	Mg	Mn	Na	Ni	P	Pb	Sc	Ti	V	Zn
Fe	1.0000											
K	-0.4020	1.0000										
Mg	0.3311	-0.2726	1.0000									
Mn	0.5263	0.0856	-0.0338	1.0000								
Na	0.2847	-0.0511	0.0788	0.3448	1.0000							
Ni	0.0869	0.3245	0.3178	-0.2247	-0.0839	1.0000						
P	0.2637	-0.0892	-0.0535	0.0550	0.7066	-0.1117	1.0000					
Pb	0.2176	-0.0751	0.4201	0.0564	0.2680	0.3623	0.1785	1.0000				
Sc	0.4467	-0.3140	-0.0460	0.7067	0.4693	-0.1874	0.1311	-0.1052	1.0000			
Ti	0.7026	-0.2443	0.5110	0.2559	0.1343	0.2258	0.2394	0.3425	0.1153	1.0000		
V	0.7882	-0.3371	0.5339	0.6078	0.4857	0.1362	0.3604	0.3730	0.5474	0.6589	1.0000	
Zn	0.3393	0.1232	0.3575	0.0895	0.0847	0.6785	0.0645	0.6333	-0.0921	0.5298	0.4446	1.0000

Table 10. Mean and maximum trace metal content of Dahlonega district lithologies
(modified from Cook and Burnell, 1985).

Map symbol	Number of samples	Ag (ppm)	As (ppm)	Sb (ppm)	Cu (ppm)	Pb (ppm)	Zn (ppm)
unu	17	1.3 (7.4)	7 (18)	0.6 (1.2)	77 (117)	13 (34)	61 (92)
plc	62	0.3 (1.1)	4 (14)	0.3 (0.8)	55 (224)	4 (42)	67 (155)
pc	42	0.1 (0.8)	4 (15)	0.5 (1.6)	35 (115)	5 (35)	73 (138)
cp	26	0.2 (1.1)	28 (100)	0.7 (4.6)	52 (80)	8 (44)	89 (155)
pcu	38	0.1 (0.5)	9 (110)	0.3 (1.2)	70 (105)	3 (20)	57 (120)
igf-1	31	0.1 (0.5)	12 (240)	2.9 (30)	52 (195)	13 (76)	62 (165)
igf-2	22	0.1 (1.0)	8 (47)	1.6 (11.6)	48 (150)	31 (240)	86 (460)
blg	13	0.1 (0.1)	4 (7)	0.3 (0.6)	24 (54)	2 (6)	71 (112)
bg, hg	32	0.1 (0.1)	3 (5)	0.7 (4.8)	17 (62)	5 (28)	40 (130)
as	20	0.3 (1.8)	4 (5)	0.4 (0.8)	57 (285)	3 (18)	56 (410)

Map Symbol	**Map Units German (1985)**	**Map Units Cook and Burnell (1985)**
unu	Univeter Formation	Chestatee massive sulfide trend amphibolite
plc	Palmer Creek Member - Canton Formation	Thin-banded variable amphibolites
pc	Proctor Creek Member - Canton Formation	Garnet-biotite-quartz schist
cp	Coarsely porphyroblastic facies of Proctor Creek Member - Canton Formation	Garnet-biotite-quartz schist coronite
pcu	Pumpkinvine Creek Formation	“Findley Ridge” amphibolite
igf-1	iron formation - Pumpkinvine Creek Formation	Chemical sediment
igf-2	sericite-quartz schist (metatuff?)-Pumpkinvine Creek Formation	Quartz-sericite schist
blg	Barlow Gneiss Member - Pumpkinvine Creek Formation	Metatuff (Barlow Gneiss)
bg, hg	biotite metatrondjhemite, hornblende metatrondjhemite	Dioritic units
as	amphibolite and mica-quartz schist	NW area amphibolite-hornblende gneiss

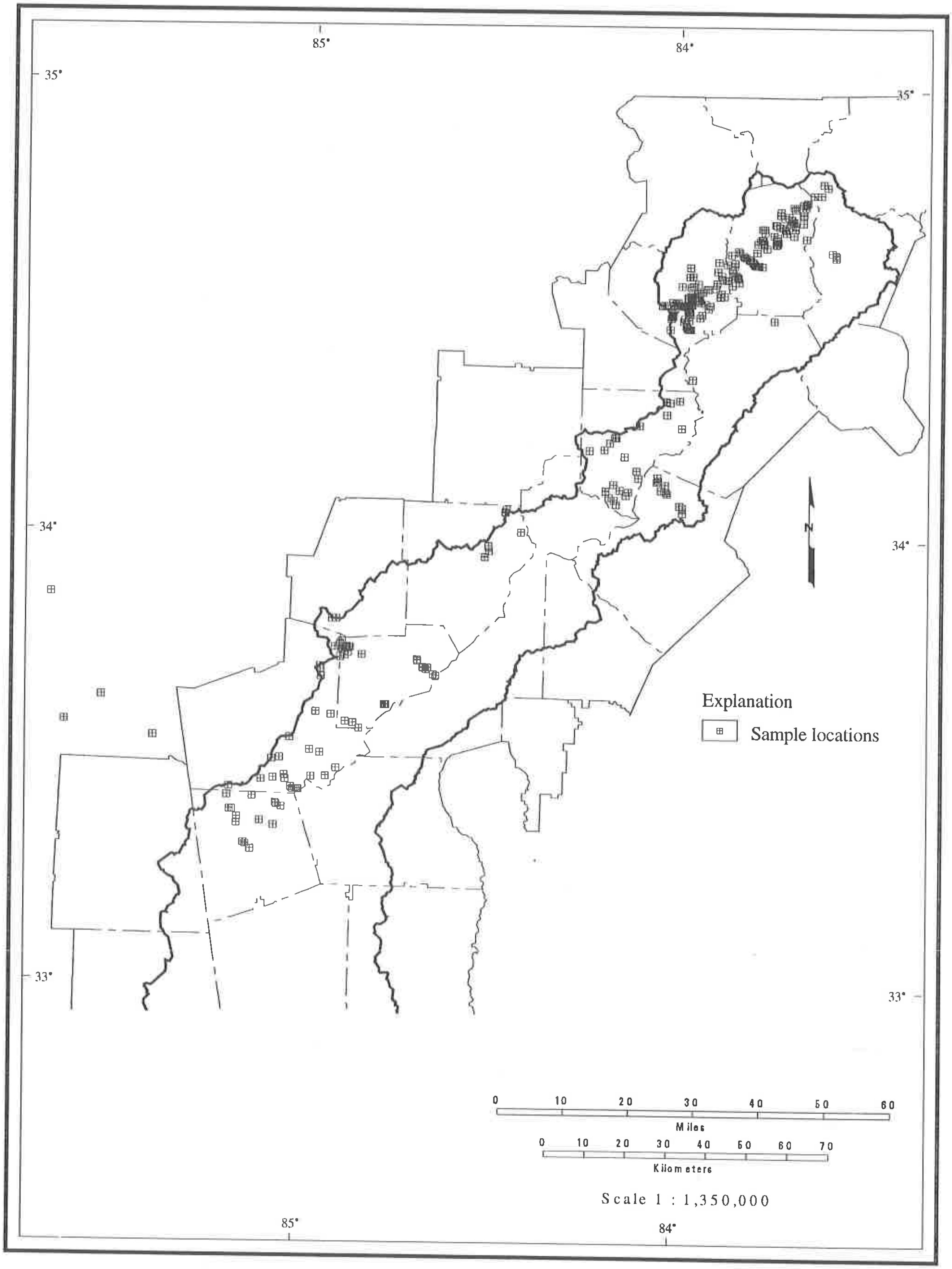

Figure 36. Lithogeochemical sample locations

Table 11. Summary trace - element geochemistry of rock, soil and saprolite samples from the Dahlonega belt.
Data from Lesure and others, 1991 and 1992. Values are in ppm.

Metal	Average	Mean	Maximum	Minimum	Standard deviation
Ag	0.45	0.06	3.0	0.25	0.46
As	7.86	5.86	135.0	5.0	10.9
Ba1*	488.52	106.09	1,317.0	57.0	259.12
Ba2**	465.96	465.96	3,000.0	15.0	427.27
Be	1.63	1.4	5.0	1.00	0.86
Co	29.36	27.07	760.0	2.50	50.02
Cr	70.85	15.21	514.0	5.0	71.65
Cr	80.63	79.2	5,000.0	1.0	260.77
Cu1*	63.71	62.1	4,100.0	2.50	228.05
Cu2**	104.57	22.71	800.0	2.50	155.86
Cu3***	122.91	122.91	15,046.30	0.50	832.52
Fe	49,011.96	49,011.96	20,000.0	600.0	35,332.77
Hg	0.92	0.12	5.0	0.09	1.12
Mg	6,601.46	6,601.46	70,000.0	25.0	8414.58
Mn	1,275.03	1,275.03	21,940.0	3.0	2,258.24
Ni1*	14.81	11.84	375.0	2.50	53.61
Ni2**	34.55	32.98	1,500.0	0.50	88.95
Pb1*	28.85	28.7	1,500.0	2.50	87.48
Pb2**	28.85	28.2	800	2.50	46.38
Sc	21.33	18.1	100.0	2.50	15.87
Ti	4,686.76	4,686.76	70,000.0	70.0	7,003.22
V	119.79	119.18	1,000.0	5.0	114.35
Zn1*	285.19	81.38	10,000.0	100.0	993.75
Zn2**	98.45	97.95	14,000.0	2.50	705.85
Zn3***	102.55	22.27	531.0	73.57	73.57

* Analysis by semiquantitative optical-emission spectrography.

** Analysis by atomic-absorption techniques at U.S. Geological Survey.

*** Analysis by atomic-absorption techniques at Skyline Labs., Inc.

Table 12. Ranking of correlation coefficients for summary trace - element geochemistry of rock, soil and saprolite samples from the Dahlonega belt. Based on data from Lesure and others, 1991 and 1992.

Ag	Zn1 (0.8685), Hg (0.6983), Ni1 (0.6488), Ba1 (0.4403)
As	
Ba1*	Ba2 (0.8747), Mg (0.4724), Ag (0.4403), Be (0.3277)
Ba2**	Ba1 (0.8747)
Be	Ba1 (0.3277)
Co	Ni2 (0.5075), Mn (0.3520), Sc (0.3409)
Cr1*	Cr2 (0.8880), Ni1 (0.8745), Ni2 (0.8241), V (0.5597), Fe (0.4677), Cu3 (0.3164)
Cr2**	Cr1 (0.8880), Ni2 (0.8761), Ni1 (0.8191), Mg (0.3361)
Cu1*	Cu2 (0.9350), Zn3 (0.5218), Zn1 (0.4207), Cu3 (0.4028)
Cu2**	Cu1 (0.9350), Cu3 (0.8905), Zn1 (0.7737), Zn2 (0.4904), Zn3 (0.4724), Pb1 (0.4049)
Cu3***	Cu2 (0.8905), Zn3 (0.4383), Cu1 (0.4028), Ni1 (0.3158)
Fe	V (0.6733), Sc (0.5447), Ni1 (0.5342), Cr1 (0.4677), Mg (0.4527), Mn (0.3206), Cr2 (0.3061)
Hg	Ag (0.6983)
Mg	Ba1 (0.4724), Fe (0.4527), Cr2 (0.3361), V (0.3275), Ni2 (0.3104), Zn3 (0.3064)
Mn	Co (0.3520), Fe (0.3206)
Ni1*	Cr1 (0.8745), Ni2 (0.8442), Cr2 (0.8191), Ag (0.6488), Sc (0.6473), V (0.5824), Fe (0.5342), Cu3 (0.3158)
Ni2**	Cr2 (0.8761), Ni1 (0.8442), Cr1 (0.8241), Co (0.5075), Mg (0.3104)
Pb1*	Zn1 (0.8191), Zn2 (0.8441), Pb2 (0.7804), Zn3 (0.5940), Cu2 (0.4049)
Pb2**	Zn1 (0.8953), Zn2 (0.8440), Pb1 (0.7804)
Sc	V (0.7320), Ni (0.6473), Fe (0.5447), Cr1 (0.5102), Co (0.3409)
Ti	
V	Sc (0.7320), Fe (0.6733), Ni2 (0.5824), Mg (0.3275)
Zn1*	Zn2 (0.9386), Pb2 (0.8953), Zn3 (0.8911), Ag (0.8685), Pb1 (0.8191), Cu1 (0.7737), Cu1 (0.4207), Cr1 (-0.4535)
Zn2**	Zn1 (0.9386), Zn3 (0.8776), Pb1 (0.8441), Pb2 (0.8440), Cu2 (0.4904)
Zn3***	Zn1 (0.8911), Zn2 (0.8776), Pb1 (0.5940), Cu1 (0.5218), Cu2 (0.4724), Cu2 (0.4724), Mg (0.3064),

*	Analysis by semiquantitative optical-emission spectrography.
**	Analysis by atomic-absorption techniques at U.S. Geological Survey.
***	Analysis by atomic-absorption techniques at Skyline Labs., Inc.

Table 13. Analyses of Hall County District veins and wallrocks. (Allen, 1986)

Sample	Cu (ppm)	Pb (ppm)	Zn (ppm)	Ag (ppm)	Au (ppb)	As (ppm)	Sb (ppm)
CU-11	10	960	28	5.0	180	33	1.0
CU-14	9	2,310	108	7.8	4,500	110	1.0
CU-24	6	1,000	670	1.8	2,100	245	1.4
CU-37	11	82	78	0.4	540	41	0.1
CU-52	5	1,630	1,300	2.6	10	75	-
RA-8	6	2,450	46	4.3	1,700	350	4.0
RA-15	7	10,000	3,150	28.0	3,700	90	35.0
RA-18	3	2,450	370	1.1	80	50	-
M-1	42	174	22	2.6	8,500	10,000	1.8
M-2	18	306	30	1.0	2,800	10,000	1.8
GNMA-12	5	34	12	0.2	120	23	0.1
LCS-12	40	46	31	0.1	120	19	0.1
LCR-3	5	75	28	0.1	40	9	0.2
LCR-3a	9	97	13	5.4	>10,000	135	0.2
LCR-7	6	10	10	0.2	9	100	0.2
HA-9	10	14	19	0.1	10	3	-
HA-11	11	32	10	3.0	5,650	135	-
HA-17	11	8	8	1.4	2,200	7	-

Analyses were done by Chemex Labs, Ltd., of North Vancouver, British Columbia, using atomic absorption spectrophotometry. Detection limits were 0.1 ppm for Ag and Sb, 0.01 ppm for Au, and 1 ppm for Cu, Pb, Zn and As (Allen, 1986).

CU-11 and 14	Curahee vein samples
CU-24 and 37	Curahee wallrock samples
RA-8 and 15	Ramsey-Maynas vein samples
RA-18	Ramsey-Maynas wallrock sample
M and GNMA	Mammoth vein samples
LCS	Simmons prospect vein sample
LCR	Shelley prospect vein samples
HA-9	Harris prospect wallrock sample
HA-11 and 17	Harris prospect vein sample

Table 14. Ranking of correlation coefficients for Hall County District rock samples.

Hall County Samples

Cu	As (0.568), Au (0.479)
Pb	Sb (0.969), Ag (0.959), Zn (0.898)
Zn	Sb (0.974), Pb (0.898), Ag (0.864)
Ag	Sb (0.974), Pb (0.898), Zn (0.961)
Au	As (0.665), Cu (0.479)
As	Au (0.665), Cu (0.479)
Sb	Zn (0.974), Pb (0.969), Ag(0.961)

Gwinnett County Samples

Cu	Ag (0.409), Au (0.407), Zn (-0.589)
Pb	Au (0.605), Ag (0.596), Zn (0.453)
Zn	Pb (0.454), Cu (-0.589), As (-0.498), Ag (-0.388), Au (-0.369)
Ag	Au (0.999), As (0.721), Pb (0.596), Cu (0.409), Zn (-0.389)
Au	Ag (0.999), As (0.725), Pb (0.596), Pb (0.606), Cu (0.407), Zn (-0.369)
As	Cu (0.906), Au (0.726), As (0.721), Zn (0.498), Pb (0.315)

correlation coefficient of 0.9183.

Two associations are suggested between the lithophile elements. Rock unit correlation coefficients indicate a good correlation between barium, potassium, and aluminum. This correlation suggests that barium is contained in potassium feldspars - a common situation. This association may be used to distinguish different types of granitic rocks in Georgia. A good correlation is suggested between sodium, scandium, and aluminum with coefficients of 0.4693 to 0.6557.

Intragroup correlation coefficients (0.4802 to 0.7463) suggest an association between the groups sodium-aluminum, iron-titanium-vanadium-manganese, pH, conductivity and alkalinity. This association has been suggested earlier on the geochemical maps (Figs. 16, 22, 23, 24, 25, 26, 28, and unpublished Georgia Geologic Survey maps). Generally higher values for sodium, aluminum, iron, titanium, vanadium, manganese, pH, conductivity and alkalinity are spatially correlative with the metavolcanic rocks of the Dadesville Complex (Fig. A-20) and other mafic metavolcanic rocks (Fig. A-3).

Table 9 shows an inverse correlation between potassium and titanium-vanadium-iron. This negative correlation may suggest separate sources or a fractionation of felsic (potassium) and mafic (iron-titanium-vanadium) components in stream sediments.

Table 9 suggests a correlation of chromium with other metals. The suite of metals may be a mixture, which reflects mixing of chromium-bearing sediments with sediments containing other metals. As discussed earlier, the large chromium anomalies in the northern part of the Chattahoochee River Basin may not be spatially related to specific rock units. This may indicate many small, unmapped sources of chromium, perhaps slices of ultramafic rocks or other rock types that are richer in chromium than has been documented.

Correlation coefficients for all NURE stream sediment and stream samples (Table 15) indicate that the strongest associations are the copper-lead-zinc-cobalt group and the iron-titanium-vanadium-manganese group. The association of nickel with the base-metals does not appear as strong. Copper may also be associated with aluminum and silver. Alkalinity and conductivity still share a strong correlation with each other. Chromium and magnesium are more closely correlated and probably reflect the association of chromite with ultramafic magnesium silicates.

CONTAMINATION

Contamination, as discussed in this report, concerns effects contemporaneous with the period of collection of the NURE samples (1976 to 1978). A considerable amount of sedimentation probably occurred in the streams of the Chattahoochee River Basin during the century prior to 1950. In addition, some alluvial deposits may be as old as the beginning of the Quaternary, 1.65 to 2.5 million years (Morrison, 1991). The goals of this section on contamination are to identify 1) possible sources of contamination that were noted during the sample collection period, and 2) stream sediment and stream analyses that may have been affected by those sources of contamination.

NURE databases contain information regarding the type of contamination-related anthropogenic activity near the sample sites that might influence the analytical results. NURE databases provide only a general type of activity and do not elaborate on the size or form of the activity. Types of activities noted for the Chattahoochee River Basin included: mining, sewage, "dumps", farming, urban, and other industrial activity. Activities noted as "dumps" in the NURE databases may include a variety of solid waste disposal sites. Because these sites are not defined or described in the NURE databases, they will be referred to in this report as waste disposal sites. Of 1,133 stream sediment and stream sample sites in the Chattahoochee River Basin, "farming" was noted for 429, waste disposal sites were indicated for 10, "other industrial" for 10, and "urban" for 7 sites (Fig. 37). All except 22 of these sites are within Georgia. Other sample sites in the Chattahoochee River Basin are considered "non-contaminated," but some may have been subject to contamination by prior activity at the site or by activity upstream. Because of the small number of sample sites near potential contamination sources other than "farming," samples with high metal contents may not be statistically significant, and the quantitative impact of such sources on geochemical results may be difficult to demonstrate. However, the data may show that some activities have contributed to anomalous hydrogeochemical or geochemical analytical results. Another factor to consider is that major urban centers such as Atlanta and Columbus were not sampled, so their impact cannot be directly addressed by the NURE data.

In contrast to the previous study of the Oconee River Basin (Cocker, 1996b), indications in the NURE data of contamination in the Georgia portion of the Chattahoochee River Basin are few and not as suggestive of anthropogenic sources. Two "urban" sites had unusually high conductivities of 360 and 485 micromhos with alkalinities of 0.44 and 1.00 meq/L respectively. A water temperature of 15 °C was recorded at the site with the higher conductivity. None of the stream sediment samples contained unusual metal values. Two "other industrial" sites had low pH (4.6 and 5.0), low water temperature (16 and 16 °C), low alkalinity (no measurement at the first site and 0.06 meq/L at the second site), and low conductivity (18 micromhos/cm at each site). Aluminum (5,100 ppm), iron (5,500 and 6,600 ppm), manganese (60 ppm), sodium (200 ppm), and vanadium (20 ppm) for these "other industrial" sites are lower than average values for the entire basin. These samples were not analyzed for heavy metals. These two sites are located within the Cretaceous Tuscaloosa Formation (*TKu*). Values for aluminum, iron, manganese, sodium, and vanadium from the two "other industrial" sites are lower than mean values for these elements from other sites within the Tuscaloosa Formation.

Hydrogeochemistry of the Chattahoochee River itself may be affected by contamination from urban activity. Basins sampled by Faye and others (1980) in and adjacent to the Atlanta area, indicate heavy-metal contamination from non-point sources. In general, stream sediment and water samples from the Chattahoochee River Basin do not indicate contamination by heavy metals. A few "urban" and "other industrial" sites had anomalous geochemistry, which may indicate contamination. Heavy metal data are lacking for these sites.

An investigation of metal contamination in flood plain stream sediments of Yahoola Creek and Chestatee River, downstream from former gold operations in the Dahlonega gold belt, indicates that these sediments contain elevated concentrations of mercury (Leigh, 1995). Mercury concentrations were one to two orders of magnitude higher than background concentrations. Much of the mercury was concentrated within 3 to 6 miles downstream from the source area. Greatest concentrations were located nearest the sources. Concentrations of up to 12.0 ppb mercury were found in sediments. Surface-water samples also contained elevated mercury in the <0.6 to 1.5 ppt range. Freshwater mussels were found to contain 0.7 ppb mercury suggesting that these organisms are accumulating mercury (Leigh, 1995). Heavy metals, including arsenic, copper, lead, and zinc were not significant contaminants. The presence of many gold operations within the Chattahoochee River Basin, and elevated concentrations of mercury remaining in stream sediments long after gold-recovery operations have ceased, suggest that mercury contamination has the potential for becoming both a local point source problem and a regional non-point source problem.

Additional potential sources of stream sediment and stream contamination that could not be addressed with the available databases include metal-rich drainage from factories, mechanized farms and sewage, metalliferous insecticides and algicides, condensates from smog and factories, roads and railway beds graded with mine waste (Rose and others, 1979), discharges from manufacturing plants, and urban runoff. Road grading is probably not a major source of contamination in Georgia because of a lack of major metal mine workings. As discussed previously, anomalously high arsenic values in soil and saprolite samples may be related to insecticides applied during the earlier part of this century.

SUMMARY

Databases created by the U.S. Department of Energy's NURE stream sediment reconnaissance program provide important baseline geochemical data from the late 1970's. Additional databases provide important background information on composition of river sediments, and lithogeochemistry of base- and precious-metal mineral deposits. Spatial distributions of these data were analyzed using a computer-based Geographical Information System to define the background geochemistry and hydrogeochemistry of the Chattahoochee River Basin. Critical factors, which control

Table 15. Correlation Coefficients for all NURE stream sediment and stream samples in the Chattahoochee River Basin.

	Temp	pH	Alkalinity	Conductivity	Ag	Al	As	Ba	Be	Co	Cr	Cu
Temperature	1.0000											
pH	-0.1473	1.0000										
Alkalinity	0.1950	0.2901	1.0000									
Conductivity	0.0476	0.2540	0.6720	1.0000								
Ag	-0.0259	-0.0426	0.1364	0.0659	1.0000							
Al	-0.3200	0.0736	0.1263	0.1779	0.3452	1.0000						
As	0.0566	0.0108	0.0694	0.0441	-0.1221	0.0100	1.0000					
Ba	-0.0576	0.1531	0.2876	0.1891	0.0987	0.3239	0.0733	1.0000				
Be	-0.0889	-0.0712	0.0500	0.0950	0.0866	0.2075	-0.4002	0.0344	1.0000			
Co	0.1495	-0.0751	0.2110	0.1155	0.2286	0.2968		0.2500	0.1147	1.0000		
Cr	-0.0534	0.0415	-0.0290	-0.0070	0.1532	0.0315		-0.0366	0.0561	0.1205	1.0000	
Cu	0.1033	0.0848	0.2214	0.1699	0.4257	0.4164	-0.0913	0.2003	0.1148	0.5829	0.1517	1.0000
Fe	-0.2584	0.0327	-0.1136	-0.0513	0.0773	0.2397	-0.1297	-0.1004	0.0561	0.1199	0.2485	0.2214
K	0.1767	0.0302	0.0584	0.0061	0.0997	0.3156		0.2636	0.2538	-0.0993	-0.0934	-0.0397
Mg	-0.0602	0.0415	0.0784	0.0378	0.1277	-0.0106		-0.0128	0.0302	0.1944	0.4355	0.1331
Mn	-0.1508	0.1607	0.1100	0.1351	0.1644	0.3023	-0.0573	0.2293	-0.0042	0.3370	0.0345	0.2697
Na	-0.1745	0.0824	0.0262	0.0923	0.0433	0.3697	0.2485	-0.0305	-0.0992	-0.2173	0.1092	-0.1273
Ni	-0.1089	0.0776	-0.0273	0.0021	0.1267	0.1427	-0.0615	0.1645	0.1780	0.1482	0.0849	0.1990
P	-0.0589	-0.1038	-0.0318	-0.0109	0.0730	0.1174	-0.1462	-0.0201	0.0795	0.0676	0.0028	0.2335
Pb	-0.0121	-0.0976	0.1957	0.0912	0.3957	0.3546	-0.2524	0.0918	0.1726	0.4760	0.1292	0.5475
Sc	-0.2410	0.2103	0.1487	0.1711	0.1915	0.6176	-0.0844	0.1027	0.0486	0.0821	0.1057	0.2534
Ti	-0.2589	0.0564	-0.0865	-0.0044	0.0028	0.0012	-0.1127	-0.0064	0.1089	0.0260	0.2400	0.0613
V	-0.3333	0.1097	0.0257	0.0810	0.1716	0.3895	-0.1575	0.0134	0.0576	0.1743	0.3268	0.2563
Zn	0.0905	0.0790	0.1557	0.1750	0.3848	0.3828	-0.1770	0.2832	0.1384	0.5818	0.1612	0.7996

	Fe	K	Mg	Mn	Na	Ni	P	Pb	Sc	Ti	V	Zn
Fe	1.0000											
K	-0.2929	1.0000										
Mg	0.2105	-0.2761	1.0000									
Mn	0.3412	-0.0748	0.0678	1.0000								
Na	0.1219	-0.0485	0.0290	0.1510	1.0000							
Ni	0.0327	0.1025	0.0495	0.0536	-0.0768	1.0000						
P	0.1005	0.0962	-0.1276	0.0231	-0.0651	0.0530	1.0000					
Pb	0.1045	-0.1331	0.2813	0.0901	-0.1328	0.1070	0.2275	1.0000				
Sc	0.3813	-0.0569	0.0975	0.3740	0.3804	0.0285	0.0559	0.1519	1.0000			
Ti	0.6156	-0.2962	0.2891	0.2925	0.0615	-0.0273	0.0522	-0.0439	0.1195	1.0000		
V	0.7990	-0.2978	0.3192	0.4377	0.2949	0.0241	0.0760	0.0985	0.5151	0.6747	1.0000	
Zn	0.0772	0.0419	0.2389	0.0827	-0.2095	0.3114	0.1686	0.5915	0.0668	-0.0295	0.0737	1.0000

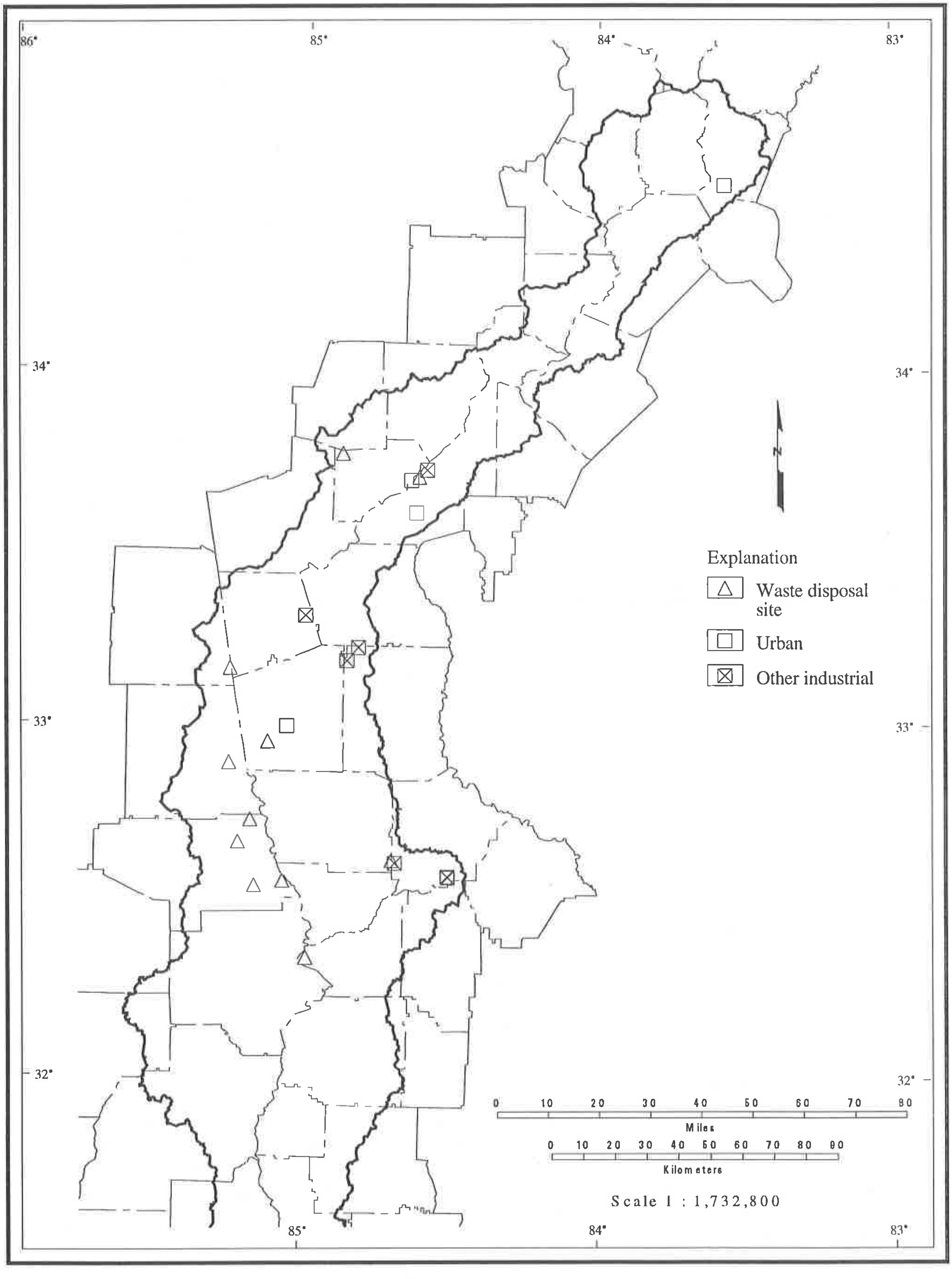

Figure 37. Potential contamination sites. Based on NURE data.

geochemistry and hydrogeochemistry within Chattahoochee River Basin streams, are regional geology and local geology. Contamination associated with urban centers may affect stream and river hydrogeochemistry. Effects on stream and river sediment geochemistry in and adjacent to urban centers are essentially undocumented. Past agricultural practices, which resulted in severe erosion have contributed abnormal amounts of sediment to the stream channels affecting stream flow and potentially water quality within the Chattahoochee River Basin.

The Chattahoochee River Basin is underlain with crystalline metamorphic and igneous rocks in the Blue Ridge and Piedmont physiographic provinces and with sedimentary rocks in the Coastal Plain physiographic province. The crystalline rocks are principally composed of biotite gneiss (24.6 percent), schists (22.7 percent), metaquartzites and metagraywackes (5.7 percent), granitic gneiss (4.3 percent), granites (5.5 percent), and amphibolite gneiss (8.6 percent). Coastal Plain rocks include sands, clays and calcareous sediments.

Major regional factors controlling distribution of metals within the Chattahoochee River Basin are differences between rocks of the Piedmont versus the Coastal Plain and between rocks of tectonostratigraphic terranes within the Blue Ridge and Piedmont. Major terranes include the Blue Ridge, Inner Piedmont, Pine Mountain, and Uchee. These terranes are separated by major faults. Most of the metamorphic rocks within the Chattahoochee River Basin are of intermediate to high metamorphic grade.

Base and precious-metal mining was previously a locally significant activity within the Chattahoochee River Basin. The principal site for such mining was within the Dahlonega belt, which cuts through Lumpkin and White Counties in the northern part of the Chattahoochee River Basin. Other base- and precious-metal mining occurred in the west-central part of the basin in Carroll, Douglas and Paulding Counties. Some mining also occurred in Hall and Gwinnett Counties. These base- and precious-metal deposits contain high concentrations of copper, lead, zinc, mercury, arsenic, antimony, iron, silver, and molybdenum. Chromite deposits were prospected in Troup County, and occurrences of ultramafic rocks in the northern part of the Chattahoochee River Basin probably also contain chromite. Most stream sediment samples were not analyzed for mercury or antimony in the NURE program, and only a few were analyzed for arsenic. Mercury may have been introduced into the drainage system, through the use of mercury to process gold placer deposits. Leigh (1995) found elevated quantities of mercury in stream sediments and soils downstream from gold operations in the Dahlonega belt.

Mining of sediment-hosted bauxite and limonite occurred in parts of the Coastal Plain province. Bauxite formed by extreme weathering of kaolin deposits in Cretaceous, Paleocene, and Eocene sediments. "Brown iron ore" deposits formed as residual deposits from extreme weathering of Paleocene carbonates.

Recent stream sedimentation related to poor agricultural practices in the 1800's and early 1900's (Trimble, 1969) is evident in each of the physiographic provinces in the Chattahoochee River Basin. Down cutting by streams and rivers has caused remobilization of the recent sedimentation. Suspended sediment derived by remobilization, particularly in urban areas, contributes a large amount of heavy metals to the water system of the Chattahoochee River Basin (Faye and others, 1980).

Streams north of the Brevard fault zone in the Blue Ridge terrane generally have low conductivities, alkalinities, and pH. Some of the lowest alkalinities in the Chattahoochee River Basin are coincident with the Blue Ridge physiographic province and may be related to the high degree of runoff. In the Inner Piedmont terrane, streams generally have higher alkalinities, conductivities, and pH. Streams south of the Towaliga fault zone in the Pine Mountain terrane also have generally low conductivities, pH, and alkalinities. South of the Goat Rock Fault, in the Uchee terrane, streams generally have higher alkalinities, conductivities, and pH.

Streams within the Coastal Plain that are spatially associated with sandy and clayey sediments have distinctly lower pH, conductivities and alkalinities than streams spatially associated with calcareous sediments. The lowest stream pH occurs in streams spatially associated with Cretaceous sandy sediments near the Fall Line. Carbonates apparently buffer rain and surface water by raising pH and alkalinity. Carbonates also contribute dissolved solids to streams, as measured by higher alkalinities and conductivities. High permeability, non-reactive compositions (i.e., quartz sand and clay), and perhaps higher amounts of decaying carbonaceous matter contribute to lower pH, conductivity and alkalinity of streams associated with noncalcareous Coastal Plain sediments.

Spatial analyses of the NURE stream sediment geochemical data suggest several base-metal trends that extend through or are cut by the Chattahoochee River Basin. These include one that appears related to a biotite gneiss *(bg1)* in northern Lumpkin and White Counties. A second base-metal trend extends from Habersham through Hall and into Forsyth County. A third trend extends through Paulding, Douglas and Carroll Counties. This may be associated with the base- and precious-metal mines in that part of the Blue Ridge. Anomalous base-metals found in Coweta, south Fulton, Troup, and Heard Counties may, in part, be related to mafic metavolcanic rocks of the Dadesville Complex. Anomalously high concentrations of nickel and chromium in the northern part of the Chattahoochee River Basin appear, in part to be related to numerous small ultramafic rocks scattered in this part of the basin. A large chromium anomaly in Hall County does not appear related to a particular rock type. Anomalously high concentrations of iron, manganese, and vanadium may be associated with the "brown iron ore" deposits in the Coastal Plain.

Statistical analyses of NURE data suggest several elemental associations: 1) iron-manganese-titanium-vanadium-magnesium; 2) copper-nickel-cobalt-zinc-lead; 3) barium-potassium-aluminum; and 4) sodium-aluminum. Association 1 may be related to iron-magnesium mafic silicates and iron-titanium oxides and reflect the distribution of mafic metavolcanic and metaplutonic rocks. Association 2 may be related to base-metal sulfides and reflect their presence as disseminated or vein mineralization. Association 3 may be related to granitic plutons. Association 4 appears to reflect the presence of sodic feldspars or sodic amphiboles. Correlation coefficients, and spatial distributions suggest that associations 1, 2 and 4 are related to each other. A spatial correlation in the northern part of the Chattahoochee River Basin between ultramafic rocks and the elements chromium, nickel and magnesium, suggests a genetic relationship.

Some stream sediment samples and associated stream samples in the NURE database may be affected by nearby human activities. These activities may have affected stream pH, conductivity and alkalinity. Activities, which appear to have affected stream sediment and water geochemistry, include: urban activities and "other industrial" sites.

Watersheds with dominantly urban land-use contribute the largest yield of lead, zinc, copper, arsenic, phosphorous, nitrogen, and organic carbon to the Chattahoochee River (Faye and others, 1980). Suspended sediment was found to contribute 60 percent or more of the total annual discharge of trace metals and phosphorous and 10 to 70 percent of dissolved nitrogen and organic carbon (Faye and others, 1980).

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APPENDIX A

GENERAL GEOLOGY

Introduction

The geology discussed in this report is based principally on the Geologic Map of Georgia (Georgia Geological Survey, 1976), the geology of the Greater Atlanta Region (McConnell and Abrams, 1984), and the Geologic Map of Alabama (Osborne and others, 1989). Additional important sources include Atkins and Lineback (1992), German (1985 and 1988), Gillon (1982), Higgins and Atkins (1981), Reinhardt and others (1980 and 1986), and Thomas and Neathery (1980). Rock units on the Geologic Map of Georgia are defined principally by the dominant lithology and secondarily by less abundant lithologies.

The Chattahoochee River Basin is located within three physiographic provinces: the Blue Ridge, the Piedmont and the Coastal Plain provinces (Fig. 10) which are described in the section on geomorphology. The Blue Ridge and Piedmont provinces, which constitutes approximately 70 percent of the Chattahoochee River Basin, are underlain by crystalline metamorphic and igneous rocks. The remaining portion of the basin is in the Coastal Plain province which is underlain by sedimentary strata. Because of significant differences in chemical composition, porosity, permeability, and origin of the different rock units within the Blue Ridge, Piedmont and Coastal Plain, these rock units and stream sediments derived from these rock units significantly influence stream hydrogeochemistry.

Within the Chattahoochee River Basin of Georgia, the most widespread rocks are gneisses representing 38.7 percent of the exposed rocks. Biotite gneisses (Fig. A-1) cover 24.6 percent; granitic gneisses (Fig. A-2) cover 5.5 percent; and amphibolite gneisses (Fig. A-3) cover 8.6 percent of the Chattahoochee River Basin. Granites (Fig. A-4) occupy 4.3 percent of the basin. Schistose rocks (Figs. A-5, A-6 and A-7) cover 18.8 percent, and quartzites (Fig. A-8) and metagraywackes (Fig. A-9) occupy 5.7 percent of the Chattahoochee River Basin. Less than 0.1 percent of the Chattahoochee River Basin is occupied by ultramafic rock units (Fig. A-10). The overall ratio of felsic (biotite gneisses plus granitic gneisses plus granites plus metasedimentary rocks) to mafic (amphibolite gneisses plus ultramafic and mafic rocks) lithologic units within the Chattahoochee River Basin is approximately 7:1. Because mafic lithologies (e.g., amphibolites) may be important constituents of the felsic units (Table 1) and likewise for felsic lithologies in mafic units shown on the Geologic Map of Georgia (Georgia Geological Survey, 1976), this ratio is only considered to be a generalization. Its importance is reflected in the mineralogical and geochemical composition of stream sediments within the Chattahoochee River Basin. Cataclastic rocks (Fig. A-11) are depicted as covering 1.6 percent of the basin. This does not include rocks within the large zone of cataclasis that marks the Brevard fault zone. This fault zone is depicted on the Geologic Map of Georgia separately from specific rock units and commonly cuts across rock unit boundaries.

Coastal Plain sediments are present over 30.2 percent of the Chattahoochee River Basin in Georgia. Lithologic map units which occur within the Chattahoochee River Basin are listed in Table 1. Approximately 63 percent of the Coastal Plain sediments are sandy and clayey sediments. These are mainly Cretaceous (Fig. A-12) and some Paleocene sediments (Fig. A-13) that are located in the northern part of the Coastal Plain. The remaining 37 percent of the Coastal Plain sediments include calcareous sediments that are mainly Paleocene and Eocene (Fig. A-14). In addition, Quaternary alluvium (*Qal*) was mapped over 1.8 percent of the Chattahoochee River Basin, and most of this alluvium is located in the Coastal Plain (Fig. A-15).

Crystalline Rocks

Intrusive Rocks

Included in this group are rock bodies that are clearly intrusive in nature such as the granites *gr1* and *gr1b* and diabase intrusions. Also included are ultramafic rocks (*um*), that may in some cases, be intrusive, and in other cases, they may be tectonic slices. Not included here are granite gneisses and perhaps some amphibolitic bodies such as the Laura Lake complex (*mm9*) rock units that are probably intrusive, but are listed as metamorphosed rocks.

Granites: Granites, which include *gr1, gr1b* and *gr4*, occupy a total of 4.3 percent of the Chattahoochee River Basin in Georgia. The largest masses of granite are two bodies of porphyritic granite (*gr1b*) in southern Fulton County (Fig. A-4). These include the Ben Hill and Palmetto granites. Most of the undifferentiated granites (*gr1*) are found in the southwestern part of the Piedmont and Blue Ridge of the Chattahoochee River Basin in Carroll, Coweta, Troup, Talbot and Harris Counties, although a small mass of *gr1* granite is located in northern Hall County. The *gr1* body in Carroll County represents the Sand Hill Gneiss. Charnockite, represented by four small masses of *gr4*, is found in Harris County.

Ultramafic Rocks: Ultramafic rock units (*um*) in Table 1 and on the Geologic Map of Georgia are shown in Fig. A-10.

The Geologic Map of Georgia shows that these rocks are located mainly in the extreme northern part of the Chattahoochee River Basin (i.e., Lumpkin, White and Habersham Counties) and in Coweta and Troup Counties in the middle part of the Chattahoochee River Basin. The northernmost occurrences define a northeastern-trending linear belt that extends across the Chattahoochee River Basin. Ultramafic rocks may be metaperidotites, serpentinites, or metadunites. Most of these rock units are small in size and as a group represent perhaps a maximum of 0.05 percent of the Chattahoochee River Basin in Georgia. The depiction of these rocks in the northern part of the Chattahoochee River Basin as similarly sized circular bodies misrepresents their true size and shape. These rock units may be igneous intrusions or remnants of oceanic crust tectonically emplaced along crustal sutures.

These ultramafic rock units generally consist of serpentine, talc, actinolite, carbonates, magnetite, chromite, and sulfides (Hopkins, 1914; Prowell, 1972) and are highly susceptible to chemical weathering. Weathering may release locally significant amounts of chromium, nickel, copper, zinc, lead, iron, titanium, manganese, magnesium, arsenic, and antimony. Anomalous metal concentrations in stream sediments, which are discussed in the text, appear to be spatially related to these rock units.

Diabase Intrusions: Diabase dikes are scattered throughout the Georgia Piedmont and the Chattahoochee River Basin. More persistent dikes are depicted on the Geologic Map of Georgia (Georgia Geological Survey, 1976). These dikes are not shown on the maps in this report, because the dikes were not digitized in the Geologic Map GIS coverage. Most dikes are on the order of a few feet to several ten's of feet in width, and may extend for ten's of miles in a northwest-southeast direction. Because of their limited areal extent, diabase dikes probably have contributed little to the stream sediment load and probably do not significantly affect stream hydrogeochemistry.

Metavolcanic Rocks

Moderate to high grade metamorphism of basaltic to rhyolitic volcanic rocks will form amphibolites to granitic gneisses, respectively. Metamorphism of hydrothermally altered volcanic rocks may form chloritic schists, biotite gneisses, mica schists, aluminous mica schists, and quartzites depending on the composition of the source rock and the type of hydrothermal alteration. Basaltic rocks generally contain higher concentrations of chromium, cobalt, nickel, zinc, and copper than rhyolitic rocks (Rose and others, 1979). Local enrichment of these metals may result from magmatic differentiation. More rhyolitic volcanic rocks may contain higher concentrations of lithium and fluorine than other less felsic volcanic rocks. The physical and chemical environment of submarine volcanism is conducive for development of hydrothermal systems which may be enriched in trace metals.

Mafic volcanic rocks generally contain higher amounts of iron, magnesium, and calcium than felsic volcanic rocks. Submarine volcanic rocks may acquire sodium from seawater and become more enriched in sodium than subaerial volcanic rocks. At low to moderate grades of metamorphism, primary calcium, magnesium and iron-bearing silicates (e.g., plagioclase and amphiboles) are commonly replaced by secondary calcium, magnesium and iron carbonates (e.g., calcite, dolomite and siderite).

Granitic Gneisses: Granitic gneisses, rock types *gg1, gg2, gg3, gg4, gg5* and *gg6* in Table 1, are more common in Paulding, Douglas, south Fulton, Meriwether, Heard and Troup Counties (Fig. A-2) than elsewhere in the northern half of the Chattahoochee River Basin in Georgia. Granitic gneisses are locally abundant in Lumpkin and White Counties (Fig. 5). These gneisses may include metamorphosed granodiorites, granodiorite gneisses, two-mica gneisses and migmatites as well as minor amphibolitic gneisses. Although granitic gneisses represent 6.5 percent of the Chattahoochee River Basin, they may locally affect stream sediment geochemistry and hydrogeochemistry.

Undifferentiated granite gneiss *(gg1)* is found as generally elongate masses scattered along the northeast trend of the Chattahoochee River Basin and Brevard fault zone. The largest *gg1* body is found in southern Lumpkin and White Counties. Two masses of augen or porphyritic granite gneiss (*gg2*), located in Douglas, Paulding and Cobb Counties (Fig. A-2) represent the Austell and Acworth Gneisses. Two bodies of muscovite granite gneiss (*gg3*) are located in south central Fulton County between the Ben Hill and Palmetto granites (Fig. A-4). Three occurrences of granite gneiss (*gg4*) are located in south central Fulton and northern DeKalb Counties. Calc-silicate granite gneiss (*gg5*) is found as three elongate masses extending from Coweta through Fulton into DeKalb County (Fig. A-4). The largest occurrence of the granite gneiss/granite (*gg6*) is located principally in northwestern Troup County (Fig. A-4). Smaller masses of this unit are found in southern Paulding County.

Intermediate (Biotite) Gneisses: Intermediate or biotite gneisses (Fig. A-1) include the rock units *fg1, fg1a, fg2, fg3, fg4, bg1* and *bg2* (Table 1) on the Geologic Map of Georgia (Georgia Geological Survey, 1976). These rocks represent nearly 16 percent of the Chattahoochee River Basin. Biotitic gneiss *fg3* is the most abundant (13.59 percent) rock type in the Georgia portion of the Chattahoochee River Basin (Fig. A-16). Most of this biotitic gneiss occurs to the northwest of the Brevard fault zone and from Douglas County to the northeast. The larger concentration of this lithologic unit is in the northernmost counties (i.e., from Fulton and Gwinnett Counties northward). Relatively minor amounts are found southeast of the Brevard fault zone such as in the Alto allochthon and in parts of DeKalb, Fulton, Coweta and Heard Counties. Distribution of this rock type strongly reflects the regional northeast lithologic trend and several major synformal and antiformal structures. Biotite gneiss/feldspathic biotite gneiss (*fg1*) is found in south central Fulton County between the Palmetto and Ben Hill granites. Undifferentiated biotite gneiss (*fg2*) is located principally in Fulton and DeKalb Counties. Biotitic gneiss with amphibolite (*fg4*) is located principally in southwestern Coweta County and would appear to represent a facies change from dominantly amphibolitic rocks of *mm3* through granitic gneisses of *gg5* (Fig. A-2). Two masses of *fg4* are located in Heard and Harris Counties.

Biotite gneiss *bg1* is the second most abundant rock type (8.8 percent) in the Chattahoochee River Basin, and this rock type occurs mainly in three large masses or clusters of large masses mainly south of the Brevard fault zone (Fig. A-17). A large mass in northern Lumpkin and White Counties constitutes what is referred to as the Richard Russell Formation (Gillon, 1982). Anomalous heavy metal concentrations in stream sediments, which are discussed in the main part of the text, are associated with this occurrence of *bg1*. Another is found in Heard and Coweta Counties. Harris, Talbot, and Muscogee Counties contain several extensive masses of *bg1*. The biotite gneiss *bg2* is a less extensive unit, occurring in southern Harris and northern Muscogee Counties (Fig. A-1).

Amphibolites and Amphibolite Gneisses: Amphibolites, amphibolitic gneisses and schists are represented by units *m2, ms1, ms3, mm1, mm2, mm3, mm4*, and *mm9* (Table 1) on the Geologic Map of Georgia (Georgia Geological Survey, 1976). These rock units represent 8.5 percent of the Chattahoochee River Basin. Amphibolites may also be present in units such as *fg3, fg4, bg2, gg4, m2, pg3, pm3a, pms2, pms3a, pms4, pms6a* and *q1b* (Table 1). Amphibolitic rocks appear to be generally grouped into three belts that intersect the Chattahoochee River Basin (Fig. A-3). Amphibolitic rocks (*mm4*) in Muscogee, Harris and Talbot Counties may be equivalent to the Phenix City Gneiss of the Uchee terrane. Abundant amphibolitic rocks (*mm3*) in Troup County are along strike of the Ropes Creek Amphibolite of the Dadeville Complex in Alabama (Steltenpohl and others, 1990). A third belt intersects the northwestern boundary of the Chattahoochee River Basin and represents metavolcanic rocks of the New Georgia Group. These amphibolitic rocks may be parts of volcanic belts extending through Georgia. Locally abundant metavolcanic and metavolcaniclastic rocks may have an important effect on nearby stream sediment geochemistry and stream hydrogeochemistry. Weathering and hydrolysis of iron, magnesium, calcium and sodium silicates and carbonates can affect pH, conductivity and alkalinity of surface and ground water that flows through metavolcanic rocks.

Hornblende gneiss *mm3* (Fig. A-3) constitutes the largest group of amphibolitic rocks in the Chattahoochee River Basin and is the fourth largest group overall at 5.4 percent (Table 1). Several relatively small occurrences of the hornblende gneiss *mm2* that are found in Heard, Coweta, Carroll, Paulding and Cobb Counties and a large mass that extends along the Brevard fault zone from Heard into Carroll County. A large elongate body of the hornblende gneiss *mm4* that extends from Muscogee County through Harris County and into Talbot County. A large V-shaped mass of amphibolitic rocks consists of *mm2, mm1*, and *mm3* in Heard, Carroll, Fulton and Coweta Counties (Fig. A-3). The only occurrence of *mm9* represents the Laura Lake Mafic Complex in northwestern Cobb County (Fig. A-3). Amphibolitic schists, *ms1* and *ms3*, were mapped in only a small portion of the Chattahoochee River Basin (Fig. A-3). Several occurrences of *ms3* are located in the central part of Lumpkin County (Fig. A-3). A singular, small occurrence of *ms1* is found in northwestern Coweta County (Fig. A-3).

Metasedimentary Rocks

Metasedimentary rock units shown on the Geologic Map of Georgia (Georgia Geologic Survey, 1976) include aluminous schists, mica schists, metagraywackes, and quartzites. These rock types appear to be concentrated in different parts of the Chattahoochee River Basin. Metagraywackes are found only in the northern end of the basin (Fig. A-9) and are the dominant rock type among these four types of rocks. Further to the south, from Douglas to Forsyth Counties, metaquartzites are most abundant (Fig. A-8). Mica schists are most abundant from the northern end of the DeKalb-Fulton-Cobb County area south to the middle part of Heard County (Fig. A-5). Aluminous schists (Fig. A-7) are abundant in the northernmost part of the Chattahoochee River Basin, in the midst of the quartzites and to the south with the mica schists. Based on these spatial relations, a northeast to southwest decrease in sediment size is suggested from the regional distribution of these rock units (Figs. A-9, A-8, A-7, A-5). Thomas and Neathery (1980) suggest a southwesterly prograding clastic wedge extending across northwestern Georgia into Alabama during the Cambrian and Ordovician. The present disposition of these metasedimentary units is compatible with that interpretation. In some geologic environments quartzites and schists may be interpreted as metamorphosed alteration zones in or near a submarine volcanic center. However, in the Chattahoochee River Basin, the association of these rock units with generally metasedimentary environments and the large extent of many of these units would suggest a sedimentary rather than a volcanic origin for these rocks.

Metagraywackes: The metagraywacke *pm2* represents the fifth largest lithologic type in the Chattahoochee River Basin in Georgia and is located principally in the northernmost part of the Chattahoochee River Basin. The largest occurrence of this rock type extends essentially along the trace of the Brevard fault zone from Habersham County through Gwinnett County (Fig. A-9). Another large mass of graywacke extends from Habersham County and into Lumpkin County. This rock type also constitutes an important part of the Tallulah Falls Dome. The metagraywacke unit *pm3a* is represented by a moderately sized mass in the north-central part of Lumpkin County (Fig. A-9). Because of the generally immature composition of graywackes, concentration of metagraywackes in this part of the Chattahoochee River Basin may have an important impact on stream geochemistry.

Quartzites: Quartzites are represented (Fig. A-8) by rock unit *q1, q1a, q1b* and *cq1* and to a certain extent *pms4* (Table 1). The quartzite *q1* is found as extensive, but narrow units generally northwest of the Brevard fault zone. Quartzite also forms part of the core of the Tallulah Falls Dome in the northern part of the Chattahoochee River Basin. Long, narrow units of the quartzite *q1a* are also located parallel to the Brevard fault zone in Douglas and Cobb Counties. A larger mass of *q1a* is located in Lumpkin and White Counties. The quartzite rock types *q1b* and *q1c* are represented by three small masses in Carroll and Douglas Counties. The *q1c* quartzite is located further to the east near Fulton County.

Schists: Mica schists, which include the rock units, *pm3a, pms1, pms2, pms3, pms3a, pms4, pms5, pms6a,* and *pms7* (Table 1) may be interpreted to be metamorphosed shales or mudstones. The association of most of the mapped mica schists with other sedimentary rock units suggests that these schists are also sedimentary in origin. Within the Inner Piedmont, biotite schist and muscovite-biotite-tourmaline schist usually contain muscovite, quartz, plagioclase, chlorite, and garnet.

Mica schists are most abundant from the northern end of the DeKalb-Fulton-Cobb County area south to the middle part of Heard County (Fig. A-5). Mica schist *pms3a* is the third most abundant (7.8 percent) rock type in the Chattahoochee River Basin (Table 1). The largest concentration of this rock type is found south of the Brevard fault zone in Troup, Harris, Talbot and Meriwether Counties. One portion of this rock type is located in Cobb County. The largest masses of the mica schists *pms4* and *pms5* are located in Heard and Carroll Counties northwest of and parallel to the Brevard fault zone. The lone occurrence of *pms6a* is in southern Coweta County. Mapped occurrences of the mica schist *pms1* are scattered throughout the northern half of the Chattahoochee River Basin with the largest occurrence located mainly in Meriwether County. One large mapped mass of the mica schist *pms3* that extends from Heard County into Douglas County constitutes the major portion of this rock type. Another intermediate sized body is located in Harris County. An occurrence of the mica schist *pms2* is located in the southern part of Lumpkin County.

Garnet mica schists include the rock units *pg1, pg2*, and *pg3*. Garnet mica schists account for a rather small portion (less than 2 percent) of the Chattahoochee River Basin. All are located northwest of the Brevard fault zone between Heard and Cobb Counties (Fig. A-6). Garnet mica schist *pg1* is generally found in Carroll and Douglas Counties. The largest occurrence of garnet mica schist extends from Heard County into southern Cobb County. Two small occurrences of *pg3* were mapped in southern Cobb County.

Aluminous schists, *pa1* and *pa2*, are generally located in three parts of the Chattahoochee River Basin (Fig. A-7). The northernmost mapped *pa1* is part of the Tallulah Falls Dome within Habersham County. Several long, narrow units of aluminous schist are found to extend through northernmost Fulton and into Forsyth County along the trace of the Brevard fault zone. Another *pa1* unit that is located in southern Fulton County is close to several *pa2* occurrences in eastern Coweta County. Aluminous schists may represent metamorphosed aluminous sediments such as kaolinitic clays or perhaps alteration clays associated with hydrothermal activity. However, the association of most of the mapped aluminous schists with rocks of sedimentary origin in the Chattahoochee River Basin suggests that the aluminous schists are most likely sedimentary in origin.

Mylonite and Flinty Crush Rock

Mylonites and flinty crush rock represent zones of intense faulting and/or shearing (A-11). Flinty crush rock (*c2*) zones represent cataclastic zones with several periods of brecciation and silicification of breccia fragments and matrix. Two small masses of flinty crush rock are found in Harris and Talbot Counties. Mylonites, represented by *c1*, are found in two separate parts of the Chattahoochee River Basin. In Forsyth County and Gwinnett and Hall Counties two narrow mylonite zones are roughly parallel to the trace of the Brevard fault zone. Slightly further to the northeast in Hall County several mylonites trend northwest approximately perpendicular to the other mylonites. Larger and more extensive mylonites were mapped further south, principally in Harris County. These mylonites mark the traces of the Towaliga fault, Bartlett's Ferry fault, and Goat Rock fault. The principal zone of cataclasis in the Chattahoochee River Basin extends along the Brevard fault zone but is not represented by specifically mapped rock units on the Geologic Map of Georgia.

Structural Geology and Tectonic Terranes

Within the Chattahoochee River Basin, four tectonostratigraphic terranes are currently recognized: the Blue Ridge, Inner Piedmont, Pine Mountain, and Uchee terranes (Fig. A-20). These terranes have previously been referred to as belts (e.g., Uchee belt). Tectonostratigraphic terranes are "fault-bounded packages of rocks of regional extent characterized by a geologic history which differs from that of neighboring terranes" (Horton and Zullo, 1991). The Brevard fault zone (Fig. A-20) separates the Inner Piedmont from the Blue Ridge terrane, also referred to as the Jefferson terrane (Horton and others, 1989). The Inner Piedmont terrane is separated from the Pine Mountain terrane (Fig. A-20) by the Towaliga fault zone (Williams, 1978). The Goat Rock fault zone separates the Pine Mountain terrane from the Uchee terrane. These tectonostratigraphic terranes, most crystalline rock units, and major faults in the Georgia Piedmont and Blue Ridge (as depicted on the Geologic Map of Georgia, Georgia Geological Survey, 1976, and the Geologic Map of Alabama, Osborne and others, 1989) strike approximately N.45°E and define the regional tectonic fabric (Fig. A-20). Recent detailed mapping (Fig. A-21) north of the Brevard zone has identified a series of smaller faults, and several synformal and antiformal structures (McConnell and Abrams, 1984). Mesozoic diabase dikes, and a few post tectonic granitic intrusions cut across the main regional fabric in a northwest to southeast direction.

Regional geologic mapping within the southeastern Piedmont suggests that distinctive rock assemblages may represent allochthonous thrust sheets emplaced one above another as a result of tectonic transport to the west during formation of the Appalachian Mountains (Cook and others, 1979; Higgins and others, 1988; Nelson, 1988; Nelson and others, 1990; Nelson and others, 1987). Boundaries between these thrust sheets are either poorly defined or are concealed (Nelson and others, 1987). Although effects of these thrust sheets are presently difficult to define, the four major tectonostratigraphic terranes noted above appear to affect composition of stream sediments and streams in the Chattahoochee River Basin. Each of these major tectonostratigraphic terranes contains metasedimentary rocks and most contain metavolcanic rocks and granitic rocks. Differences in composition and volumes of these rock units, as well as metamorphic and structural development, influence regional geochemistry and hydrogeochemistry of the Chattahoochee River Basin. Major geologic structures determine the spatial distribution of rock units within the river basin, and thereby influence it's geology and geochemistry. Faults may juxtapose rocks with different geochemical signatures and result in significant differences in stream chemistry over a short distance or between adjacent drainage basins. Faults and folds may structurally repeat or remove rock types which have a unique geochemical signature. Although major faults in the Chattahoochee River Basin are generally not mineralized, secondary structures related to these faults may be important hosts to metal mineralization.

Within the Chattahoochee River Basin, the traces of major faults (Fig. A-20) that extend through the basin are marked by intensely sheared cataclastic rocks - predominantly mylonites and flinty crush rock (Fig. A-11). Major faults include the Hayesville fault, Allatoona fault, Shope Fork fault, Chattahoochee fault, Blairs Bridge fault, Brevard fault zone, Towaliga fault zone, and Goat Rock fault. Each of these faults have influenced the geology and geochemistry of the Chattahoochee River Basin by controlling location and extent of certain rock units. Primary rock unit lithogeochemistry and secondary mineralization perhaps controlled by structural development influenced stream sediment geochemistry and stream hydrogeochemistry.

The Brevard fault zone (Fig. A-20, A-21) is the largest and most extensive of these structures, extending from Alabama through Georgia into South Carolina. Distinctive metasedimentary rocks are common within the Brevard fault zone. In Alabama, the Jacksons Gap Group is the dominant rock unit. To the northeast, the Sandy Springs Group is the dominant lithology. McConnell and Abrams (1984) include only ductilely sheared rocks such as protomylonite, mylonite, blastomylonite, button schist and phyllonite in the Brevard fault zone and not rocks with a well-developed secondary "cataclastic" foliation as suggested by Crawford and Medlin (1973). Interpretations of this linear zone of ductile shearing are numerous and are complicated by different episodes of movement.

Location and extent of rocks in the Blue Ridge terrane are controlled by the Allatoona, Shope Fork, Hayesville and Chattahoochee faults (Fig. A-21). The Dahlonega gold belt is particularly affected by these faults. This belt of rocks and mineralization is elongate and narrow because of these faults. Secondary structures resulting from movement on these faults may have acted as conduits for ore fluid movement and sites of ore deposition. Northwest of the Shope Fork fault is the Richard Russell Formation.

The Towaliga fault zone (Fig. A-20) is 4 to 6 miles wide. This fault consists of a variety of cataclastic rock types including blastomylonite, porphyroblastic blastomylonite, mylonite, mylonite gneiss, mylonite schist, mylonite quartzite, micro breccia (Fig. A-11), as well as fault slices of metasedimentary rocks of the Pine Mountain terrane(Thomas and Neathery, 1980).

The Goat Rock fault zone (Figs. A-11 and A-20) is 5 miles wide and contains blastomylonite, porphyroblastic blastomylonite, mylonite, ultramylonite, mylonite gneiss, pencil gneiss, and minor units of mylonite amphibolite (Thomas and Neathery, 1980). This fault zone consists of the Bartletts Ferry fault along the northwestern part of the zone and the Goat Rock fault near the middle of the zone.

Regional synformal and antiformal structures within the Blue Ridge terrane are shown in Fig. A-21. Most of these structures strike to the northeast and are overturned to the northwest. General effects of these structures are to repeat the stratigraphy and, on occasion, to control drainage patterns. A large synformal structure south of the Brevard fault zone controls distribution of the metamorphic stratigraphy in the Atlanta area (Fig. A-21).

An allochthonous sheet, the Alto allochthon, of high metamorphic grade rocks overlying lower metamorphic grade rocks of the Chauga Belt is found adjacent to the Brevard fault zone in northeast Georgia and northwestern South Carolina (Fig. A-20). Rocks within this allochthon are sillimanite grade mica and granitic gneisses, muscovite-biotite schist, aluminous schist, amphibolite and quartzite (Hatcher, 1978).

Blue Ridge Terrane

In the Greater Atlanta Region within the Chattahoochee River Basin and north of the Brevard fault zone, rocks of the Blue Ridge terrane are divided into the Sandy Springs Group, New Georgia Group, and the Richard Russell Formation (Fig. A-21). Rocks of the New Georgia Group are generally thought to be equivalent to rocks of the Ashland Supergroup in Alabama. Similar lithologies in the Sandy Springs Group and Wedowee Group in Alabama suggest correlation between these two groups. Bimodal volcanic rocks of the New Georgia Group may represent back-arc basin volcanics that formed on attenuated (rifted) continental crust. Graywackes, argillites and subordinate volcanic rocks of the Sandy Springs Group may be flysch facies rocks deposited in the basin as volcanic activity waned. Rocks of both groups are believed to be late Precambrian to early Paleozoic in age (McConnell and Abrams, 1984). Numerous mineral deposits containing heavy metals are spatially and genetically associated with the rocks in the Blue Ridge terrane.

Rock units of the New Georgia Group include the Mud Creek Formation, Univeter Formation, Pumpkinvine Creek Formation, Canton Formation, Acworth Gneiss and Kellogg Creek Mafic Complex (Fig. A-21). Also present are unnamed rock units that contain chlorite schist, chlorite-anthophyllite schist, sulfide-, magnetite- or manganese-bearing quartzites, kyanite-quartz granofels, meta-ultramafic rocks, felsic gneiss, and garnet-kyanite-quartz-sericite schist. All except the Kellogg Creek Mafic Complex are found within the Chattahoochee River Basin. The Mud Creek Formation contains locally garnetiferous, hornblende-plagioclase amphibolite and hornblende gneiss interlayered with garnet-biotite-quartz-plagioclase gneiss and biotite schist. Interlayered magnetite quartzites are interpreted to be banded iron formations. Biotite-quartz-plagioclase orthogneiss (the Villa Rica Gneiss) is interpreted to be a metadacite. Rocks of the Univeter Formation include hornblende-plagioclase amphibolite, hornblende gneiss, lenses and layers of banded iron formation, garnet-biotite-muscovite schist, and garnet-hornblende-muscovite-quartz schist. Garnet-sericite schist interlayered with garnet-graphite schists that may contain kyanite, micaceous quartzite and metagraywacke make up the Canton Formation. The Pumpkinvine Creek Formation consists of hornblende-plagioclase amphibolite, garnet-hornblende-plagioclase gneiss, sericite phyllite, banded iron formation, hornblende-quartz-plagioclase gneiss to biotite-muscovite-quartz-plagioclase gneiss, and actinolite-chlorite schist. Rock types of the Acworth Gneiss include a biotite-quartz-plagioclase orthogneiss with accessory muscovite and epidote (McConnell and Abrams, 1984).

The Laura Lake Mafic Complex (Figs. A-3 and A-21) is a large, pre-metamorphic, intrusive-extrusive complex approximately 80 square miles in size. It is elongate to the northeast with the regional fabric. This complex is composed predominantly of migmatitic garnet amphibolite with smaller amounts of clinopyroxene-bearing metagabbro, felsic gneiss, meta-ultramafic lithologies and banded iron formation (McConnell and Abrams, 1984).

Rock units of the Chauga River Formation consist of a lower phyllite member, a middle carbonate member, and an upper phyllonite. Structurally above the phyllite is a carbonate member consists of dolomitic marble that may locally contain pyrite and sphalerite (Allen, 1986). Structurally overlying the marble is a chlorite-muscovite phyllonite with interbeds of massive quartzite and metagraywacke. The Chauga River Formation extends along the Brevard Zone from Suwanee into North Carolina.

Overlying the Chauga River Formation are rocks of the Sandy Springs Group (Fig. A-21) which consists of the Dog River Formation, Andy Mountain Formation, Bill Arp Formation in a western belt, Powers Ferry Formation, Chattahoochee Palisades Quartzite, Factory Shoals Formation in an eastern belt, and various unnamed rock units (McConnell and Abrams, 1984). This Sandy Springs Group is correlative with the Jacksons Gap Group in Alabama and the Tallulah Falls Formation in northeast Georgia (Allen, 1986). The Dog River Formation contains muscovite-biotite-quartz-feldspar gneiss interpreted as metagraywacke, garnet-muscovite schist and amphibolite (McConnell and Abrams, 1984). Rock types within the Andy Mountain Formation include a biotite-garnet-plagioclase-muscovite-quartz schist, a feldspathic, micaceous garnet quartzite, and a clean quartzite. Lithologies that comprise the Bill Arp Formation include garnet-biotite-muscovite-plagioclase-quartz schist, muscovite schist, quartz-muscovite-biotite schist, muscovite-biotite-quartz-plagioclase schist and metagraywacke. The Powers Ferry Formation consists of biotite-quartz-plagioclase gneiss interpreted as metagraywacke with interbedded amphibolite and mica schist (McConnell and Abrams, 1984; Allen, 1986). Principal rock type of the Chattahoochee

Palisades Quartzite is a massive quartzite. Lithologies of the Factory Shoals Formation include light gray, garnet-biotite-oligoclase or muscovite-biotite-plagioclase metagraywacke, kyanite-quartz schist, and staurolite-muscovite quartz schist (McConnell and Abrams, 1984).

North of the Brevard fault zone in Carroll, Coweta, and Cobb Counties are found the Austell Gneiss and Sand Hill Gneiss (Figs. A-4 and 21). The Austell Gneiss is a blastoporphyritic to nonporphyritic gneiss. Compositionally similar to the Austell Gneiss, the Sand Hill Gneiss contains greater amounts of muscovite, quartz and plagioclase and lesser amounts of microcline. These gneisses are pre- to syn-metamorphic, granitic to quartz monzonitic intrusions. Abrams and McConnell (1981) and McConnell and Abrams (1984) suggest a common differentiation trend and a common source magma for these two gneisses.

To the northwest of the Shope Fork fault (Fig. A-21), the Richard Russell Formation is represented by the *bg1* unit in Lumpkin and White Counties (Fig. A-17). This unit contains mainly migmatitic biotite gneiss, with lesser amounts of pebbly metasandstone, garnet-sillimanite-biotite schist, garnet-biotite-augen muscovite schist, calc-silicate granofels, amphibolite, tonalite gneiss and ultramafic schist (Gillon, 1982).

Within the Chattahoochee River Basin in Alabama, the Blue Ridge terrane (Fig. A-20) consists of the Wedowee and Emuckfaw Groups with the Jacksons Gap Group occupying much of the Brevard fault zone in Alabama (Osborne and others, 1989). Allen (1986) suggests that this group is correlative with the Sandy Springs Group.

The Wedowee Group (Fig. A-20) consists of the Cragford Phyllite, Cutnose Gneiss, Hackneyville Schist, and Cornhouse Schist. Lithologies of the Cragford Phyllite include graphite-chlorite-sericite schist, phyllite, garnet-sericite schist, graphite-quartz-sericite phyllite, feldspathic biotite gneiss, calc-silicate rock, and quartzite. Rock types found within the Cutnose Gneiss are quartz-biotite feldspathic gneiss, graphite-chlorite-sericite schist, and quartzite. Within the Hackneyville Schist are quartz-plagioclase-almandine-kyanite-biotite-muscovite schist, graphite-muscovite schist, and biotite-bearing quartzite. The Cornhouse Schist contains plagioclase-garnet-biotite-muscovite-quartz schist interlayered with chlorite-biotite-garnet schist (Osborne and others, 1989).

Rock types found within the Emuckfaw Group (Fig. A-20) include the Glenoch Schist and an interlayered sequence of muscovite-garnet-biotite schist, metagraywacke, calc-silicate rock, quartzite, and graphitic schist. Lithologies of the Glenoch schist are graphite-garnet-muscovite schist and metagraywacke (Osborne and others, 1989).

Generally correlative with the Brevard fault zone, the Jacksons Gap Group (Fig. A-20) consists of graphitic-sericite-quartz schist, sericite phyllonite, blastomylonite, porphyroclastic blastomylonite schist, and mylonite quartzite, quartzite and metaconglomerate (Osborne and others, 1989).

Inner Piedmont Terrane

In the Greater Atlanta Region within the Chattahoochee River Basin and south of the Brevard fault zone (Figs. A-20 and A-21), rocks of the Inner Piedmont terrane are divided into the Atlanta Group and the Sandy Springs Group. Rocks of the Atlanta Group and Sandy Springs Group are believed to be late Precambrian to early Paleozoic in age. Formations within the Atlanta Group include the Intrenchment Creek Quartzite, Norcross Gneiss, and the Camp Creek, Big Cotton Indian, Clarkston, Stonewall, Wahoo Creek, Senoia, Clairmont, Promised Land, Wolf Creek, Inman Yard, and Snellville Formations. All but the Snellville Formation are found within the Chattahoochee River Basin. Rocks of the Atlanta Group crop out in a major regional synform, the Newnan-Tucker synform. Rocks of the Atlanta Group within the Chattahoochee River Basin are exposed along the western limb of this synform. Protoliths are believed to be graywackes, aluminous shales, shales, sandstones, manganiferous sandstones, banded iron formation, porphyritic granites, metaplutonic, basaltic tuffs, volcaniclastic rocks, and felsic and mafic volcanic rocks. These rocks are thought to represent eugeosynclinal, flysch-type sedimentation in a rapidly subsiding, deep-water basin. Base-metal mineralization is more localized than in the Blue Ridge terrane, perhaps because of the genetically different rock types in these terranes.

Brief descriptions of the formations that follow are in order of oldest to youngest based on the assumption that the synform is synclinal with the oldest units at the base (Higgins and Atkins, 1981). Rocks found within the Inman Yard Formation include porphyroblastic biotite-quartz-plagioclase gneiss, porphyroblastic granite gneiss and sillimanite-muscovite schist. The principal rock type of the Wolf Creek Formation is an amphibolite interlayered with biotite-muscovite schist. Lithologies of the Promised Land Formation include biotite granite gneiss with amphibolite, quartzite and muscovite quartz schist. The Norcross Gneiss is an epidote-biotite-muscovite-plagioclase gneiss that contains local amphibolite. Found within the Clairmont Formation are a biotite-plagioclase gneiss and a hornblende-plagioclase amphibolite. Rocks of the Senoia Formation include a garnet-biotite-muscovite schist with amphibolite, and spessartine quartzite, sillimanite schist and biotite gneiss. The Wahoo Creek Formation contains muscovite-plagioclase-quartz gneiss, amphibolite, mica schist and epidote-calcite-diopside gneiss. Within the Stonewall Formation are biotite gneiss, hornblende-plagioclase amphibolite, and sillimanite-biotite schist. Principal lithologies of the Clarkston Formation include sillimanite-garnet-quartz-plagioclase-biotite-muscovite schist with interlayered hornblende-plagioclase amphibolite. Contained within the Big Cotton Indian Formation are porphyritic biotite-plagioclase gneiss, hornblende-plagioclase amphibolite, and biotite-muscovite schist. The Intrenchment Creek Quartzite is a spessartine quartzite with spessartine-mica schist. Within the Camp Creek Formation is a massive granite gneiss interlayered with thin, fine-grained hornblende-plagioclase amphibolite. Lithonia Gneiss is a muscovite-biotite-microcline-oligoclase-quartz granite gneiss.

In Alabama, the Inner Piedmont (Fig. A-20) is divided into the Dadeville and Opelika Complexes (Osborne and others, 1989). Rocks of these units extend into Georgia, but have not been mapped according to these rock units. Metamorphosed metavolcaniclastic, felsic and mafic rocks of the Dadeville Complex are also found with localized garnetiferous mica schist, amphibolite and biotite gneiss. These felsic and mafic rocks consist of granitic gneiss, hornblende gneiss, amphibolite and ultramafic rocks. The Opelika Complex is a metasedimentary sequence consisting of aluminous schists, quartzites, biotite gneisses, and mica schists (Osborne and others, 1989). Both complexes have undergone kyanite- and/or sillimanite-zone peak-metamorphism and retrograde metamorphism to greenschist and lower amphibolite-facies assemblages (Steltenpohl and others, 1990). This group contains thin amphibolites and quartz monzonite plutons. The Stonewall Line, a major structural discontinuity, separates the Dadeville and Opelika Complex.

Formations within the Dadeville Complex (Fig. A-20) include the Agricola Schist, Ropes Creek Amphibolite, Waverly Gneiss, Waresville Schist, ultramafic and mafic intrusive rocks, granites and felsic gneisses (Osborne and others, 1989). Agricola Schist consists of interlayered biotite-muscovite and muscovite-biotite-garnet schist, biotite gneiss and thin interbedded amphibolite and hornblende gneiss. Biotite gneisses may be kyanite- or sillimanite-rich. Ropes Creek Amphibolite contains hornblende with lesser amounts of plagioclase, quartz, opaque oxides, sphene, diopside, garnet, and epidote (Steltenpohl and others, 1990). Rocks of the Ropes Creek Amphibolite are interpreted as metamorphosed tholeiitic basalts generated by partial melting of undepleted mantle beneath a back-arc basin (Stow and others, 1984). Steltenpohl and others (1990) suggest that rocks belonging to the Zebulon Formation that were described by Higgins and others (1988) may be part of the Ropes Creek Amphibolite. Waverly Gneiss includes feldspathic gneiss, interlayered amphibolite, calc-silicate rock, garnet quartzite, and muscovite schist. Rocks of this unit may actually be part of the Ropes Creek Amphibolite suite as suggested by Steltenpohl and others (1990). Waresville Schist is composed of amphibolite, chlorite-actinolite schist, actinolite-feldspar metaquartzite, and chlorite metaquartzite (Bentley and Neathery, 1970). Rocks of this unit may also be part of the Ropes Creek Amphibolite (Stow and others, 1984). Ultramafic and mafic intrusive rocks occur as sills, layered intrusions and dikes that may represent two episodes of mafic intrusion (Neilson and Stow, 1986). Metanorite, meta-orthopyroxenite, amphibolite and actinolite schist constitute the Doss Mountain suite. Intrusions of the Slaughters suite are metagabbros.

Metaplutonic rocks of the Camp Hill Gneiss and Chattasofka Gneiss contain quartz, plagioclase, biotite, hornblende, epidote, microcline, accessory sphene, opaque oxides, zircon and garnet (Steltenpohl and others, 1990). The Chattasofka Gneiss may be equivalent to the Farmville Metagranite intrusions.

Rock units found within the Opelika Complex (Fig. A-20) include the Loachapoka Schist, Auburn Gneiss, and Farmville Metagranite. Lithologically, the Loachapoka Schist consists of a kyanite or sillimanite-garnet-plagioclase-muscovite-biotite-quartz schist, amphibolites, and quartzites (Steltenpohl and others, 1990). Within the Auburn Gneiss are a biotite gneiss and a migmatitic muscovite-biotite schist. Pods and layers of calc-silicates (tremolite, garnet, and hornblende) are scattered throughout the Auburn Gneiss. Biotite gneiss contains plagioclase, quartz, biotite, garnet, magnetite, muscovite, sphene, apatite and chlorite. Muscovite-biotite schist contains muscovite, biotite, garnet, magnetite, tourmaline, plagioclase and quartz. These rocks are interpreted as a metamorphosed sequence of graywacke and pelitic sediments (Bentley and Neathery, 1970). Found as concordant sills within the Loachapoka Schist and Auburn Gneiss, the Farmville Metagranite is believed to be syntectonic intrusions that contain quartz, potassium feldspar, plagioclase, biotite; muscovite and tourmaline. Individual bodies are metamorphosed, strongly foliated and contain gneissic banding along their margins. This metagranite is believed (Steltenpohl and others, 1990) to be similar to the Cedar Rock complex in west-central Georgia (Atkins and Lineback, 1992). Chemical analyses indicate that the Cedar Rock complex (Atkins and Lineback, 1992) is higher in SiO_2 and lower in Al_2O_3 than the Farmville Metagranite (Steltenpohl and others, 1990). This compositional difference may reflect slightly different source materials for the granitic melts. Steltenpohl and others (1990) suggest that the Farmville melts were concentrated along the structural top of the Opelika Complex during syntectonic emplacement within a ductile shear zone.

Two types of pegmatites are reported in the migmatitic schists and metagranite of the Opelika Complex. Pegmatites in the metagranite are narrow, are parallel to and crosscut foliation, and are composed mainly of potassium feldspar and quartz. Pegmatites in the migmatitic schists are larger veins and pods that are composed of quartz, plagioclase, potassium feldspar and large books of muscovite (Steltenpohl and others, 1990). Pegmatites of this type were examined and sampled in the Opelika Complex in and adjacent to Troup County in

Georgia (Cocker, 1992c and 1994). These pegmatites are of the muscovite-class described by Cerny (1982). Numerous occurrences of beryl in this second group of pegmatites may be reflected in the stream sediment geochemistry.

Two large intrusions, the Ben Hill Granite and Palmetto Granite, are located principally in southern Fulton and northern Coweta counties (Figs. A-4 and A-21). The southernmost portion of the Palmetto Granite extends into the Flint River Basin. These granites are post-metamorphic batholithic intrusions believed to be emplaced into rocks of the Atlanta Group about 300 to 325 m.y. ago (Higgins and Atkins, 1981; McConnell and Abrams, 1984). Post-metamorphic ductile shearing affected the northernmost portions of these intrusions in the vicinity of the Brevard fault zone (Fig. A-21). These intrusions are generally lower in SiO_2 than the Austell Gneiss and Sand Hill Gneiss. Lithologically, the Ben Hill Granite is a coarse-grained, porphyritic, muscovite-biotite-quartz-plagioclase-microcline granite. The Palmetto Granite is a coarse-grained, porphyritic granite containing microcline, quartz, plagioclase, biotite, muscovite, perthite, sphene, apatite, epidote, and zircon.

Further to the south, in Troup and Meriwether counties, several large, irregularly shaped granitic intrusions (Figs. A-4 and A-21) that lie along strike between granites of the Cedar Rock complex (Atkins and Lineback, 1992) in Georgia and the Farmville Metagranite within the Opelika Complex in Alabama (Steltenpohl and others, 1990) appear to be similar to granites of the Farmville Metagranite and Cedar Rock Complex.

Pine Mountain Terrane

The Pine Mountain terrane (also known as the Pine Mountain Belt) is bounded by the Towaliga fault zone on the north and the Goat Rock fault zone on the south (Fig. A-20). This terrane consists of a billion year old (Odom and others, 1973) basement complex called the Wacoochee Complex and an overlying metasedimentary sequence called the Pine Mountain Group. Rock units of the Wacoochee Group (or Complex) include Jeff Davis Granite, Woodland Gneiss, Cunningham Granite, and Whatley Mill Gneiss. Jeff Davis Granite is a strongly foliated, hypersthene-bearing, (Rankin and others, 1993) garnetiferous, biotite granite (Clarke, 1952). Cunningham Granite is similar to Jeff Davis Granite but only moderately foliated (Rankin and others, 1993). Woodland Gneiss is a biotite granite gneiss(Clarke, 1952). Whatley Mill Gneiss is a biotite-muscovite-oligoclase augen gneiss. Large augens in the Whatley Mill Gneiss are potassium feldspar (Osborne and others, 1989).

Rocks of the Pine Mountain Group are found within the Pine Mountain window in Georgia and Alabama. Metasedimentary rocks of this group are complexly folded and thrust faulted into an overturned nappe structure (Sears and others, 1981). This group is composed of (from oldest to youngest) Sparks Schist, Hollis Quartzite, and Manchester Formation. Lithologically, the Sparks Schist (equivalent to the Halawaka Schist in Alabama) is composed of feldspathic muscovite-biotite schist, quartz diorite gneiss, muscovite-graphite schist, and amphibolite (Osborne and others, 1989). Hollis Quartzite (Fig. 11) is a quartzite with minor mica, feldspar, and pyrite (Osborne and others, 1989). Rocks comprising the Manchester Formation include muscovite-quartz schist and quartzite that may contain garnet, sillimanite and graphite (Osborne and others, 1989). Rocks of the Pine Mountain Group are interpreted as a transgressive sedimentary sequence (Thomas and Neathery, 1980).

Uchee Terrane

Rocks of the Uchee terrane (previously known as the Uchee Belt) are found between the Goat Rock fault zone (Fig. A-20) and Upper Cretaceous strata of the Coastal Plain. In Alabama and adjacent parts of Georgia, the Uchee terrane is divided into the Phenix City Gneiss and Hospilika Granite. The Phenix City Gneiss is a coarsely crystalline, highly contorted migmatitic gneiss complex. This complex consists of biotite-epidote quartz diorite gneiss, biotite-hornblende gneiss and epidote-biotite amphibolite (Thomas and Neathery, 1980). Hospilika Granite is a massive epidote-muscovite quartz diorite to granodiorite (Osborne and others, 1989). In central Georgia, geochemical signatures of the Carolina terrane are similar to and continuous with that of the Uchee terrane. Together with the presence of sericite schists in the Uchee terrane, which were examined by Cocker during a study on pegmatites, the geochemical data suggest that the Uchee and Carolina terrane are equivalent terranes.

Coastal Plain Strata

The Coastal Plain within the Georgia portion of the Chattahoochee River Basin contains sixteen rock units that include Late Cretaceous to Eocene strata as well as Quaternary alluvium. Outcrop patterns of these strata are generally in the form of southwardly pointed V's resulting from the geometry of the generally southeasterly dip and the gradient of the Chattahoochee River. Intricate dendritic map patterns are displayed by the younger Cretaceous and Paleocene strata (Figs. A-12 and A-13). Sandy and clayey sediments are dominant in the Cretaceous rocks, and carbonate sediments are more abundant in Paleocene and Eocene strata. Paleocene to middle Eocene rocks are mixed carbonate and clastic sediments. Late Eocene and Oligocene rocks are mainly pure carbonates.

Discussion of the distribution of stratigraphic units is based mainly on the Geologic Map of Georgia (Georgia Geological Survey, 1976). This discussion excludes Alabama, because a GIS coverage of the Coastal Plain in Alabama is not presently available. Although more recent geologic mapping and stratigraphic analyses of the Georgia Coastal Plain by Huddlestun (1988 and 1993), Hetrick (1990 and 1992), and Hetrick and Friddell (1990) have redefined the stratigraphy and distribution of sedimentary formations in Georgia's Coastal Plain, most of this work has been to the east of the Chattahoochee River Basin. Other recent studies by Reinhardt and Donovan (1986) and Reinhardt and others (1980) focused on the older sediments (i.e., Cretaceous and Paleocene) in the Chattahoochee River Basin. The Chattahoochee River Basin lies along an axis of varied and rapidly changing depositional environments that change both from east to west and north to south and with time (Reinhardt and Donovan, 1986; Reinhardt and others, 1980).

Cretaceous

Cretaceous sediments occupy a total of 14.7 percent of the Chattahoochee River Basin (Fig. A-12). In Georgia, most of these sediments are located in Quitman, Stewart, Chattahoochee, Muscogee, and Marion Counties. The Providence Sand and the Blufftown Formation cover half of this area. As the lowermost unit, the Tuscaloosa Formation lies directly on crystalline basement rocks of the Piedmont. Average dips are low, on the order of 30 to 50 feet per mile to the southeast. Most are composed of micaceous, feldspathic, quartzose sand. Mapping by Reinhardt and Donovan (1986) suggests that the distribution of continental lithofacies in the Tuscaloosa Formation was controlled by north-south drainage systems that generally corresponded to the present Chattahoochee and Flint River systems. Post-Tuscaloosa Cretaceous sedimentation in this area was controlled by a series of marine transgressions and regressions (Reinhardt and Donovan, 1986). In the Chattahoochee River Basin, the Tuscaloosa Formation (*Kt*) consists of fine- to coarse-grained, gravelly, arkosic, micaceous, cross-bedded, nonmarine sands with lesser amounts of silt and sandy clay. Average thickness is 250 feet and may be as much as 433 feet thick at Fort Benning. The Eutaw Formation (*Ke*) is composed of two units. Sediments of the basal unit include coarse-grained, feldspathic, quartzose sand. This unit ranges in thickness from 18 feet to 40 feet. The upper unit consists of micaceous, carbonaceous, silty sand, sandy silt and silty, sandy clay. Thickness of this unit is 75 to 100 feet. Lithologically, the Blufftown Formation (*Kb*) consists of a lower unit of coarse-grained quartzose sand overlain by sandy, carbonaceous, highly micaceous clay. Thicknesses are about 150 and 260 feet, respectively. The Cusseta Sand (*Kc*) consists of coarse-grained to gravelly sands containing kaolin balls and kaolin lenses. Thickness is approximately 185 feet. Sediments of the Ripley Formation (*Kr*) include 135 feet of calcareous, clayey, fine- to coarse-grained sand. Two lithologic members make up the Providence Sand (*Kp*) - a lower member which is 30 feet thick and an upper member which is 119 feet thick. Sediments in the lower member are carbonaceous, micaceous silt and fine sand, and are medium- to very coarse-grained, micaceous, feldspathic sands in the upper member (Marsalis and Friddell, 1975). The Providence Sand is an important aquifer, especially in the upper part of the Coastal Plain (McFadden and Perriello, 1983) because of saturated, permeable sands. Dominance of sandy sediments should have a strong impact on stream sediment composition and stream and ground-water hydrogeochemistry.

Paleocene

In Georgia, Paleocene age sediments occupy a total of 5.8 percent of the Chattahoochee River Basin (Fig. A-13). Most of these sediments are found in Clay, Randolph, Quitman, and southeastern Stewart Counties in the southern part of the Chattahoochee River Basin. The Clayton Formation (*Pc*) contains a lower, 35 foot thick unit of conglomerate overlain by sandy, earthy, shelly crystalline limestones and sands; a middle, 42 foot thick limestone; and an upper, 80 to 90 foot thick massive limestone. Leaching of limestones left a sandy clay residuum that is locally rich in iron. Limonite, an iron oxide, may contain up to 58 percent iron. This residuum has been extensively mined. Limestones in the middle of this formation and contiguous permeable sands in the upper and lower parts of the formation host the Clayton aquifer (McFadden and Perriello, 1983). Lithologically, the Porters Creek Formation (*Pcn*) consists of calcareous, micaceous, clayey fine- to medium-grained sand, sandy calcareous clay, and thin-bedded, clayey limestone (Osborne and others, 1989). The Alabama Geological Survey includes the Porters Creek Formation with the Clayton Formation in the eastern part of Alabama because lithologic similarities make mapping distinctions difficult. Nonmarine updip facies of the Nanafalia Formation (*Pnf*) consist of highly micaceous, carbonaceous sand with some kaolinitic clay. Bauxites were mined from this unit at Eufala, Alabama and Springvale, Georgia. Marine portions of this formation are highly micaceous, carbonaceous silt and fine sand. Marine sediments are located to the west and south of the Eufala bauxite district in Alabama (Clarke, 1992). The Nanafalia Formation is located mainly in Clay County according to Fig. A-13. Composed mainly of interlaminated clay, silty clay, and fine quartzose sand, the Tuscahoma Formation (*Ptu*) also contains highly glauconitic, coarse-grained sand at its base. Thicknesses range from 90 to

153 feet. The Tuscahoma Formation extends from Early into Stewart County.

Eocene

Eocene sediments cover 7.6 percent of the Chattahoochee River Basin in Georgia (Fig. A-14). Dips range from 13 to 17 feet per mile to the southeast. Eocene sediments cover most of Seminole and Early Counties and eastern parts of Clay and Randolph Counties. The Hatchetigbee Formation lies between the Tuscahoma and Tallahatta (*Eta*) formations (Pickering and Hurst, 1989). In the Chattahoochee River Basin, this unit contains the Bashi Marl member which consists of 7 to 23 feet of glauconitic, calcareous sand (Marsalis and Friddell, 1975). The Bashi Marl member is included with the Tuscahoma Formation on the Geologic Map of Georgia, but the Hatchetigbee Formation does not appear in the GIS clip of the Geologic Map of Georgia coverage. Sediments of the Tallahatta Formation (*Eta)* include 39 to 67 feet of slightly calcareous, glauconitic, clayey sand. Osborne and others (1989) describe the Tallahatta Formation as containing thin-bedded to massive siliceous claystone, interbedded with clay, sandy clay, and glauconitic sand and sandstone. Permeable sands in the Tallahatta and Hatchetigbee formations host the Claiborne aquifer (McFadden and Perriello, 1983). Lithologically, the Lisbon Formation (*Eli*) consists of calcareous, glauconitic sands, limestone, and clayey sands. Thickness of this unit is 110 feet (Marsalis and Friddell, 1975). Osborne and others (1989) describe the Lisbon Formation as calcareous, glauconitic, clayey sand, marl, carbonaceous sand, carbonaceous silty clay and coarse glauconitic, quartz sand. The Claiborne Formation (*Ec*) is the updip equivalent of the Tallahatta and Lisbon Formations and is located essentially in northern Clay County, Georgia.

Upper Eocene strata represent the largest percentage of the Eocene sediments with 5.8 percent. In western Georgia, these strata consist of the Ocala Group (*Eo*) which is found in Early and Seminole Counties. In central Georgia, the Ocala Group consists of the lower Tivola Limestone and the upper Ocmulgee Formation separated by the Twiggs Clay Member of the Dry Branch Formation (Huddlestun and Hetrick, 1986). Sediments included within the Tivola Limestone are generally fine to coarse, bioclastic limestone with subordinate montmorillonite, kaolinite, illite, glauconite, disseminated pyrite, and quartz sand. Undifferentiated Eocene and Oligocene residuum (*Eo-Os*) are included with the Upper Eocene strata.

Quaternary

Quaternary age stream alluvium and stream terrace deposits (Fig. A-15) cover less than 2 percent of the Chattahoochee River Basin in Georgia (*Qal*) on the Geologic Map of Georgia. Some of these deposits may actually be Tertiary (Hetrick and Friddell, 1990). Alluvium consists of poorly sorted sand, clayey sand and gravel. Iron oxide cement is reported in the older deposits of alluvium (Hetrick and Friddell, 1990).

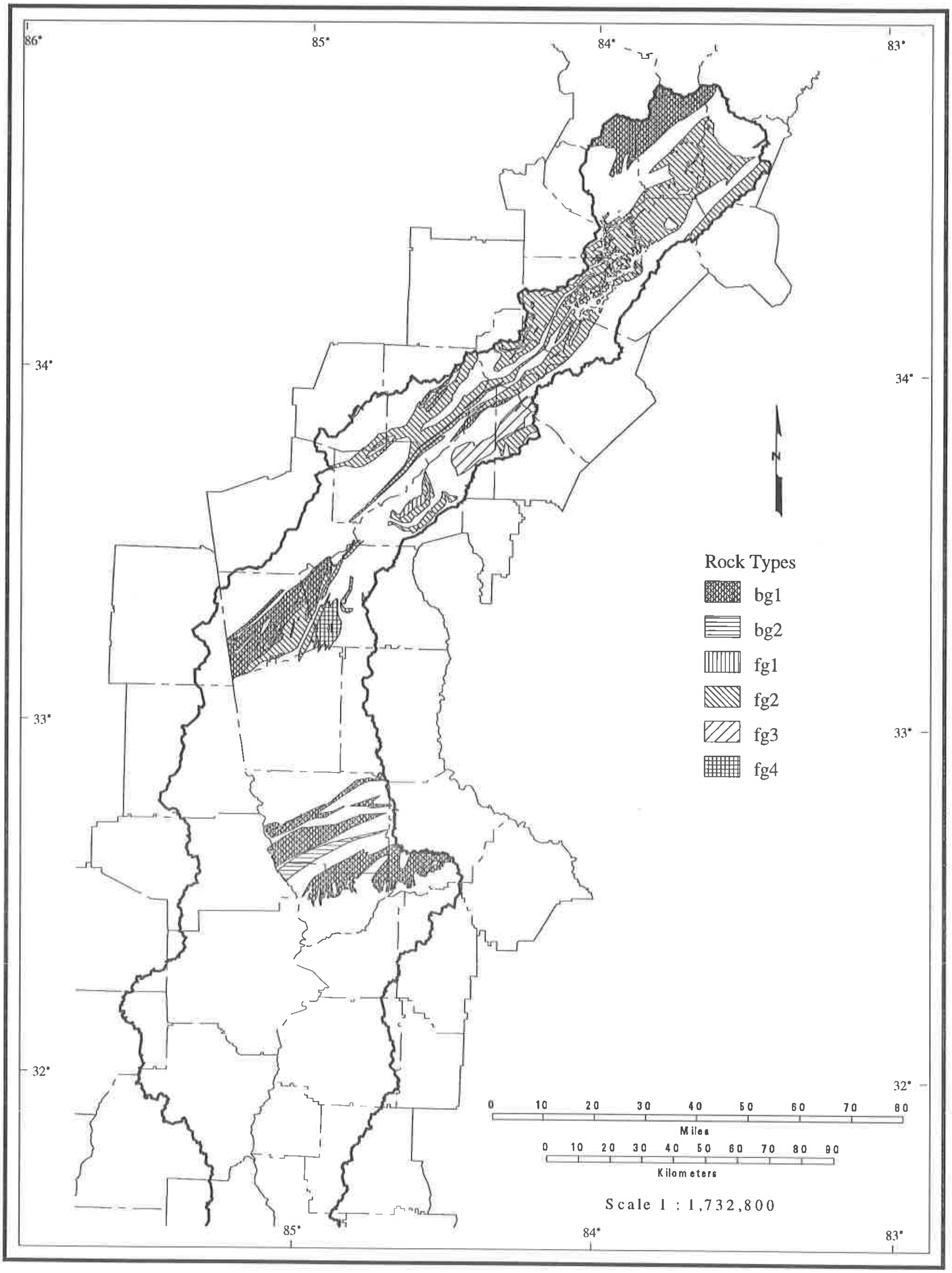

Figure A – 1. Biotite gneisses. Rock types as in Table 1 and in Appendix.

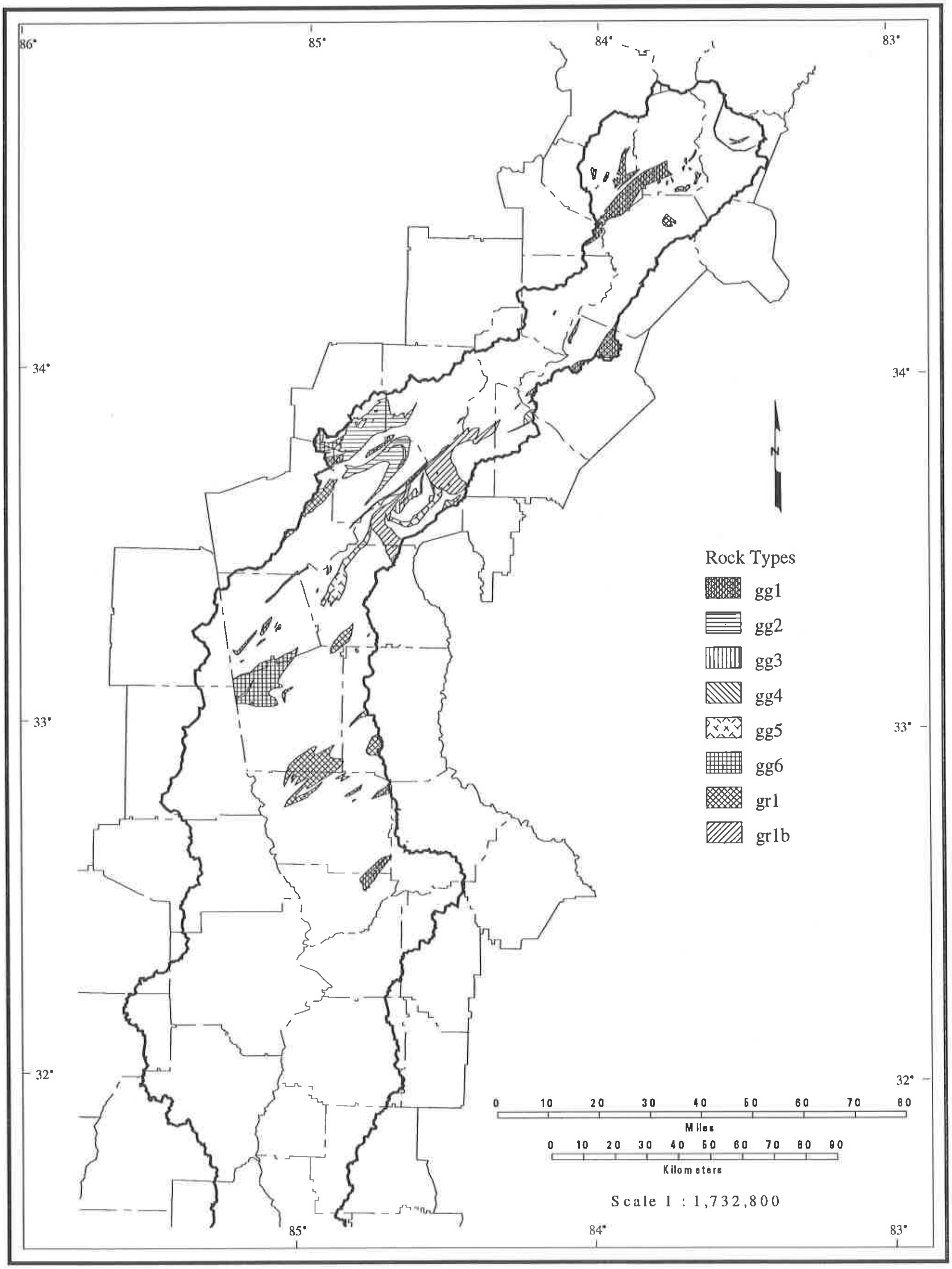

Figure A – 2. Granitic gneisses. Rock types as in Table 1 and in Appendix.

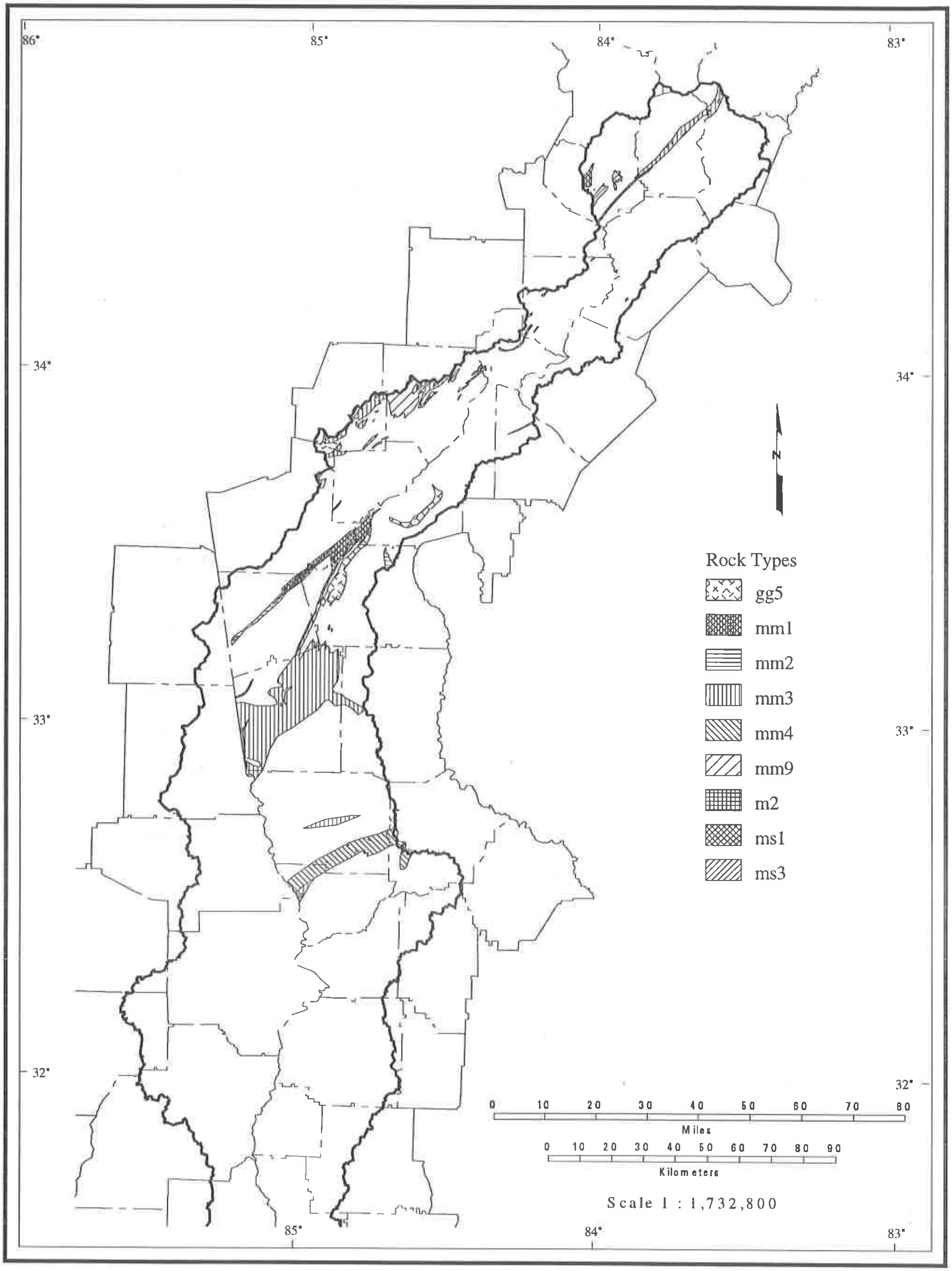

Figure A – 3. Amphibolitic rocks. Rock types as in Table 1 and in Appendix.

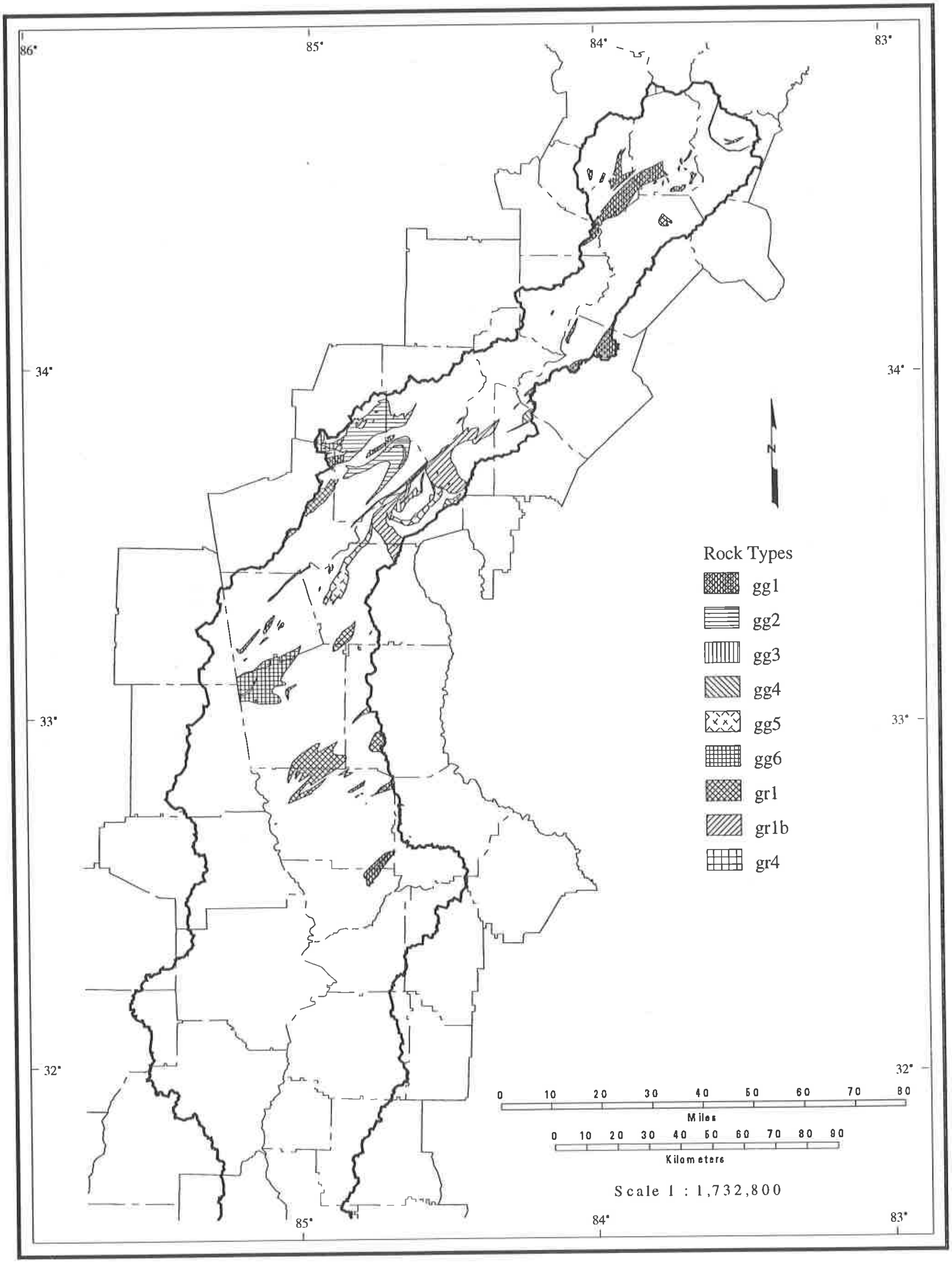

Figure A – 4. Granitic rocks. Rock types as in Table 1 and in Appendix.

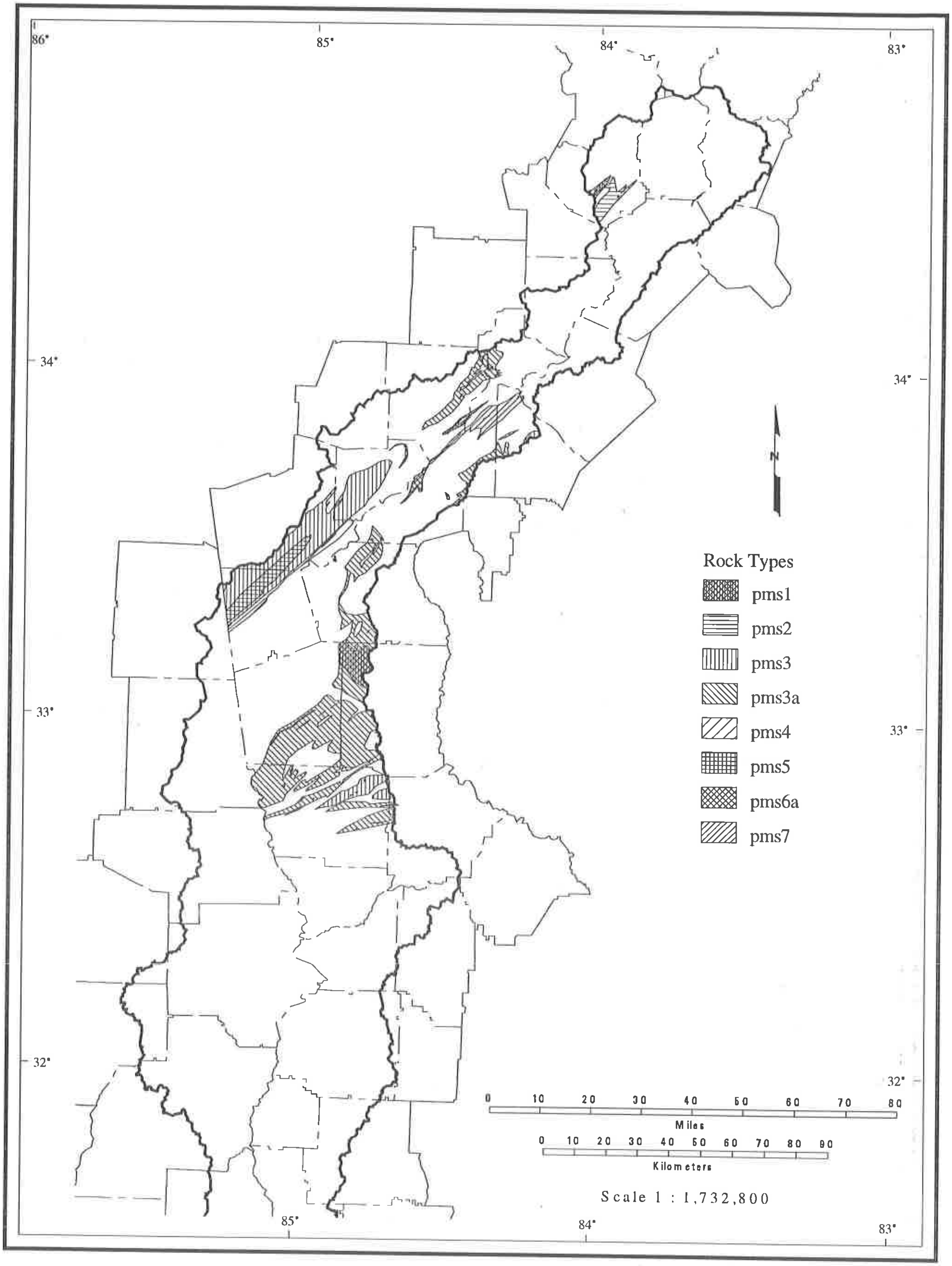

Figure A – 5. Mica schists. Rock types as in Table 1 and in Appendix.

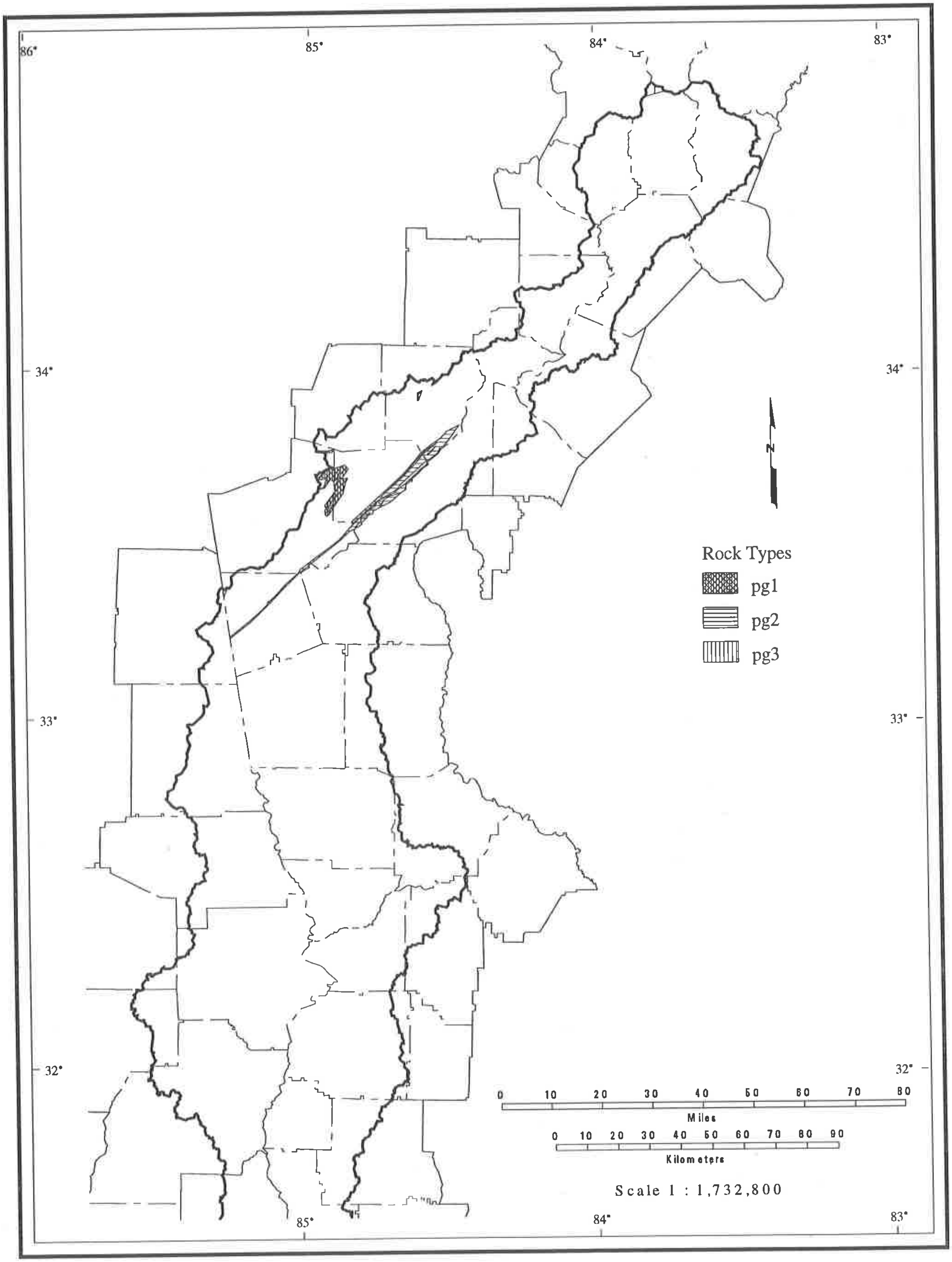

Figure A – 6. Garnet schists. Rock types as in Table 1 and in Appendix.

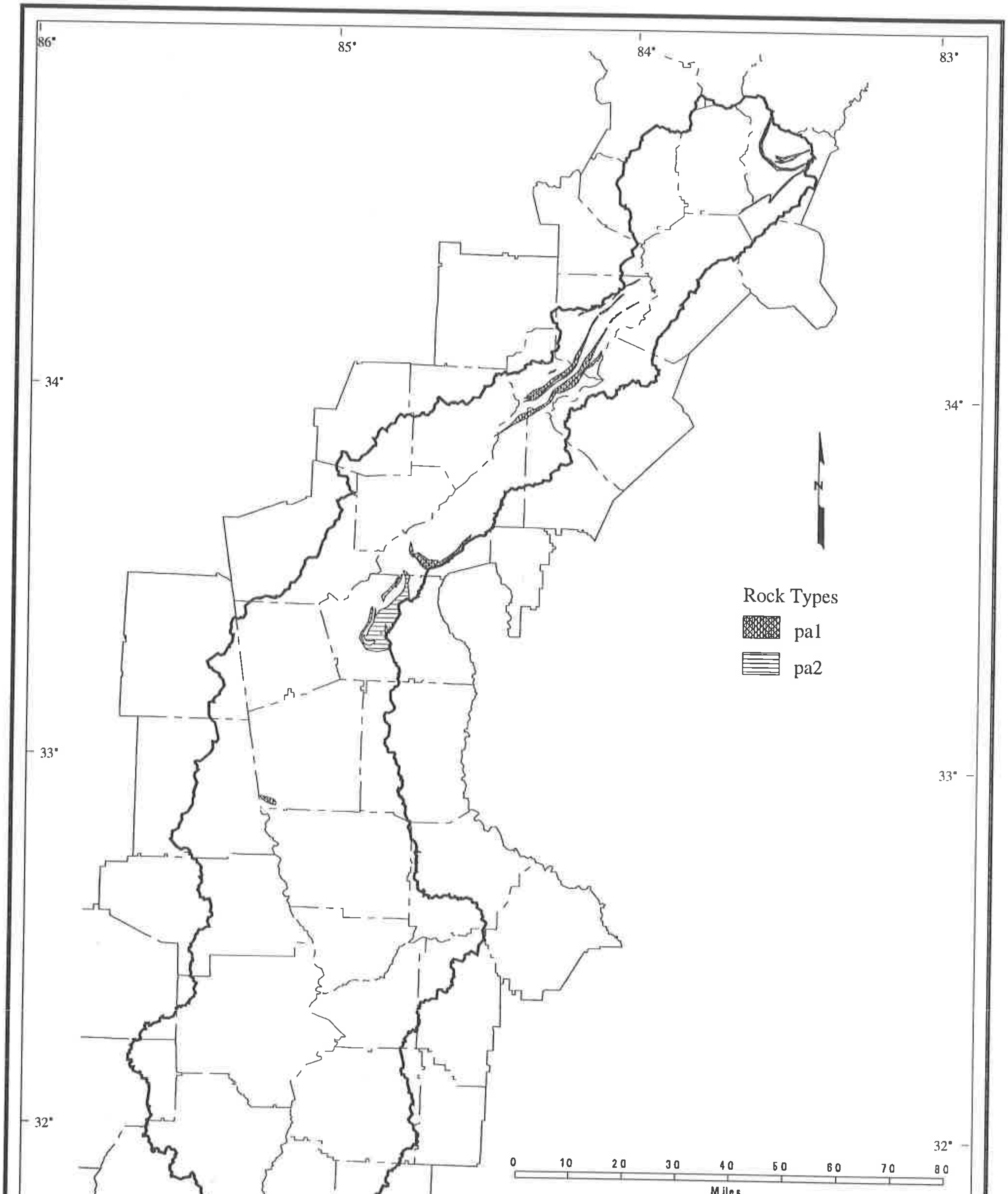

Figure A – 7. Aluminous schists. Rock types as in Table 1 and in Appendix.

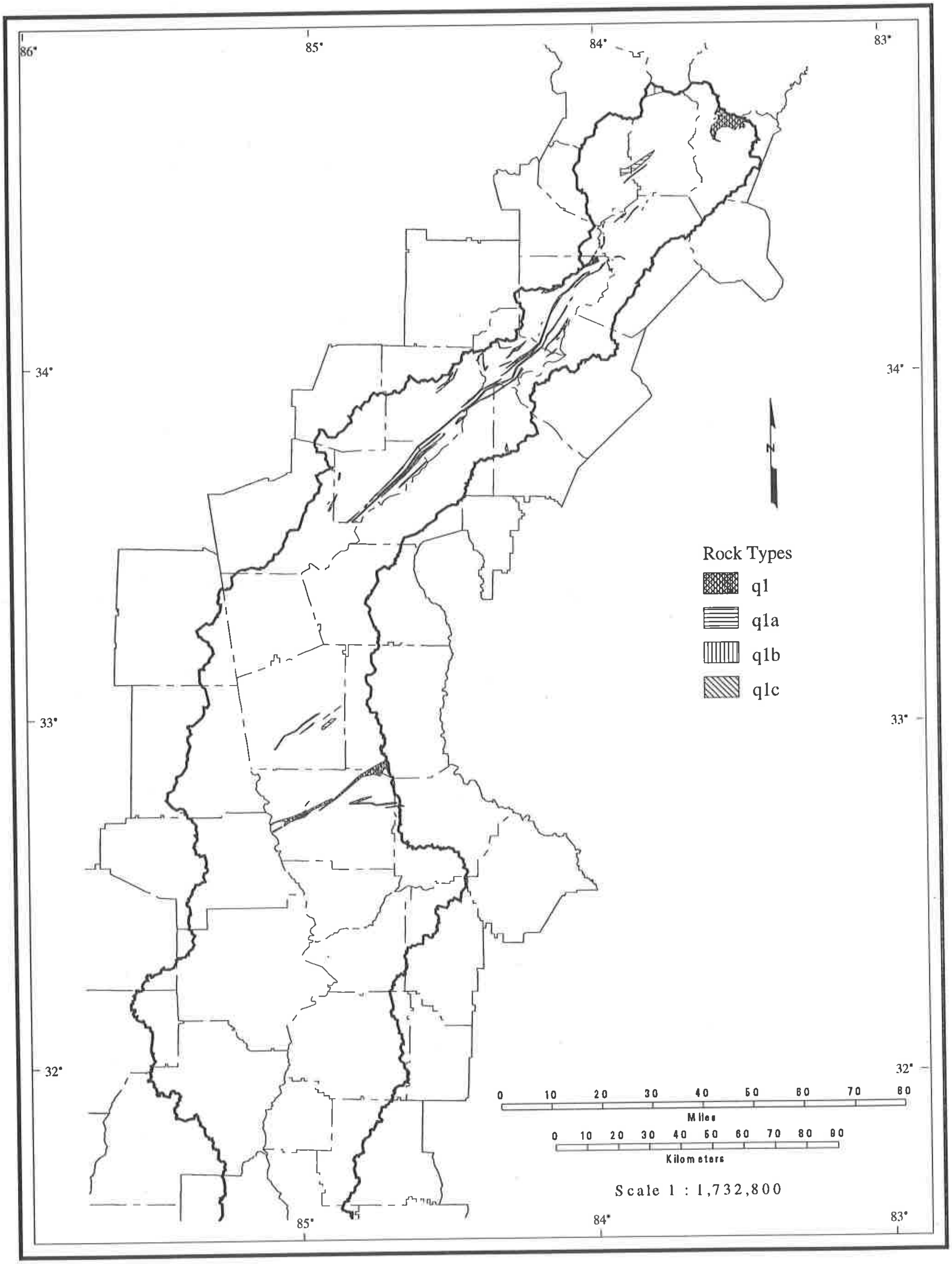

Figure A – 8. Quartzites. Rock types as in Table 1 and in Appendix.

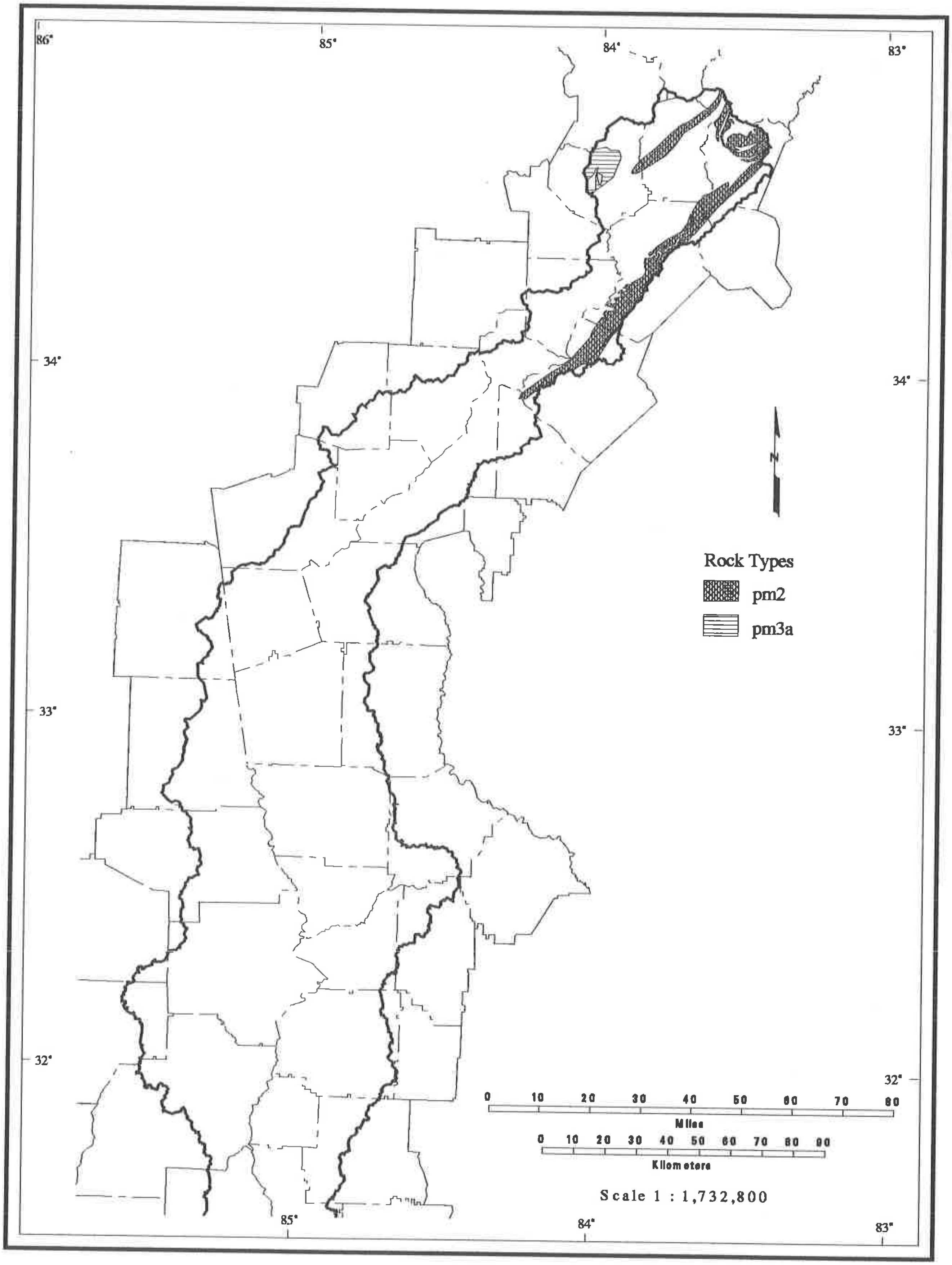

Figure A –9. Metagraywackes. Rock types as in Table 1 and in Appendix.

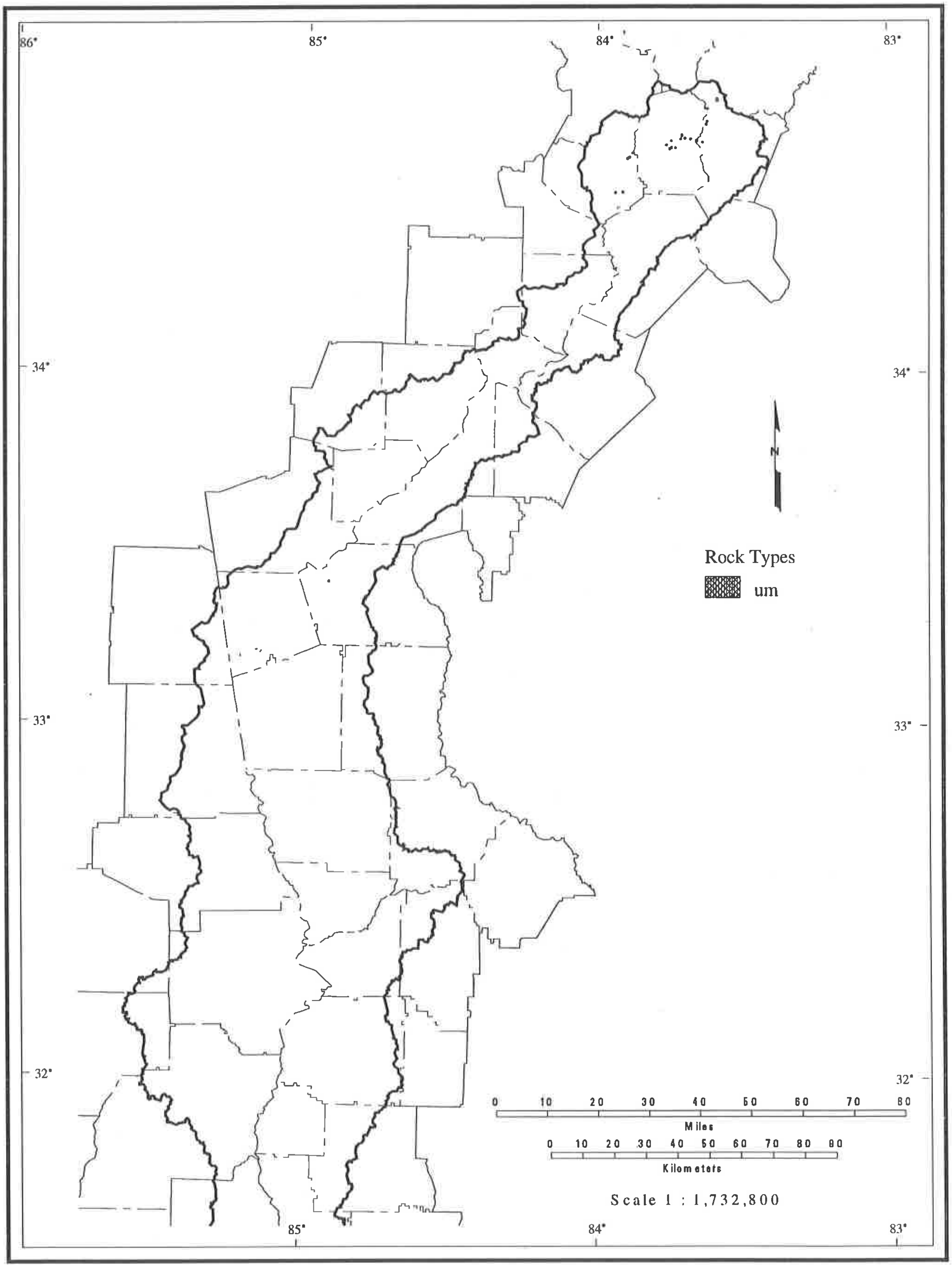

Figure A – 10. Ultramafic rocks. Rock types as in Table 1 and in Appendix.

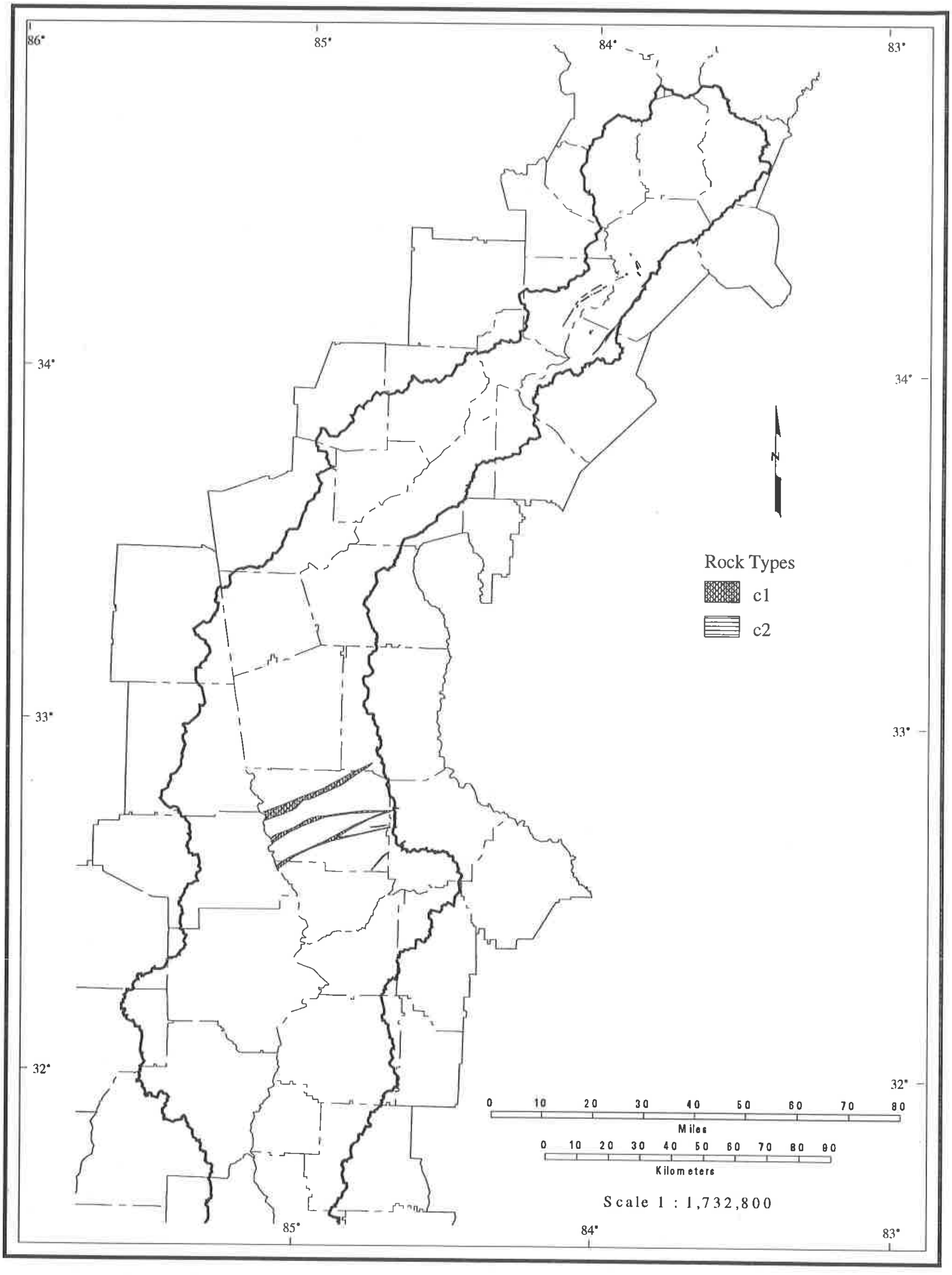

Figure A – 11. Mylonites and flinty crush rock. Rock types as in Table 1 and in Appendix.

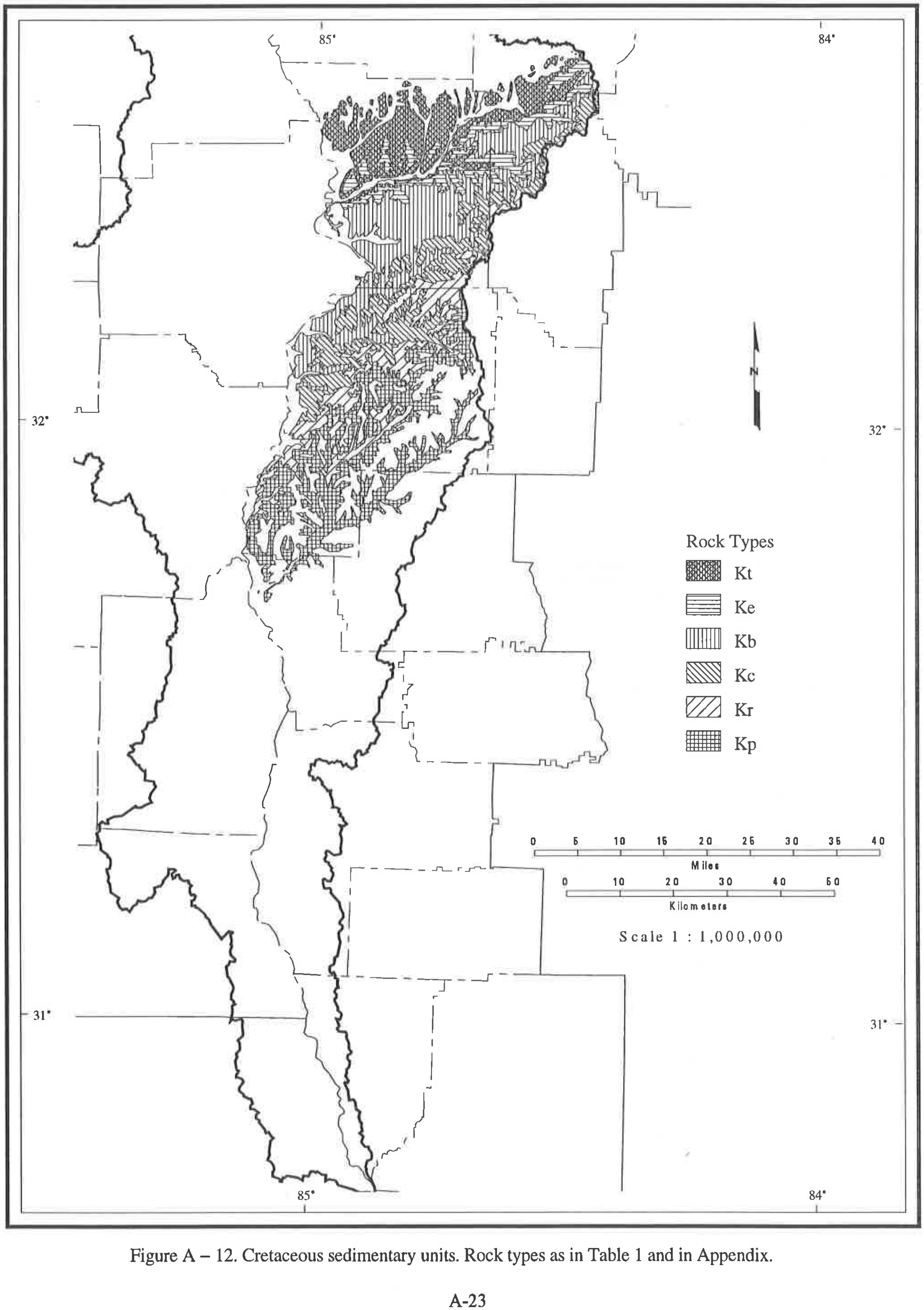

Figure A – 12. Cretaceous sedimentary units. Rock types as in Table 1 and in Appendix.

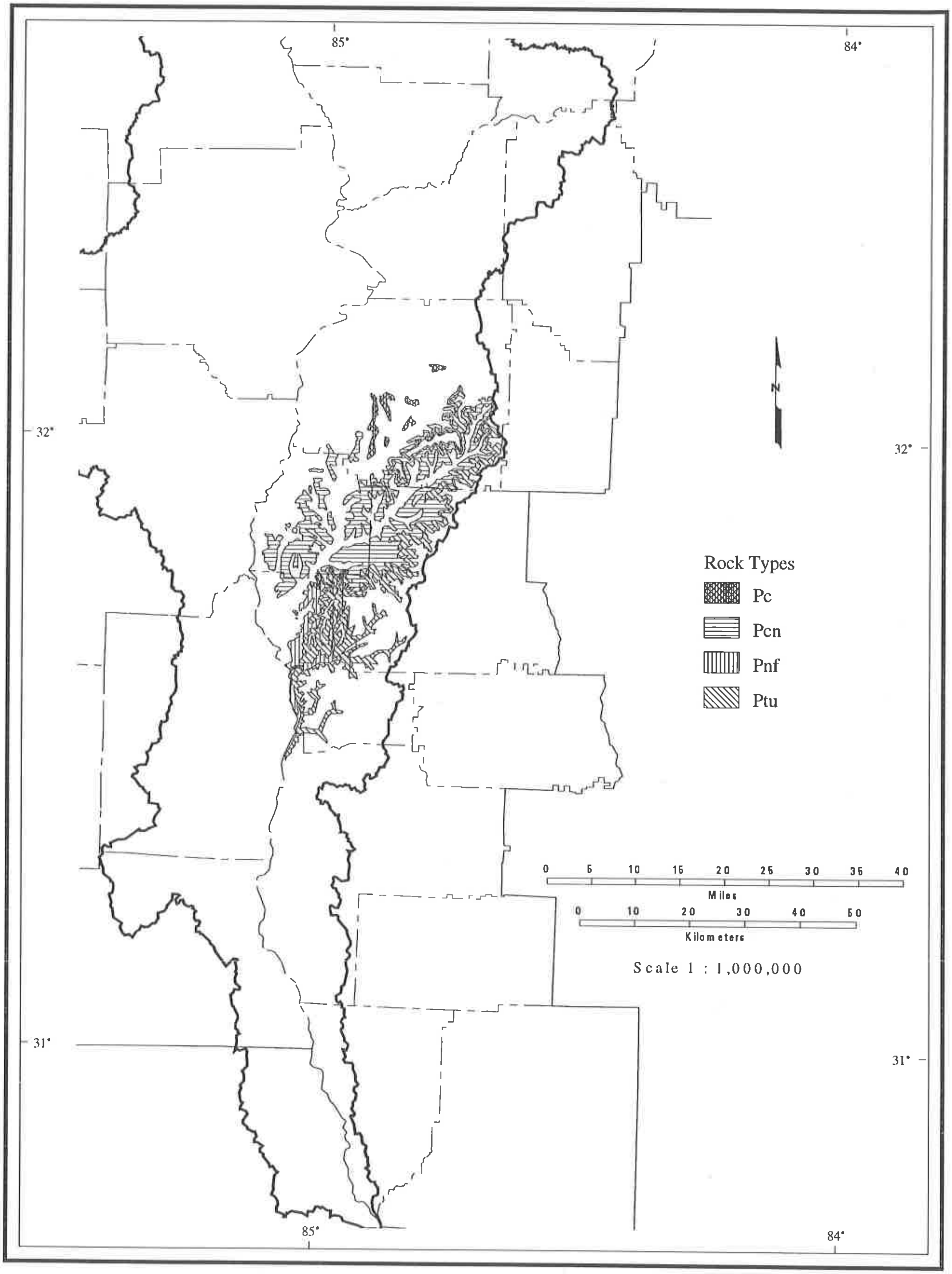

Figure A – 13. Paleocene sedimentary units. Rock types as in Table 1 and in Appendix.

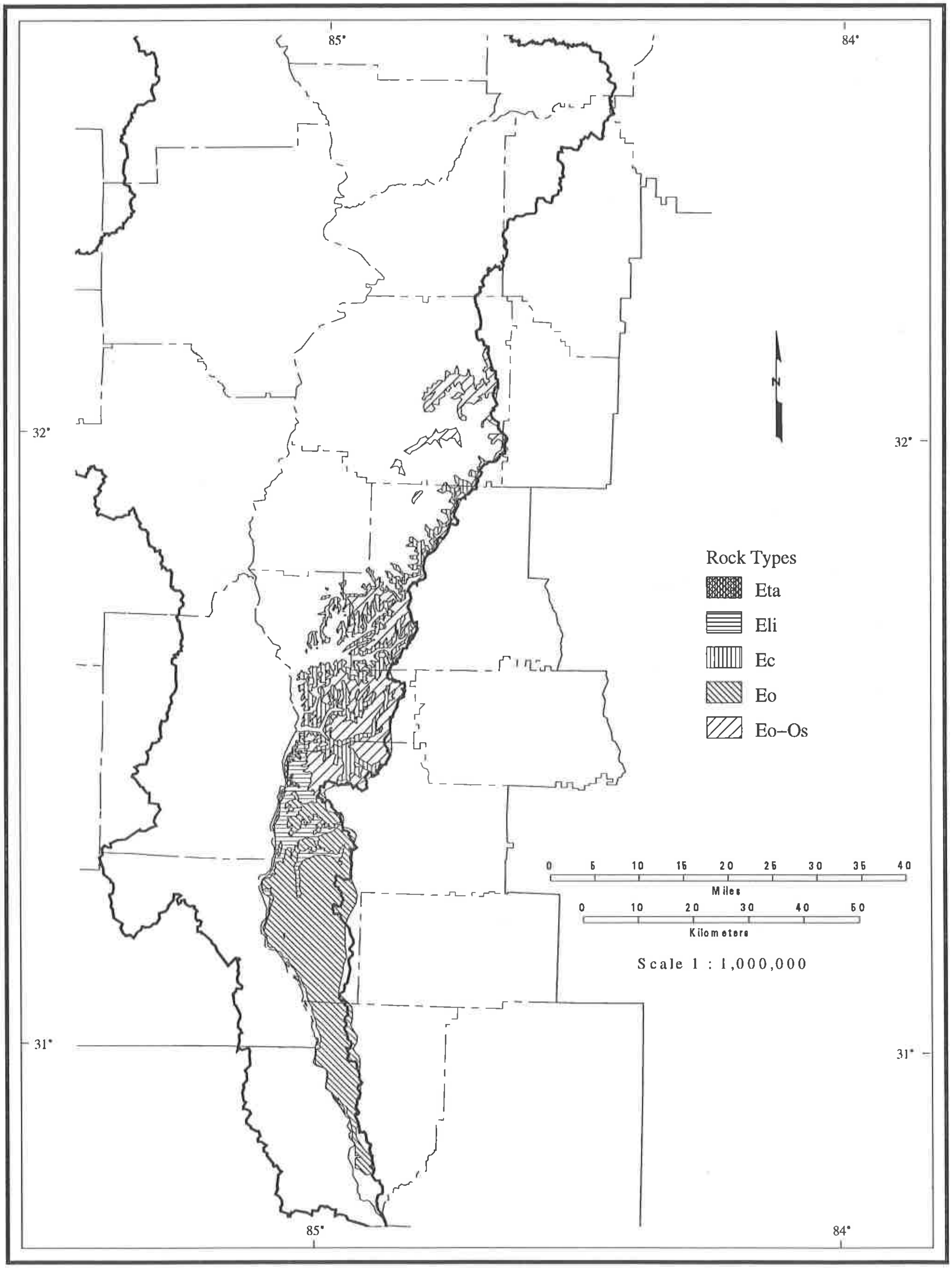

Figure A – 14. Eocene sedimentary units. Rock types as in Table 2 and in Appendix.

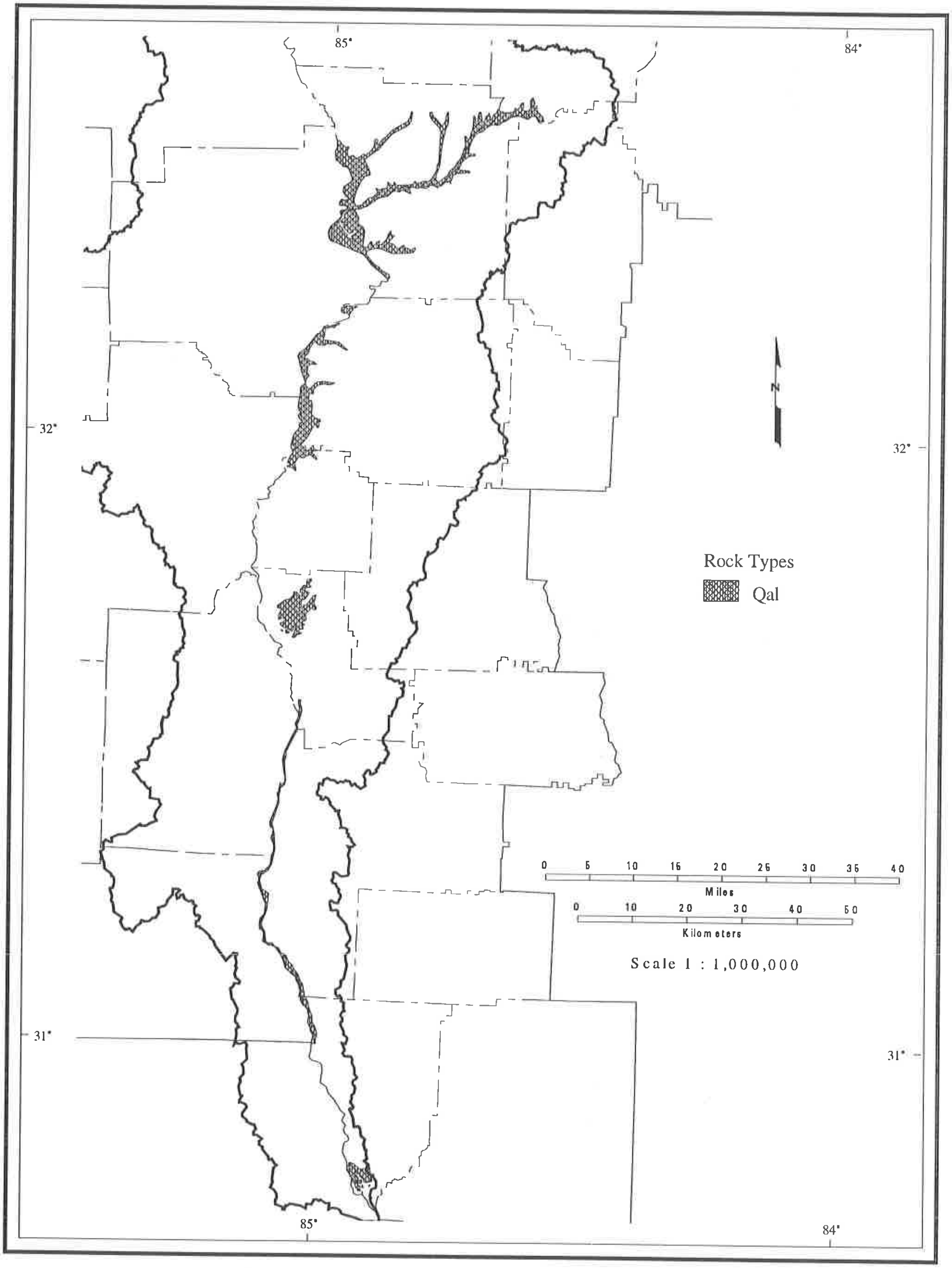

Figure A – 15. Quaternary alluvium. Rock types as in Table 2 and in Appendix.

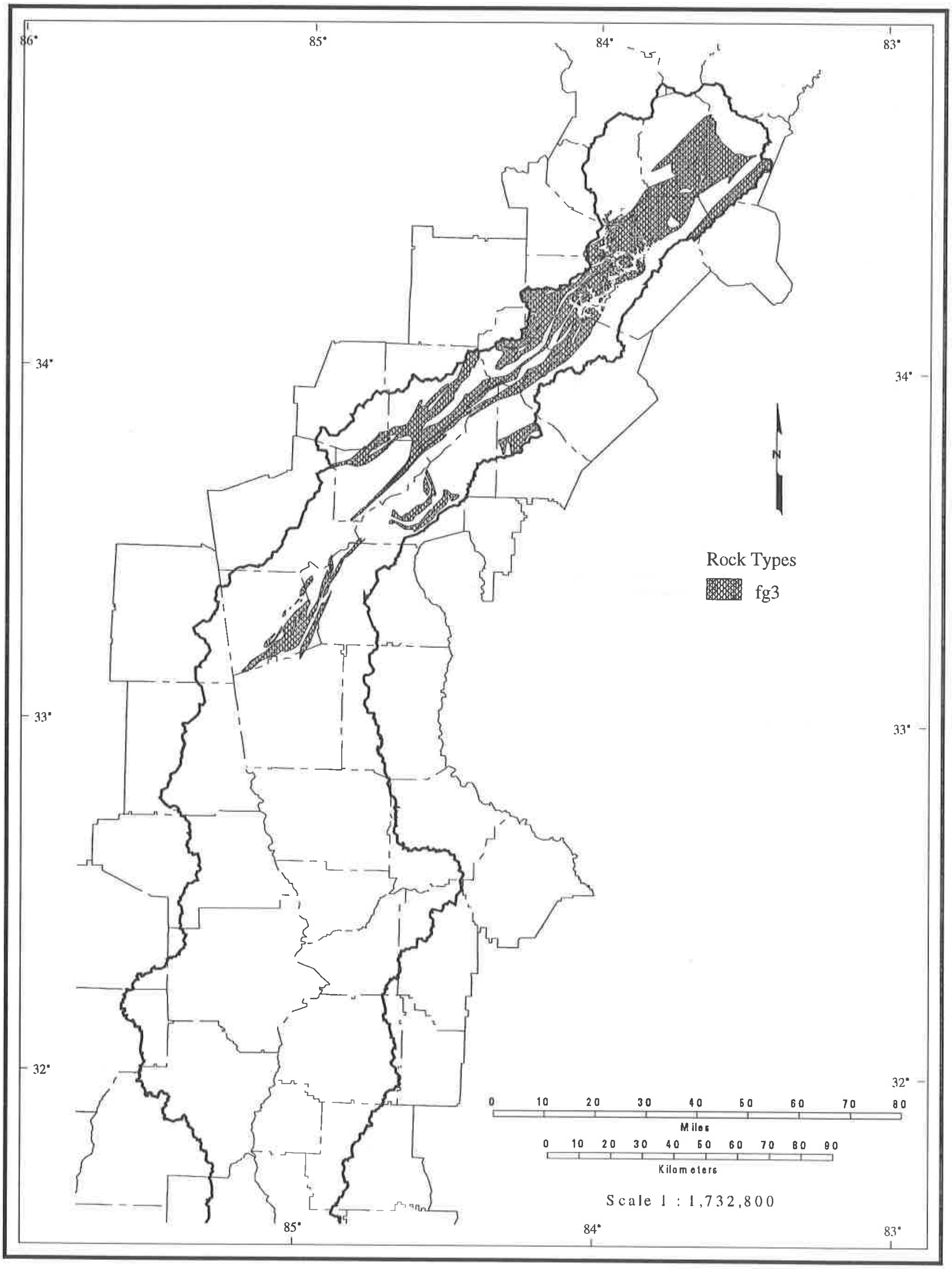

Figure A – 16. Biotite gneiss – fg3. Rock type as in Table 2 and in Appendix.

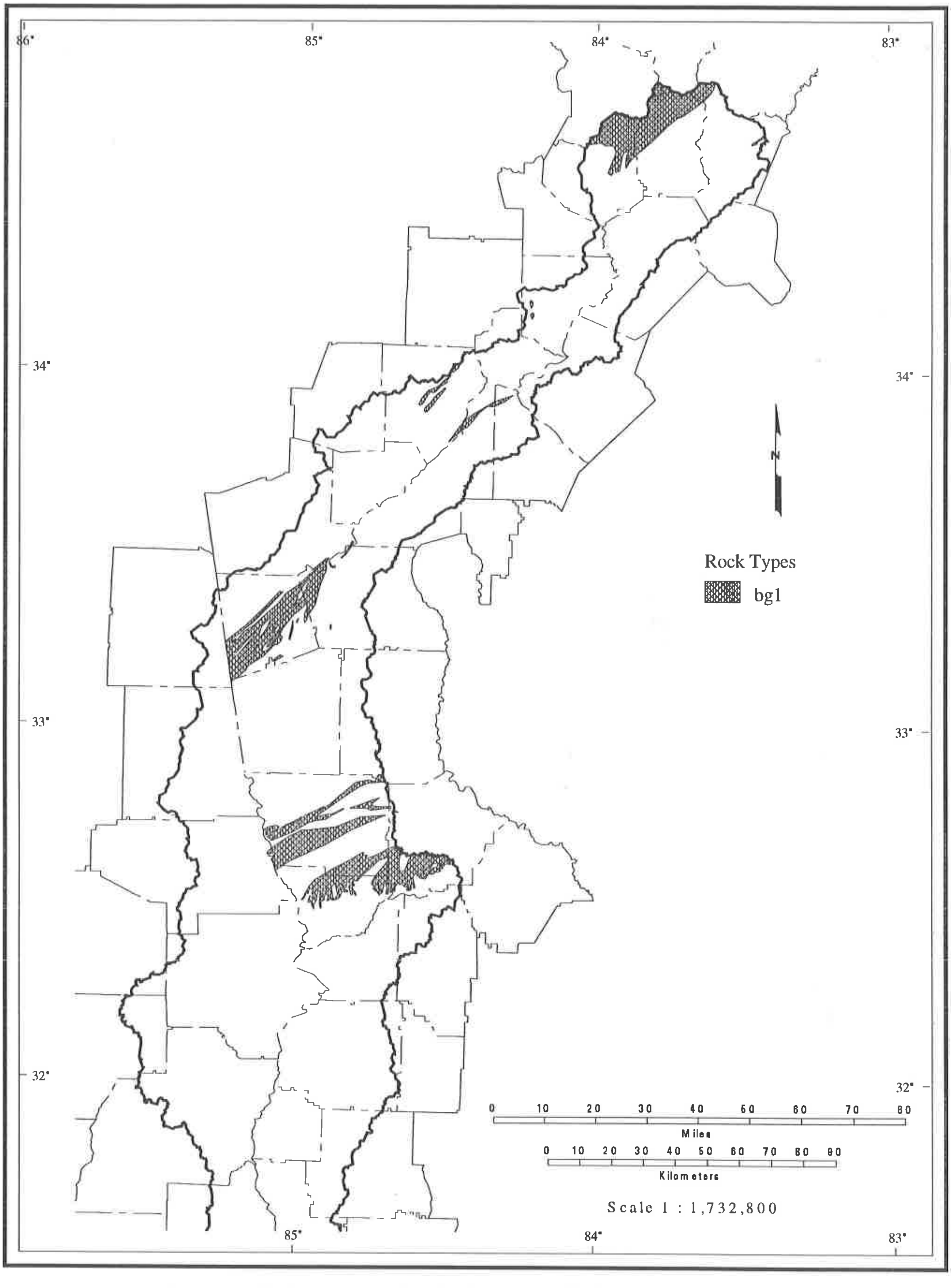

Figure A – 17. Biotite gneiss – bg1. Rock types as in Table 2 and in Appendix.

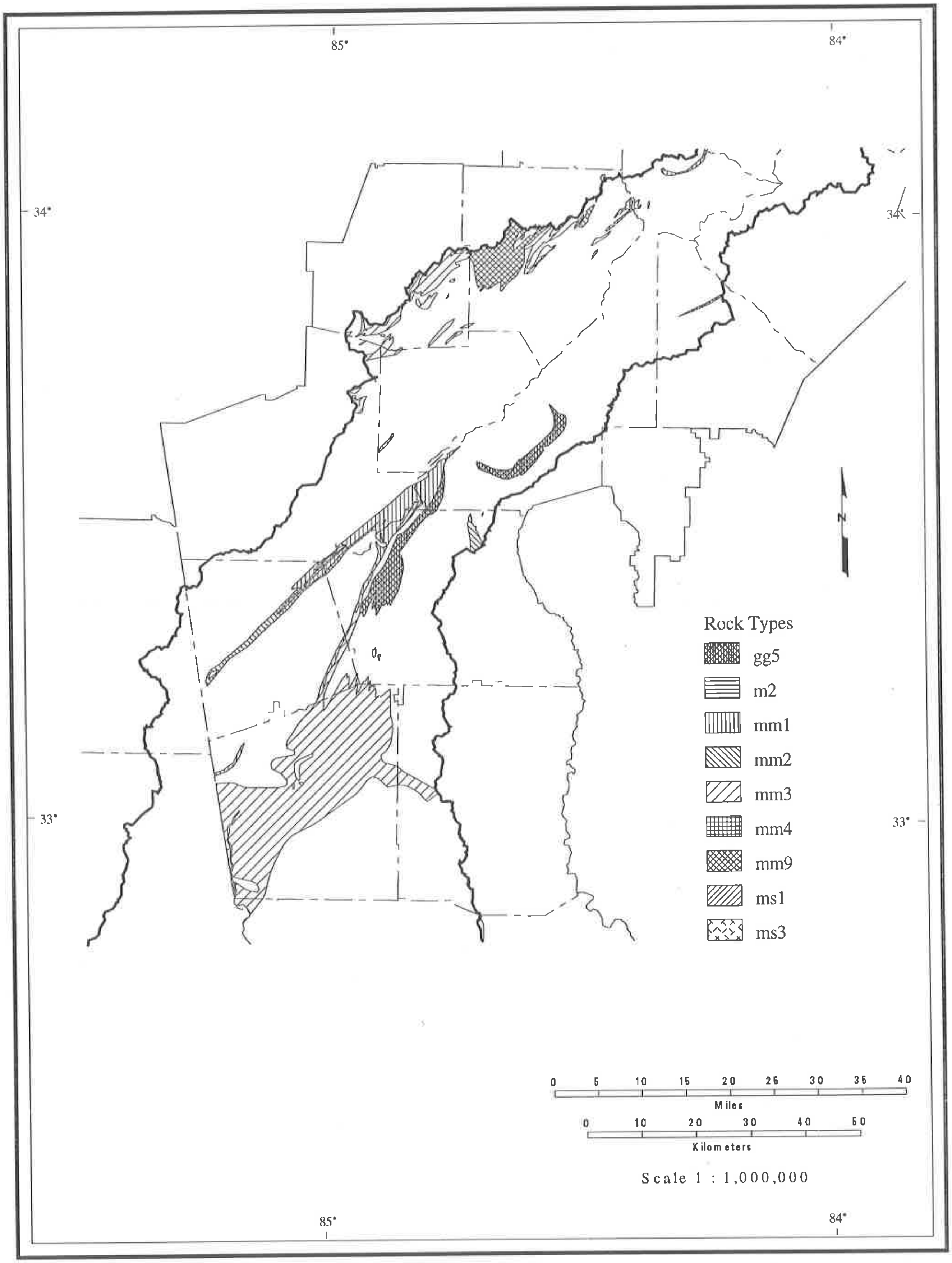

Figure A – 18. Amphibolitic rocks in Heard, Fulton and Coweta Counties. Rock types as in Table 1 and in Appendix.

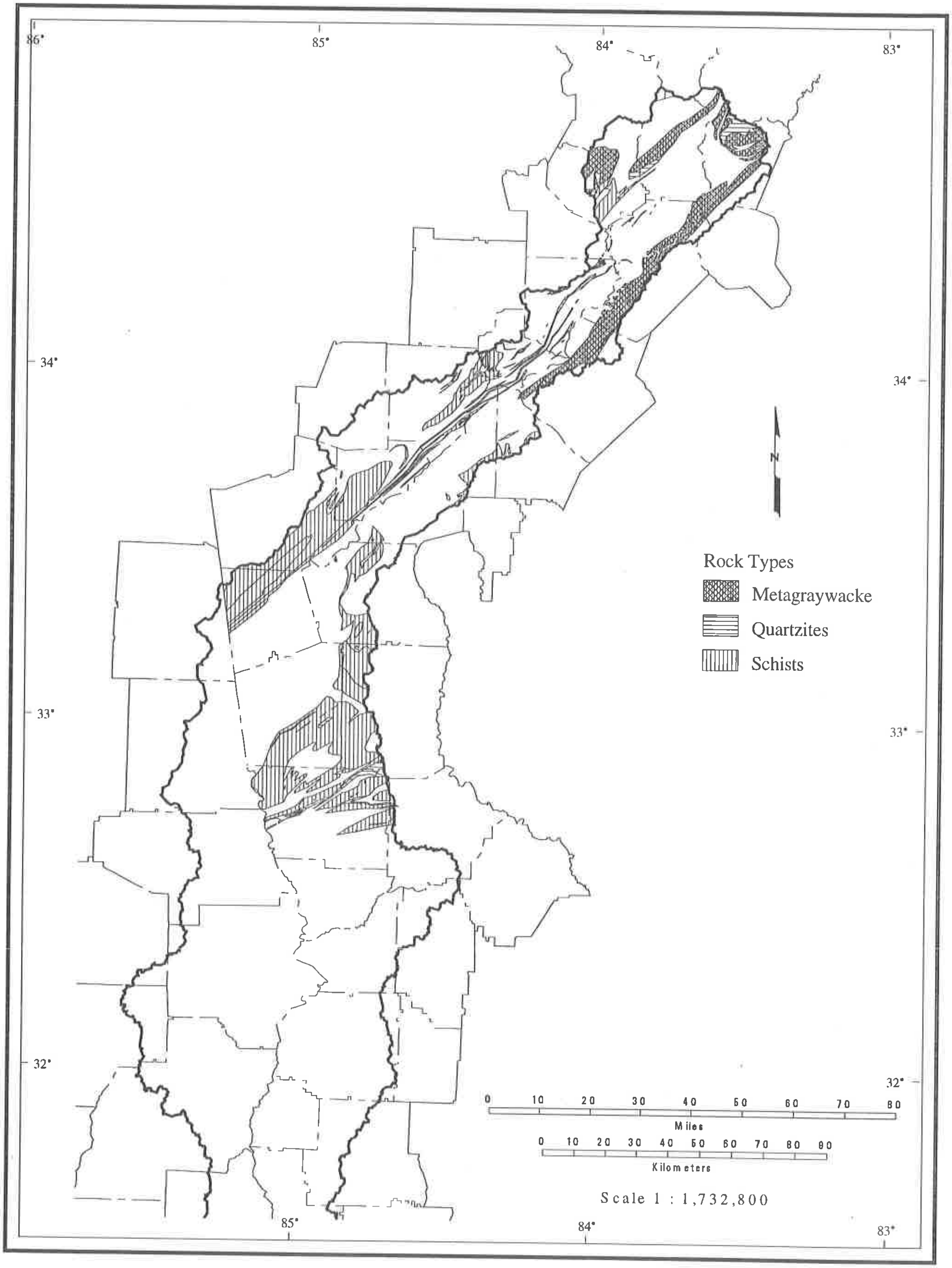

Figure A – 19. Metagraywackes, metaquartzites and schists. Rock types as in Table 1 and Appendix.

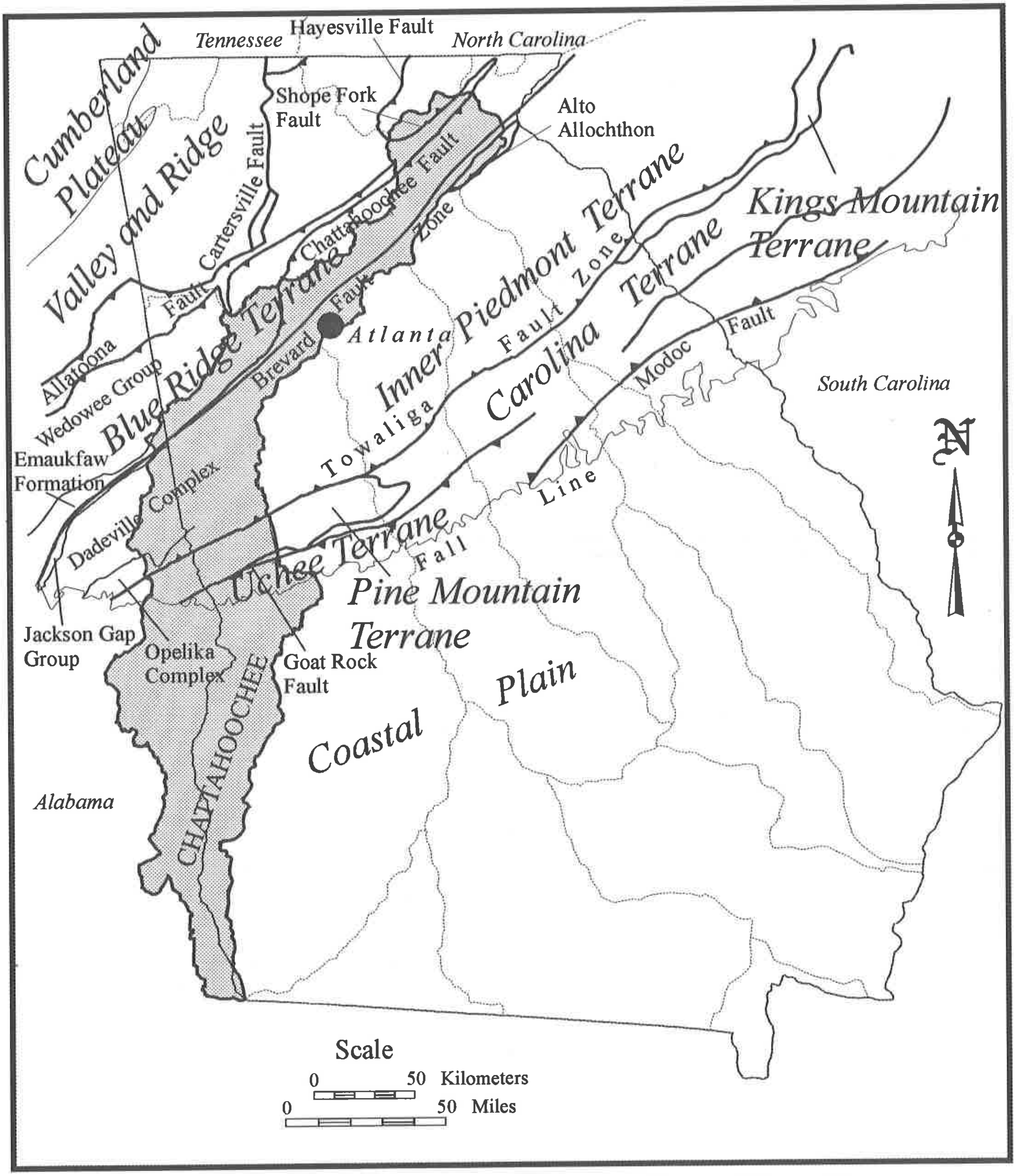

Figure A-20. Tectonic terranes and major fault structures. (Modified after Williams, 1978). Also shown are major tectonic elements in Alabama (modified from Osborne et al., 1989).

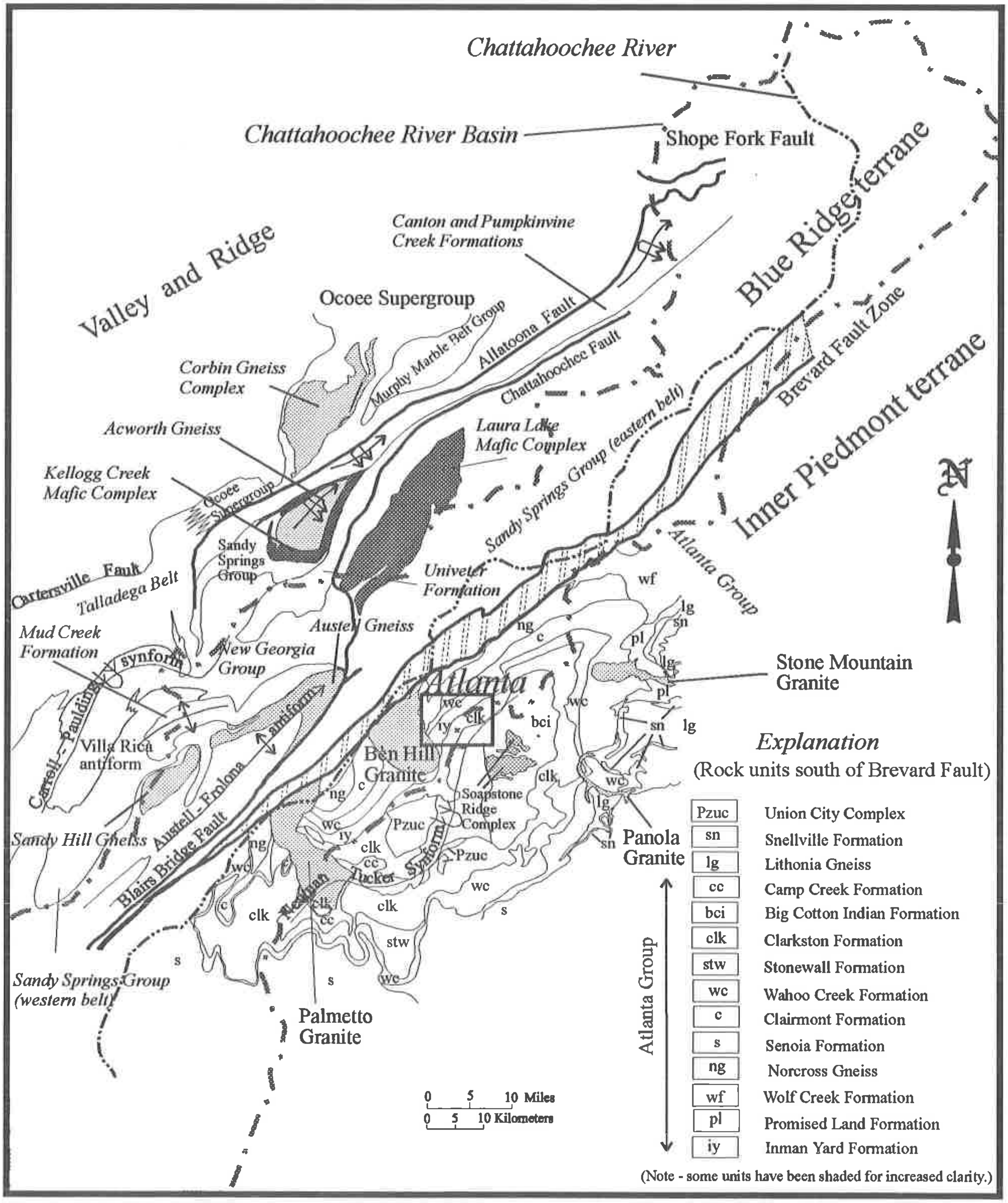

Figure A-21. Major structures and generalized geology of the Blue Ridge and Inner Piedmont terranes of the Greater Atlanta Region. Modified from McConnell and Abrams (1984); Higgins and Atkins (1981).

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