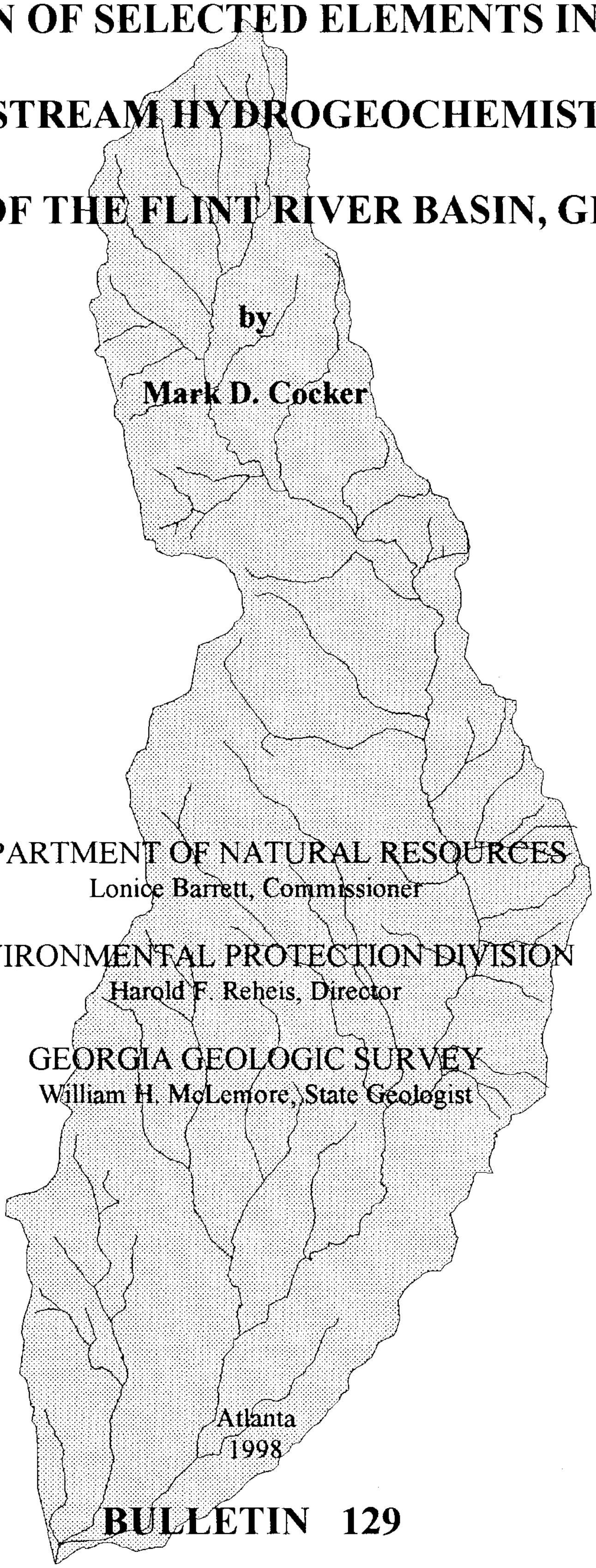
# DISTRIBUTION OF SELECTED ELEMENTS IN STREAM SEDIMENTS, STREAM HYDROGEOCHEMISTRY, AND GEOLOGY OF THE FLINT RIVER BASIN, GEORGIA



by

**Mark D. Cocker**

DEPARTMENT OF NATURAL RESOURCES
Lonice Barrett, Commissioner

ENVIRONMENTAL PROTECTION DIVISION
Harold F. Reheis, Director

GEORGIA GEOLOGIC SURVEY
William H. McLemore, State Geologist

Atlanta
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## BULLETIN 129

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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 Flint 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 Flint River Basin; generally the coverage extends to the south end of Webster, Sumter and Crisp Counties. Average sampling density in that area is one sample per 6.8 square miles.

Because NURE data are from stream sediments and water, that 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 Flint River Basin extends from the Atlanta metropolitan area, across the Piedmont and through the Coastal Plain for a distance of 349 miles. Basin size is 8,502 square miles. The Flint River joins the Chattahoochee River to form the Apalachicola River in Florida.

Differences in regional geology from the northern to the southern end of the Flint River Basin are reflected in the stream sediment geochemistry and stream hydrogeochemistry. Approximately 24 percent of the basin in Georgia is underlain by Precambrian and Paleozoic age crystalline rocks of the Piedmont province. The remaining 76 percent of the basin is underlain by sedimentary strata of the Coastal Plain province. The crystalline rocks in the northern part of the basin are predominantly schists (approximately 10 percent) and gneiss (approximately 8 percent) with lesser amounts of granites (approximately 4 percent), amphibolitic rocks (approximately 2 percent), and metaquartzites (approximately 1 percent). Coastal Plain sediments range in age from Cretaceous to Miocene with older sediments occurring to the north and younger sediments to the south. Cretaceous sediments in the northern part of the Coastal Plain are dominantly sand- and clay-rich formations. Further south, Paleocene and Eocene sediments are a mixture of clastic sedimentary rocks and carbonate rocks. Oligocene sedimentary rocks are dominantly carbonate rocks. Miocene rocks along the southern rim of the basin are a mixture of clastic sedimentary rocks and magnesium-rich carbonate rocks. At least half of the Flint River Basin is underlain by carbonate rocks. Cretaceous through Oligocene strata are also significant recharge zones for major Coastal Plain aquifer systems.

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. Rock and stream sediments may serve as important buffering agents on natural and anthropogenic contamination, and this will be reflected in stream hydrogeochemistry. As much of the Coastal Plain sediments in the Flint River Basin are significant recharge zones, rock geochemistry may have significantly impact the hydrogeochemistry of the various aquifers.

This study examined the spatial relations of the following metals in stream sediments: aluminum, barium, beryllium, chromium, cobalt, copper, lead, nickel, zinc, iron, magnesium, manganese, silver, titanium and vanadium. Iron, magnesium, manganese, titanium and vanadium are included because of their influence on availability of heavy metals to stream water or their potential use in interpreting the distribution of heavy metals. Most metal concentrations can be spatially related to either the regional geology, structural trends, or the local effects of individual rock units as documented in the section on the Flint River Basin's geology. Gaps in analyses for barium, beryllium, chromium, cobalt, copper, lead, nickel, and zinc do not allow a comprehensive analysis of the spatial distribution of these metals.

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. Higher concentrations of copper, cobalt, lead, manganese, aluminum, and potassium in stream sediments and lower pH in streams may have resulted from some anthropogenic activities. Activities that appear to have affected stream sediment and stream compositions include urban centers and sewage facilities. Increased concentrations of dissolved solids are apparent downstream from major urban centers. 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. The Flint River Basin is the third river basin to be systematically documented with respect to its background geochemistry. Documentation of the Oconee River Basin geochemistry (Cocker, 1996b) and the Chattahoochee River Basin geochemistry (Cocker, 1998) have been recently completed.

In contrast with this present report and those on the Oconee and Chattahoochee River Basins (Cocker, 1996b, 1998) which are concerned with detailed stream sediment geochemistry, several investigations by the U.S. Geological Survey focus primarily on the rivers and river chemistry. The U.S. Geological Survey's National Water Quality Assessment Program (NAWQA) has recently published several summary reports on the Apalachicola-Chattahoochee-Flint River Basin (Couch and others, 1996; Frick and others, 1998). An earlier investigation by Cherry (1961) provides data on patterns in natural surface-water chemistry that are the basis of interpretations for the more recent studies (Couch and others, 1996).

The Flint River Basin is located in west central to southwestern Georgia (Fig. 1), and is bordered by the Ocmulgee, Suwannee, and Ochlocknee River Basins to the east and by the Chattahoochee River Basin on the west side. The Flint River Basin extends from Fulton and Clayton Counties, south to Seminole and Decatur Counties (Fig. 2) and includes parts or all of 36 counties. These include Baker, Calhoun, Clayton, Colquitt, Coweta, Crawford, Crisp, Decatur, Dooly, Dougherty, Early, Fayette, Fulton, Henry, Lamar, Lee, Macon, Marion, Meriwether, Mitchell, Monroe, Peach, Pike, Randolph, Schley, Seminole, Spalding, Stewart, Sumter, Talbot, Taylor, Terrell, Turner, Upson, Webster, and Worth. Albany, Atlanta, Bainbridge, Forest Park, Griffin, Montezuma, Peachtree City, and Thomaston are the largest cities within the Flint River Basin.

Geochemistry and geology of a river basin provide an important and relatively stable framework with which to evaluate the hydrogeochemistry of that river. Stream sediment geochemistry represents the average composition of rocks within each drainage from which those sediments are derived. Stream sediment geochemistry is a more consistent database than stream hydrogeochemistry because of temporal changes in Eh-pH conditions related to variations in landscape type and precipitation. Temporal variations in precipitation and runoff also affect the concentrations of metals in stream water. The natural hydrogeochemistry of streams and rivers is principally derived from 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, 1996a, b; Simpson and others, 1993; Xie and Ren, 1993). Soil contamination that is related to atmospheric deposition also may be reflected in the drainage (Frick and others, 1998). Contaminants temporarily stored in flood plain sediments may be continuously released to streams by erosion of those stream sediments (Leigh, 1995; Cocker, 1995, 1996b, 1998).

Stream sediments within the Flint River Basin are probably affected 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. As streams begin to reestablish grade and cut into the thick accumulations of sediments (Trimble, 1969), sediments are 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 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 (Koch and others, 1979; Koch, 1988; Darnley, 1990; Bolviken and others, 1990; McMillan and others, 1990; Kerr and Davenport, 1990; Reid, 1993; Birke and Rauch, 1993; Davenport and others, 1993; Simpson and others, 1993; Xie and Ren, 1993; Cocker, 1995a, 1996a, b, 1998). 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 such data (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 work begun by Cocker (1996a,b) by examining, in detail, stream sediment and stream geochemistry of the Flint River Basin in Georgia. This investigation focused on the following trace elements which are regarded as primary pollutants in Water Quality Standards or Drinking Water Standards: antimony, arsenic, beryllium, cadmium, chromium, copper, lead, mercury, nickel, selenium, silver, thallium, and zinc. Data are absent in the Flint River Basin for antimony, arsenic, cadmium, mercury, selenium, and thallium. Most data used in this study are from stream sediment and stream water samples. NURE stream sediment sampling extends from the northern part of the basin south to the southern edges of Webster, Sumter and Crisp Counties.

This report may serve as a guide for other government agencies as reports described by Simpson and others (1993) for the United Kingdom and Cocker (1996a, b) for the Oconee River Basin (Cocker, 1996b) and for the Chattahoochee River Basin in Georgia (Cocker, 1998). 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. Those 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). Cocker (1996a, b, 1998) described the use of the NURE data and GIS to document and interpret background geochemistry and hydrogeochemistry of the Oconee and Chattahoochee River Basins. Regional tectonostratigraphic terranes that differed in origin and composition strongly affected the observed stream sediment geochemistry and hydrogeochemistry. That geochemical mapping highlighted known mineralized areas and suggested additional "unprospected" areas as potential sources of high base metals and heavy minerals such as monazite and ilmenite (Cocker, 1997). Those studies of the Oconee and Chattahoochee River Basins 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 to perform spatial operations on 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 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, hydrologic units, county boundaries, geology, major lakes, major roads, soils, physiography, and land use. Hydrography databases include streams and rivers. Hydrologic unit databases are U.S. Geological Survey defined units for drainage basins and smaller divisions within those drainage basins. Additional databases 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 format of the report and are at a scale of 1:1,712,636. This scale is the same as that used in the Chattahoochee River Basin report (Cocker, 1998). Geochemical data were interpreted from 1:500,000 scale versions of those maps and 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 sample point coverages. Contoured geochemical maps were developed through use of 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 Flint River Basin is located within eight 1° x 2° National Topographic Map Series (NTMS) quadrangles, these databases were combined and contoured as a single coverage. This contoured coverage was clipped with the outline of the Flint River Basin to include only those sample points and contours within the Flint River Basin. This method was used to elimi-

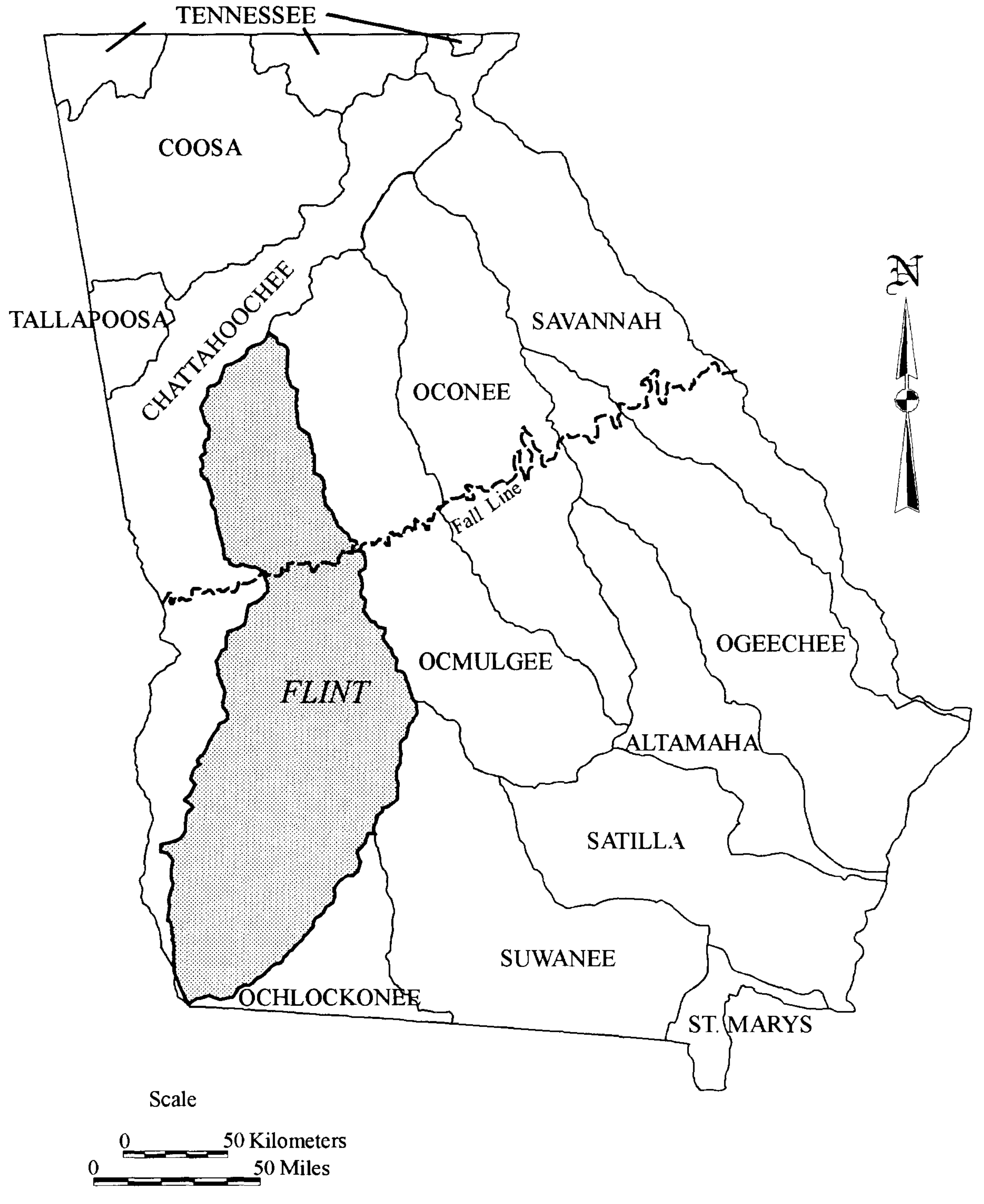

Figure 1. Location of the Flint River Basin.

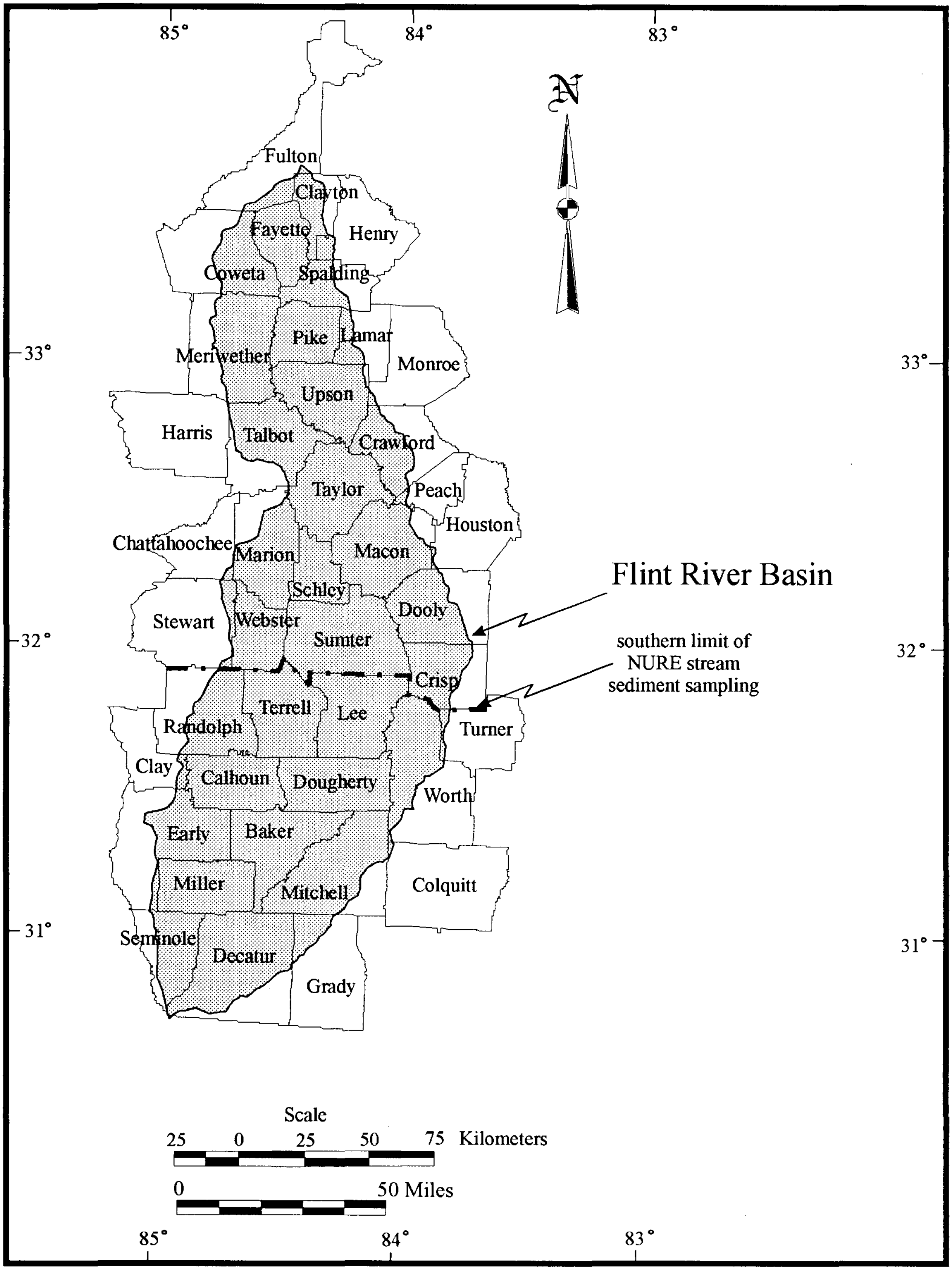

Figure 2. Counties within the Flint River Basin. Southern limit of NURE stream sediment sampling is shown by heavy dashed line.

nate or reduce edge effects created by the contouring software. Edge effects occur 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 Flint River Basin were created by selecting a particular rock type or groups of rock types (Table 1) from the GIS coverage developed from the Geologic Map of Georgia (Georgia Geologic 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 maps that have not been digitized into coverages were scanned, traced and edited in CorelDraw.

Maps showing metal, kaolin and pegmatite mines are derived from several coverages. The kaolin mines coverage was developed from a map showing the distribution of kaolin and fuller's earth mines (Shrum, 1970). Iron ore districts are as noted on the Mineral Resource Map of Georgia (Georgia Geologic Survey, 1969). Locations of pegmatites and pegmatite mines were derived from field studies on pegmatites in the Georgia Piedmont (Cocker, 1992a, b, 1995b and unpublished data).

## GENERAL GEOLOGY

The following discussion is a generalized summary of the geology of the Flint River Basin. A more detailed description is presented in Appendix A.

Geology strongly influences the physiography, geochemistry, soils, surface and ground water resources of the Flint River Basin. The Flint River Basin is underlain by older (Precambrian and Paleozoic) crystalline rocks in the northern quarter of the basin and by younger (Cretaceous and Tertiary) sedimentary rocks in the southern three quarters of the basin. Crystalline rocks are predominantly schists and gneiss (approximately 10 percent each ) with lesser amounts of granites (approximately 4 percent) metamorphosed volcanic (amphibolitic) rocks (approximately 2 percent), and metamorphosed sandstones (approximately 1 percent). Individual rock units of the Flint River Basin are summarized in Table 1.

Crystalline rocks in the Piedmont physiographic province north of the Fall Line are divided into three principal geologic terranes (the Inner Piedmont, Pine Mountain and Uchee terranes), which are separated by the Towaliga and Goat Rock fault zones (Fig. A-1). These terranes contain a large volume of 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 Uchee terrane immediately north of the Fall Line. Higher concentrations of metals such as copper, zinc, lead, and iron are associated with these amphibolites. Beryllium-bearing pegmatites are found in the Thomaston-Barnesville pegmatite district which extends through the basin (Fig. 3).

The southern three quarters of the basin is underlain by Cretaceous and Tertiary sedimentary rocks of the Coastal Plain. Older sediments, predominantly sandy and clayey strata, crop out near the Fall Line, and younger carbonate rocks are dominant in the southern half of the basin. Coastal Plain rocks dip gently to the southeast at a few tens of feet per mile. Several importantaquifers (the Providence, Clayton, Claiborne and Floridan aquifer systems) are associated with the more permeable rock units. Recharge areas for these aquifers are generally located with the extent of the outcropping rock units and cover most of the Coastal Plain in this basin. Rock composition and permeability have a strong influence on the geochemistry of the water that flows through them and should impact both surface and ground waters. The effects of rock composition on surface waters are summarized by Cherry (1961), and those on ground water are noted by Davis (1990). Quaternary alluvium deposits are found in stream and river valleys, with the larger and thicker deposits found in the major river valleys.

## MINERAL DEPOSITS AND THEIR GEOCHEMISTRY

Mineral deposits may have an effect on water quality because of the natural occurrence of high concentrations of heavy metals, the effects of weathering of sulfide minerals, and anthropogenic contamination related to mining and processing of the mineral deposits. The discussion in the present section focuses on the composition of the ores and mineral deposits.

Mineral deposits that have been developed within crystalline rocks of the Flint River Basin include: granitic rocks (for crushed and dimension stone), sand and gravel, and mica. Gold, pyrite, kyanite, sillimanite, beryl, and various heavy minerals have been prospected or have undergone minor production. Important mineral resources that include bauxite, industrial sand, iron ore, kaolin, limestone, "fuller's earth" in the form of palygorskite and opaline claystones, and sand and gravel have been produced from or prospected for in the Coastal Plain sediments of the Flint River Basin. Clastic sediments in the Coastal Plain also have the potential for heavy mineral deposits (Cocker, in press).

Mineral deposits are commonly concentrated in elongate bands or "belts", which, in general, extend through the Flint River Basin and adjacent areas from southwest to northeast (Figs. 3, 4, 5). Concentrations of mineral deposits are also referred to as mineral districts. Mineral belts or districts in the Piedmont include the Piedmont monazite belt, pegmatite dis-

**Table 1. Area and relative size of lithologic map units in the Flint River Basin within Georgia.**
(Source: Geologic Map of Georgia, Georgia Geologic Survey, 1976)

| Symbol | Lithologic Map Unit | Area (Miles$^2$) | Percentage of basin |
|---|---|---|---|
| Ec | Eocene - Claiborne undifferentiated | 264.16 | 3.11 |
| Eo | Eocene - Ocala Limestone | 2,513.32 | 29.56 |
| Eo-Os | Eocene and Oligocene residuum undifferentiated | 1,077.81 | 12.68 |
| Etw | Eocene - Twiggs Clay | 4.42 | 0.05 |
| Eu | Eocene - undifferentiated | 141.42 | 1.66 |
| Kb | Cretaceous - Blufftown Formation | 47.51 | 0.56 |
| Kc | Cretaceous - Cusseta Sand | 160.22 | 1.88 |
| Kcbe | Cretaceous - Cusseta, Blufftown and Eutaw Formations | 31.45 | 0.37 |
| Ke | Cretaceous - Eutaw Formation | 45.45 | 0.53 |
| Kp | Cretaceous - Providence Sand | 293.48 | 3.45 |
| Kr | Cretaceous - Ripley Formation | 271.61 | 3.19 |
| Kt | Cretaceous - Tuscaloosa Formation | 73.83 | 0.87 |
| Mh | Miocene - Hawthorne Formation | 40.65 | 0.48 |
| Nm | Neogene - Miccosukee Formation | 134.03 | 1.58 |
| Nu | Neogene - undifferentiated | 237.31 | 2.79 |
| Os | Oligocene - Suwanee Limestone | 496.91 | 5.84 |
| Pc | Paleocene - Clayton Formation | 4.63 | 0.05 |
| Pcn | Paleocene - Nanafalia, Porters Creek + Clayton Formations | 58.86 | 0.69 |
| Pnf | Paleocene - Nanafalia Formation | 54.15 | 0.64 |
| Ptu | Paleocene - Tuscahoma Sand | 193.43 | 2.28 |
| Qal | Quaternary - stream alluvium and stream terrace deposits | 291.71 | 3.43 |
| Qas | Quaternary - aeolian sand deposits | 2.00 | 0.02 |
| bg1 | biotite gneiss | 301.66 | 3.55 |
| c1 | mylonite and ultramylonite | 5.06 | 0.06 |
| c2 | flinty crush rock | 0.52 | 0.01 |
| fg1 | biotite gneiss/feldspathic biotite gneiss | 30.30 | 0.36 |
| fg3 | biotitic gneiss/mica schist/amphibolite | 81.35 | 0.96 |
| gg1 | granite gneiss undifferentiated | 126.62 | 1.49 |
| gg4 | granite gneiss/amphibolite | 112.26 | 1.32 |
| gr1 | granite undifferentiated | 248.16 | 2.92 |
| gr1b | porphyritic granite | 17.19 | 0.20 |
| gr3 | granite/biotitic gneiss/amphibolite | 4.73 | 0.06 |
| gr4 | charnockite | 27.17 | 0.32 |
| mm1 | amphibolite | 5.16 | 0.06 |
| mm2 | hornblende gneiss | 64.47 | 0.76 |
| mm3 | hornblende gneiss/amphibolite | 0.32 | 0.00 |
| mm4 | hornblende gneiss/amphibolite/granite gneiss | 77.75 | 0.91 |
| mm5 | hornblende-biotite gneiss/amphibolite | 27.27 | 0.32 |
| mm9 | amphibolite/mica schist/biotitic gneiss | 5.31 | 0.06 |
| pa1 | aluminous schist | 6.66 | 0.08 |
| pa2 | sillimanite schist | 61.83 | 0.73 |
| pms1 | mica schist | 90.27 | 1.06 |
| pms3 | mica schist/gneiss | 10.54 | 0.12 |
| pms3a | mica schist/gneiss/amphibolite | 654.87 | 7.70 |
| q1 | quartzite | 51.98 | 0.61 |
| um | ultramafic rocks undifferentiated | 0.32 | 0.00 |
| Water | | 51.58 | 0.61 |
| Total | | 8,501.71 | 100.00 |

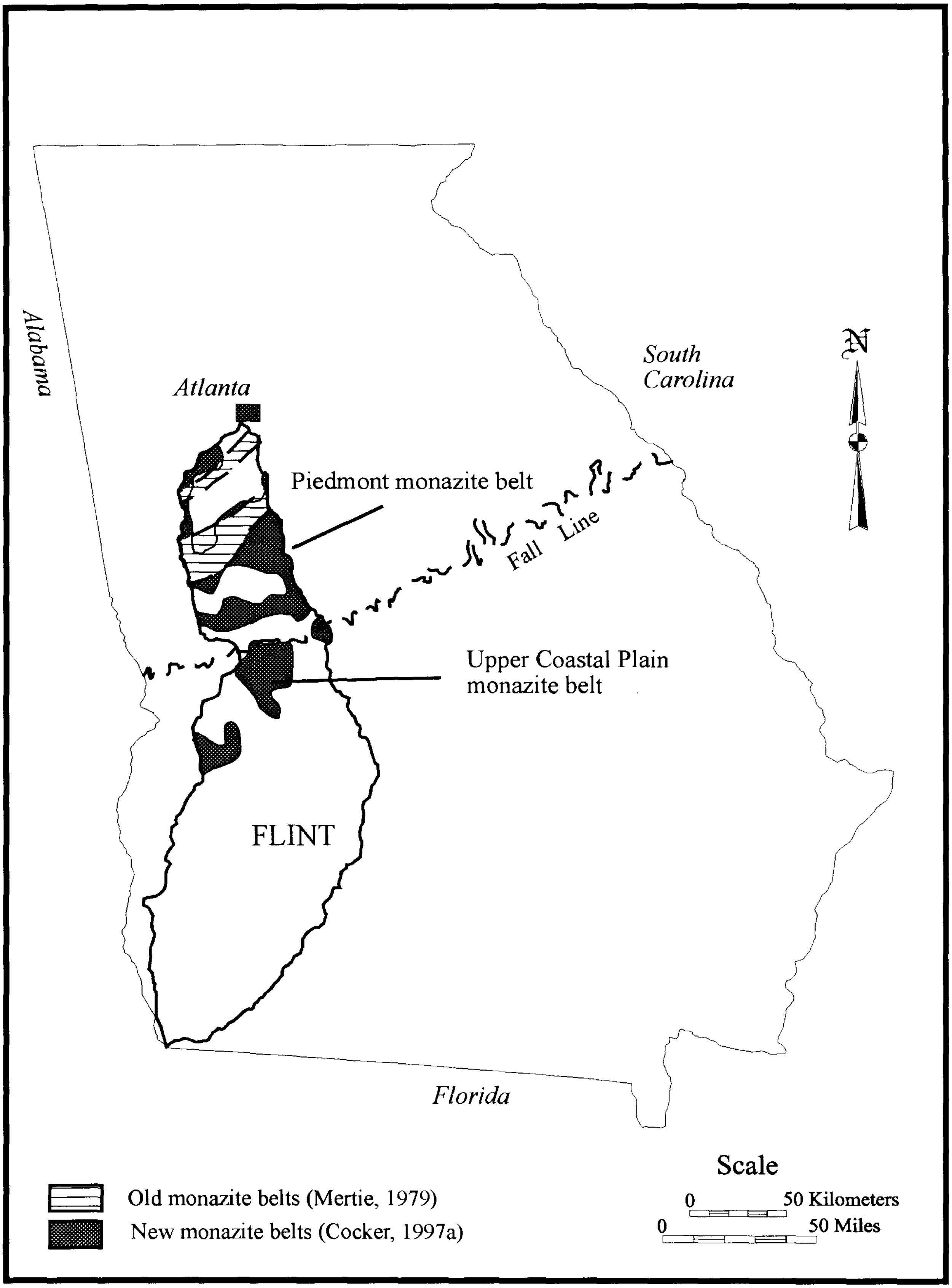

Figure 3. Monazite belts in the Flint River Basin.

districts, and perhaps an extension of the Carolina slate belt (gold and base metals). Base metals, chromite and asbestos associated with mafic and ultramafic intrusive igneous rocks have been prospected or may have economic potential. In the Coastal Plain, the kaolin (plus bauxite) belt, the Upper Coastal Plain heavy mineral belt, and the Meigs attapulgite district extend through the Flint River Basin (Fig. 5).

## Piedmont

### *Monazite Belt*

The Piedmont monazite belt (Fig. 3) contains phosphates, oxides and silicates of thorium, uranium, cerium, dysprosium, europium, hafnium, lanthanum, lutetium, samarium, titanium, ytterbium, and zirconium (Mertie, 1979). Monazite, xenotime, and zircon, plus titanium oxides such as rutile, ilmenite and leucoxene form the bulk of economically important heavy mineral deposits. In the Piedmont monazite belt, these minerals were thought to occur principally within granitic and intermediate/biotitic gneisses and migmatitic rocks north of the Towaliga Fault Zone (Mertie, 1979). Redefinition of the monazite belts in the Piedmont and Blue Ridge suggest that monazite, zircon and xenotime are concentrated in a series of aluminous schists, biotite gneisses, mica schists and graywackes that may represent paleoplacer deposits (Cocker, 1997). Heavy minerals are effectively concentrated by sedimentary processes and may be found in higher concentrations (detrital placer deposits) in stream sediments and shoreline deposits.

### *Pegmatites*

Pegmatite deposits in Georgia are located in the southern Appalachian pegmatite province (Fig. 4). The Piedmont pegmatite belt of the southern Appalachian pegmatite province is intersected by the Flint River Basin. The largest producer of sheet mica in the southeastern United States was the Thomaston-Barnesville district. This district is principally located within the Flint River Basin. Investigations in the early part of the 1900's focused on mineralogy, internal zoning, production, and locations of pegmatites within Georgia (Galpin, 1915; Furcron and Teague, 1943; Beck, 1948; Jahns and others, 1952; Heinrich and others, 1953). More recent studies examined the geochemistry of trace metals in muscovite, potassium feldspar, and tourmaline from pegmatites in the Thomaston-Barnesville district (Cocker, 1992b, c). Pegmatites exhibit a range in the degree of pegmatite trace element fractionation, and district-scale zoning in trace metals in the Thomaston-Barnesville may be an indication of pegmatite fractionation in that district (Cocker, 1992a, b, c,). Anomalous trace metals, such as beryllium, may be found in stream sediments near the more fractionated pegmatites in that district.

## Coastal Plain

### *Heavy Minerals*

Heavy mineral concentrations are also found in two belts in the Upper Coastal Plain (Fig. 4) and are associated with Cretaceous and Paleocene - Eocene- strata (Cocker, in press). Those strata are believed to represent former fluviatile and shoreline to shallow marine clastic deposits. Heavy mineral mineralogy is similar to that noted in the Piedmont and those minerals are believed to be derived from the Piedmont heavy mineral belt.

### *Iron Ore*

Within the Coastal Plain, large quantities of "brown iron ore" were mined from the Paleocene Clayton Formation (Figs. 5, A-11). One to two zones of iron ore are located near the base of the Clayton Formation. These zones are three to ten feet thick and are three to six feet apart (Kirkpatrick, 1959; Furcron and Ray, 1957). The ore is an intimate mixture of limonite and goethite. The known compositions of these ores are presented in Table 2. Trace or heavy metals are undocumented in these iron ores, but could be present because of the scavenging effects of iron oxides.

In Pulaski, Houston and Dooly Counties, residual iron ore occurs in a residuum of clay and chert derived from weathering of Oligocene-age strata (Pickering, 1961). The iron ore is principally goethite with some limonite and hematite. The known compositions of these ores are presented in Table 2. The Oligocene iron ore (Table 3) has a generally higher manganese and lower alumina content than the Paleocene ore (Table 2) and may contain more heavy metals because of adsorption.

### *Kaolin and Bauxite*

In Georgia, kaolin and bauxite deposits are located in the kaolin belt which is found within Cretaceous to Eocene age strata near the Fall Line (Fig. 5). Kaolin and bauxite deposits have been prospected and developed in the Andersonville district within Sumter and Macon Counties and the Springvale district within Randolph County (Fig. 5). These deposits are found within fluvial, lacustrine, and marginal marine sediments of the Paleocene Nanafalia Formation (Fig. A-11). In the Andersonville district, the Nanafalia Formation unconformably overlies the Clayton Formation. Micaceous, kaolinitc sand grades laterally and vertically through sandy kaolin into relatively pure lenticular beds of clay. Bauxite and

Sample numbers 1-7 are from Furcron and Ray (1957), 8-21 are from Furcron (1956), and 22 is from O'Neill (1965). Sample 22 is an inferred resource calculation from numerous analyses from 103 drill holes. bauxite clay may occur as thin lenses within the kaolin. To the west and south, the Nanafalia Formation is represented by dark-gray, lignitic sand and silt with scattered thin lenses of kaolin. Kaolins from the Flint River Basin are high in alumina (Table 4). Although the kaolin deposits have not been analyzed for trace metals, the extreme chemical leaching necessary to form kaolinitic sediments may have removed most trace metals.

Bauxite was discovered in 1916 associated with kaolinitic sediments of the Springvale district. Primary minerals of bauxite are diaspore and gibbsite. Bauxites have an alumina content of 52 to 61 percent. Bauxitic clays have an alumina content of 40 to 52 percent and are a mixture of bauxite and kaolin (Smith, 1929). Bauxite deposits at Andersonville and Eufaula may be the result of weathering desilicification of kaolinitic clays in the Nanafalia Formation (Burst, 1974). In these bauxites, $Fe_2O_3$ and $TiO_2$ are generally present in the 1.5 to 2.5 percent range (Smith, 1929). Bauxites and bauxitic clays have not been analyzed for trace metals. Trace metals are expected to be essentially non-existent because of the extreme leaching necessary to produce bauxite. Additional sources regarding the geology of the Springvale district include Clark (1943) and the Andersonville district (Cofer and Fredericksen, 1982).

### *Fuller's earth*

Fuller's earths are highly absorbent clays which, in Georgia, include palygorskite or attapulgite, sepiolite and montmorillonite clays and opaline claystones. Montmorillonite clays and opaline claystones are found principally in marine sediments of the Eocene age Twiggs Clay (Fig. A-11). These clays are also used as a source of alumina in the production of Portland cement. Palygorskite or attapulgite and sepiolite clays are principally found in upper Oligocene and Miocene marginal marine sediments (Figs. A-13, A-14) in southern Georgia and adjacent parts of Florida (Weaver and Beck, 1982). Primary montmorillonite in the Gulf Trough (Fig. A-15) and Southeastern Georgia Embayment was converted to palygorskite by the addition of silica and magnesium from seawater (Weaver and Beck, 1982). Small deposits of palygorskite are noted by Koch and thers (1989) in the Flint River Basin. Larger economic deposits are found slightly further to the east in Georgia and adjacent parts of Florida (Fig. 5). Palygorskite clays (Table 4) are higher in magnesium iron and silica than the kaolin clays. Trace metal content of these clays is also unknown, but may be higher than that of the kaolin clays.

### *Limestone*

Limestones are an important source of lime and crushed stone in southern Georgia. Furcron and Perry (1958) and Furcron and Forston (1960) examined the potential of the Tertiary limestones in the Flint River Basin (Figs. A-12, A-13). Most of these limestones are high in CaO and low in MgO (Tables 5, 6). Trace metal content of these limestones is unknown, but is probably negligible.

# SURFICIAL GEOLOGY

## Precipitation

Precipitation affects surficial geology through weathering and erosion of rocks and soils, and in the volume and composition of stream discharge. Average annual precipitation in the Flint River Basin ranges from 46 inches in the east-central part of the basin to 54 inches in the southernmost part of the basin (Fig. 6), but most parts of the basin receive between 46 and 52 inches of precipitation (Carter and Stiles, 1983; Hodler and Schretter, 1986). Annual precipitation can vary significantly from year to year. Average pH of precipitation in Georgia has declined from 5.6 in 1955 to 4.5 in 1980 (Hodler and Schretter, 1986). This may be reflected in increased dissolution of rocks and soils resulting in an increase in dissolved metals.

## Geomorphology

River basin geomorphology is controlled by rock composition, structural development, precipitation, weathering, and erosional history. In turn, river basin geomorphology may affect ground water residence time, the flow rate of water through the basin, and the type of geological materials through which water may acquire its chemical characteristics.

### *Flint River*

The size of the Flint River Basin is 8,502 square miles. The Flint River has a total length of 349 miles (U,S, Army Corps of Engineers, 1985) and joins the Chattahoochee River to form the Apalachicola River. The ratio of basin area to river length for the Flint River Basin is 24 miles. Basin width averages about 30 miles in the Piedmont, but the basin is as wide as 60 miles in the Coastal Plain. A graph of cumulative length versus cumulative drainage area indicates that each mile of the river drains an average area of about 1.6 square miles in the Piedmont and about 4 square miles in the remain-

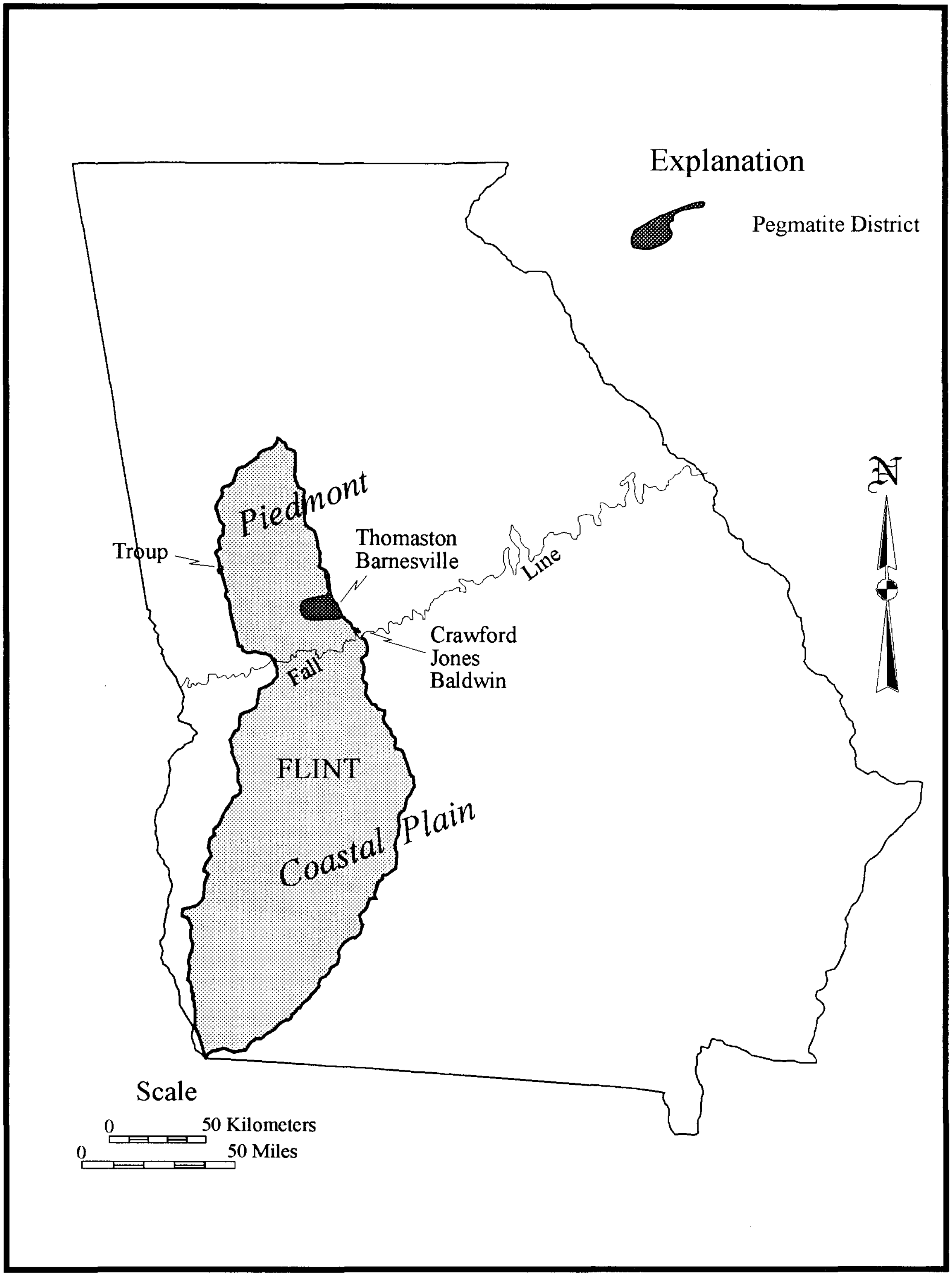

Figure 4. Pegmatite Districts in the Flint River Basin.

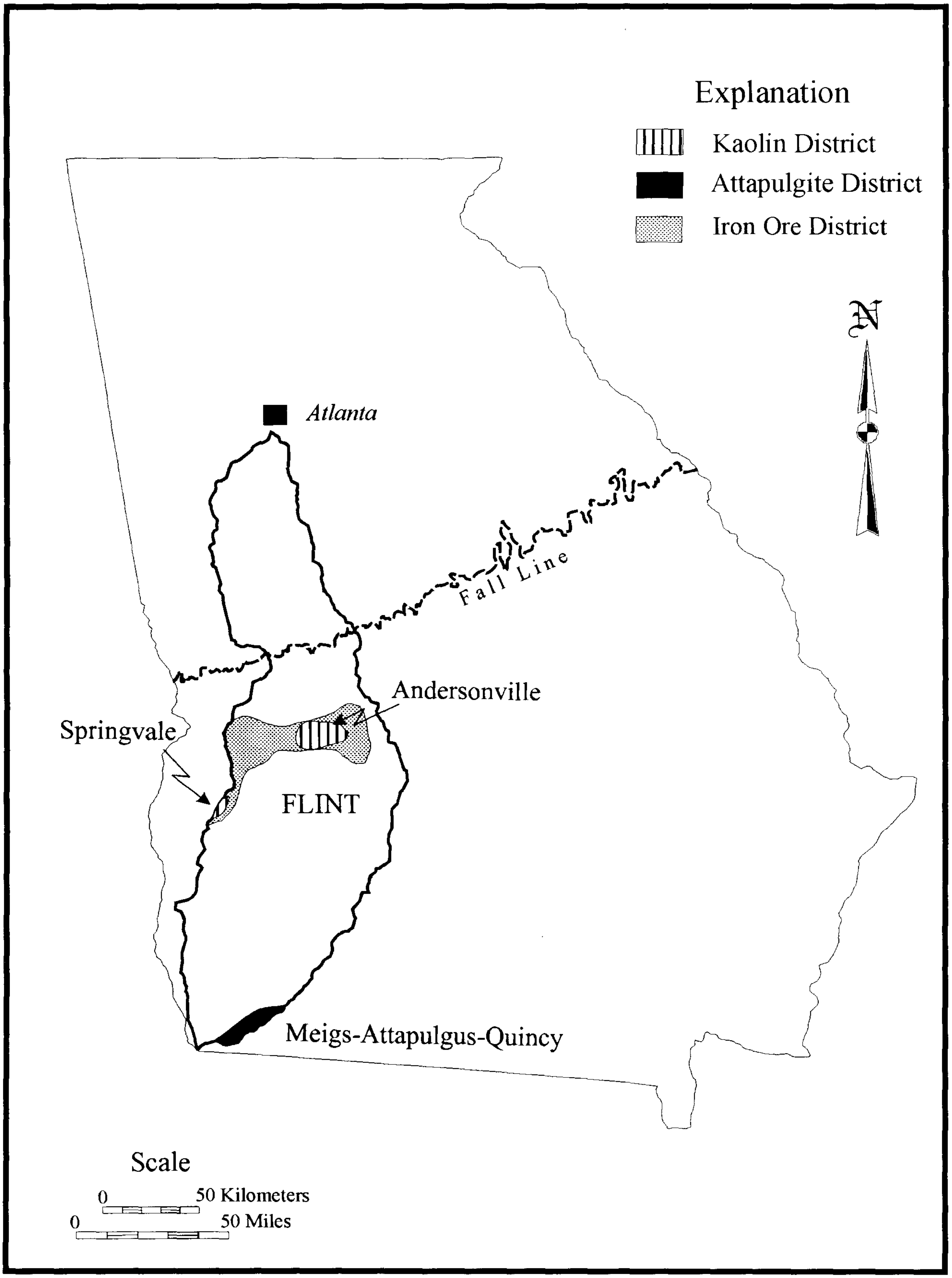

Figure 5. Mineral districts in the Coastal Plain.

**Table 2. Analyses of iron ores from Webster, Stewart and Quitman Counties.**
Values are in weight percent. LOI is Loss on Ignition.

| Sample Number | Moisture | LOI | $Al_2O_3$ | $Fe_2O_3$ | MnO | $P_2O_5$ | $SiO_2$ | P | S | Mn | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.05 | 11.45 | 3.83 | 69.27 | 0.27 | 0.12 | 15.30 | 0.05 | 0.03 | 0.21 | 48.44 |
| 2 | 0.06 | 11.95 | 4.94 | 77.82 | 0.26 | 0.02 | 4.30 | 0.009 | 0.25 | 0.20 | 54.21 |
| 3 | 0.04 | 10.26 | 7.31 | 67.85 | 0.28 | 0.00 | 14.80 | 0.00 | 0.41 | 0.22 | 47.44 |
| 4 | 0.06 | 11.35 | 4.81 | 67.45 | 1.24 | 0.16 | 16.50 | 0.07 | 0.11 | 0.96 | 47.03 |
| 5 | 0.12 | 12.62 | 3.96 | 78.38 | 0.31 | 0.22 | 4.86 | 0.10 | 0.03 | 0.24 | 54.80 |
| 6 | 1.01 | 10.71 | tr | 80.57 | 0.28 | 0.21 | 4.84 | 0.09 | 0.16 | 0.22 | 56.34 |
| 7 | 0.95 | 11.04 | 1.00 | 70.28 | 0.10 | 0.13 | 15.86 | 0.05 | 0.08 | 0.08 | 49.15 |
| 8 | | | | | 0.02 | 5.50 | | | | 0.01 | 56.65 |
| 9 | | | | | 0.007 | 64.32 | | | | 0.01 | 9.88 |
| 10 | | | | | 0.01 | 5.80 | | | | 0.01 | 56.39 |
| 11 | | | | | 0.01 | 50.60 | | | | 0.01 | 23.82 |
| 12 | | | | | 0.18 | 4.40 | | | | 0.96 | 54.49 |
| 13 | | | | | 0.08 | 3.60 | | | | 0.02 | 58.73 |
| 14 | | | | | 0.05 | 2.84 | | | | 0.02 | 57.91 |
| 15 | | | | | 0.18 | 10.88 | | | | 0.02 | 52.72 |
| 16 | | | | | 0.32 | 2.90 | | | | 0.01 | 57.80 |
| 17 | | | | | 0.00 | 4.28 | | | | 0.44 | 57.76 |
| 18 | | | | | 0.00 | | | | | 0.36 | 56.96 |
| 19 | | | | | 0.00 | 4.04 | | | | | 58.3 |
| 20 | | | | | 0.00 | 2.80 | | | | | 57.66 |
| 21 | | | | | 0.00 | 3.60 | | | | | 55.76 |
| 22 | | 9.3 | 10.3 | | | 37.7 | 0.2 | | | 0.4 | 27.6 |

Sample numbers 1-7 are from Furcron and Ray (1957), 8-21 are from Furcron (1956), and 22 is from O'Neill (1965). Sample 22 is an inferred resource calculation from numerous analyses from 103 drill holes.

**Table 3. Analyses of iron ores from the Perry Quadrangle, Pulaski County (Pickering, 1961).**

Values are in weight percent. LOI is Loss on Ignition.

| Sample Number | Moisture | LOI | $Al_2O_3$ | $Fe_2O_3$ | MnO | $P_2O_5$ | $SiO_2$ | P | S | Mn | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 2.32 | 11.75 | 1.14 | 77.18 | 0.72 | 0.41 | 4.92 | 0.18 | 0.04 | 0.56 | 53.97 |
| 3 | 0.90 | 11.50 | 2.36 | 78.02 | 0.03 | 0.23 | 5.30 | 0.10 | 0.03 | 0.02 | 54.56 |
| 4 | 0.90 | 11.45 | 1.70 | 77.80 | 2.00 | 0.21 | 3.48 | 0.09 | 0.04 | 1.55 | 54.41 |
| 6 | 3.75 | 11.70 | 1.06 | 73.35 | 0.53 | 0.14 | 3.18 | 0.06 | 0.04 | 0.41 | 50.14 |
| 7 | 1.23 | 11.40 | 2.16 | 78.89 | trace | 0.09 | 4.10 | 0.04 | 0.01 | trace | 55.17 |
| 7a | 2.30 | 11.70 | 2.93 | 74.42 | 0.24 | 0.28 | 7.10 | 0.12 | 0.04 | 0.19 | 52.05 |
| 9 | 1.05 | 12.30 | 1.65 | 66.83 | 6.19 | 0.44 | 3.40 | 0.19 | 0.02 | 4.77 | 46.74 |
| 10 | 1.15 | 11.85 | 1.20 | 68.31 | 2.60 | 0.21 | 4.78 | 0.09 | 0.03 | 2.01 | 47.78 |
| 11 | 1.38 | 9.55 | 2.18 | 83.52 | 0.56 | 0.23 | 2.58 | 0.10 | 0.38 | 0.43 | 58.41 |
| 12 | 2.85 | 8.31 | 1.00 | 82.26 | 1.45 | 0.21 | 4.12 | 0.09 | 0.49 | 1.12 | 57.53 |
| 13 | 1.05 | 11.40 | 1.69 | 82.47 | 1.23 | 0.16 | 3.22 | 0.07 | 0.54 | 0.95 | 57.68 |
| 14 | 2.75 | 10.00 | 1.17 | 78.66 | 0.48 | 034 | 5.80 | 0.15 | 0.54 | 0.37 | 55.01 |
| 15 | 1.60 | 12.70 | 5.20 | 71.29 | 1.25 | 0.11 | 7.85 | 0.05 | 0.07 | 0.97 | 49.85 |
| 16 | 0.54 | 11.12 | 1.40 | 79.09 | 0.14 | 0.53 | 7.18 | 0.23 | 0.66 | 0.11 | 55.31 |
| 17 | 0.57 | 11.55 | 1.30 | 82.68 | 0.09 | 0.28 | 3.52 | 0.12 | 0.04 | 0.07 | 57.82 |
| 18 | 0.55 | 10.95 | 0.61 | 79.50 | 1.29 | 0.30 | 6.80 | 0.13 | 0.21 | 1.00 | 55.60 |

**Table 4. Analyses of kaolins and other clays from the Flint River Basin.**

Data from Furcron and Forston (1960). Values are in weight percent.

| Sample | Moisture | LOI | $Na_2O$ | $K_2O$ | CaO | MgO | $Al_2O_3$ | $Fe_2O_3$ | $CO_2$ | $TiO_2$ | $SO_3$ | $P_2O_5$ | $SiO_2$ | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | 4.72 | trace | 1.37 | 2.02 | 3.88 | 10.54 | 2.70 | | trace | trace | 0.71 | 73.88 | 100.00 |
| 2 | | 9.28 | | | 2.00 | 6.35 | 17.97 | 3.65 | | trace | trace | 0.94 | 59.62 | 100.00 |
| 3 | | 8.08 | 0.36 | 1.41 | 1.29 | 0.06 | 13.23 | 2.90 | 0.00 | 0.29 | 0.25 | 0.56 | 70.85 | 99.45 |
| 4 | | 12.11 | 0.43 | 0.78 | 0.56 | 1.03 | 16.61 | 5.01 | 0.32 | 0.82 | 0.00 | 0.36 | 61.93 | 99.96 |
| 5 | | 9.50 | 0.28 | 0.55 | 1.54 | 4.51 | 17.30 | 3.63 | 0.00 | 0.49 | 0.04 | 1.42 | 60.97 | 100.55 |
| 6 | | 8.52 | 0.61 | 0.27 | 0.42 | 0.15 | 19.85 | 7.40 | | 0.94 | 0.00 | 0.42 | 62.34 | 100.92 |
| 7 | 0.48 | 14.24 | 0.40 | trace | 0.00 | 0.00 | 39.30 | 1.41 | | 1.35 | 0.05 | 0.10 | 43.18 | 100.51 |
| 8 | 2.24 | 13.30 | trace | trace | 0.00 | trace | 38.04 | 1.49 | | 1.63 | | trace | 43.13 | 99.83 |
| 9 | 1.48 | 13.30 | 0.20 | 0.16 | 0.00 | trace | 36.80 | 1.25 | | 1.35 | | trace | 45.54 | 100.08 |
| 10 | 0.62 | 14.24 | 0.43 | 0.35 | 0.00 | 0.08 | 38.86 | 1.33 | | 1.62 | | 0.09 | 42.64 | 100.26 |
| 11 | | 13.73 | | | | | 42.00 | 0.53 | | 1.50 | | | 36.00 | 93.76 |
| 12 | | 14.12 | | | | | 33.37 | 1.95 | | 1.48 | | | 47.27 | 98.19 |
| 13 | | 17.7 | | | | | 43.4 | 0.7 | | 1.8 | | | 35.3 | 98.9 |
| 14 | | 19.80 | | | | | 44.27 | 1.63 | | 1.76 | | | 31.56 | 99.02 |
| 15 | | 13.96 | | | | | 38.37 | 1.14 | | 1.67 | | | 43.60 | 98.74 |
| 16 | | 13.8 | | | | | 37.7 | 1.5 | | 1.8 | | | 44.8 | 99.6 |

| **Sample** | **Location** | **Mineralogy*** |
|---|---|---|
| 1 | Faceville, Decatur County | Palygorskite |
| 2-5 | Attapulgus, Decatur County | Palygorskite |
| 6 | Bainbridge | Palygorskite |
| 7-8 | Springvale, Randolph County | Kaolin |
| 9 | Troutman, Stewart County | Kaolin |
| 10-12 | Sumter County | Kaolin |
| 13-15 | Macon County | Kaolin |
| 16 | Sumter County | Kaolin |

* Clay mineralogy is not noted by Furcron and Forston (1960). Mineralogy is inferred by location of the sample and its composition.

**Table 5. Analyses of limestones in Lee County.** Data from Furcron and Perry (1958). Values are in weight percent.

| Sample | Moisture | LOI | $Na_2O$ | $K_2O$ | CaO | MgO | $Al_2O_3$ | $Fe_2O_3$ | $CO_2$ | $TiO_2$ | $SO_3$ | $P_2O_5$ | $SiO_2$ | Undetermined | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.38 | 38.48 | trace | 0.03 | 46.68 | trace | 3.99 | 0.73 | | 0.03 | 0.00 | 0.03 | 8.41 | | 99.76 |
| 2 | 0.45 | | | | 52.98 | 0.51 | 0.49 | 1.01 | 41.87 | | | | 2.54 | 0.15 | 100.00 |
| 3 | 0.42 | | | | 51.36 | 0.28 | 0.30 | 0.34 | 40.15 | | | | 7.02 | 0.13 | 100.00 |
| 4 | | | 0.02 | trace | 52.68 | 0.18 | 1.78 | | 41.38 | | | 0.06 | 3.90 | | 100.00 |
| 5 | 0.4 | | | | 53.76 | 0.58 | 0.27 | 0.67 | 42.43 | | | | 1.94 | | 100.10 |
| 6 | 0.52 | | | | 54.38 | 0.59 | 0.31 | 0.67 | 42.00 | | | | 1.88 | | 100.35 |
| 7 | 0.31 | | | | 54.54 | 0.51 | 0.26 | 0.50 | 42.10 | | | | 1.82 | | 100.04 |
| 8 | 0.80 | | | | 52.56 | 0.58 | 0.25 | 1.05 | 41.45 | | | | 3.32 | | 100.01 |
| 9 | | | trace | trace | 53.98 | 0.14 | 0.46 | | 42.74 | | | 0.04 | 2.64 | | 100.00 |
| 10 | 0.41 | | | | 53.90 | 0.51 | 0.39 | 0.67 | 42.18 | | | | 1.86 | | 100.00 |
| 11 | 0.39 | | | | 54.02 | 0.76 | 0.67 | 0.51 | 42.16 | | | | 1.64 | | 100.15 |
| 12 | 0.40 | | | | 54.52 | 0.56 | 0.03 | 0.67 | 42.28 | | | | 1.68 | | 100.14 |
| 13 | 0.34 | | | | 54.24 | 0.51 | 0.00 | 0.58 | 42.56 | | | | 1.74 | | 100.00 |
| 14 | 0.20 | | | | 55.00 | 0.48 | 0.28 | 0.52 | 42.29 | | | | 1.40 | | 100.17 |
| 15 | 0.28 | | | | 54.82 | 0.56 | 0.56 | 0.42 | 42.44 | | | | 1.14 | 0.16 | 100.00 |
| 16 | 0.63 | | | | 53.08 | 0.57 | 0.57 | 0.79 | 41.69 | | | | 2.90 | 0.19 | 100.00 |

**Table 6. Analyses of limestones in the Flint River Basin south of Albany, Georgia.**
Data from Furcron and Forston, 1960. Values in weight percent.

| Sample | Moisture | $Na_2O$ | $K_2O$ | CaO | MgO | $Al_2O_3$ | $Fe_2O_3$ | $CO_2$ | $P_2O_5$ | $SiO_2$ | Undetermined | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | 0.44 | 0.44 | 42.22 | 0.47 | 1.48 | | | 0.04 | 22.07 | 32.84 | 100.0 |
| 2 | | 0.32 | 0.20 | 41.30 | 0.90 | 1.04 | | | trace | 23.11 | 33.13 | 100.0 |
| 3 | 1.27 | | | 42.24 | 6.55 | 0.46 | 0.64 | 40.01 | 0.05 | 8.56 | 0.22 | 100.0 |
| 4 | 1.09 | | | 47.52 | 2.05 | 0.79 | 0.49 | 39.15 | 0.07 | 8.68 | 0.16 | 100.0 |
| 5 | 0.93 | 0.38 | 0.93 | 45.18 | 1.05 | 1.22 | 0.76 | 35.67 | 0.22 | 13.90 | | 100.2 |
| 6 | | trace | trace | 54.54 | 0.30 | 0.68 | 0.00 | | 0.95 | | 43.53 | 100.0 |
| 7 | 0.22 | trace | 0.64 | 53.72 | 0.76 | 0.71 | 0.67 | 42.00 | 0.02 | 1.5 | | 100.2 |
| 8 | 0.19 | 0.32 | 0.45 | 53.23 | 0.92 | trace | 2.19 | 39.30 | | 3.52 | | 100.2 |
| 9 | | | | 53.78 | 0.53 | 1.50 | | 41.94 | | 2.30 | 0.04 | 100.0 |
| 10 | 0.13 | | | 55.20 | 0.21 | 0.11 | 0.29 | 43.27 | 0.02 | 0.76 | 0.01 | 100.0 |
| 11 | 0.01 | trace | trace | 50.50 | 0.80 | 1.54 | 0.92 | 41.56 | | 4.78 | | 100.2 |
| 12 | 0.18 | trace | trace | 52.78 | 0.81 | 3.06 | 0.92 | 38.57 | | 3.88 | | 100.2 |
| 13 | 0.13 | trace | trace | 49.42 | 0.26 | 2.04 | 1.00 | 36.35 | | 10.66 | 0.14 | 100.0 |
| 14 | 0.14 | trace | trace | 52.44 | 0.81 | 1.14 | 1.52 | 36.00 | | 8.16 | | 100.2 |
| 15 | 0.15 | trace | trace | 53.16 | 0.57 | 2.07 | 0.57 | 39.98 | | 3.76 | | 100.2 |
| 16 | 0.03 | trace | trace | 50.10 | 0.37 | 2.35 | 1.27 | 37.35 | | 8.48 | | 100.0 |

| **Samples** | **Locations** | **Samples** | **Locations** |
|---|---|---|---|
| 1-2 | Decatur County | 10 | Worth County |
| 3-5 | Grady County | 11-16 | Dougherty County |
| 6-9 | Mitchell County | | |

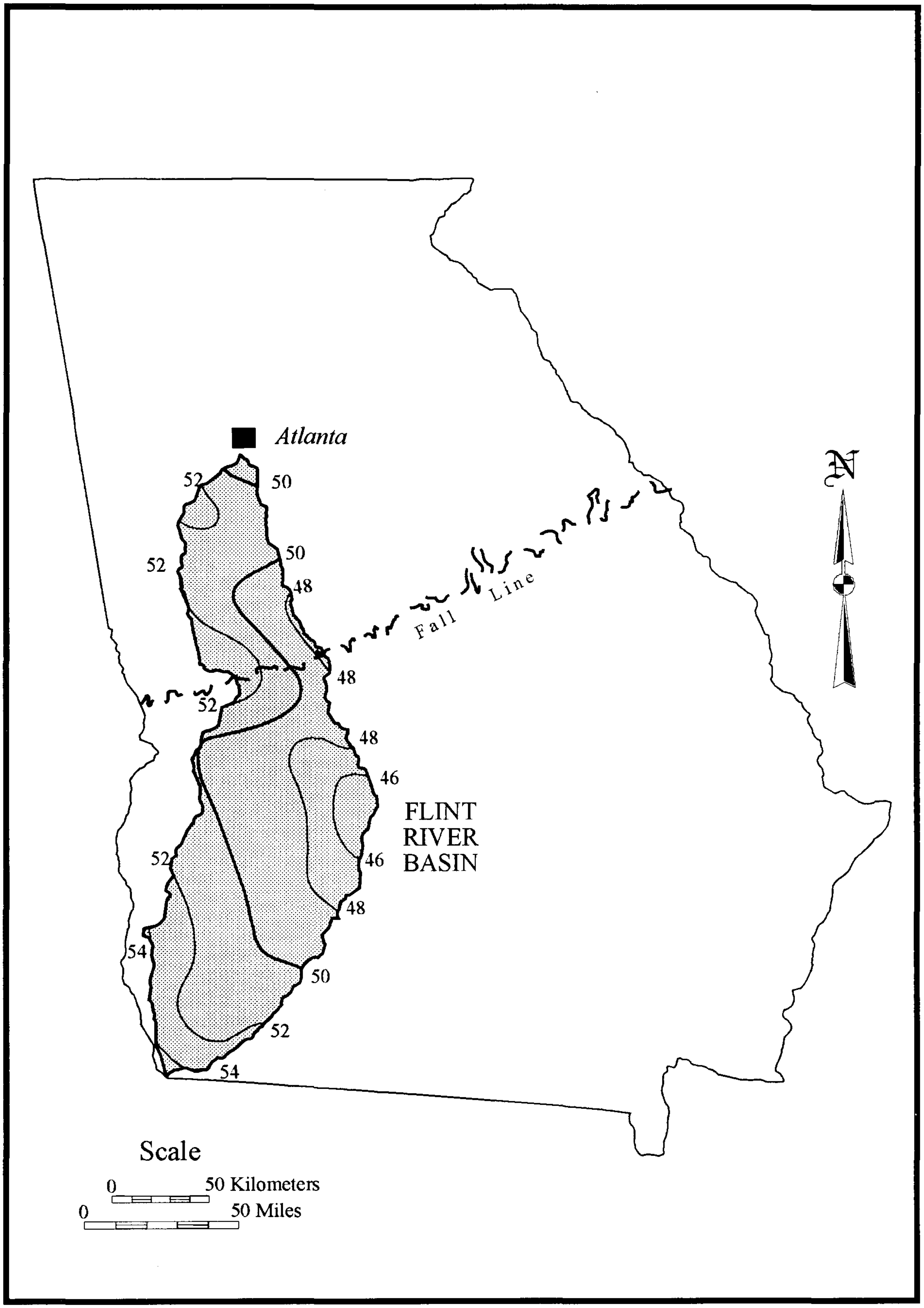

Figure. 6. Average annual rainfall in the Flint River Basin. Contour lines are isopleths that indicate rainfall in inches. Modified from Carter and Stiles (1983).

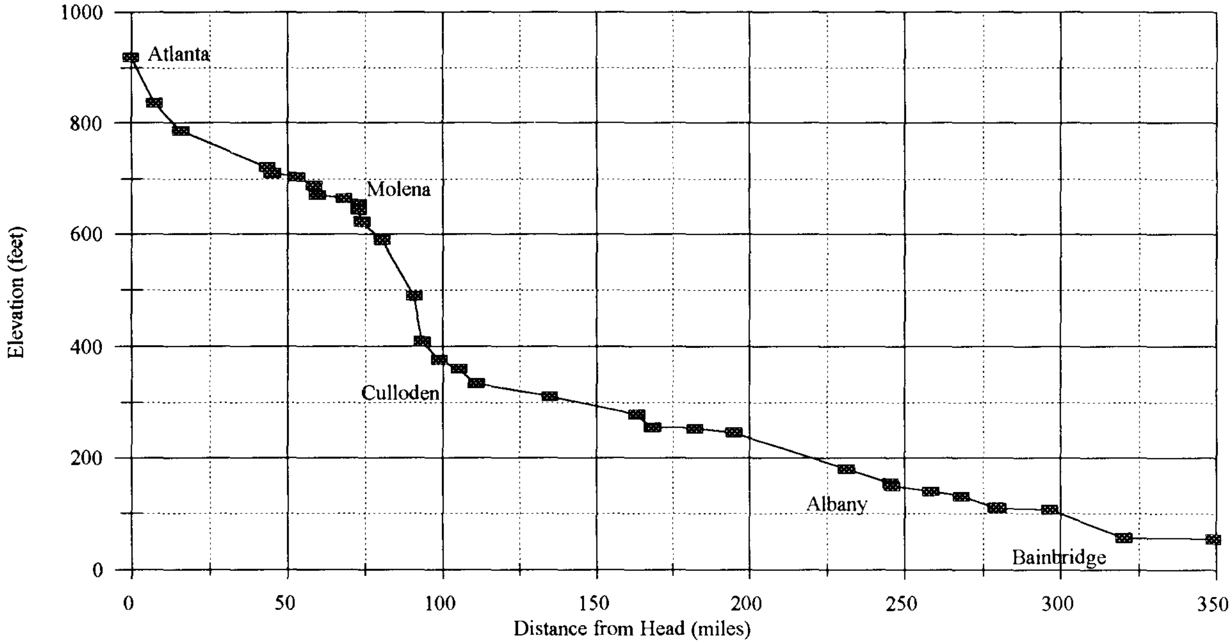

Figure 7. Profile of the Flint River.

der of the basin (United States Army Corps of Engineers - Mobile District, 1985). Principal tributaries of the Flint include Big Slough, Chickasawhatchee Creek, Elkins Creek, Ichawaynochaway Creek, Kinchafoonee Creek, Lazier Creek, Muckafonee Creek, Line Creek, Muckalee Creek, Pachitla Creek, Patsiliga Creek, Potato Creek, Redoak Creek, Spring Creek, Whiteoak Creek, and Whitewater Creek. Most of the larger tributaries are in the Coastal Plain including the three largest - Muckafonee Creek, Ichawaynochaway Creek and Big Slough. In the Coastal Plain, most drainages are on the western and northwestern side of the Flint River. The origin of the drainage asymmetry may be related to regional dip of the strata (to the southeast) and to lithologic variations in the carbonate strata. Karst geomorphologic features developed in the lower Flint River Basin carbonate rocks result in fewer low order streams and larger through-going streams or creeks. Flow in most of these streams is dominated by ground-water discharge directly into the stream bed (Couch and others, 1996). A profile of the Flint River (Fig. 7) shows the steepest gradients from the headwaters to Culloden at mile 110 which is just north of the Fall Line (Fig. 8). The Fall Line marks the boundary between the Piedmont and Coastal Plain physiographic provinces and is commonly defined by an abrupt change in slope. Rapids and shoals are frequently found at the Fall Line. The gradient of the Flint River is steeper (generally 2 to 11 feet per mile) in the Piedmont and gentler (generally less than 1 to 2 feet per mile) in the Coastal Plain (Fig. 8).

Discharge on the Flint River at Newton during the period 1977-92 was 4,030 cubic feet per second (Couch and others, 1996). Hess and Stamey (1993) provide data on annual peak discharges and stages for gaging stations through 1990. Higher flow rates occur during the winter months in the Flint River and the Coastal Plain streams. Normally the Chattahoochee River provides a greater flow to the Appalachicola River than the Flint River because of greater precipitation in the Chattahoochee River Basin. During extended dry periods baseflow is sustained by greater ground-water discharge from the carbonate rocks in the Coastal Plain, and the Flint River contributes a greater flow to the Appalachicola River than does the Chattahoochee River (Couch and others, 1996).

## *Land Surfaces*

The Flint River Basin extends from the Piedmont physiographic province through, and nearly across the Coastal Plain physiographic province (Fig. 9). Three quarters of the Flint River Basin lies within the Coastal Plain province. Couch and others (1996) provide a more regional description of the Apalachicola-Chattahoochee-Flint River Basin's physiography.

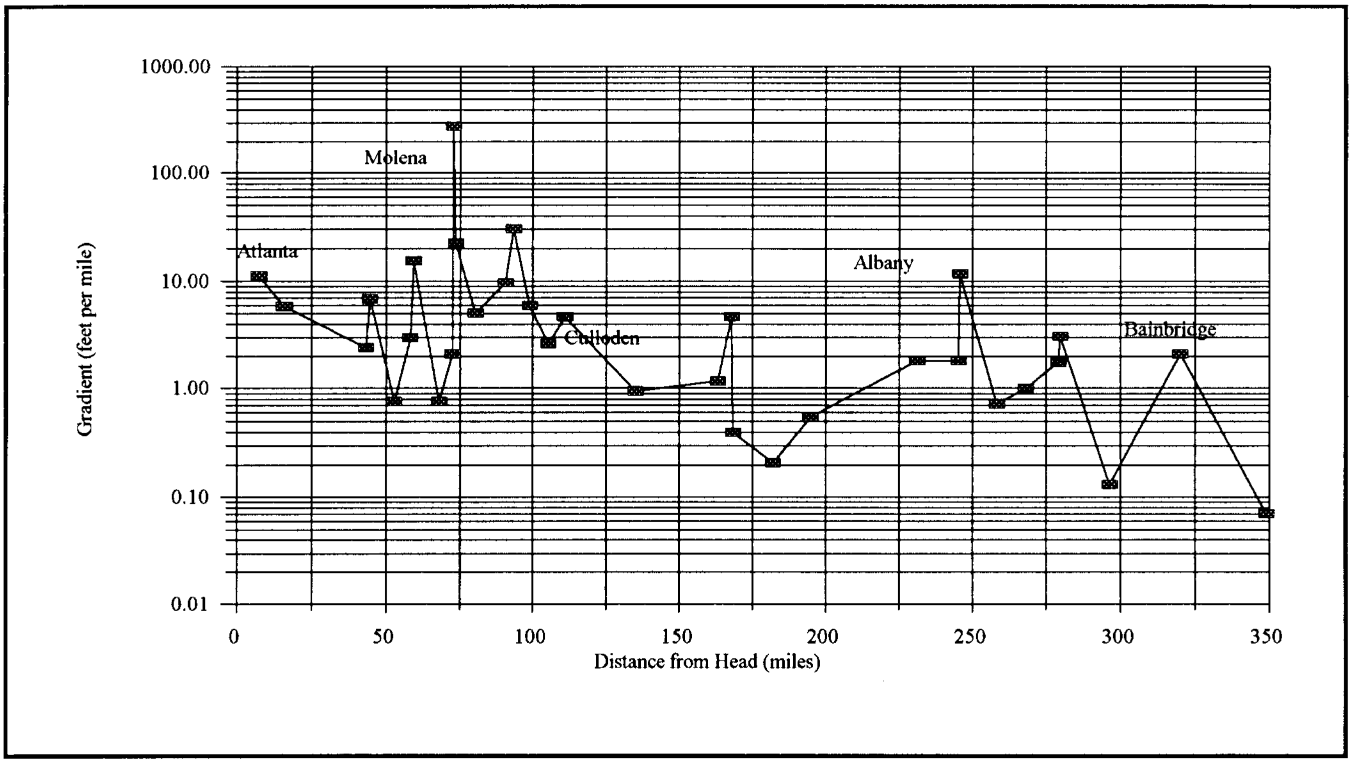

Figure 8. River gradient of the Flint River. Abnormally high gradient near Molena is along a 0.02 mile length of the river.

The Piedmont is characterized by broadly undulating topography. This surface is broken by low knobs or ridges and by valleys 56 to 330 feet deep (Thornbury, 1965). Much of the Piedmont topography resulted from prolonged exposure to deep weathering. Piedmont geomorphology may be locally controlled by lithology and structure.

Within the Flint River Basin, the Coastal Plain is characterized by dissected hilly terrain near the Fall Line in Marion, Taylor and Macon Counties. The terrain becomes more gentle in the southern end of the Flint River Basin. Within the Flint River Basin, the Coastal Plain may be divided into four topographic divisions: 1) Fall Line Hills, 2) Fort Valley Plateau, 3) Dougherty Plain, and Tifton Upland (LaForge and others, 1925).

Dominantly dendritic patterns are prominent in the Piedmont province near the Fall Line and in the northern part of the Coastal Plain province, particularly in clastic sediments of Cretaceous, Paleocene, and Eocene age. Superposition of south-flowing master streams on the Piedmont during the Cretaceous Period may have controlled some present major drainage patterns (Staheli, 1976; Reinhardt and Donovan, 1986). In the Coastal Plain, the entrenchment of the Flint River channel approximately 15 feet into its flood plain (La Forge and others, 1925) may have resulted from a general regional uplift.

## Surficial Deposits

### *Saprolite*

Saprolite is weathered bedrock with its original structure preserved. Saprolite is 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). Average saprolite thickness in the Piedmont rarely exceeds 70 feet, but the thickness can vary widely within a short distance. A considerable volume of ground water is stored in and flows through the saprolite and recharges streams in the Piedmont. Saprolite will increase the storage and residence time of water in a basin. Ground water in saprolite may transport large amounts of dissolved metals. Saprolite is easily eroded when covering vegetation and soil are removed.

### *Transported Regolith*

Colluvium deposits, perhaps of Pleistocene age, are best developed in the 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).

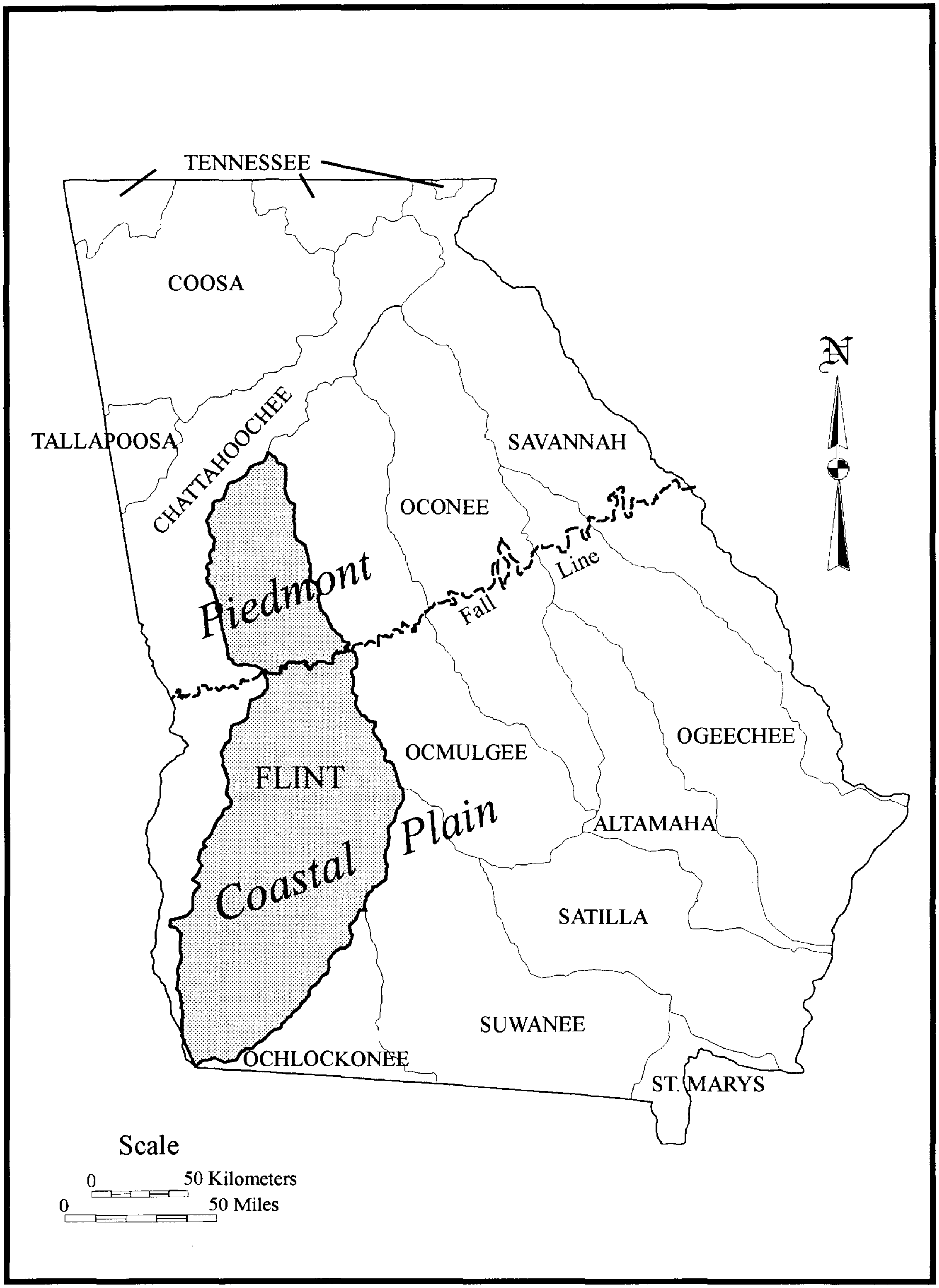

Figure 9. Physiographic provinces.

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 at the same time as 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).

### *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 province are sandy loam clay to fine sandy loam. 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 Flint River Basin (Kennedy, 1964). When covering vegetation is removed, soils are easily eroded and no longer protect the underlying saprolite from erosion. 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 Flint River Basin. In a study of the northern part of the nearby Chattahoochee River Basin, Faye and others (1980) found that land-use, soil-type, topography and climate contribute to erosion and transport of sediment. Faye and others (1980) concluded that sheet erosion is the dominant type of erosion in the northern part of the Chattahoochee basin. In the Oconee River Basin, severe erosion of agricultural land, which occurred prior to the 1940's, caused rapid deposition of sediments in headwater streams (Trimble, 1969; Cocker, 1996b). Erosion related to land clearing and poor farming practices during the 1800's and early 1900's was also noted in Stewart County in the Chattahoochee River Basin (Cocker, 1998). Although there are no known pertinent studies in the Flint River Basin, it is likely that similar conditions of erosion and sedimentation existed during the 1800's and early 1900's.

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 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. Kennedy collected suspended sediment data from a site on the Flint River at Culloden from December, 1958 to May, 1959. Discharge during that period ranged from 680 cubic feet per second to 11,100 cubic feet per second. Lowest discharges were in December and highest were in March. Suspended sediment concentrations ranged from 7 ppm to 436 ppm. A sample collected at low flow had a lower percentage of sand and a higher percentage of clay than samples collected during higher discharge periods. Suspended sediment load during that period was calculated to be 80,000 tons. During a flood in early June of 1959, the suspended sediment load was estimated to be 300,000 tons. From that data, Kennedy (1964) estimated that the suspended sediment load for 1959 was 400,000 tons.

# 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 7). 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. Average concentrations of metals in some streams in the United States are listed in Table 8.

Arsenic is found in many 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 which are commonly found in or near sulfide deposits and argillaceous rock units (e.g., 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 concentra-

**Table 7. Median concentrations of elements in average crustal rocks.** Values are in ppm.

| Element | Ultramafic Rocks | Mafic Rocks | Granitic Rocks | Limestones | Sandstones | Shales | Average Crustal Rocks |
|---|---|---|---|---|---|---|---|
| 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.

**Table 8. Trace element composition of some streams in the United States.** Data are from Turekian (1969). Values are in ppb.

| Element | Concentration |
|---|---|
| Al | 3.3 |
| Sb | 1.1 |
| As | 1.6 |
| Ba | 11 |
| Cr | 1.4 |
| Co | 0.19 |
| Cu | 12 |
| F | 88 |
| Pb | 2.3 |
| Li | 3.3 |
| Mn | 4.0 |
| Hg | 0.074 |
| Mo | 1.8 |
| Ni | 0.3 |
| P | 19 |
| Sc | 0.004 |
| Ag | 0.39 |
| Ti | 2.7 |
| W | 0.03 |
| U | 0.026 |
| V | 0.9 |
| Zn | 16 |

tions of chromium with up to 3,400 ppm in an average ultramafic rock (McGrath, 1995). Chromite is the primary ore and source of most chromium. High amounts of chromium may also be found in micas (Cocker, 1992), garnets, chlorites, and tourmalines. 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, which are generally found in ultramafic and mafic igneous rocks. Other hosts for cobalt are the minerals olivine, pyroxene, amphiboles and biotite. These minerals are most abundant in mafic and ultramafic igneous 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 rocks 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 in sulfides, but may be locally abundant in sulfosalts, oxides, carbonates, native copper, and silicates. Oxides, carbonates and the silicate chrysocolla are generally weathering by-products of sulfides and sulfosalts. Chalcopyrite, the most abundant source of copper, may occur as a primary massive ore, disseminated in a host 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. Many of the world's largest ore deposits occur in these sedimentary 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 may be 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, because of substitution for potassium in clays and feldspars, and the abundance of 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., the Kupferschiefer in Germany and the Zambian copper belt in Africa). Lead is apparently relatively immobile in a humid weathering environment, as it is commonly fixed by organic material and adsorbed by silts and clays (Davies, 1995).

Primary hosts of manganese are manganese oxides, carbonates, and ferromagnesium silicates. Highest manganese concentrations are in sediments and 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 environment.

The most important manganese ores are formed by 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. Manganese is an essential requirement of higher plants, and its availability to plants is important, especially in alkaline and oxidizing soils (Smith and Paterson, 1995).

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 is usually 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 the Piedmont of Georgia (Columbia, DeKalb, and Troup Counties) associated with ultramafic bodies (Cook, 1978) and may be associated with other ultramafic rocks in the Piedmont. 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, 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 found 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 are mainly governed by the source rocks (Kiekens, 1995).

Primary hosts of silver are sulfide minerals (e.g., galena and argentite), native silver, sulfosalts, and tellurides. Silver is generally relatively abundant in organic-rich shales. Silver is strongly influenced by pH and redox conditions. Soil organic material tends to strongly bind and accumulate silver (Edwards and others, 1995).

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 minerals. 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.

During their formation, some sedimentary lithologies may become enriched in metals. The occurrence of heavy minerals in Flint River Basin sedimentary and metasedimentary rocks is an example of such metal enrichment. 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 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. Potential remobilization of heavy minerals may be occurring in present-day river systems. 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 levels of 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. 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 silicates 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; and
5) Organic matter that incorporated the metals during growth;

## *Anthropogenic Sources*

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

Agricultural activities provide 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 Flint River Basin. Potential metals introduced through agricultural activities include arsenic, cadmium, chromium, lead, manganese, mercury, molybdenum, nickel, uranium, vanadium, and zinc (Alloway, 1995). Within the Flint River Basin, during the first half 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 Flint River Basin, a significant concern is the potential widespread introduction of lead into the environment through the previous use of gasoline containing lead additives. Lack of lead enrichment in sediments from Lake Blackshear or Lake Seminole may reflect lack of significant urban sources for lead in the Flint River Basin (Frick and others, 1998).

Household, municipal and industrial waste has the potential to introduce several metals into the environment including cadmium, copper, lead, tin, and zinc (Alloway, 1995). Improper disposal of batteries may introduce lead and other metals into the environment.

## Geochemical Databases for Georgia

Geochemical databases that exist for the Flint River Basin are quite varied in their scope, quality, size, and type of sample. Stream sediments, stream water, ground water, and soils within the Flint 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.

Most of these other geochemical and mineralogical databases were examined during 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 databases. Some of the data may be used to confirm some of the relations observed in the NURE data. Within the Flint River Basin other geochemical data include:

* 17 soil samples collected from 12 sites by the Georgia Environmental Protection Division (J.German, personal communication, 1995).

* 1,968 stream sediment samples collected from nine counties that cover part of the Chattahoochee and Flint River Basins. Counties within the Flint River Basin include Coweta, Meriwether, Pike, 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 by Hurst and Long (1971).

* Water samples from 12 water quality monitoring stations of which 11 have some chemical data, and two have heavy metal analyses (Arnsdorff and others, 1991).

* 25 water samples from streams, large tributaries and the Flint River, 51 water samples from wells, 8 water samples from springs, and 15 bottom-sediments from large tributaries and the Flint River were collected as part of the U.S. Geological Survey's National Water-Quality Assessment (NAWQA) Program. Data are available at the NAWQA Home Page on the Internet by using the Universal Resources Locator (URL): http://wwwrvares.er.usgs.gov/nawqa/nawqa_home..html (Frick and others, 1998).

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 half of the Flint River Basin. These data are important because the samples were collected within a short period (1976 to 1978), and thus provide 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 National Uranium Resource Evaluation (NURE) Program was established to evaluate domestic uranium resources in the continental United States and to identify areas favorable for uranium exploration. NURE geochemical data for the conterminous United States are 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. Chemical analyses were performed either by the SRL (for the main group of elements) or by contractor (for supplemental elements). 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 Flint River Basin includes parts of the Atlanta, Phenix City, Macon, 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 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 database. 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 1,000 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 determined. 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 five square miles, for a total of 1,413 sites per NTMS quadrangle. Sample sites cover the Flint River Basin from the northern headwaters south to Webster, Sumter and Crisp Counties (Fig. 10). The area sampled includes approximately 53 percent of the Flint River Basin representing a total area of 8,502 square miles.

### *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 volumes 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 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 9) for all the sample sites for which there was a sample. Conductivity, pH, alkalinity and temperature were measured in the field from water samples collected at each site. Analyses of samples from many sample

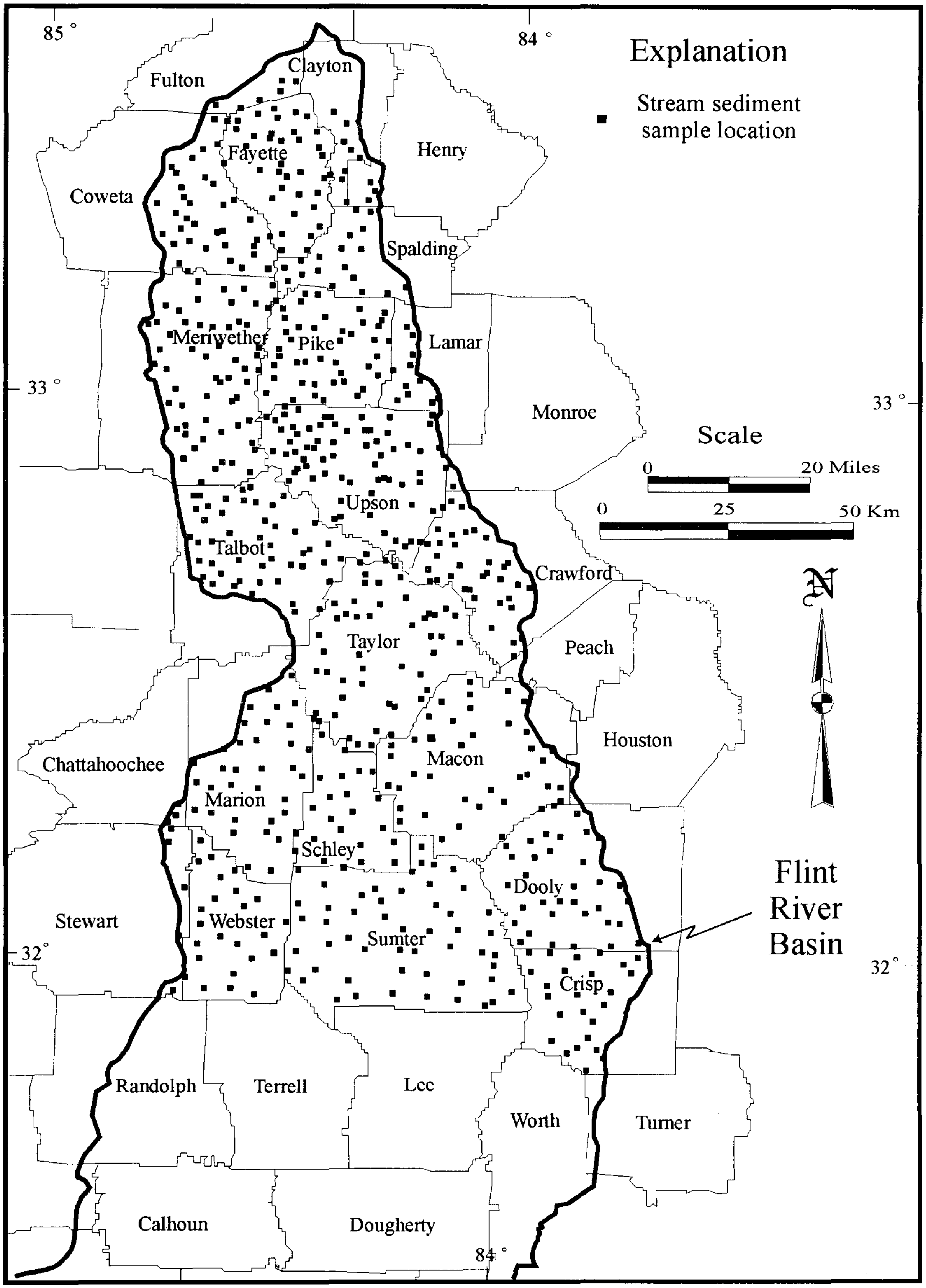

Figure 10. Stream sediment sample locations.

sites were conducted for a second suite of elements. For the Flint River Basin, this resulted in "incomplete" data sets for the Phenix City and Dothan quadrangles (Table 9). Stream and ground-water hydrogeochemistry is "complete" for all four quadrangles. The term "complete" is relative, as some sample sites have no analyses or measurements. Also, 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. Thus, in the following discussions on geochemistry, minimum concentrations may be shown as being below detection limit for that element. This procedure is commonly used by exploration geochemists and the U.S. Geological Survey (A. Grosz and J. McNeal, 1997, personal communications). NURE data used by Koch (1988) were also treated in this fashion.

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 shown in Table 10. Summary statistics were calculated for each element within the Flint River Basin (Table 11) and for each element per rock unit (Table 12). Samples which were not analyzed for a particular element (e.g., copper) were not included in the calculations.

## Identification of Data Gaps

Analysis of the background geochemistry of the Flint River Basin is incomplete because of important gaps in sample coverage, and gaps in analyses of base (heavy) metals. Important data gaps in the NURE stream sediment database 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 was made between total metal versus extractable metals in the analyses, no data are included on sediment grain-size distributions, and no data are given on size-fraction geochemical analysis.

Analyses for several primary pollutant metals (e.g., antimony, thallium, and mercury) are lacking for all the NURE stream sediment samples in Georgia. NURE stream sediment sample data for the Dothan and Phoenix City 1° x 2° quadrangles do not include analyses for silver, beryllium, cobalt, chromium, copper, lithium, molybdenum, nickel, phosphorous, lead, and zinc. Because these elements are only included in parts of the Atlanta, Macon, Dothan and Phoenix City databases, a complete basin analysis is not possible for these metals (Table 9).

Metal content of most rocks within the Flint River Basin is undocumented. High metal concentrations in some stream sediment analyses suggest that unknown sources for these metals exist within the Flint River Basin, and 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 the grain size distribution 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 stream sediment geochemical programs.

## Stream Hydrogeochemistry

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

Within the Flint River Basin, regional trends in relief, stream pH, stream sediment iron and manganese content, as well as organic-rich environments are important factors that will affect water chemistry. Along with its generally humid climate, regions in the Flint 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

**Table 9. Elements analyzed in NURE stream sediment samples.**

| Element | Analyzed in all databases | Analyzed in Dothan database | Analyzed in Phenix City database | Analyzed in Atlanta database |
|---|---|---|---|---|
| Ag | | | Ag* | Ag |
| Al | Al | Al | Al | Al |
| As | | | As* | As |
| Ba | | | Ba | Ba |
| Be | | | Be* | Be |
| Ce | Ce | Ce | Ce | Ce |
| Co | | | Co* | Co* |
| Cr | | Cr | | |
| Cu | | Cu | | |
| Dy | Dy | Dy | Dy | Dy |
| Eu | Eu | Eu | Eu | Eu |
| Fe | Fe | Fe | Fe | Fe |
| Hf | Hf | Hf | Hf | Hf |
| K | | | K* | K* |
| La | La | La | La | La |
| Li | | | Li | Li |
| Lu | Lu | Lu | Lu | Lu |
| Mg | | | Mg* | Mg* |
| Mn | Mn | Mn | Mn | Mn |
| Mo | | | Mo* | Mo |
| Na | Na | Na | Na | Na |
| Nb | | | Nb* | Nb |
| Ni | | | Ni* | Ni |
| P | | | P* | P |
| Pb | | | Pb* | Pb |
| Sc | Sc | Sc | Sc | Sc |
| Sn | | | Sn* | Sn |
| Sr | | | | |
| Th | Th | Th | Th | Th |
| Ti | Ti | Ti | Ti | Ti |
| U | U | U | U | U |
| V | V | V | V | V |
| W | | | W* | W |
| Y | | | Y* | Y |
| Yb | Yb | Yb | Yb | Yb |
| Zn | | | Zn* | Zn |

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

**Table 10. Number and percentage of stream sediment sample sites per rock unit.**

| Symbol | Lithologic Map Unit | Sample Sites | Percent | Base Metal Sites | Percent |
|---|---|---|---|---|---|
| Ec | Eocene - Claiborne Formation | 27 | 4.1 | 0 | 0 |
| Eo | Eocene - Ocala Limestone | 26 | 3.9 | 0 | 0 |
| Eo-Os | Eocene and Oligocene residuum undifferentiated | 27 | 4.1 | 0 | 0 |
| Etw | Eocene - Twiggs Clay | 0 | 0 | 0 | 0 |
| Eu | Eocene - undifferentiated | 13 | 2.0 | 1 | 0.5 |
| Kb | Cretaceous - Blufftown Formation | 3 | 0.5 | 0 | 0 |
| Kc | Cretaceous - Cusseta Sand | 25 | 3.8 | 0 | 0 |
| Kcbe | Cretaceous - Cusseta, Blufftown and Eutaw Formations | 5 | 0.8 | 5 | 2.3 |
| Ke | Cretaceous - Eutaw Formation | 7 | 1.1 | 5 | 2.3 |
| Kp | Cretaceous - Providence Sand | 42 | 6.4 | 0 | 0 |
| Kr | Cretaceous - Ripley Formation | 35 | 5.3 | 0 | 0 |
| Kt | Cretaceous - Tuscaloosa Formation | 17 | 2.6 | 10 | 4.5 |
| Mh | Miocene - Hawthorne Formation | 0 | 0 | 0 | 0 |
| Nm | Neogene - Muccosukee Formation | 0 | 0 | 0 | 0 |
| Nu | Neogene - undifferentiated | 1 | 0.2 | 0 | 0 |
| Os | Oligocene - Suwanee Limestone | 26 | 3.9 | 0 | 0 |
| Pc | Paleocene - Clayton Formation | 0 | 0 | 0 | 0 |
| Pcn | Paleocene - Nanafalia, Porters Creek + Clayton Formations | 8 | 1.2 | 0 | 0 |
| Pnf | Paleocene - Nanafalia Formation | 16 | 2.4 | 0 | 0 |
| Ptu | Paleocene - Tuscahoma Sand | 8 | 1.2 | 0 | 0 |
| Qal | Quaternary - stream alluvium and stream terrace deposits | 10 | 1.5 | 1 | 0.5 |
| Qas | Quaternary - aeolian sand deposits | 0 | 0 | 0 | 0 |
| bg1 | biotite gneiss | 63 | 9.5 | 21 | 9.5 |
| c1 | mylonite and ultramylonite | 0 | 0 | 0 | 0 |
| c2 | flinty crush rock | 0 | 0 | 0 | 0 |
| fg1 | biotite gneiss/feldspathic biotite gneiss | 5 | 0.8 | 3 | 1.4 |
| fg3 | biotitic gneiss/mica schist/amphibolite | 15 | 2.3 | 15 | 6.8 |
| gg1 | granite gneiss undifferentiated | 25 | 3.8 | 0 | 0 |
| gg4 | granite gneiss/amphibolite | 12 | 1.8 | 12 | 5.5 |
| gr1 | granite undifferentiated | 48 | 7.3 | 45 | 20.5 |
| gr1b | porphyritic granite | 5 | 0.8 | 5 | 2.3 |
| gr3 | granite/biotitic gneiss/amphibolite | 1 | 0.2 | 1 | 0.5 |
| gr4 | charnockite | 4 | 0.6 | 0 | 0 |
| mm1 | amphibolite | 0 | 0 | 0 | 0 |
| mm2 | hornblende gneiss | 8 | 1.2 | 8 | 3.6 |
| mm3 | hornblende gneiss/amphibolite | 0 | 0 | 0 | 0 |
| mm4 | hornblende gneiss/amphibolite/granite gneiss | 13 | 2.0 | 0 | 0 |
| mm5 | hornblende-biotite gneiss/amphibolite | 3 | 0.5 | 3 | 1.4 |
| mm9 | amphibolite/mica schist/biotitic gneiss | 0 | 0 | 0 | 0 |
| pa1 | aluminous schist | 1 | 0.2 | 1 | 0.5 |
| pa2 | sillimanite schist | 12 | 1.8 | 12 | 5.5 |
| pms1 | mica schist | 20 | 3.0 | 20 | 9.1 |
| pms3 | mica schist/gneiss | 2 | 0.3 | 0 | 0 |
| pms3a | mica schist/gneiss/amphibolite | 113 | 17.1 | 50 | 22.7 |
| q1 | quartzite | 13 | 2.0 | 6 | 2.7 |
| um | ultramafic rocks undifferentiated | 1 | 0.2 | 1 | 0.5 |

**Table 11. Summary of Flint River Basin geochemistry.** Number of samples analyzed for most elements is 660; number of analyses for base metals is 220. Temperature is in degrees Centigrade; alkalinity is in meq/L; conductivity is in micromhos/cm; elements are in parts per million (ppm). Values below detection limit are explained on page 35.

| | **Average** | **Mean** | **Standard Deviation** | **Maximum** | **Minimum** |
|---|---|---|---|---|---|
| Water Temperature | 21.8 | 21.2 | 4.0 | 34.0 | 10.0 |
| pH | 6.5 | 6.4 | 0.5 | 8.1 | 4.1 |
| Alkalinity | 0.3 | 0.3 | 0.3 | 2.24 | 0.02 |
| Conductivity | 43.2 | 42.0 | 32.1 | 385.0 | 0.10 |
| Ag | 0.26 | 0.09 | 0.23 | 3.00 | 0.05 |
| Al | 28,123 | 24,624 | 20,429 | 124,000 | 2,400 |
| Ba | 39.7 | 0.1 | 50.4 | 323.0 | 3.0 |
| Be | 0.81 | 0.26 | 0.51 | 3.00 | 0.30 |
| Co | 6.0 | 1.9 | 5.2 | 38.0 | 2.5 |
| Cr | 3.5 | 1.1 | 1.3 | 11.0 | 3.0 |
| Cu | 5.0 | 1.6 | 2.0 | 39.0 | 1.0 |
| Fe | 23,903 | 22,706 | 20,132 | 154,000 | 2,500 |
| K | 13,457 | 3,839 | 9,444 | 43,000 | 2,500 |
| Mg | 1,419 | 456 | 936 | 7,400 | 100 |
| Mn | 692 | 582 | 945 | 9,530 | 30 |
| Na | 2,155 | 1,615 | 3,310 | 25,300 | 100 |
| Ni | 5.2 | 1.7 | 3.9 | 31.0 | 3.0 |
| Pb | 7.3 | 2.2 | 4.6 | 25.0 | 1.0 |
| Ti | 10,0056 | 8,072 | 9,750 | 80,500 | 1,000 |
| V | 53.7 | 46.1 | 41.3 | 290 | 10.0 |
| Zn | 19.1 | 6.1 | 16.1 | 113.0 | 3.0 |

sampling (Rose and others, 1979).

## *Acidity (pH)*

NURE hydrogeochemical data provide detailed information of stream pH in the northern half of the Flint River Basin. Although the average pH (6.5) of the 660 stream samples in the Flint River Basin is near neutral, pH in the Flint River Basin varies from 4.1 to 8.1. The pH varies considerably within different areas of the Piedmont and within the Coastal Plain (Fig. 11). These differences can generally be directly attributed to the principal type of host rock in which the stream pH was measured. The Flint River Basin cuts across five zones in which the pH changes from acidic to alkaline. Three of these zones may be related directly to differences in tectonostratigraphic/lithologic terranes within the Piedmont and are similar to those described in the Oconee River Basin (Cocker, 1996b) and the Chattahoochee River Basin (Cocker, 1998). The other two zones may be related to types of sediments in the Coastal Plain.

Streams within the northern part of the Coastal Plain in Taylor, Marion, Crawford, Macon and Schley Counties (Fig. 11) have the lowest pH (4.1 to 6.7) 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 12). Rock units (Table 1) which contain streams with the lowest average pH (Table 12) include: *Kb* - Blufftown Formation (5.1), *Ke* - Eutaw Formation (5.5), *Kcbe* - Cusseta, Blufftown and Eutaw Formations (5.9), *Kc* - Cusseta Sand (6.0), *Kp* - Providence Sand (6.1), *Kt* - Tuscaloosa Formation (6.1), *Nu* - Neogene undifferentiated (6.1), *Eo-Os* - undifferentiated Eocene - Oligocene residuum (6.1), *Pnf* - Nanafalia Formation (6.1), *Kr* - Ripley Formation (6.2), *Qal* - alluvium (6.2), *Os* - Suwanee Limestone (6.3), *Ec* - Clayton Formation (6.3), and *Eu* - undifferentiated Eocene (6.3). Similar low pH values (6.0 to 6.8) were also described for Coastal Plain sediments in the Oconee River Basin (Cocker, 1996b) and (5.6 to 6.5) in the Chattahoochee River Basin

**Table 12. Average geochemical values per rock unit.** Temperature is in degrees Centigrade; alkalinity is in meq/L; conductivity is in micromhos/cm; elements are in parts per million (ppm). Values less than detection limit are explained on page 35.

| Rock | Temp | pH | Alk | Cond | Ag | Al | Ba | Be | Co | Cr | Cu | Fe | K | Mg | Mn | Na | Ni | Pb | Sc | Ti | V | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ec | 24.7 | 6.3 | 0.32 | 36.3 |  | 22,196 |  |  |  |  |  | 21,696 |  |  | 310 | 131 |  |  | 3.8 | 5,708 | 46.8 |  |
| Eo | 18.3 | 6.6 | 0.47 | 62.3 |  | 27,296 |  |  |  |  |  | 15,324 |  |  | 384 | 163 |  |  | 4.2 | 4,868 | 41.2 |  |
| Eo-Os | 26.5 | 6.1 | 0.40 | 47.8 |  | 27,609 |  |  |  |  |  | 21,735 |  |  | 174 | 1163 |  |  | 4.5 | 4,917 | 50.0 |  |
| Eu | 23.5 | 6.3 | 0.39 | 53.8 | 0.30 | 14,820 | 20.0 | 0.50 | 5.0 | 3.0 | 5.0 | 16,664 | 6,000 | 500 | 177 | 143 | 3.0 | 15.0 | 3.7 | 4,880 | 34.0 | 42.0 |
| Kb | 19.0 | 5.1 | 0.04 | 13.7 |  | 4,866 |  |  |  |  |  | 7,283 |  |  | 180 | 100 |  |  | 15.5 | 26,400 | 90.0 |  |
| Kc | 22.8 | 6.0 | 0.23 | 29.4 |  | 24,961 |  |  |  |  |  | 13,852 |  |  | 108 | 176 |  |  | 5.5 | 5,761 | 44.8 |  |
| Kcbe | 20.6 | 5.9 | 0.14 | 27.6 | 0.30 | 19,500 | 14.8 | 0.34 | 3.0 | 3.6 | 7.2 | 10,060 | 4,800 | 680 | 330 | 7,100 | 3.8 | 10.2 | 3.5 | 4,650 | 36.7 | 24.4 |
| Ke | 21.1 | 5.5 | 0.05 | 20.3 |  | 11,160 |  |  |  |  |  | 9,114 |  |  | 142 | 100 |  |  | 5.2 | 9,980 | 40.0 |  |
| Kp | 24.9 | 6.1 | 0.21 | 23.1 |  | 12,779 |  |  |  |  |  | 14,021 |  |  | 184 | 176 |  |  | 3.6 | 8,238 | 38.6 |  |
| Kr | 25.5 | 6.2 | 0.28 | 28.5 |  | 10,340 |  |  |  |  |  | 10,469 |  |  | 150 | 180 |  |  | 3.2 | 7,732 | 33.2 |  |
| Kt | 19.6 | 6.1 | 0.11 | 25.4 | 0.30 | 13,667 | 22.1 | 0.52 | 2.5 | 3.5 | 1.3 | 7,088 | 5,571 | 780 | 195 | 1,917 | 3.2 | 5.6 | 4.6 | 7,977 | 34.6 | 15.8 |
| Nu | 21.0 | 6.1 | 0.20 | 50.0 |  | 14,800 |  |  |  |  |  | 9,500 |  |  | 360 | 200 |  |  | 3.0 | 3,600 | 20.0 |  |
| Os | 17.7 | 6.3 | 0.30 | 53.3 |  | 21,922 |  |  |  |  |  | 15,130 |  |  | 247 | 200 |  |  | 3.7 | 4,378 | 33.9 |  |
| Pcn | 28.1 | 6.5 | 0.36 | 31.4 |  | 14,600 |  |  |  |  |  | 13,043 |  |  | 177 | 183 |  |  | 3.0 | 5,729 | 30.0 |  |
| Pnf | 25.2 | 6.1 | 0.17 | 25.0 |  | 15,746 |  |  |  |  |  | 23,462 |  |  | 258 | 100 |  |  | 2.7 | 4,423 | 30.8 |  |
| Ptu | 29.0 | 6.8 | 0.28 | 21.5 |  | 9,738 |  |  |  |  |  | 12,975 |  |  | 175 | 112 |  |  | 3.0 | 7,238 | 30.0 |  |
| Qal | 20.7 | 6.2 | 0.39 | 57.6 | 0.30 | 21,550 | 13.0 | 0.30 | 2.5 | 3.0 | 3.0 | 16,590 | 3,000 | 1,200 | 203 | 183 | 3.0 |  | 3.8 | 5,200 | 36.0 | 20.0 |
| bg1 | 19.2 | 6.9 | 0.39 | 56.5 | 0.30 | 33,231 | 41.1 | 0.52 | 8.6 | 3.8 | 5.7 | 28,044 | 4,857 | 1,529 | 1,002 | 6,714 | 5.9 | 5.0 | 6.3 | 13,260 | 84.3 | 35.5 |
| fg1 | 20.8 | 6.5 | 0.18 | 34.2 | 0.47 | 38,580 | 53.7 | 0.60 | 6.7 | 3.0 | 7.3 | 20,500 | 7,333 | 967 | 824 | 920 | 10.3 | 5.0 | 4.8 | 9,125 | 52.0 | 16.7 |
| fg3 | 21.9 | 6.8 | 0.28 | 59.3 | 0.36 | 45,400 | 42.2 | 1.05 | 5.5 | 3.3 | 7.3 | 31,800 | 10,933 | 1,533 | 984 | 3,333 | 3.9 | 6.0 | 9.7 | 8,509 | 57.5 | 21.9 |
| gg1 | 19.1 | 6.5 | 0.19 | 42.8 |  | 30,290 |  |  |  |  |  | 33,604 |  |  | 413 | 4,750 |  |  | 7.5 | 19,320 | 54.7 |  |
| gg4 | 21.5 | 6.8 | 0.31 | 57.7 | 0.34 | 50,720 | 36.0 | 0.88 | 5.5 | 3.3 | 4.8 | 23,610 | 20,083 | 1,717 | 1,056 | 4,202 | 4.1 | 5.7 | 6.5 | 8,017 | 51.3 | 24.2 |
| gr1 | 22.2 | 6.7 | 0.30 | 48.1 | 0.25 | 43,925 | 68.1 | 0.94 | 5.2 | 3.3 | 4.2 | 28,431 | 20,614 | 1,084 | 1,368 | 2,740 | 5.9 | 8.2 | 6.3 | 12,483 | 53.3 | 13.4 |
| gr1b | 21.6 | 6.8 | 0.26 | 49.0 | 0.15 | 51,320 | 11.5 | 1.45 | 11.5 | 3.5 | 9.3 | 28,780 | 11,750 | 1,450 | 1,398 | 2,600 | 3.5 | 10.8 | 7.3 | 7,950 | 93.3 | 25.8 |
| gr3 | 23.0 | 6.9 | 0.30 | 42.0 | 0.10 | 39,300 |  | 2.50 | 10.0 | 3.0 | 8.0 | 18,500 | 25,000 | 900 | 640 | 1,550 | 3.0 | 5 | 4.8 |  | 40.0 | 30.0 |
| gr4 | 17.3 | 7.1 | 0.20 | 32.0 |  | 23,750 |  |  |  |  |  | 44,550 |  |  | 595 | 3,725 |  |  | 7.6 | 21,950 | 45.0 |  |
| mm2 | 22.0 | 6.8 | 0.29 | 46.6 | 0.16 | 42,075 | 21.5 | 1.09 | 7.3 | 3.0 | 4.4 | 35,771 | 13,429 | 1,543 | 1,359 | 7,057 | 4.1 | 10.3 | 9.0 | 12,771 | 87.5 | 15.9 |
| mm4 | 17.4 | 7.2 | 0.45 | 56.6 |  | 33,429 |  |  |  |  |  | 27,300 |  |  | 860 | 4,400 |  |  | 6.8 | 6,429 | 71.4 |  |
| mm5 | 21.0 | 6.8 | 0.24 | 43.0 | 0.23 | 52,200 | 32.7 | 0.93 | 5.2 | 4.3 | 5.3 | 47,300 | 9,333 | 1,933 | 973 | 1,300 | 3.7 | 5.0 | 17.1 |  | 56.7 | 18.3 |
| pa1 | 25.0 | 6.9 | 0.24 | 35.0 | 0.40 | 51800 | 43.0 | 1.00 | 8.0 | 3.0 | 10.0 | 29,000 | 11,000 | 2,300 | 590 | 1,300 | 5.0 | 5 | 6.5 | 6,900 | 80.0 | 33.0 |
| pa2 | 20.2 | 6.7 | 0.34 | 60.4 | 0.25 | 31,925 | 37.5 | 0.89 | 10.6 | 3.9 | 8.0 | 37,992 | 6,800 | 1,230 | 2,373 | 1,340 | 7.3 | 8.6 | 6.3 | 17,633 | 84.2 | 23.3 |
| pms1 | 22.7 | 6.8 | 0.19 | 37.0 | 0.22 | 30,770 | 30.7 | 0.81 | 6.2 | 4.1 | 3.8 | 29,405 | 14,312 | 1,794 | 1,135 | 1,847 | 5.0 | 7.6 | 5.9 | 13,160 | 70.5 | 18.6 |
| pms3 | 17.5 | 6.6 | 0.20 | 27.5 |  | 31,200 |  |  |  |  |  | 37,100 |  |  | 920 | 1,650 |  |  | 4.0 | 21,800 | 55.0 | 55.0 |
| pms3a | 21.2 | 6.8 | 0.28 | 44.6 | 0.24 | 32,933 | 42.9 | 0.76 | 5.5 | 3.3 | 5.1 | 33,783 | 12,068 | 1,736 | 1,111 | 2,132 | 5.8 | 7.5 | 5.9 | 15,310 | 67.6 | 15.1 |
| q1 | 21.2 | 6.6 | 0.23 | 38.3 | 0.25 | 17,183 | 18.3 | 0.53 | 2.9 | 3.0 | 1.8 | 14,254 | 5,667 | 783 | 423 | 683 | 3.3 | 5.0 | 2.5 | 8,850 | 30.8 | 10.3 |
| um | 19.0 | 6.5 | 0.12 | 38.0 | 0.10 | 51,600 |  | 0.50 | 8.0 | 6.0 | 2.0 | 20,300 | 23,000 | 2,400 | 1,140 | 7,200 | 3.0 | 5 | 7.7 |  | 60.0 | 10.0 |

(Cocker, 1998). Rock units with the lowest pH are all Coastal Plain sandy sediments.

South of the more acidic streams in the Coastal Plain is a zone (Fig. 11) of more alkaline streams. Stream pH measurements range from 7.0 to 7.9 in parts of Dooly, Crisp, Sumter, Webster, Stewart, and Marion Counties. This area is underlain by carbonate rocks that appear to buffer stream water.

In the Piedmont, a narrow zone of neutral to alkaline streams (pH of 7.0 to 7.7) in Talbot, Upson, Taylor, and Crawford Counties (Fig. 42) is underlain by metavolcanic and metavolcaniclastic rocks of the Uchee terrane (Fig. A-1). Neutral to alkaline water may result from weathering of carbonate minerals in metamorphic rocks and by hydrolysis of iron-magnesium silicate minerals.

The northern part of the Flint River Basin, north of mid-Meriwether County (Fig. 42), is characterized by small clusters of slightly alkaline (pH of 7.0 to 7.5) streams within a broader area of slightly acidic (pH of 6-6.9) 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 of Georgia. These may include lenses or thin layers of amphibolite. Rock units which contain streams with the highest mean pH include: *mm4* - hornblende gneiss (7.2), *gr4* - charnockite (7.1), *bg1* - biotite gneiss (6.9), *pa1* - aluminous schist (6.9), and *gr3* - granite (6.9).

Several water samples collected near anthropogenic activities that might influence the analyses had low pH values (4.6 to 5.5). An unusually low pH (4.4) in the vicinity of Thomaston is two pH levels below that in surrounding streams.

## *Specific Conductivity*

Conductivity is a measure of the ability of water to conduct an electrical current and is measured in micromhos/cm. 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 dissolution of iron-bearing materials such as naturally occurring silicates, oxides, sulfides, and man-made metallic objects.

Conductivity in the Flint River Basin is within a range of 0.1 to 385 micromhos/cm. Average conductivity for the basin is 43.2 micromhos/cm. Different portions of the Piedmont and the Coastal Plain of the Flint River Basin may be distinguished by conductivities that are either above or below 43 micromhos/cm (Fig. 12). Regional trends that were noted further to the east in the Oconee River Basin (Cocker, 1996b) are present within the Flint River Basin but are generally not as well defined. The Flint River Basin cuts across five regions that differ in conductivity and may be related directly to different tectonostratigraphic/lithologic terranes in the Piedmont and to sedimentary units in the Coastal Plain. These regions are generally similar in extent to the regions of different pH and alkalinity.

In the Inner Piedmont, higher conductivities are generally in the 40 to 70 micromhos/cm range. Higher conductivities were measured in streams within *pms3a* - mica schist in Coweta and Fulton counties. Streams located south of the Towaliga fault zone within the Pine Mountain terrane (Fig. A-1) have low conductivities, generally in the 20 to 40 micromhos/cm range (Fig. 12). In the Uchee terrane (Fig. A-1), conductivities range from 50 to 185 micromhos/cm. Immediately south of the Fall Line, conductivities are generally 1 to 45 micromhos/cm (Fig. 12). Further to the south, conductivities increase to 40 to 220 micromhos/cm (Fig. 12).

The region of high conductivity streams (greater than 50 micromhos/cm) in the Uchee terrane (Fig. 12) appears to be similar to that previously documented for the Carolina terrane in eastern and central Georgia (Cocker, 1996b) and the Uchee terrane to the west (Cocker, 1998). Rocks within the Uchee terrane are not well documented but may be geochemically similar to those of the Carolina terrane further to the east. 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. 13.

Increasing conductivities to the south correspond to a greater volume of carbonate rocks in that part of the basin. Further to the south, the basin is principally underlain by carbonate rocks, and conductivities may be expected to be in the 50 to 250 micromhos/cm range.

Rock units (Table 1) which contain streams with the lowest average conductivities (Table 12) include: *Kb* - Blufftown Formation (13.7 micromhos/cm), *Ke* - Eutaw Formation (20.3 micromhos/cm), *Ptu* - Tuscahoma Sand (21.5 micromhos/cm), *Kp* - Providence Sand (23.1 micromhos/cm) and *Pnf* - Nanafalia Formation (25.0 micromhos/cm), *Kt* - Tuscaloosa Formation (25.4 micromhos/cm), *pms3* - mica schist (27.5 micromhos/cm), *Kcbe* - Cusseta, Blufftown and Eutaw Formations (27.6 micromhos/cm), *Kr* - Ripley Formation (28.5 micromhos/ cm), Kc - Cusseta Sand (29.4 micromhos/cm), and *Pcn* - Nanafalia, Porters Creek and Clayton Formations (31.4 micromhos/cm). Most of these rock

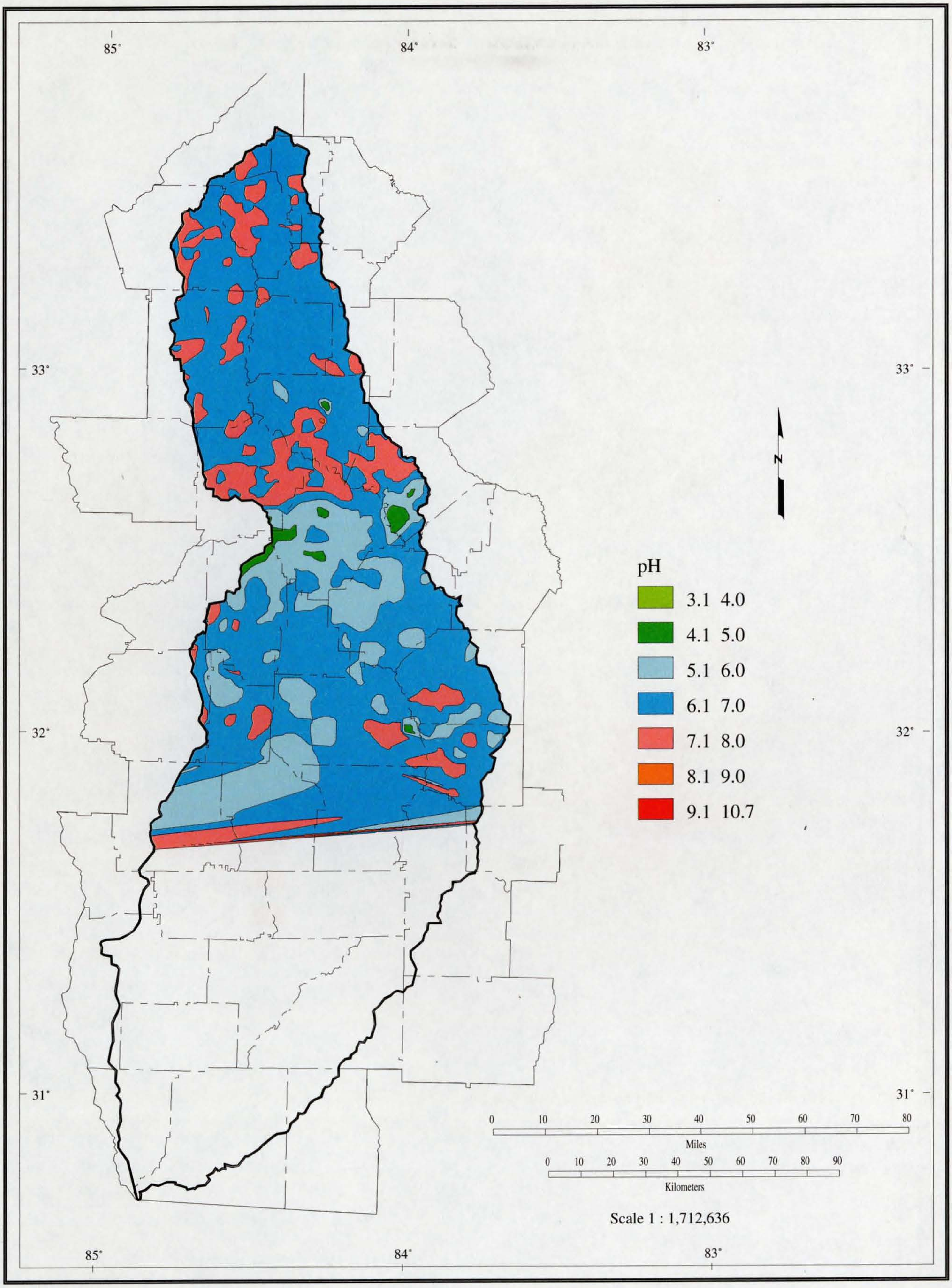

Figure 11. pH of stream water. Absence of data in parts of Webster, Sumter and Crisp Counties may cause contouring artifacts.

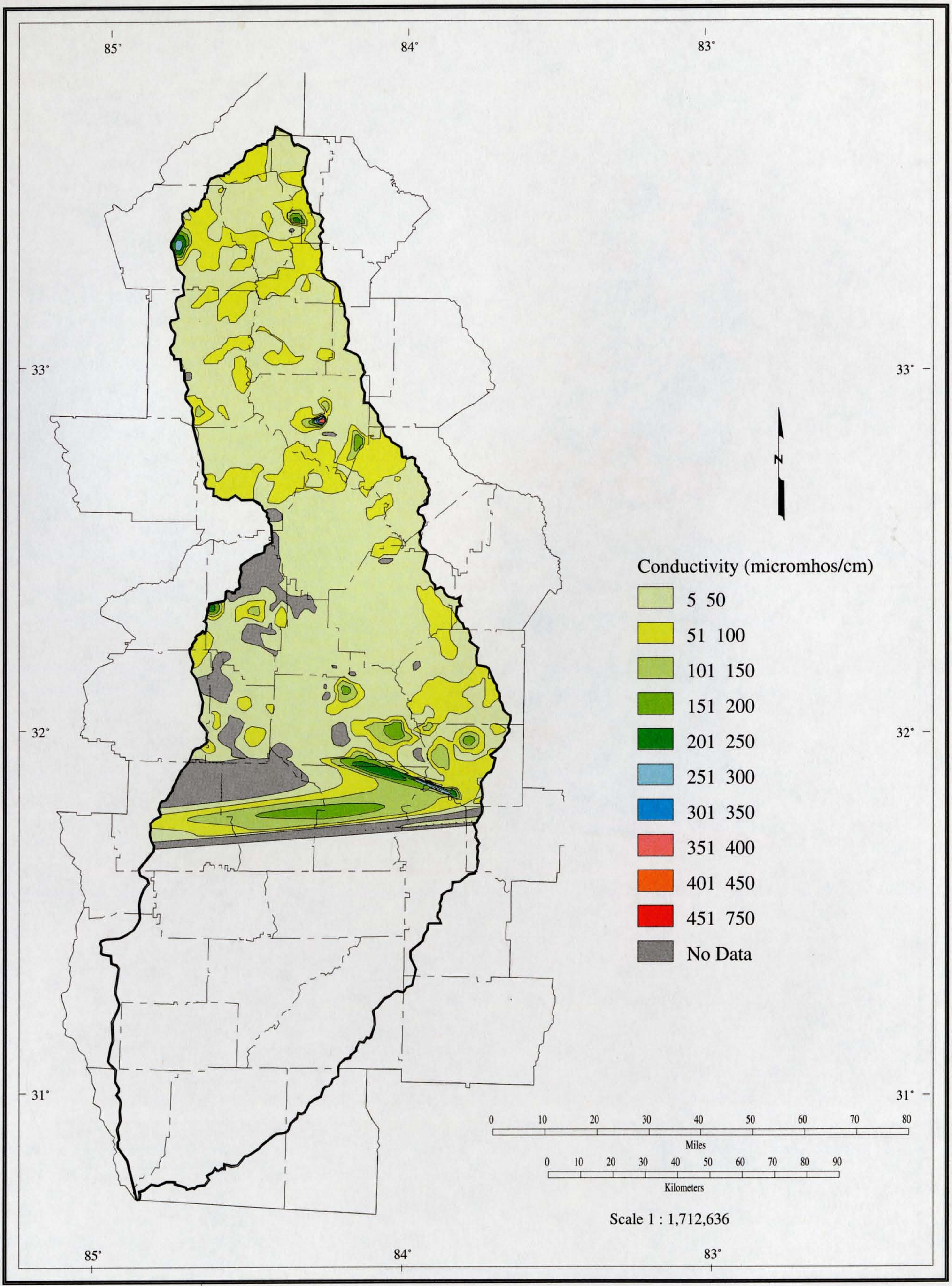

Figure 12. Conductivity of stream water. Absence of data in parts of Webster, Sumter and Crisp Counties may cause contouring artifacts.

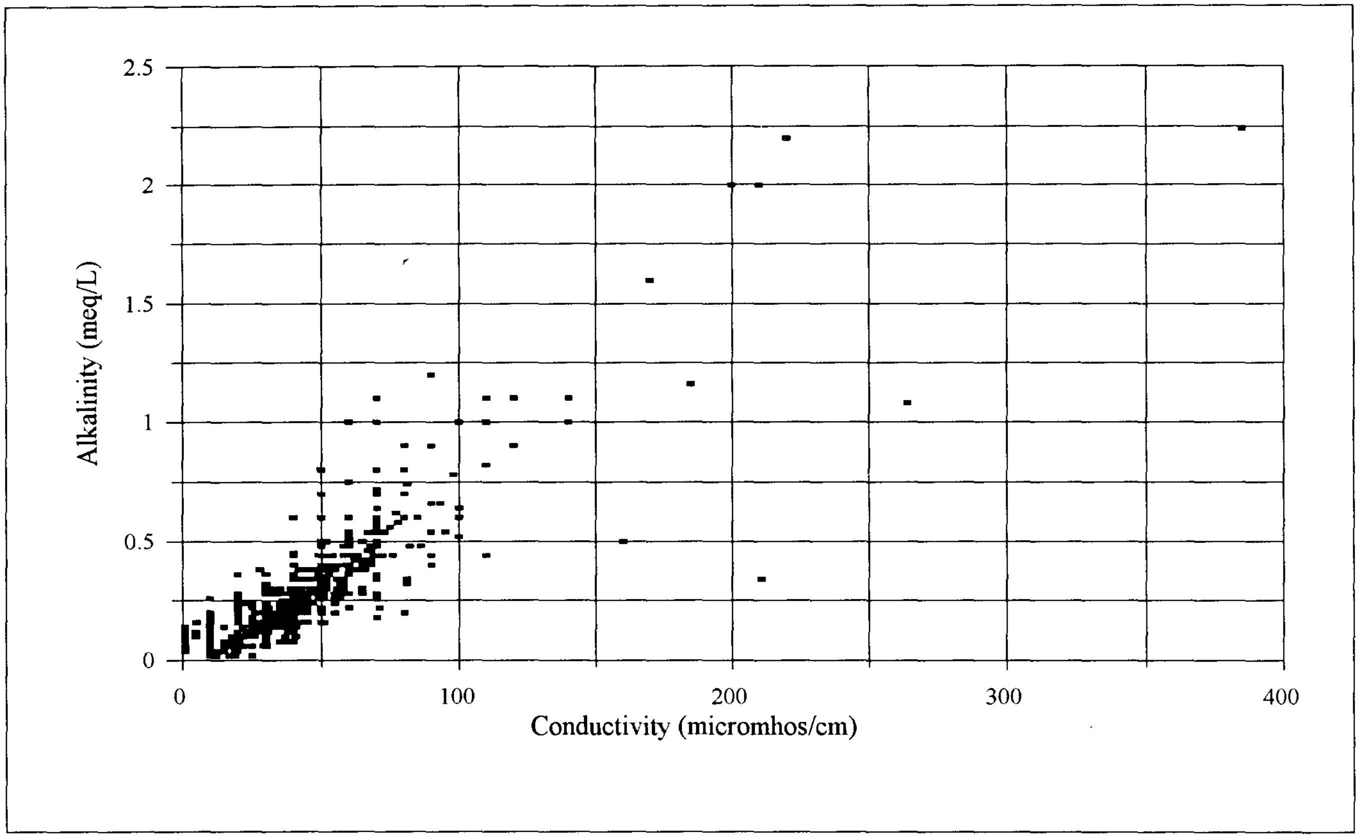

Figure 13. Variation of alkalinity with conductivity.

units are Coastal Plain sandy sediments.

Rock units which contain streams with the highest average conductivities include: *Eo* - Ocala Limestone (62.3 micromhos/cm), *pa2* - sillimanite schist (60.4 micromhos/cm), *fg3* - biotite gneiss (59.3 micromhos/cm), *gg4* - granite gneiss (57.7 micromhos/cm), *Qal* - alluvium (57.6 micromhos/cm), *mm4* - hornblende gneiss (56.6 micromhos/cm), and *bg1* - biotite gneiss (56.5 micromhos/cm), *Eu* - undifferentiated Eocene (53.8 micromhos/cm), *Os* - Suwanee Limestone (53.3 micromhos/cm), and *Nu* - undifferentiated Neogene (50.0 micromhos/cm).

Conductivities of streams in the NURE study that were near anthropogenic activities suggest contamination of those streams. The highest conductivity measured in the Flint River Basin (385 micromhos/cm) is in the vicinity of Thomaston in Upson County. Second highest (264 micromhos/cm) is in the vicinity of Newnan in Coweta County. Highest conductivities in the northern part of the Flint River may be related to discharge from the Atlanta urban area.

### *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 Flint River Basin is 0.3 meq/L with a range of 0.02 to 2.24 meq/L. Alkalinities in the Flint River Basin show a strong positive correlation with conductivity.

Alkalinity of streams within the Flint River Basin may be divided into five principal zones: high alkalinity in the Inner Piedmont, low alkalinity in the Pine Mountain terrane, higher alkalinity in the Uchee terrane (Fig. A-1), low alkalinity in older sediments of the Coastal Plain, and higher alkalinity in younger sediments of the Coastal Plain (Fig. 14).

In the Inner Piedmont terrane, alkalinities are generally 0.2 to 0.5 meq/L (Fig. 14). One stream measured 1.08 meq/L in this area. Streams within the Pine Mountain terrane and over some granitic rocks north of the Towaliga fault zone are generally in the 0.1 to 0.3 meq/L range (Fig. 14). 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 1.16 meq/L. Streams immediately south of the Fall Line have very low alkalinities, generally 0.02 to 0.10 meq/L (Fig. 14). Alkalinities increase further south with values commonly 1.00 to 2.00 meq/L (Fig. 14).

Rock units (Table 1) which contain streams with the lowest average alkalinity (Table 12) include: *Kb* - Blufftown Formation (0.04 meq/L), *Ke* - Eutaw Formation (0.05 meq/L), *Kt* - Tuscaloosa Formation (0.11 meq/L), *um* -ultramafic rocks (0.12 meq/L), *Kcbe* - Cusseta, Blufftown, and Eutaw Formations (0.14 meq/L), *Pnf* - Nanafalia Formation (0.17 meq/L), *fg1*- biotite gneiss (0.18 meq/L), *gg1* - granite gneiss

(0.19 meq/L) and *pms1* - mica schist (0.19 meq/L). Several of these rock units (*Kb, Ke, Kt, Pnf*) are Coastal Plain sandy sediments.

Rock units with the highest average alkalinity include: *Eo* - Ocala Limestone (0.47 meq/L), *mm4* - hornblende gneiss (0.45 meq/L), *Eo-Os* - undifferentiated Eocene - Oligocene residuum (0.40 meq/L), *Qal* - alluvium (0.39 meq/L), *Eu* - undifferentiated Eocene (0.39 meq/L), *bg1* - biotite gneiss (0.39 meq/L ) and *Pcn* - Nanafalia, Porters Creek and Clayton Formations (0.36 meq/L), *pa2* - sillimanite schist (0.34 meq/L), *Ec* - Claiborne undifferentiated (0.32 meq/L), *gg4* - granite gneiss (0.31 meq/L), *Os* - Suwanee Limestone (0.30 meq/L), *gr3* - granite (0.30 meq/L), and *gr1* - granite (0.30 meq/L). Several of these rock units (*Eo, Eo-Os, Eu, Pcn, Ec, and Os*) are Coastal Plain calcareous sediments. The rock units *Eo, Os, Eu, Qal, pa2, gg4, mm4,* and *bg1* also have higher than average conductivities. Higher than average alkalinities appear related to urban centers. Highest alkalinity (2.24 meq/L) in the Flint River Basin is in the vicinity of Thomaston in Upson County. Highest alkalinity (1.08 meq/L) in the Inner Piedmont terrane (Fig. A-1) is in the vicinity of Newnan in Coweta County.

### *Water Temperature*

Recorded temperatures of stream water during sample collection range from 10 to 34° C with an average temperature of 21.8°C. Water temperature did not display any correlation with alkalinity, conductivity or pH. Water temperatures were generally warmer (21-27°C) in the northern part of the Piedmont than in the southern part of the Piedmont (16-24°C). In the Coastal Plain, water temperature was highest (25-34°C) in the southwestern part of the sampled area. This roughly corresponds to the area underlain by Paleocene to Eocene sediments. Rock units with the highest average water temperatures included *Ptu* - Tuscahoma Formation (29.0°C), *Pcn* - Nanafalia, Porters Creek and Clayton Formations (28.1°C), *Eo-Os* - undifferentiated Eocene - Oligocene residuum (26.5°C), *Kr* - Ripley Formation (25.5°C), *Pnf* - Nanafalia Formation (25.2°C) and *pa1* - aluminous schists (25.0°C). In areas underlain by Cretaceous (18-24°C) and Miocene/Neogene (10-24°C) sediments, water was generally cooler. An explanation for these regional differences in water temperature is beyond the scope of this study, because supporting data are not available or were not collected at that time. As the data were generally collected during the summer months, seasonal differences in temperature are probably not a factor. Differences in the volume of runoff water versus ground water supplied to the streams may affect the water temperatures. Those differences may be influenced by such factors as geology, relative precipitation, relief, land use, and vegetation.

## Discussion of Stream and River Hydrogeochemistry

The Flint 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.

Acidity of ground water and surface water, as measured by its pH, is strongly influenced by several factors including: 1) composition of rocks and sediments with which the water is in contact, 2) permeability of the rock or sediments, 3) amount of organic activity; 4) flow rate of the ground water or surface water, 5) temperature, and 6) precipitation. Weathering of sulfides causes a decrease in pH while weathering of carbonates and silicates will increase pH. Carbonates and silicates buffer the naturally weak acidity of rain water. Certain types of contamination may also influence pH.

The composition of rocks and sediments influences the pH of water during chemical weathering. Major factors that facilitate chemical weathering include: solution, hydration, oxidation, and hydrolysis. As in the Oconee River Basin (Cocker, 1996b) and Chattahoochee River Basin (Cocker, 1998), solution and hydrolysis of carbonates and hydrolysis of silicates may be the principal factors controlling pH of surface waters in the Flint 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 $H_4SiO_4$. Hydrolysis of silicates may involve carbonic acid in addition to water. Solution or hydrolysis of carbonates and hydrolysis of silicates produce 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. Carbonate minerals generally react with acidic solutions at a faster rate than silicate minerals. Carbonate minerals may be abundant in silicate rocks because of low-grade metamorphism or hydrothermal alteration. Hydrolysis of mafic silicate minerals such as olivine, amphiboles, pyroxenes, epidote, calcium-bearing feldspars, and biotite occurs at a faster rate than hydrolysis of felsic silicate minerals such as quartz and sodium- or potassium-bearing feldspars. Water in contact with mafic silicates may 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.

LeGrand (1958) identified two characteristic types of ground water in North Carolina that are derived from crystalline bedrock. One type is a soft, slightly acidic water

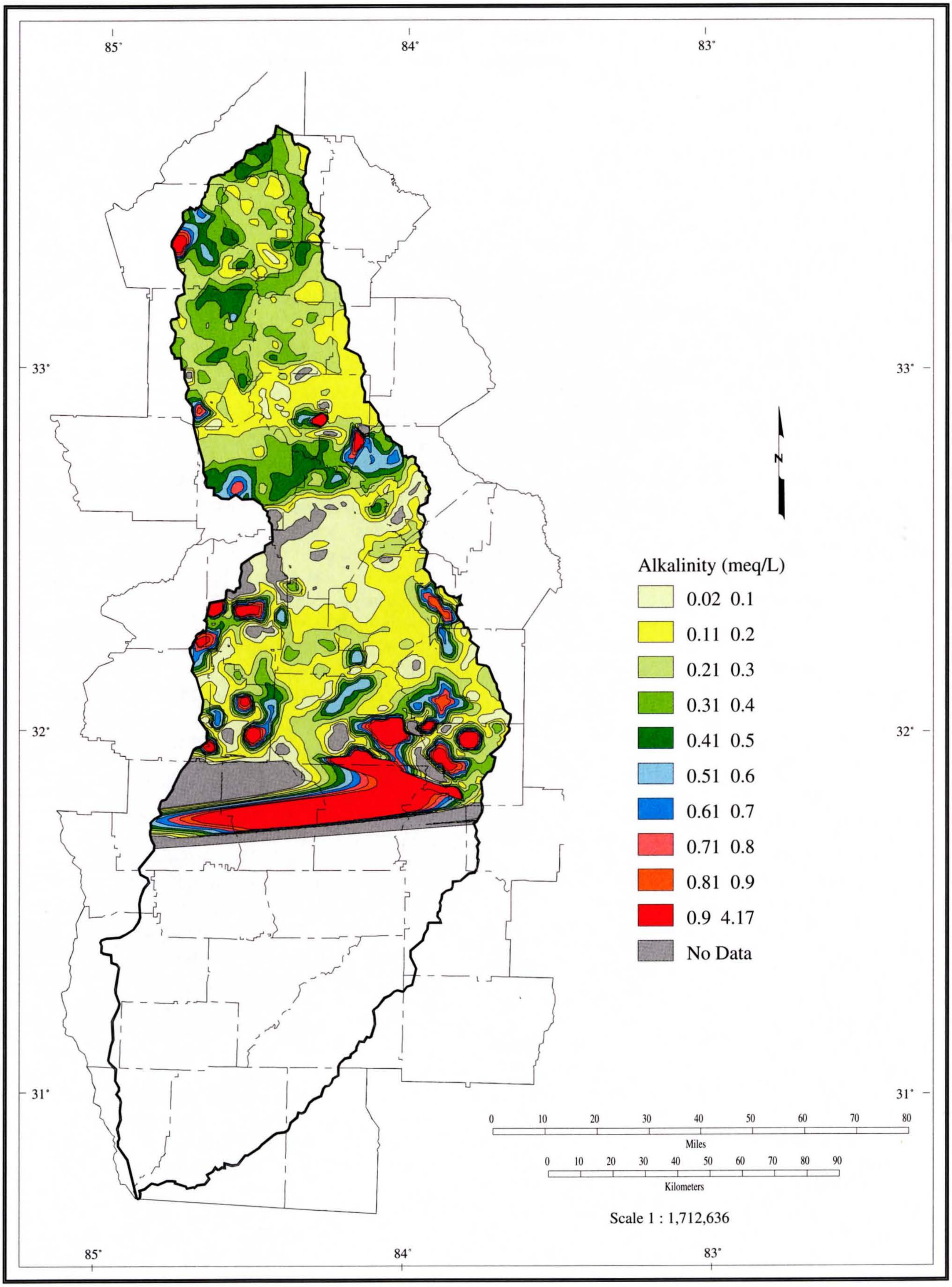

Figure 14. Alkalinity of stream water. Absence of data in parts of Webster, Sumter and Crisp Counties may cause contouring artifacts.

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 the other dissolved constituents. Ground water from granitic rocks contains 5 ppm calcium, 35 ppm bicarbonate, 75 ppm dissolved solids and is thus 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, 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.

Within the Flint River Basin, carbonate-rich rocks occur in the southern part of the Coastal Plain and as small units within the Pine Mountain terrane. Carbonate-rich rocks are principally located in the Paleocene, Eocene, Oligocene, and Miocene strata. Carbonate minerals may be present as bands or layers of carbonate, or as disseminated secondary carbonate minerals in metavolcanics, metavolcaniclastic rocks, ultramafic and mafic rocks (Cocker, 1996b). Within the Flint River Basin, carbonate-poor silicate rocks are prevalent in the Inner Piedmont, 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 the poorly cemented quartzose sands on the Coastal Plain, allow a relatively rapid flow of water. Therefore, such rocks have little effect 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 Flint River Basin. Decaying organic matter tends to increase the acidity of the water. Decaying organic matter, organic respiration, and the dissolution of carbonate rocks are the main sources of carbonate and bicarbonate ions in ground water (Driscoll, 1986). Organic activity also increases the amount of carbon available to form carbonic acid and therefore increases 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. Low correlation coefficients suggest that temperature did not greatly affect pH in the Flint River Basin.

The rate of water flow through or over rocks and sediments will determine how much time water can react with rocks or sediments. A high flow rate generally results in the pH remaining about the same as rain water. As noted earlier, average pH of precipitation in Georgia has declined from 5.6 in 1955 to 4.5 in 1980. In areas with a high flow rate, an increase in precipitation will shift the pH toward the pH of rainwater. The area south of the Fall Line with pH values as low as 4.1 is underlain by permeable sandy sediments. Flow rates through these sediments should be high and pH should be low, approaching that of rainwater. Flow rates will also affect how long decaying vegetation remains in contact with the water. In areas of low flow rates and high organic matter content, an increase in precipitation may raise pH. Effects of precipitation on pH in Flint River Basin streams cannot 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 has 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.

LeGrand (1958) found that ground water derived from dioritic rocks in North Carolina had significantly higher conductivities than ground water derived from granitic rocks. In that study, ground water in dioritic rocks contained a total of 269 ppm dissolved solids versus 75 ppm dissolved solids for ground water in granitic rocks. Major cations in the dioritic waters were calcium (49 ppm), magnesium (12 ppm), and sodium plus potassium (14 ppm). Major cations in the granitic water were calcium (5 ppm), magnesium (2 ppm), and sodium plus potassium (7 ppm). Median pH is 7.1 for dioritic water and 6.5 for granitic water (LeGrand, 1958).

Streams with high alkalinity, conductivity and pH are primarily located south of the Goat Rock fault zone. Such streams generally correlate with metavolcanic and metavolcaniclastic rocks. Within the Carolina terrane, streams with the highest alkalinity, conductivity and pH generally correlate with ultramafic and mafic rocks such as serpentinites, norites, gabbros, diorites (Cocker, 1996b). Streams within predominantly metasedimentary rocks of the Inner Piedmont terrane have lower pH, conductivity and alkalinity. Streams within the Inner Piedmont that have higher pH, conductivity and alkalinity may have some local lithologic (metavolcanic?) control.

Measurements of pH in the Piedmont of the Flint River Basin range from 6.9 to 7.7 and are in relative agreement with those for 50,701 samples for the entire Piedmont of the eastern

United States (Briel, 1997). Mean pH for those samples was 7.2, and the pH for the 25th to 75th percentile was 6.8 to 7.5. Compared to conductivities reported by Briel (1997), conductivities in the Flint River Basin are significantly lower than the mean of 228 michromhos/cm for 53,795 samples in the eastern United States Piedmont, and the 20 to 185 michromhos/cm in the Flint River Basin compares with the 37 to 141 range for the 5th to 50th percentile in the eastern United States Piedmont. Median alkalinity reported for 24,242 stream samples in the Piedmont is 34 mg/L and average alkalinities in counties within the Flint River Basin appear to range from 6.5 to 34.2 mg/L (Briel, 1997). Mean alkalinities for Piedmont streams within the Flint River Basin in the NURE sampling range from 0.12 to 0.45 meq/L. Conversion of these NURE values from meq/L to mg/L yields a range of 6 to 22 mg/L which fall within the range of data shown by Briel (1997).

The relatively high pH and alkalinities in Macon, Dooly, Crisp, Sumter, Webster and Marion Counties may reflect the influence of Tertiary carbonate rocks in those areas. Increased pH, alkalinities, conductivities, and total dissolved solids in the lower (southern) part of the Flint River (Cherry, 1961) result from reaction of surface and ground waters with those carbonate rocks (Couch and others, 1996). The increase in dissolved solids in the southern part of the Flint River is due to include calcium, magnesium, and bicarbonate are (Cherry, 1961).

## 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 (i.e., aluminum), and several other metals (i.e., iron, manganese) which are not defined as heavy minerals. These other metals were included, because they may influence the distribution of heavy metals in the sediments and water.

### *Aluminum (Al)*

As in the Oconee River Basin (Cocker, 1996b) and Chattahoochee River Basin (Cocker, 1998) stream sediments in the Coastal Plain of the Flint River Basin are distinctly different in aluminum content from sediments in the Piedmont (Fig. 15). Concentrations of aluminum in most Coastal Plain stream sediments are generally less than 20,000 ppm, and in the Piedmont, aluminum concentrations are generally greater than 20,000 ppm. Average aluminum concentration in the Flint River Basin is 28,123 ppm with a maximum of 124,000 ppm and a minimum of 2,400 ppm. Rock units (Table 1) with the lowest average aluminum (Table 12) include: *Kb* - Blufftown Formation (4,866 ppm), *Ptu* - Tuscahoma Sand (9,738 ppm), *Kr* - Ripley Formation (10,340 ppm), *Ke* - Eutaw Formation (11,160 ppm), *Kp* - Providence Sand (12,779 ppm), *Kt* - Tuscaloosa Formation (13,667 ppm), *Pcn* - Nanafalia, Porter Creek and Clayton Formations (14,600 ppm), *Nu* - undifferentiated Neogene (14,800 ppm), *Eu* - undifferentiated Eocene (14,820 ppm), and *Pnf* - Nanafalia Formation (15,746 ppm). These are all Coastal Plain sedimentary formations. Highest aluminum concentrations (80,000 ppm to 124,000 ppm) in Coastal Plain stream sediments occur in Marion, Webster, Sumter, Dooly, Taylor, and Crisp Counties (Fig. 15). This areas correspond approximately with areas underlain by *Kc* - Cusseta Sand, *Ec* - Claiborne Formation, and *Eo-Os* - undifferentiated Eocene and Oligocene residuum.

Rock units (Table 1) with the highest mean aluminum (Table 12) include: *mm5* - hornblende - biotite gneiss (52,200 ppm), *pa1* - aluminous schist (51,800 ppm), *um* - ultramafic rocks (51,600 ppm), and *gr1b* - porphyritic granite (51,320 ppm) , *gg4* - granite gneiss (50,720 ppm), *fg3* - biotite gneiss (45,400 ppm), *gr1* - granite (43, 925 ppm), and *mm2* - hornblende gneiss (42,075 ppm). The majority of these rock units are mafic and granitic rocks. These concentrations are similar to the high median concentrations (Table 7) in crustal mafic (76,300 ppm) and granitic rocks (73,300 ppm). Aluminum is generally highest (greater than 25,000 ppm) in the northern part of the Flint River Basin that is north from Meriwether and Pike Counties. Higher concentrations (greater than 50,000 ppm) are spatially coincident with *gr1b* - porphyritic granite, *mm2* - hornblende gneiss, *mm5* - hornblende - biotite gneiss, *gg4* - granite gneiss and *pms3a* - mica schist. Aluminum is generally low (7,500 ppm to 35,000 ppm) in the Pine Mountain terrane (Fig. 43). Higher aluminum (generally 25,000 ppm to 50,000 ppm) occurs in the Uchee terrane. Aluminum has a relatively good correlation with magnesium, manganese, pH, iron, potassium, sodium, cobalt, vanadium, barium, and scandium (Tables 13, 14).

### *Barium (Ba)*

Barium analyses are limited to stream sediments in Fulton, Clayton, Fayette, Spalding, Pike, Meriwether, Crawford, and part of Coweta Counties in the Flint River Basin (Fig. 16). Average barium concentration in the Flint River Basin is 40 ppm with a maximum of 323 ppm and a minimum of 3 ppm. Of the 17 rock units that contain samples analyzed for barium, highest average barium (Table 12) was found in rock units: *gr1* - granite (68.1 ppm), *fg1* - biotite gneiss (53.7 ppm), *pa1* - aluminous schist (43.0 ppm), *pms3a* - mica schist (42.9 ppm), *fg3* - biotite gneiss (42.2 ppm), and *bg1* - biotite gneiss (41.1 ppm). Lowest barium concentrations (Table 12) were found in *gr1b* - porphyritic granite (11.5 ppm), *Qal* - alluvium (13.0 ppm), *Kcbe* - Cusseta, Blufftown and Eutaw Formations (14.8 ppm), *q1* - quartzite (18.3 ppm), and *Eu* - undifferentiated Eocene (20.0 ppm). Because very

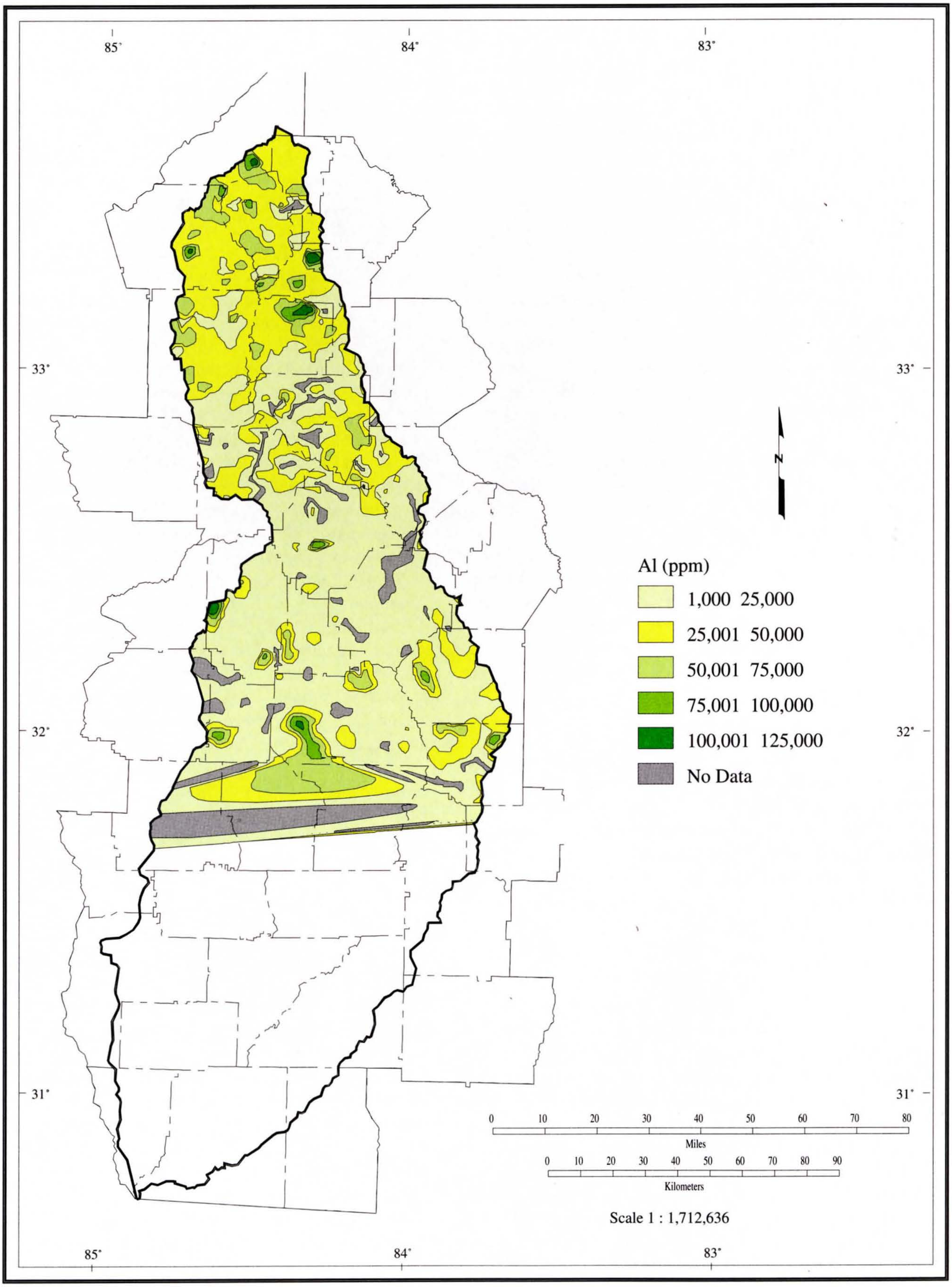

Figure 15. Aluminum in stream sediments. Absence of data in parts of Webster, Sumter and Crisp Counties may cause contouring artifacts.

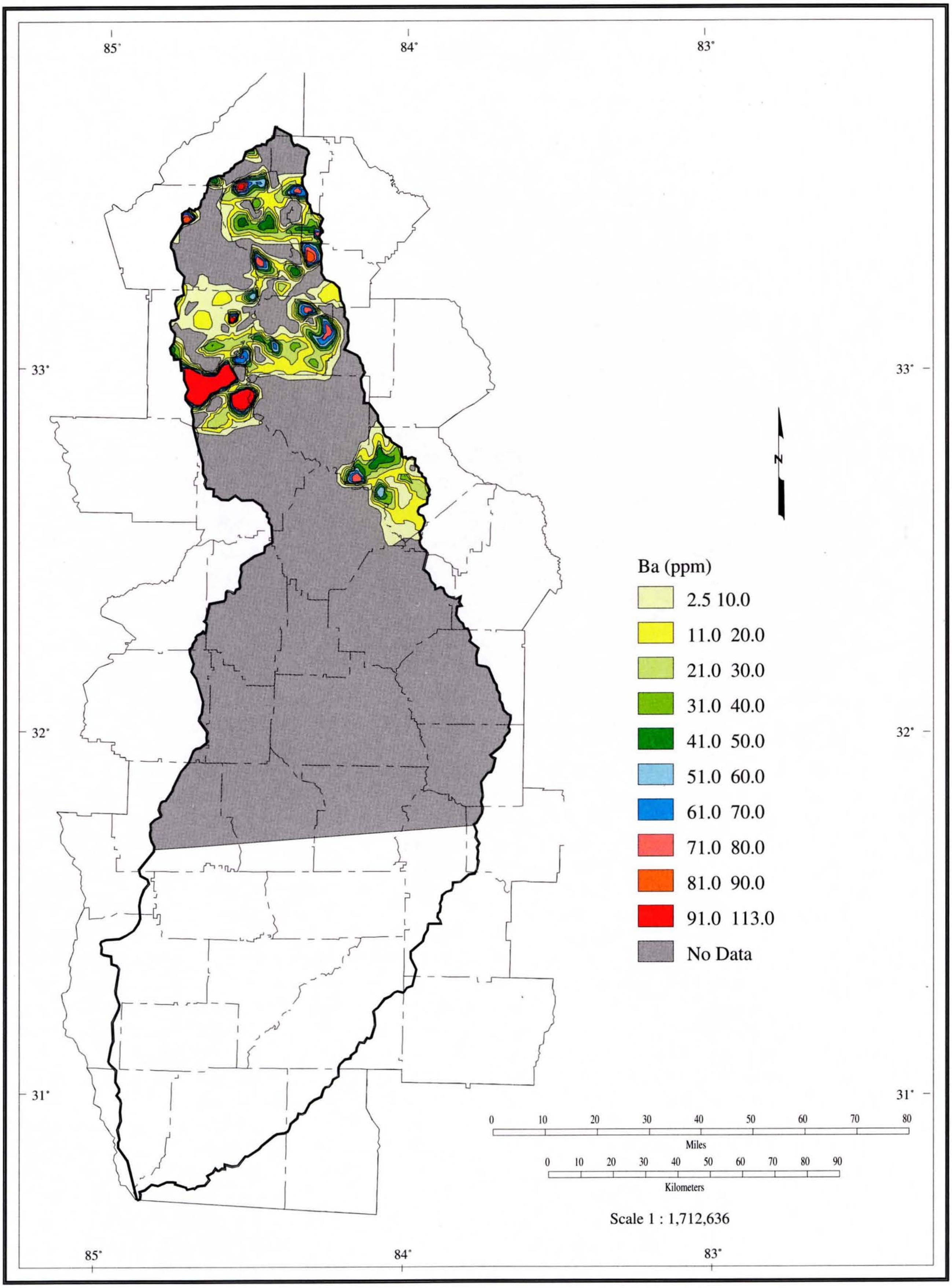

Figure 16. Barium in stream sediments.

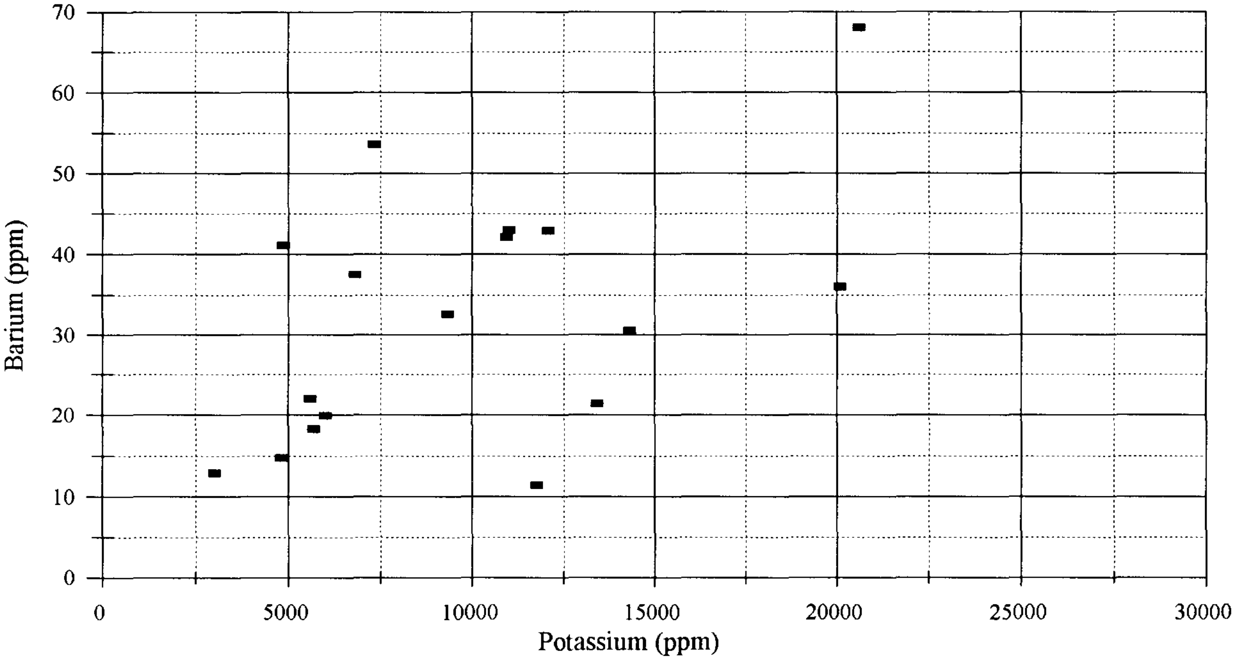

Figure 17. Variation of barium with potassium. A plot of average compositions per rock unit.

few analyses for barium are found in *gr1b* and the Coastal Plain sediments, these samples may not be representative.

High barium (138 to 323 ppm) is sporadically associated with *gr1* - granite in Meriwether County (Fig. A-2). High barium is associated with *bg1* - biotite gneiss (Fig. A-4) in the Pine Mountain terrane in Meriwether County (40 to 80 ppm) and in the Uchee terrane (158 to 215 ppm). High barium concentrations (40 to 98 ppm) are scattered through the Piedmont.

Correlation coefficients for barium were highest with nickel (0.6924) (Table 14). There is no known mineral association that would produce this correlation. Barium appears to correlate to some degree with potassium (Fig. 17) and may reflect the substitution of barium for potassium in potassic feldspars. The low number of samples with both barium and potassium analyses (n=16) does not lend to either statistically reliable correlations or to meaningful data plots. Highest mean concentrations of barium in average crustal rocks (Table 7) are in granite (840 ppm), shale (550 ppm) and mafic rocks (330 ppm) (Rose and others, 1979).

### *Beryllium (Be)*

Primary sources for beryllium in stream sediments in the Piedmont are probably granites (Table 7) and pegmatites that contain the beryllium-bearing mineral beryl. The beryllium content of stream sediments in the Flint River Basin ranges from below the detection limit of 0.5 ppm to 3.0 ppm. Average beryllium concentration in the Flint River Basin is 0.8 ppm. High beryllium concentrations (up to 3 ppm) are found in Coweta County, generally associated with *pa2* - sillimanite schist and *mm9* - amphibolite (Fig. 18). Regional trends in the contoured data are not immediately apparent on the map of the Flint River Basin. Spatial correlation with granitic rocks (Fig. A-2) suggests that the primary sources for beryllium are granitic rocks and pegmatites. Sporadic high beryllium concentrations (1 to 2.5 ppm) that are found in an area extending northeast from Marion County through Pike County and into Spalding County are generally coincident with *gr1* - granite and a northeast trend in high potassium concentrations (10,000 to 43,000 ppm). High beryllium concentrations (1 to 2.5 ppm) in Fayette and Clayton Counties occur with *fg3* - biotite gneiss and *gg4* - granite gneiss.

Rock units (Table 1) with the lowest mean beryllium content (Table 12) include: *Kcbe* - Cusseta, Blufftown and Eutaw Formations (0.34 ppm), E*u* - undifferentiated Eocene (0.50 ppm), *um* - ultramafic rocks (0.50 ppm), and *Kt* - Tuscaloosa Formation (0.52), *bg1* - biotite gneiss (0.52), and *q1*- quartzite (0.53 ppm). Rock units (Table 1) with the highest mean beryllium content (Table 12) include: *gr3* - granite (2.50 ppm), *gr1b* - porphyritic granite (1.45 ppm),

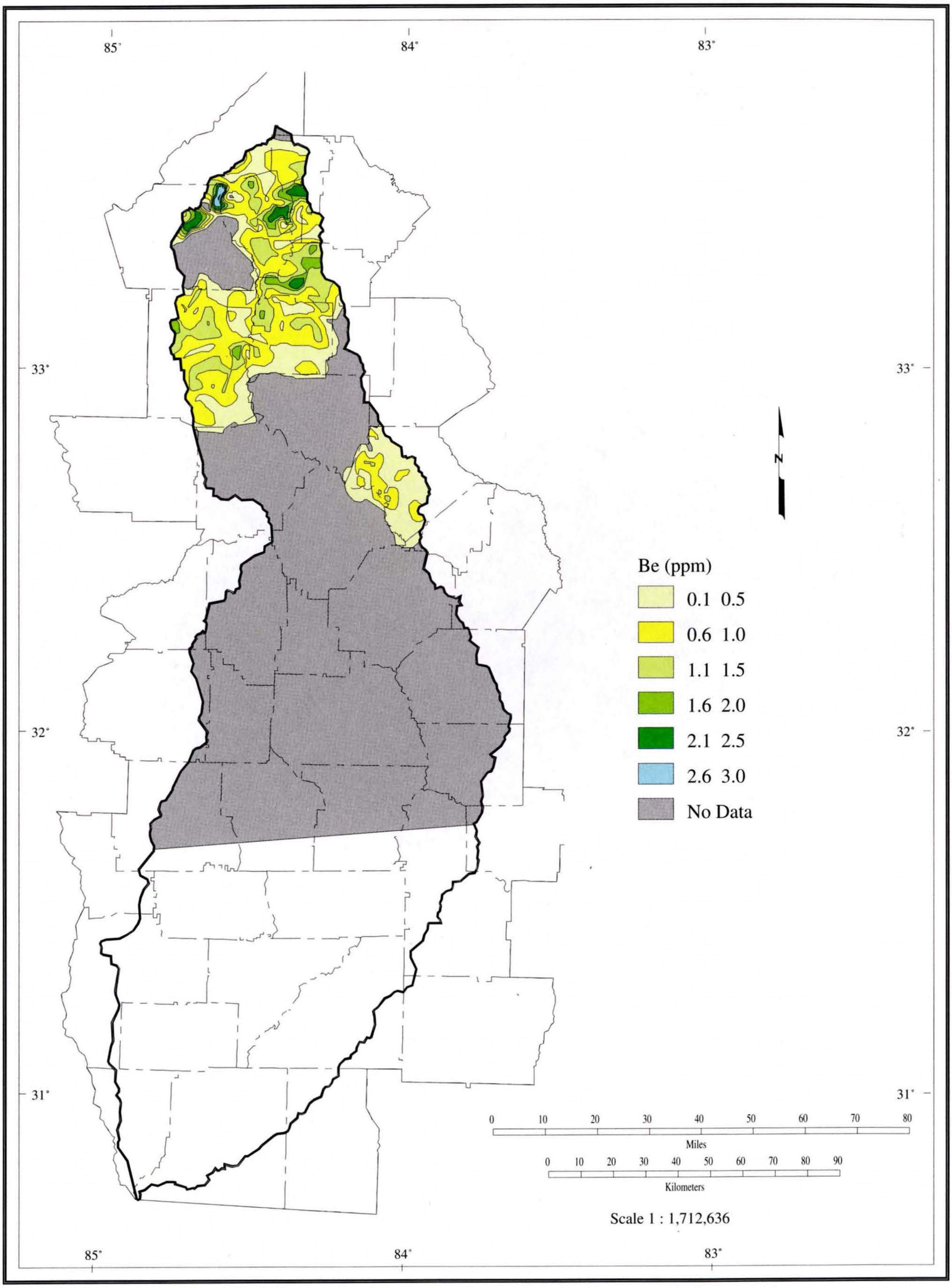

Figure 18. Beryllium in stream sediments.

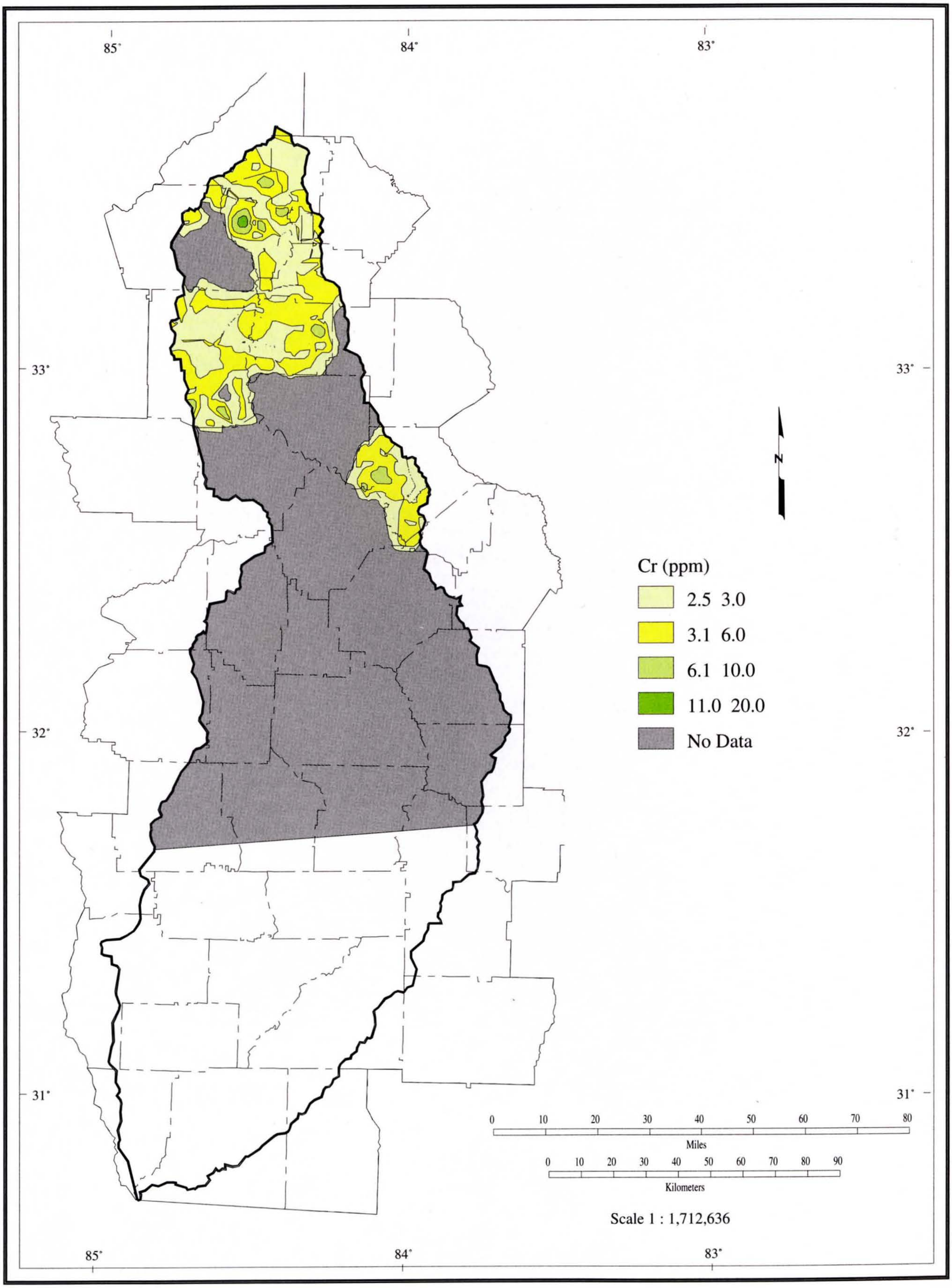

Figure 19. Chromium in stream sediments.

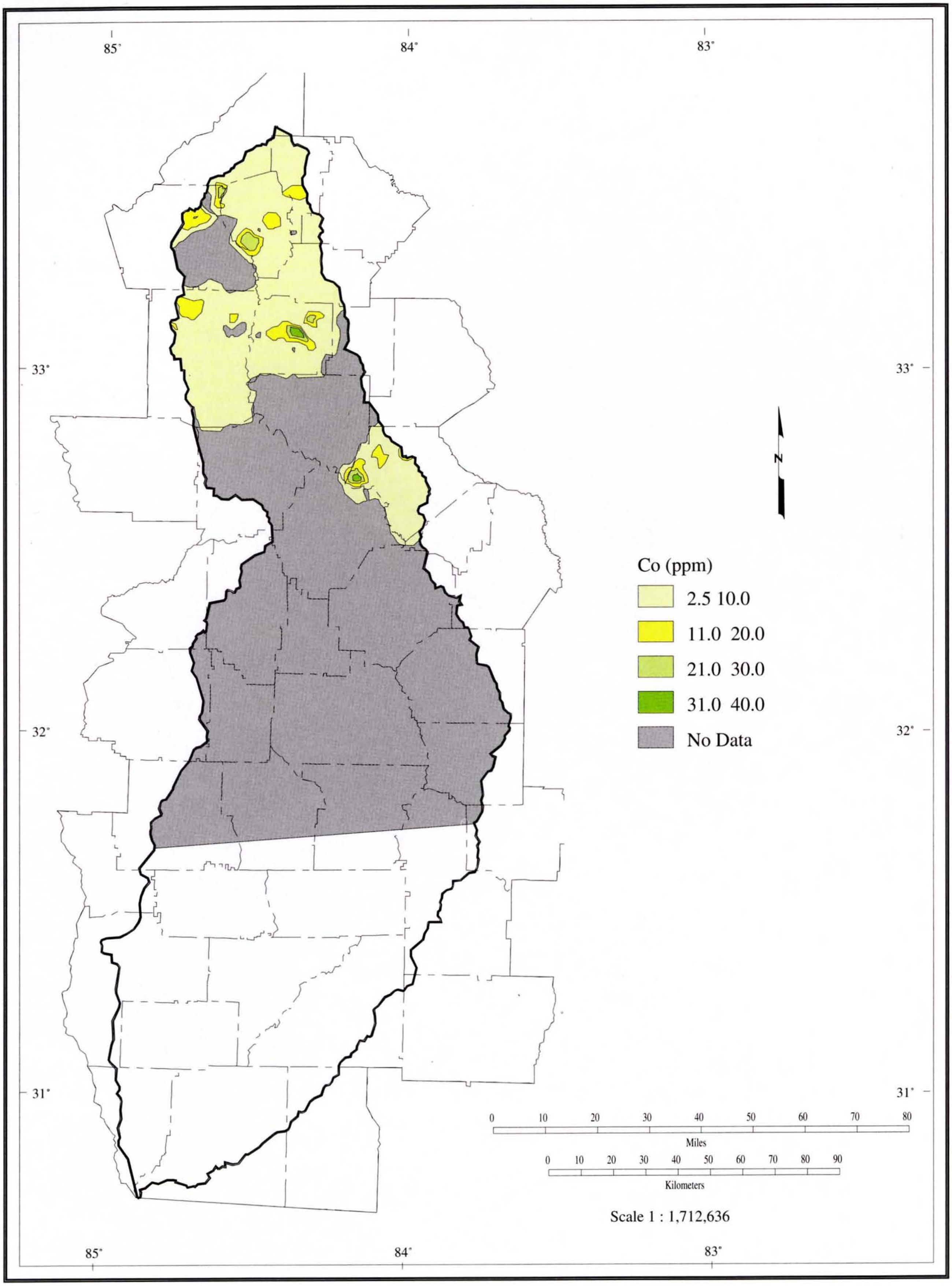

Figure 20. Cobalt in stream sediments.

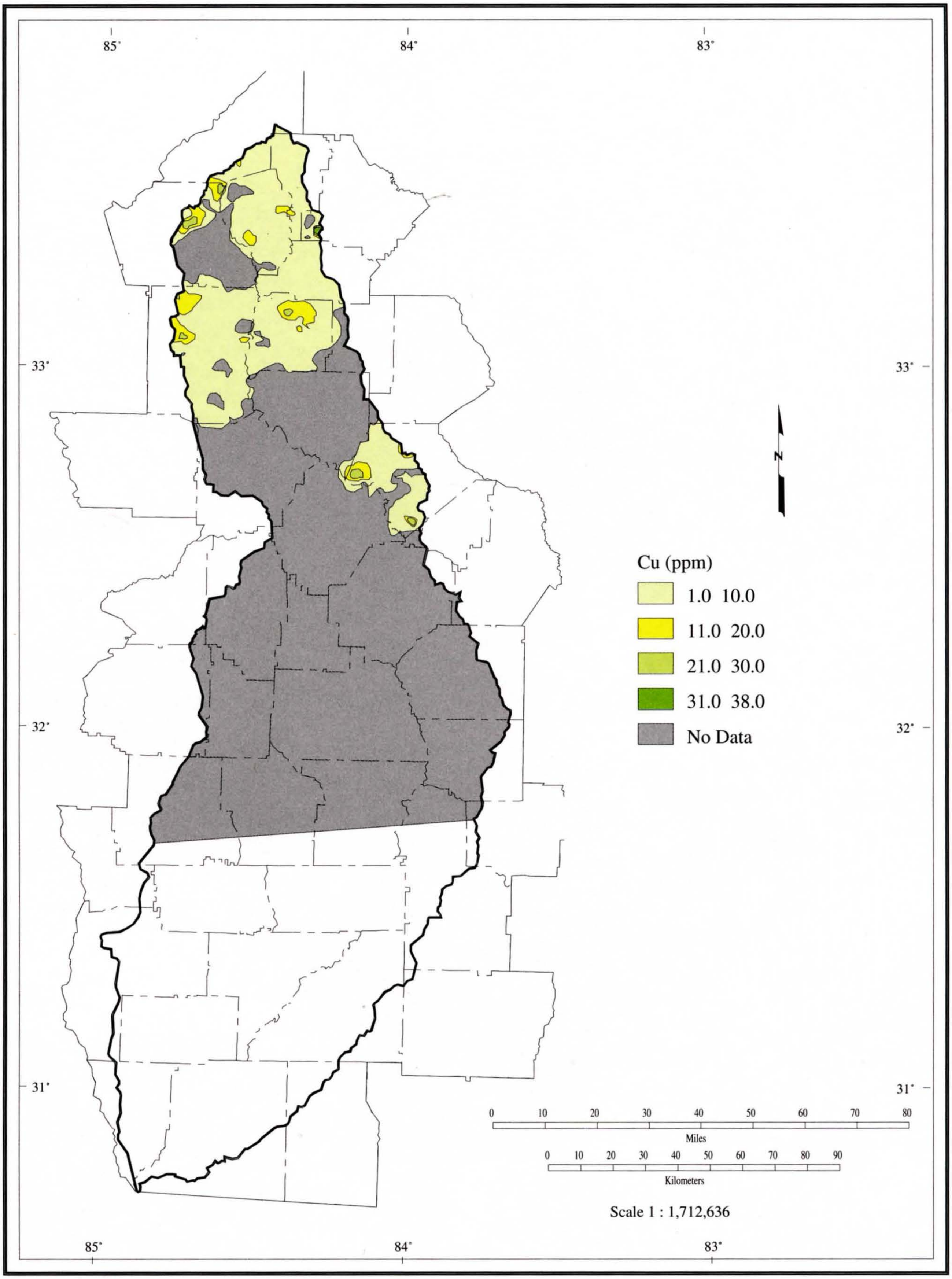

Figure 21. Copper in stream sediments.

*mm2* - (1.09 ppm), *fg3* - biotite gneiss (1.05 ppm), *pa1* - (1.00 ppm), *gr1* - granite (0.94 ppm), and *mm5* - hornblende - biotite gneiss (0.93 ppm). The concentration of beryllium in average crustal granitic rocks and shale (3 ppm, Table 7) is consistent with the higher beryllium values measured in granitic rocks in the Flint River Basin. High beryllium in gneisses and schists may be related to beryl-bearing pegmatites in or near those rock units. Beryllium has the highest correlations with cobalt and potassium in the Flint River Basin (Table 14). The spatial coincidence with high potassium concentrations was noted above.

## *Chromium (Cr)*

Primary sources for chromium are ultramafic rocks and, to a lesser extent, amphibolites and shales. Median crustal concentrations (Table 7) for these rock types 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 hosts may include chromium-bearing muscovite and fuchsite, a chromium mica commonly associated with volcanogenic gold deposits. Relatively good spatial correlation of chromium with many of the ultramafic occurrences in Georgia or fault-related trends suggest that chromium anomalies may be used to identify and locate poorly exposed ultramafic rocks.

Chromium analyses are only available for Fulton, Clayton, Fayette, Spalding, Pike, Meriwether, Crawford, and part of Coweta Counties in the Flint River Basin (Fig. 19). Average chromium concentration in the Flint River Basin is 3.5 ppm with a maximum of 11 ppm and a minimum of 2.5 ppm (half of the detection limit of 5 ppm). Rock units (Table 1) with the lowest average values (Table 12) include: *Eu* - undifferentiated Eocene (3.0 ppm), *gr3* - granite (3.0 ppm), *pa1* - aluminous schist (3.0 ppm), *Qal* - alluvium (3.0 ppm), *mm2* - hornblende gneiss (3.0 ppm), *fg1* - biotite gneiss (3.0 ppm), and *q1* - quartzite (3.0 ppm). Rock units (Table 1) with the highest average chromium (Table 12) include: *um* - ultramafic rocks (6.0 ppm), *mm5* - hornblende-biotite gneiss (4.3 ppm), *pms1* - mica schist (4.1 ppm), *pa2* - sillimanite schist (3.9 ppm), and *bg1* - biotite gneiss (3.8 ppm). High chromium values in Fayette County are spatially associated with the occurrence of ultramafic rocks (Fig. A-2). Several higher chromium values (up to 11 ppm) are spatially associated with *pms1* - mica schist in Fayette County (Fig. A-7). The source of the chromium may be nearby unidentified ultramafic rocks or chromium-rich mica in the schist. Other chromium values are too scattered and relatively low to relate to a particular rock unit. A comparison with Coastal Plain sediments in the Oconee River Basin and further to the east suggests that scattered anomalous chromium may be related to heavy mineral deposits in the Coastal Plain.

## *Cobalt (Co)*

Natural sources of cobalt include ultramafic rocks (110 ppm), amphibolites (48 ppm), and shales (19 ppm) (Table 7) (Rose and others, 1979). Cobalt analyses are only available for Fulton, Clayton, Fayette, Spalding, Pike, Meriwether, Crawford, and part of Coweta Counties. Average cobalt concentration in the Flint River Basin is 6 ppm with a maximum of 38 ppm and a minimum of 2.5 ppm (half of the detection limit of 5 ppm). Stream sediments that are principally within Coweta and adjacent parts of Fulton Counties contain 10 to 23 ppm cobalt (Fig. 20). Natural rock unit sources for the cobalt south of Atlanta are not readily apparent from the state geologic map. Rock units (Table 1) with average cobalt concentrations below the detection limit of 5 ppm (Table 12) include: *Qal* - alluvium (2.5 ppm), *Kt* - Tuscaloosa Formation (2.5 ppm), *q1* - quartzite (2.9 ppm), and *Kcbe* - Cusseta, Blufftown, and Eutaw Formations (3.0 ppm). Highest cobalt concentrations (Table 12) are in rock units: *gr1b* - porphyritic granite (11.5 ppm), *pa2* - sillimanite schist (10.6 ppm), and *gr3* - granite (10.0 ppm). Anomalous cobalt concentrations (25 to 38 ppm) occur as scattered anomalies in Fayette, Coweta, Pike and Crawford Counties. Some of the anomalies in Crawford County are coincident with copper and nickel anomalies. Anomalous cobalt in Coweta County may be spatially related to *pa2* - sillimanite schist. As noted above, high cobalt concentrations may be expected in ultramafic rocks and metamorphosed shales (schists).

No cobalt analyses are available for Coastal Plain stream sediments in the Flint River Basin. A comparison with Coastal Plain sediments in the Oconee River Basin and further to the east suggests that scattered anomalous cobalt may occur in association with heavy mineral deposits in Cretaceous to Eocene sedimentary formations.

Cobalt shows a relatively good correlation with vanadium, manganese, pH, copper, beryllium, and aluminum (Table 14). The association with aluminum, vanadium, and manganese suggests some lithologic controls on cobalt. Cobalt may also be adsorbed on manganese oxides.

## *Copper (Cu)*

Natural sources of copper (Table 7) include ultramafic rocks (42 ppm), mafic rocks (72 ppm) and shales (42 ppm) (Rose and others, 1979). Within the Flint River Basin, copper analyses are only available for Fulton, Clayton, Fayette, Spalding, Pike, Meriwether, Crawford, and part of Coweta Counties. Average copper concentration in the Flint River Basin is 5 ppm with a maximum of 39 ppm and a minimum below the detection limit of 2 ppm. Within the Flint River Basin, stream sediments generally contain less than 10 ppm copper (Fig. 21).

Rock units (Table 1) with the lowest copper content (Table 12) include: *Kt* - Tuscaloosa Formation (1.3 ppm), *q1* - quartzite (1.8 ppm), *um* - ultramafic rocks (2.0 ppm), and *Qal* - alluvium (3.0 ppm). Rock units with the highest copper content (Table 12) include: *pa1* - aluminous schist (10.0 ppm), *gr1b* - porphyritic granite (9.3 ppm), *gr3* - granite (8.0 ppm), and *pa2* - sillimanite schist (8.0 ppm). Rocks with the highest copper content are aluminous schists, which may be due to high copper concentrations in the protolith (shale) for these rocks (Rose and others, 1979). Scattered anomalous copper (21 to 29 ppm) is found in western Henry County, western Meriwether County, northern Pike County and western Crawford County. Most of these anomalous copper occurrences do not appear directly related to a particular rock unit.

Copper shows a good correlation with zinc and cobalt (Table 14) which suggests the presence of base-metal sulfides in the stream sediments. The correlation with aluminum (Tables 13, 14) may be related to copper or base-metal mineralization in aluminous schists.

## *Lead (Pb)*

Lead analyses are only available for Fulton, Clayton, Fayette, Spalding, Pike, Meriwether, Crawford, and part of Coweta Counties in the Flint River Basin. Average lead concentration in the Flint River Basin is 7.3 ppm with a maximum of 25 ppm and a minimum of 5 ppm (half of the detection limit of 10 ppm). Rock units with the lowest lead (5 ppm) include: *q1* - quartzite, *pa1* - aluminous schist, *um* - ultramafic rocks, *gr3* - granite, and *fg1* - biotite gneiss. Fourteen of the analyzed rock units had average lead below the detection limit of 10 ppm (Table 12). Rock units with the highest average lead (Table 12) include: *Eu* - undifferentiated Eocene (15.0 ppm), *gr1b* - porphyritic granite (10.8 ppm), *mm2* - hornblende gneiss (10.3 ppm), and *Kcbe* - Cusseta, Blufftown and Eutaw Formations (10.2 ppm). Highest lead concentrations are found in Coweta, Fayette, Spalding, and Pike Counties (Fig. 22). Sources of these anomalies are presently unidentified. An elongate lead anomaly oriented to the northeast into the central part of Coweta County appears to be spatially coincident with a lead anomaly in alluvium noted by Hurst and Long (1971). That lead anomaly (Hurst and Long, 1971) is also coincident with elongate copper, manganese, cobalt, and zinc anomalies in the NURE data. Coincidence of multi-element anomalies from different surveys suggests some base-metal mineralization may be present.

Anomalous lead in stream sediments may be derived from granitic rocks, shales or sandstones that have median crustal concentrations of 18 ppm, 25 ppm, and 10 ppm, respectively (Table 7). Some anomalous lead in these rocks may be in potassium-feldspars.

## *Nickel (Ni)*

Nickel analyses are only available for Fulton, Clayton, Fayette, Spalding, Pike, Meriwether, Crawford, and part of Coweta Counties in the Flint River Basin. Average nickel concentration in the Flint River Basin is 5.2 ppm with a maximum of 31 ppm and a minimum below the detection limit of 5 ppm. Concentrations of nickel in stream sediments within the Flint River Basin are generally less than 10 ppm, and most of those samples contain less than the detection limit of 5 ppm.

Rock units (Table 1) with less than the detection limit of 5 ppm nickel (Table 12) include: *Qal* - alluvium (3.0 ppm), *um* - ultramafic rocks (3.0 ppm), *Eu* - undifferentiated Eocene (3.0 ppm), *gr3* - granite (3.0 ppm), *Kt* - Tuscaloosa Formation (3.2 ppm), *q1* - quartzite (3.3 ppm), *gr1b* - porphyritic granite (3.5 ppm), *Kcbe* - Cusseta, Blufftown and Eutaw Formations (3.8 ppm), *fg3* - biotite gneiss (3.9 ppm), *gg4* - granite gneiss (4.1 ppm), and *mm2* - hornblende gneiss (4.1 ppm). Rock units with the highest average nickel content (Table 12) include: *fg1* - biotite gneiss (10.3 ppm), and *pa2* - sillimanite schist (7.3 ppm). Distribution of nickel may be related to rock composition, with higher values correlative with the distribution of ultramafic and amphibolitic rock units (Figs. A-2, A-5). High nickel concentrations in Meriwether and Pike Counties (Fig. 23) correspond roughly with parts of *gr1* - granite (Fig. A-2), *pa2* - sillimanite schist (Fig. A-8), *fg1* - biotite gneiss (Fig. A-and *pms3a* - mica schist. High concentrations of nickel (10 to 31 ppm) are found in western Crawford, Pike, Meriwether, Fayette and Spalding Counties. The highest concentration of nickel (31 ppm) is located in Crawford County and is spatially related to high copper and cobalt. As discussed in the Oconee River Basin study (Cocker, 1996b), scattered and isolated nickel anomalies may be present in Coastal Plain sediments, perhaps associated with concentrations of heavy minerals.

Natural sources of nickel are commonly ultramafic rocks, and to a lesser extent, amphibolites and shales with median crustal concentrations of 2000 ppm, 130 ppm, and 68 ppm, respectively (Table 7 and Rose and others, 1979). Strongest correlations for nickel are with barium, titanium, silver and manganese (Table 14). These correlations do not appear to reflect natural mineral associations.

## *Silver (Ag)*

Silver analyses are only available for Fulton, Coweta, Clayton, Fayette, Spalding, Pike, Meriwether and Crawford Counties in the Flint River Basin (Fig. 24). Average silver concentration in the Flint River Basin is 0.26 ppm with a maximum of 3.0 ppm and a minimum of 0.05 ppm. Most stream sediments within the Flint River Basin contain less than 0.30 ppm silver.

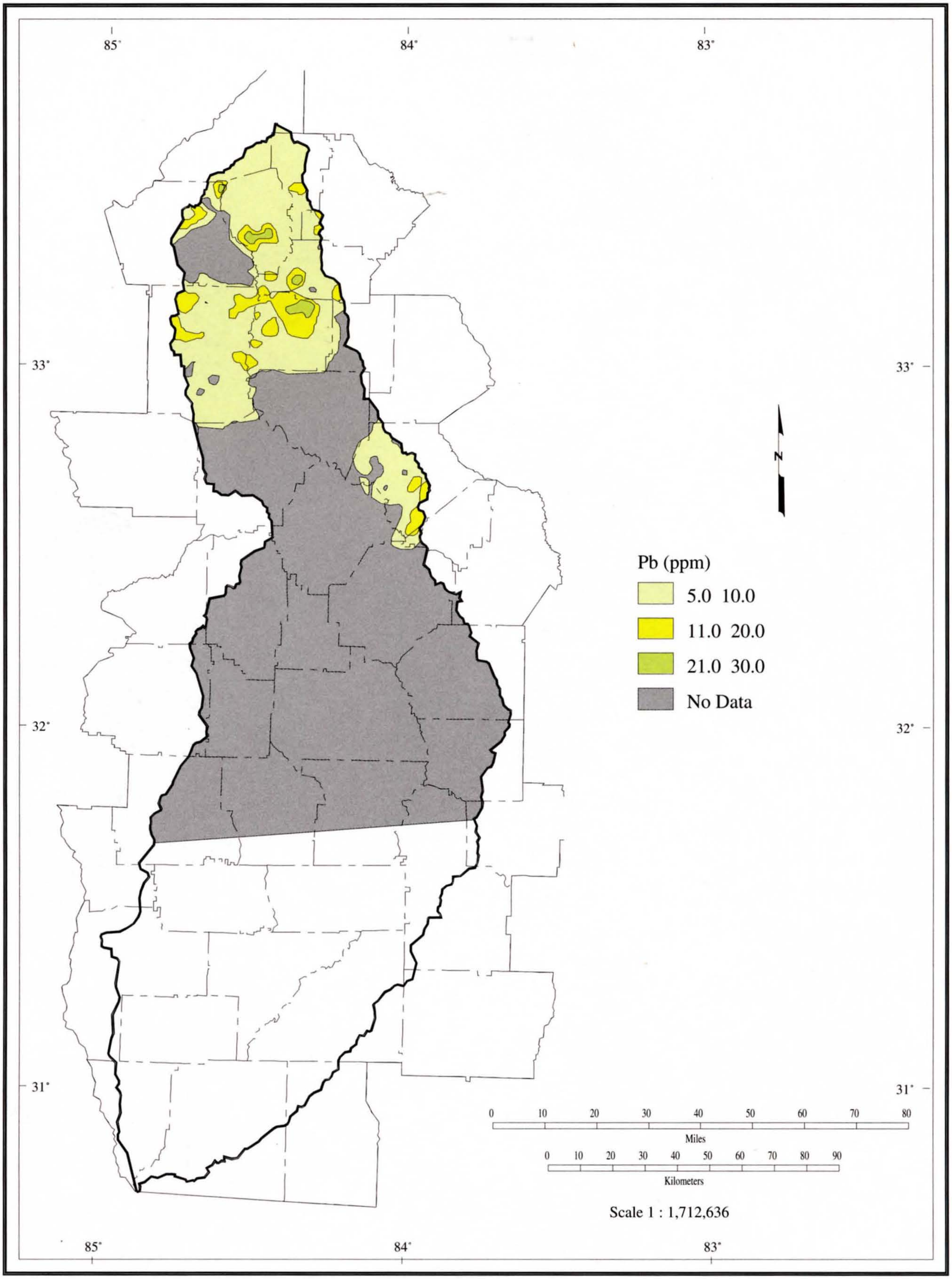

Figure 22. Lead in stream sediments.

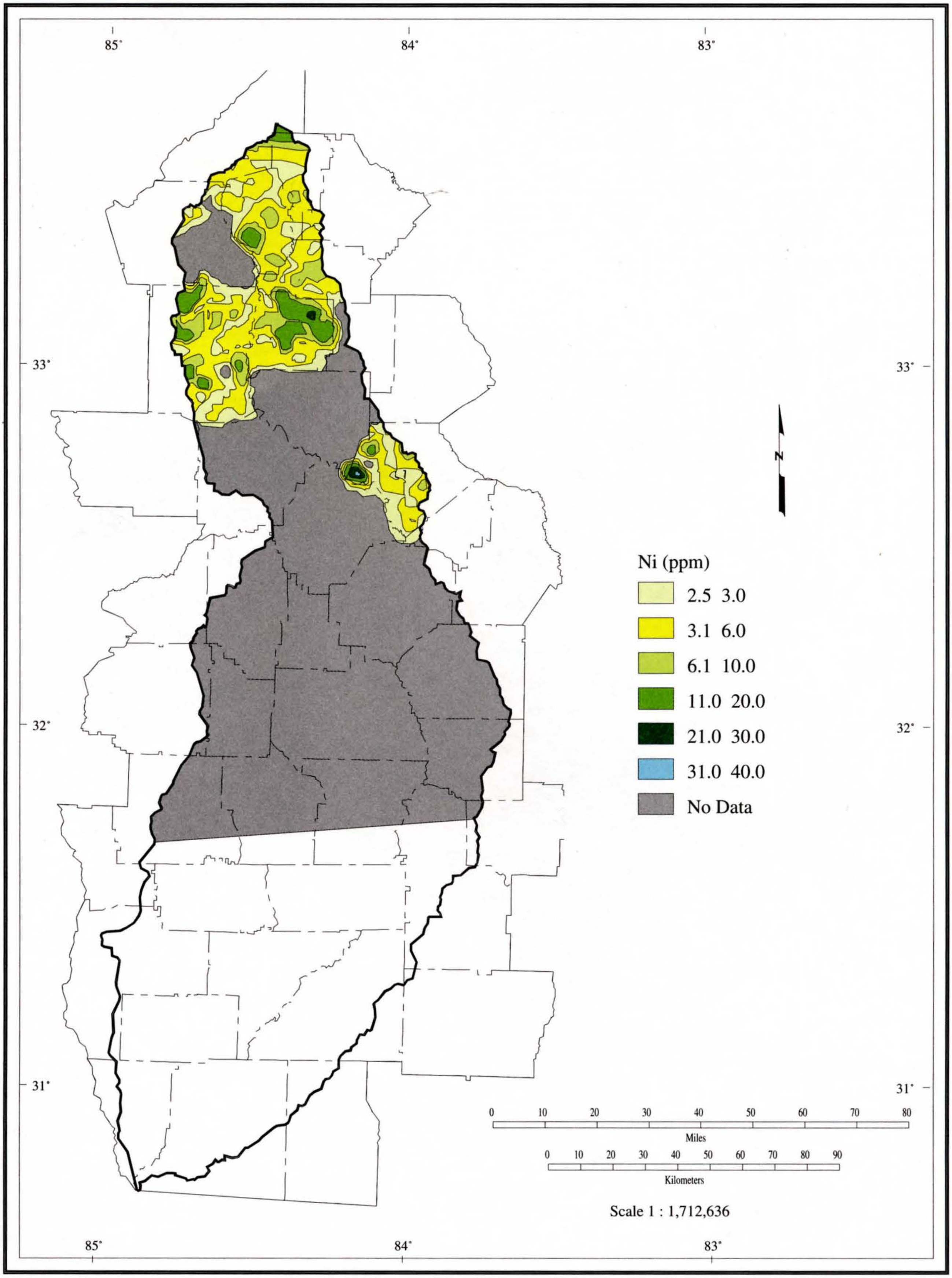

Figure 23. Nickel in stream sediments.

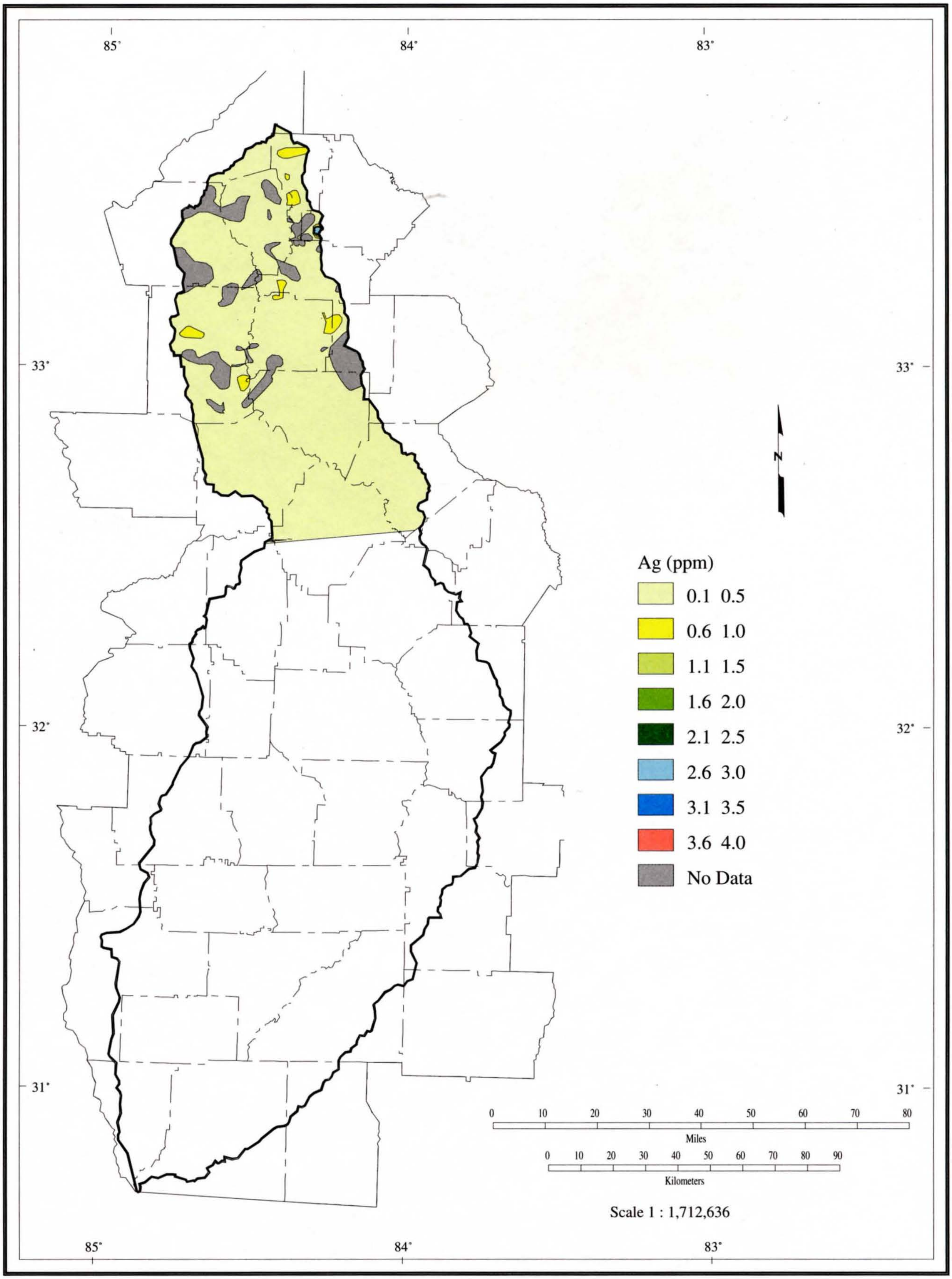

Figure 24. Silver in stream sediments.

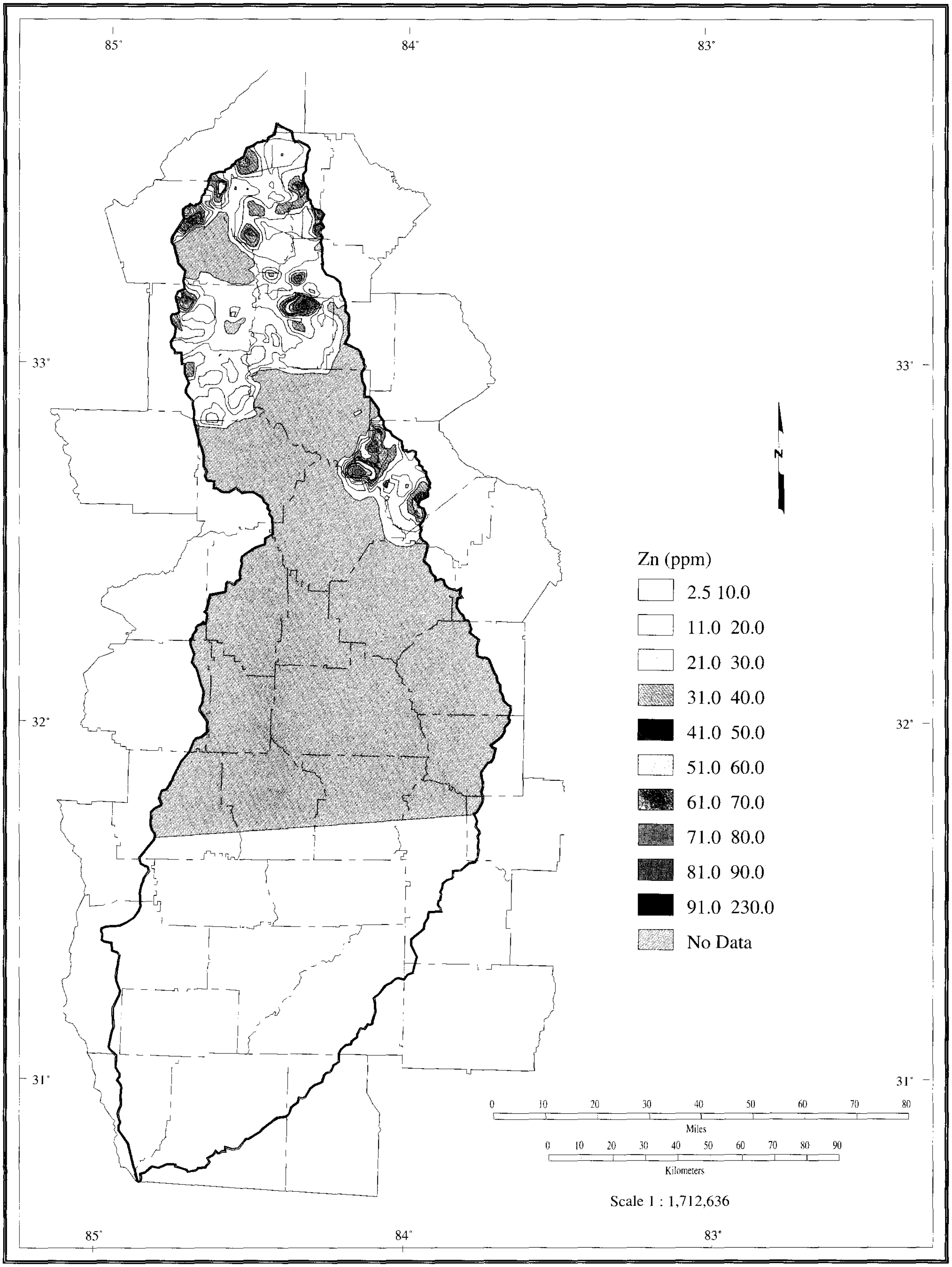

Figure 25. Zinc in stream sediments.

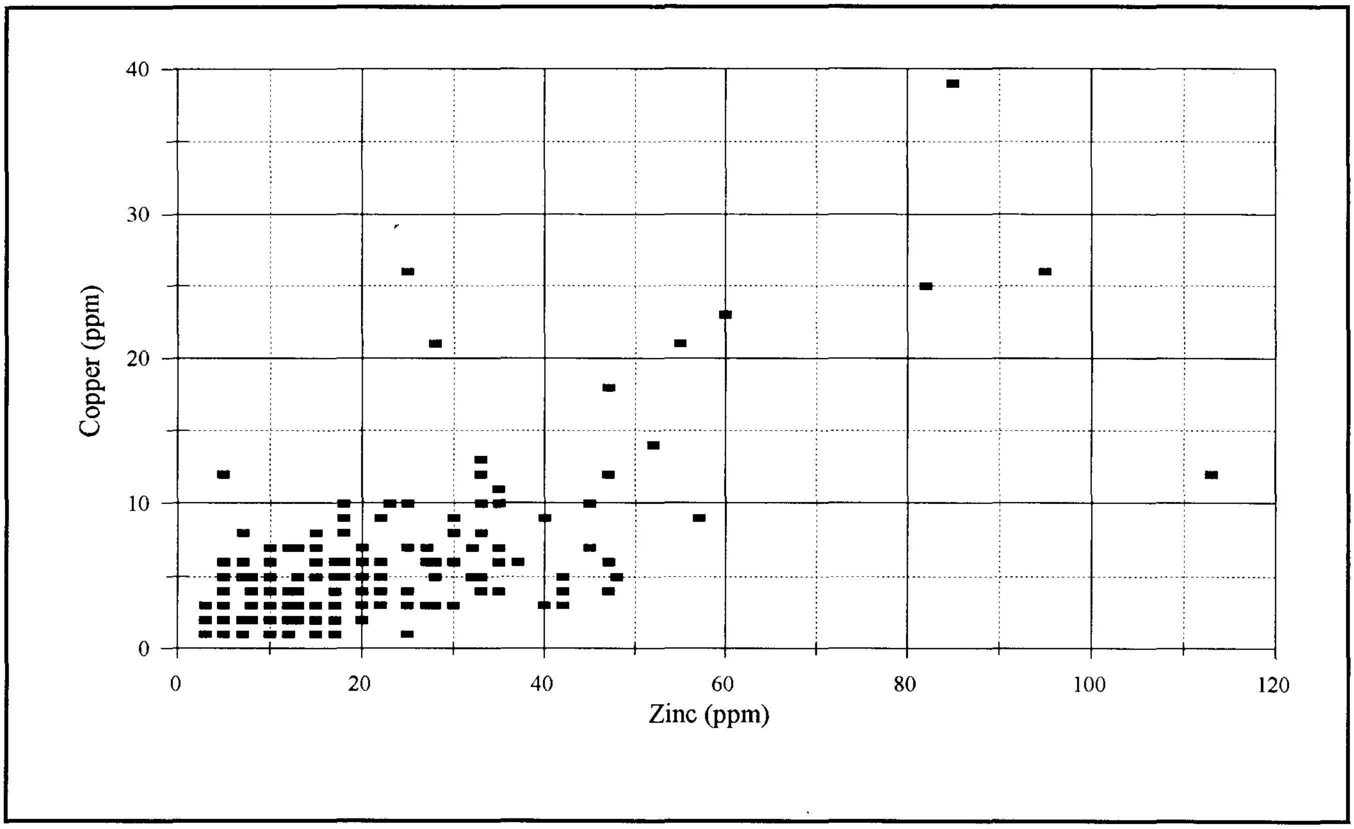

Figure 26. Variation of copper with zinc. A plot of average compositions per rock unit.

Rock units with the highest silver concentrations (Table 12) are: *fg1* - biotite gneiss (0.47 ppm), and *pa1* - aluminous schist (0.40 ppm). Lowest silver concentrations are in rock units: *um* - ultramafic rocks (0.10 ppm), *gr3* - granite (0.10 ppm), gr1b - porphyritic granite (0.15 ppm), and *mm2* - hornblende gneiss (0.16 ppm). Highest silver concentration (3.0 ppm) is spatially associated with biotite gneiss - *fg3* in Henry County (Fig. 51). The strongest correlation of silver is with nickel (Table 18).

### *Zinc (Zn)*

Zinc analyses are only available for Fulton, Coweta, Clayton, Fayette, Spalding, Pike, Meriwether, and Crawford Counties in the Flint River Basin. Average zinc concentration in the Flint River Basin is 19.1 ppm with a maximum of 113 ppm and a minimum of 2.5 ppm (half of the detection limit of 5 ppm).

Rock units (Table 1) with the lowest zinc content (Table 12) include: *um* - ultramafic rocks (10.0 ppm), *q1* - quartzite (10.3 ppm), *gr1* - granite (13.4 ppm), *pms3a* - mica schist (15.1 ppm), *Kt* - Tuscaloosa Formation (15.8 ppm), and *mm2* - hornblende gneiss (15.9 ppm). Rock units with the highest zinc content (Table 12) include: *Eu* - undifferentiated Eocene (42.0 ppm), *bg1*- biotite gneiss (35.5 ppm), and *gr3* - granite (30.0 ppm). High zinc concentrations are found in Crawford, Pike, Clayton, and Coweta Counties (Fig. 25). A northeast-trending anomaly in south Fulton and Coweta Counties contains up to 95 ppm zinc. A zinc anomaly in Meriwether County is an extension of a zinc anomaly identified in the Chattahoochee River Basin (Cocker, 1998). This anomaly is spatially correlative with *pa2* - sillimanite schist and *mm9* - amphibolite. High zinc concentrations, up to 113 ppm, in northern Pike County and scattered anomalies up to 40 ppm lie along a northeast trend of *pms3a* - mica schist that extends into Meriwether County. Zinc contents of sedimentary units in the Coastal Plain are expected to be low as in the case of the Oconee River Basin (Cocker, 1996b).

Mafic rocks and shales may be important sources of zinc in stream sediments as suggested by median crustal concentrations of 94 ppm and 100 ppm, respectively (Rose and others, 1979). Strongest correlation of zinc is with copper (Table 14 and Fig. 26).

### *Iron (Fe)*

Iron has an important influence on water quality and provides important information regarding the effects of lithology on water quality. The direct effect of iron on water quality is its tendency to form iron oxide or iron hydroxide crusts that may cause the precipitation or absorption of heavy metals. Iron is soluble under acidic and reducing conditions and insoluble under alkaline and oxidizing conditions. Increased oxidation may change the iron from dissolved ferrous iron to semisolid ferric iron. This transformation commonly results in the precipitation of iron coatings. Precipitation of iron bicarbonate will also form coatings. Precipitation of iron causes the coprecipitation of other metals.

Iron bacteria such as Crenothrix, Gallionella, and Leptothrixbacteria 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.

The amount of iron in stream sediments is an indication of the abundance of iron-bearing minerals. Iron compounds are probably the most important inorganic reducing agents. Organic-free waters 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 as well as 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).

Average iron concentration in the Flint River Basin is 23,903 ppm with a maximum of 154,000 ppm and a minimum of 2,500 ppm. Low iron content in stream sediments in the upper Coastal Plain (Fig. 27) correlates spatially with streams that have very low pH. 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 14 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 25,000 ppm (Fig. 28). With stream pH below 6.1, iron is less than 15,000 ppm. Highest iron concentrations in stream sediments are in streams with a pH of 6.5 to 7.1. 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 12) include: *Kt* - Tuscaloosa Formation (7,088 ppm), *Kb* - Blufftown Formation (7,283 ppm), *Ke* - Eutaw Formation (9,114 ppm), *Nu* - undifferentiated Neogene (9,500 ppm), *Kcbe* - Cusseta, Blufftown and Eutaw Formations (10,060 ppm), *Kr - Ripley Formation* (10,469 ppm), *Ptu* - Tuscahoma Sand (12,975 ppm), *Pcn* - Nanafalia, Porters Creek and Clayton Formations (13,043 ppm), *Kc* - Cusseta Sand (13,852 ppm), *Kp* (14,021 ppm), and *q1* - quartzite (14,254 ppm). Most of these rock units are Coastal Plain sandy sediments. As in the Oconee and Chattahoochee river basins (Cocker, 1996b; 1998), Coastal Plain stream sediments in the Flint River Basin, particularly sandy sediments where stream pH is low, generally contain the lowest amount of iron (Fig. 27). The highest iron concentration (154,000 ppm) is in Sumter County. High iron concentrations in Sumter, Marion, and Webster Counties appear to be underlain by the Clairborne Formation (Ec).

In the Piedmont, the highest iron concentration is found in Meriwether County and is underlain by mica schist (*pms3a*). Rock units (Table 1) with the highest iron content (Table 12) include: *mm5* - hornblende-biotite gneiss (47,300 ppm), *gr4* - charnockite (44,550 ppm), *pa2* - sillimanite schist (37,992 ppm), *pms3* - mica schist (37,100 ppm), *mm2* - hornblende gneiss (35,771 ppm), *pms3a* - mica schist (33,783 ppm), and *gg1* - granite gneiss (33,604 ppm). Most of these rock units are schistose or amphibolitic. Two bands of moderately high iron (25,000 to 112,000 ppm) extend across the northern side of the Pine Mountain terrane and through the Uchee terrane. The southern band correlates with *bg1* - biotite gneiss. The band in the Pine Mountain terrane correlates with *bg1* - biotite gneiss, *gr4* - charnockite, and *pms3*, and *pms3a* - mica schists. Irregular areas of high iron (25,000 to 125,000 ppm) in the northern part of the Flint River Basin are coincident with *pa2* - sillimanite schist, *pms3a* - mica schist, *mm9* -amphibolite, and *fg3* - biotite gneiss.

Strongest correlations for iron are with titanium, vanadium, scandium, and manganese (Tables 13, 14). 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, and copper.

## *Magnesium (Mg)*

Magnesium analyses are only available for Fulton, Clayton, Fayette, Spalding, Pike, Meriwether, and Crawford Counties in the Flint River Basin (Fig. 29). Rock units with the highest concentrations of magnesium in the stream sediments (Table 12) include: *um* - ultramafic rocks (2,400 ppm), *pa1* - aluminous schist (2,300 ppm), *mm5* - hornblende - biotite gneiss (1,933 ppm) *pms1* - mica schist (1,794 ppm), *pms3a* - mica schist (1,736 ppm), and *gg4* - granite gneiss (1,717 ppm). These concentrations are similar to those reported for ultramafic and mafic rocks and, to a lesser extent, carbonate rocks and shales (Table 7). High magnesium in sediments associated with mica schists may reflect the magnesium content of the micas. Rock units (Table 1) with the lowest magnesium (Table 12) include: *Eu* - undifferentiated Eocene (500 ppm), *Kcbe* - Cusseta, Blufftown and Eutaw Formations (680 ppm), *Kt* - Tuscaloosa Formation (780 ppm), and *q1* - quartzite (783 ppm). Low magnesium in stream sediments in Coastal Plain sediments may reflect physicochemical controls similar to those affecting manganese

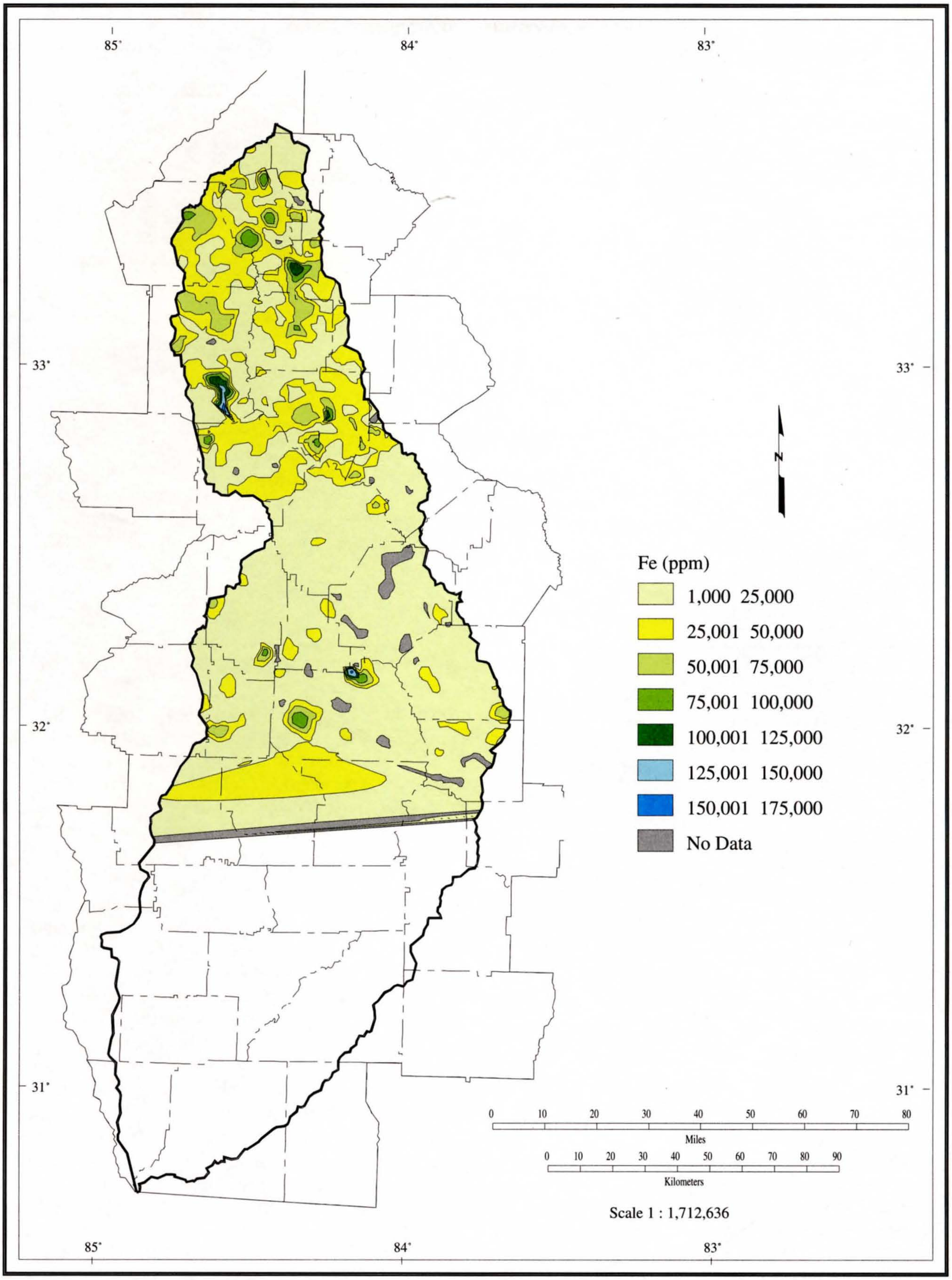

Figure 27. Iron in stream sediments. Absence of data in parts of Webster, Sumter and Crisp Counties may cause contouring artifacts.

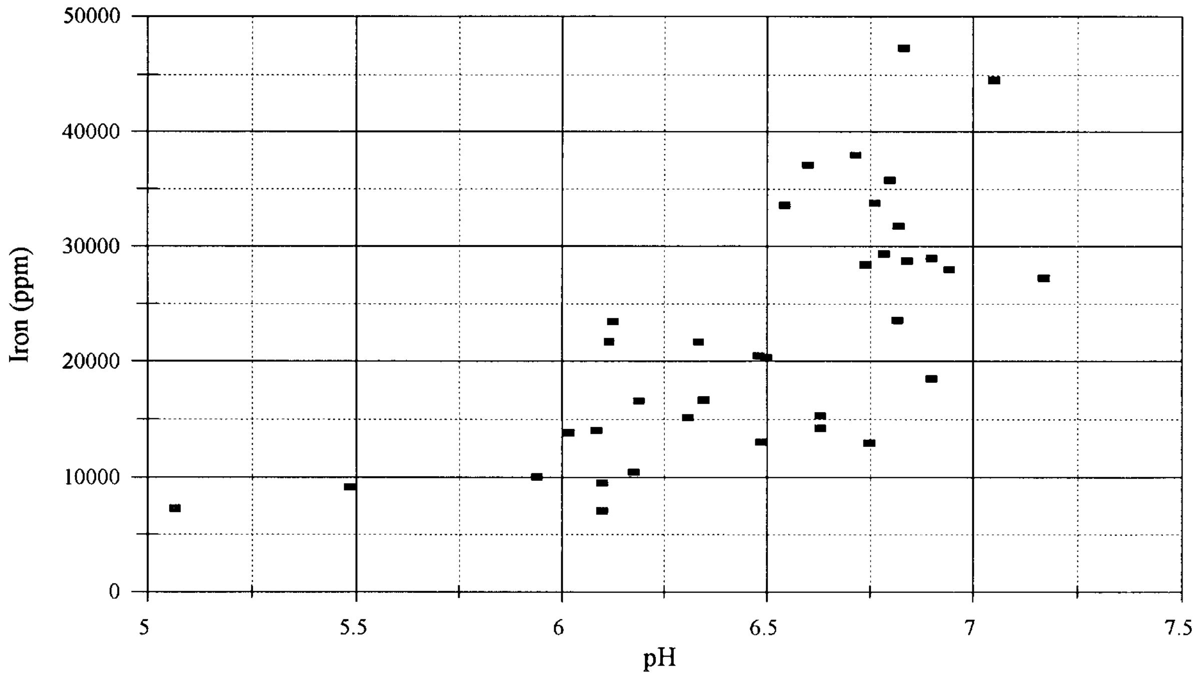

Figure 28. Variation of iron with pH. A plot of average compositions per rock unit.

and iron.

Average magnesium concentration in the Flint River Basin is 1,419 ppm with a maximum of 7,400 ppm and a minimum of 100 ppm. Highest (7,400 ppm) magnesium is found in northern Meriwether County within a moderately sized area of high magnesium (greater than 2,000 ppm). Mica schist (*pms3a*) underlies this anomaly (Fig. A-7). Another area of moderately high magnesium is found in Fayette and Clayton Counties. Hornblende-biotite gneiss (*mm5*), ultramafic rocks (*um*), and mica schist (*pms1*) underlie parts of this area (Figs. A-5, A-2, A-7).

Strongest correlations for magnesium are with iron, vanadium, aluminum, manganese, titanium, sodium and alkalinity (Table 14). Figure 30 illustrates the relationship between magnesium and iron.

## *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 soil and water (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. Metal enrichment by adsorption is thus generally greater for manganese oxides than for iron oxides. Excess manganese in water can clog pipes and 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 14) show a relatively good correlation of manganese with conductivity, pH, aluminum, cobalt, and iron. A plot of manganese versus pH shows that the manganese content of stream sediments is generally less than 400 ppm where stream pH is less than 6.5. Manganese content is generally greater than 600 ppm, when stream pH is greater than 6.5. These relationships suggest that manganese may be in solution under low pH conditions and as manganese oxides under high pH conditions.

Average manganese concentration in the Flint River Basin is 692 ppm with a maximum of 9,530 ppm and a minimum of 30 ppm. Rock units with the highest manganese (Table 12) include: *pa2* - sillimanite schist (2,373 ppm), *gr1b* - porphyritic granite (1,398 ppm), *gr1* - granite (1,368 ppm), *mm2* - hornblende gneiss (1,359 ppm), *um* - ultramafic rocks (1,140 ppm), *pms1* - mica schist (1,135 ppm), *pms3a* - mica

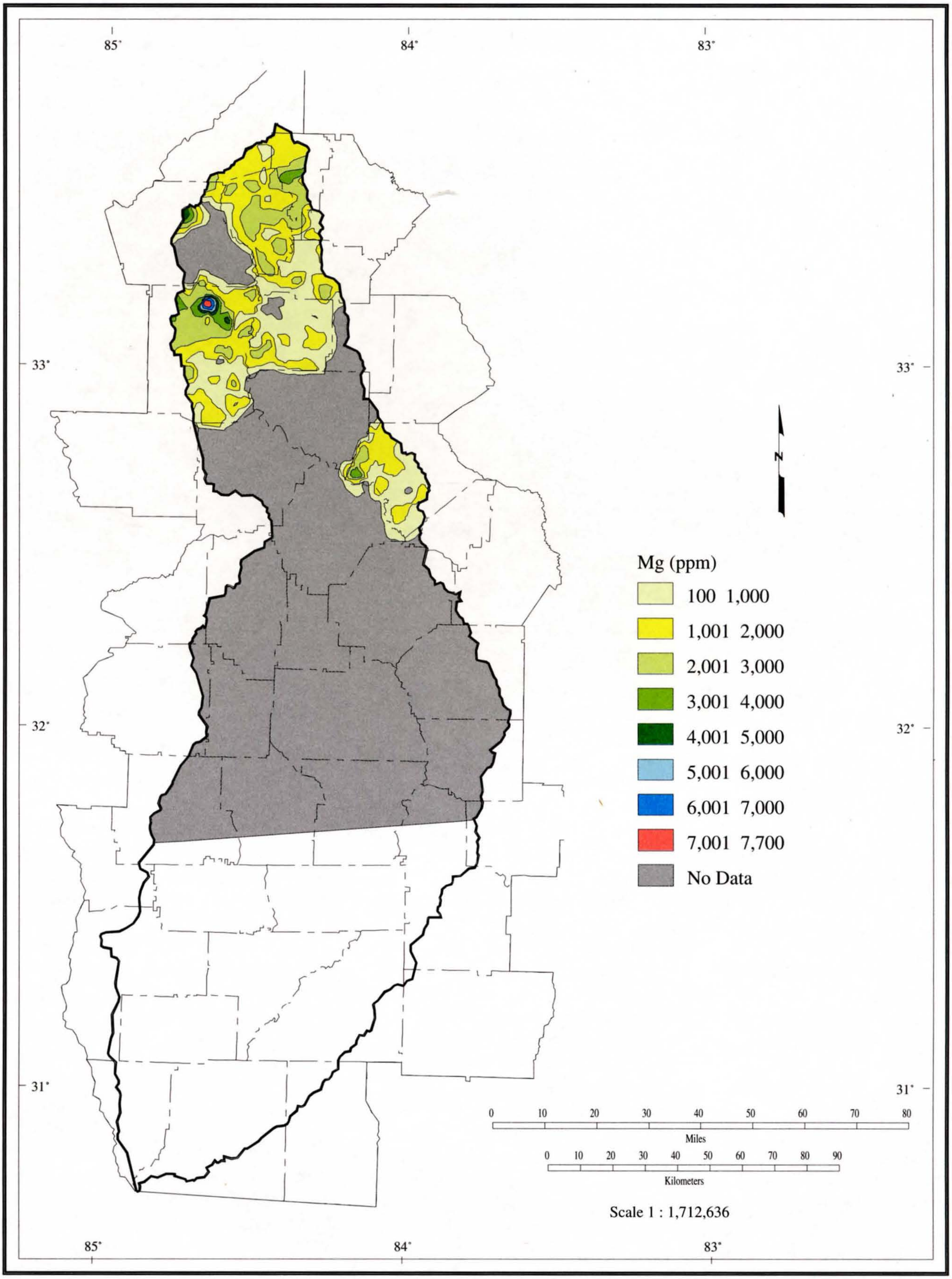

Figure 29. Magnesium in stream sediments.

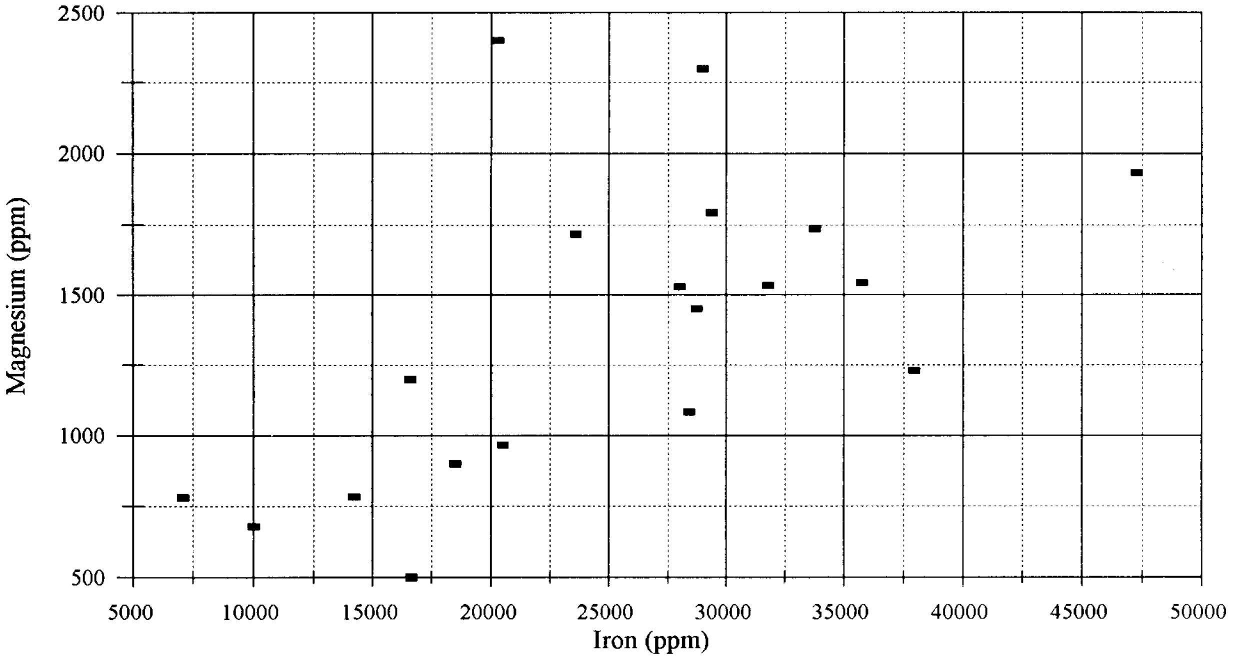

Figure 30. Variation of magnesium with iron. A plot of average compositions per rock unit.

schist (1,111 ppm), *gg4* - granite gneiss (1,056 ppm), and *bg1* - biotite gneiss (1,002 ppm). Highest manganese concentrations are in Pike (9,530 ppm), Fayette (8,300 ppm) and Spalding (5,760 ppm) Counties (Fig. 31). High manganese concentrations in Meriwether, Spalding and Pike Counties are generally coincident with *gr1*- granite (Fig. A-2) and *pms3a* - mica schist (Fig. A-7). High manganese concentrations in Fayette County are associated with *pms1* - mica schist (Fig. A-7). Manganese is generally lower in the Pine Mountain terrane (60 to 700 ppm). In the Uchee terrane manganese is somewhat higher (200 to 3600 ppm). A band of anomalous manganese, iron, vanadium, and scandium corresponding to the Uchee terrane suggests a geochemical affinity with the Carolina terrane to the east. Correlation coefficients also show a strong positive correlation with scandium, aluminum, vanadium, iron (Fig. 32), pH, and conductivity (Table 14).

Lowest manganese concentrations in the Flint River Basin (Table 12) are found in Coastal Plain stream sediments with average values that range from 108 to 384 ppm. Rock units include: *Kc* - Cusseta Sand (108 ppm), *Ke* - Eutaw Formation (142 ppm), *Kr* - Ripley Formation (150 ppm), *Eo-Os* - Eocene - Oligocene residuum (174 ppm), *Ptu* - Tuscahoma Sand (175 ppm), *Pcn* - Nanafalia, Porters Creek and Clayton Formations (175 ppm), *Eu* - undifferentiated Eocene (177 ppm), *Kb* - Blufftown Formation (180 ppm), *Kp* - Providence Sand (184 ppm), *Kt* - Tuscaloosa Formation (195 ppm), *Qal* - alluvium (203 ppm), *Os* - Suwanee Limestone (247 ppm), *Pnf* - Nanafalia Formation (258 ppm), *Ec* - Claiborne Formation (310 ppm), *Kcbe* - Cusseta, Blufftown and Eutaw Formations (330 ppm), *Nu* - undifferentiated Neogene (360 ppm), and *Eo* - Ocala Limestone (384 ppm). Manganese was not retained in sediments derived from most Coastal Plain rock units that were sampled, perhaps due to the low pH of most streams in the areas concerned or low original manganese content of those rocks. Lowest concentrations of manganese in the Coastal Plain are generally 30 to 900 ppm. Slightly anomalous manganese concentrations found in the lower part of the Flint River Basin may be related to carbonate rocks. Higher concentrations (200 to 900 ppm) are found in the southern part of the sampled area in Dooly, Crisp, Sumter, Webster, Stewart, Chattahoochee, Schley, and Marion Counties.

### *Titanium (Ti)*

Average titanium concentration in the Flint River Basin is 10,056 ppm with a maximum of 80,500 ppm and a minimum of 1,000 ppm. Rock units with the highest titanium content (Table 12) include: *Kb* - Blufftown Formation (26,400 ppm), *gr4* - charnockite (21,950 ppm), *pms3* - mica schist (21,800 ppm), *gg1* - granite gneiss (19,320 ppm), *pa2* -sillimanite

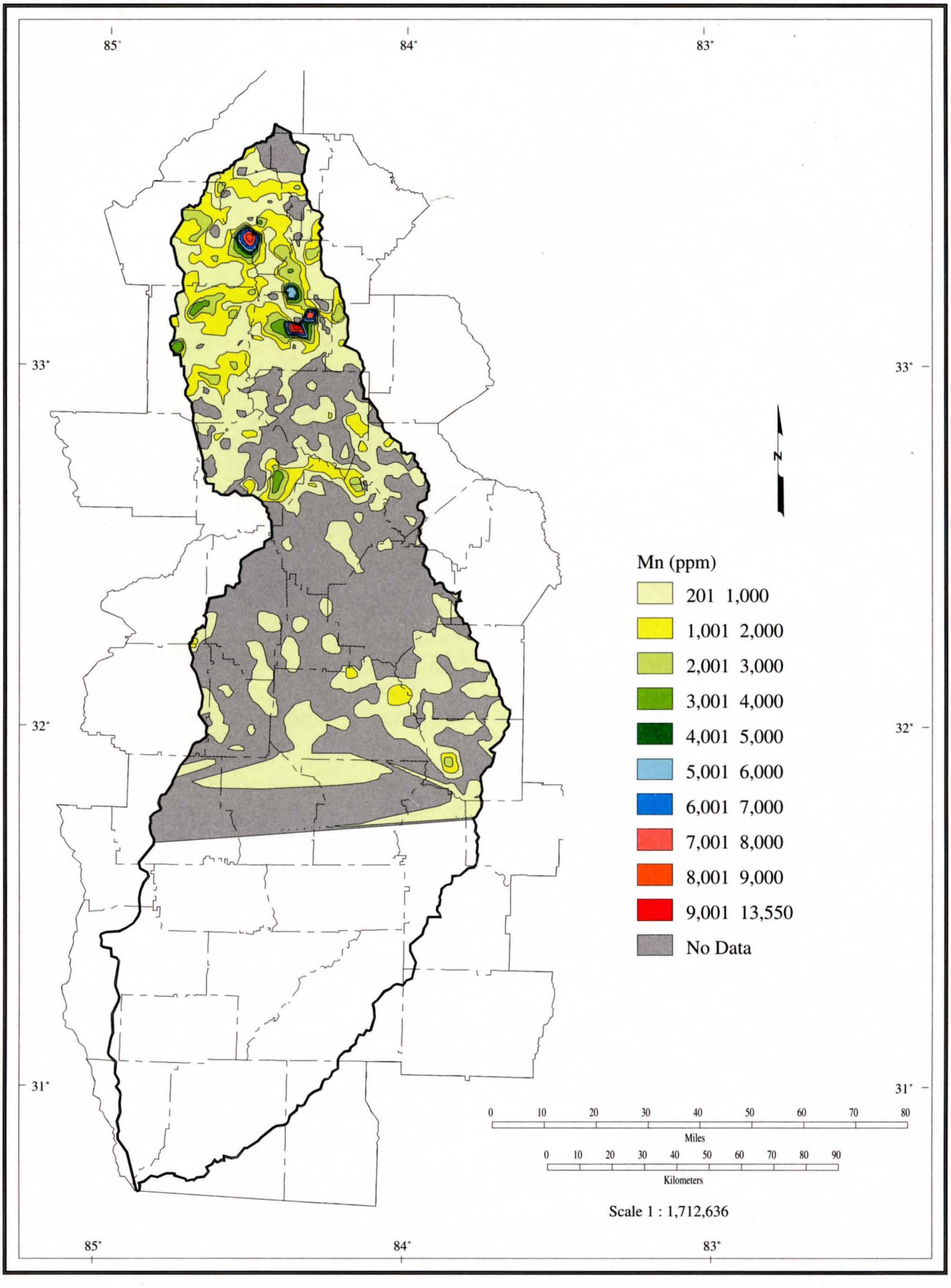

Figure 31. Manganese in stream sediments.

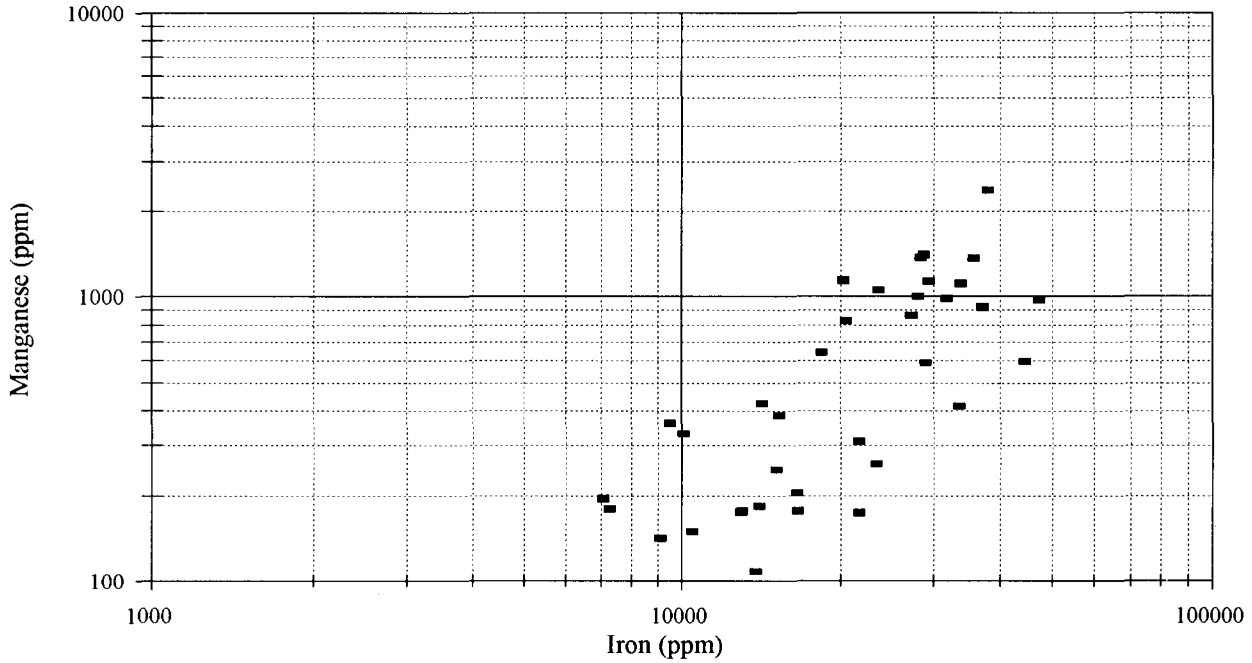

Figure 32. Variation of manganese with iron. A plot of average compositions per rock unit.

schist (17,633 ppm), and *pms3a* - mica schist (15,310 ppm). Rock units *um* - ultramafic rocks and *gr3* - granite did not contain any sediments analyzed for titanium. Highest concentrations of titanium in the Blufftown Formation (Fig. A-10) correlate spatially with the highest concentrations of rare-earth metals and thorium (unpublished Georgia Geological Survey geochemical maps), suggesting the presence of a high concentration of heavy minerals in the Blufftown Formation. Low concentrations of iron in this unit suggests that the titanium is present as rutile or leucoxene. Rock units *gr4* - charnockite (Fig. A-2), *pa2* -sillimanite schist (Fig. A-8), and *pms3a* - mica schist (Fig. A-7) also contain high iron. Together they may indicate the presence of abundant titanium-iron oxides such as ilmenite and magnetite.

Highest titanium concentrations are in Coweta (62,000 ppm), Meriwether (50,900 ppm), Lamar (51,110 ppm), Crawford (80,500 ppm), and Stewart (70,500 ppm) Counties. Approximately half of the stream sediments in the Piedmont have greater than 10,000 ppm titanium. A regional belt of higher titanium extends through the Flint River Basin and is coincident with the Uchee terrane in Talbot, Taylor, Upson and Crawford Counties. This is spatially coincident with high iron, vanadium, sodium and scandium concentrations.

Approximately 90 percent of the stream sediments in the Coastal Plain have less than 10,000 ppm titanium. Rock units with the lowest titanium content (Table 12) include: *Nu* - undifferentiated Neogene (3,600 ppm), *Os* - Suwanee Limestone (4,378 ppm), *Pnf* - Nanafalia Formation (4,423 ppm), *Kcbe* - Cusseta, Blufftown and Eutaw Formations (4,650 ppm), *Eo* - Ocala Limestone (4,868 ppm), *Eu* - undifferentiated Eocene (4,880 ppm), and *Eo-Os* - undifferentiated Eocene and Oligocene residuum (4,917 ppm). Many of these rock units are marine carbonate rocks that may be expected to have little or no concentrations of titanium or heavy minerals. Coastal Plain rock units that are more favorable for containing concentrations of heavy minerals would include those that are terrestrial to shallow marine in origin. Favorable geochemical data would include higher mean concentrations of rare-earth elements, hafnium, thorium, uranium, and titanium with low Fe/Ti ratios. Based on their geochemistry, the Cretaceous age Tuscaloosa Formation, undifferentiated Cretaceous and Tertiary, and Eocene age Irwintown Sand, Twiggs Clay, and McBean Formation, are the most favorable units for containing heavy mineral deposits (Cocker, in press). These units would correspond to the Cretaceous Tuscaloosa and Gaillard Formations, Paleocene to Middle Eocene Huber Formation, and Upper Eocene Dry Branch Formation based on recent revisions in the stratigraphy.

Median crustal abundances of titanium (Table 7) are 3,000 ppm in ultramafic rocks, 9,000 ppm in basalt, 8,000 ppm in granodiorite (Levinson, 1974), and 2,300 ppm in granitic

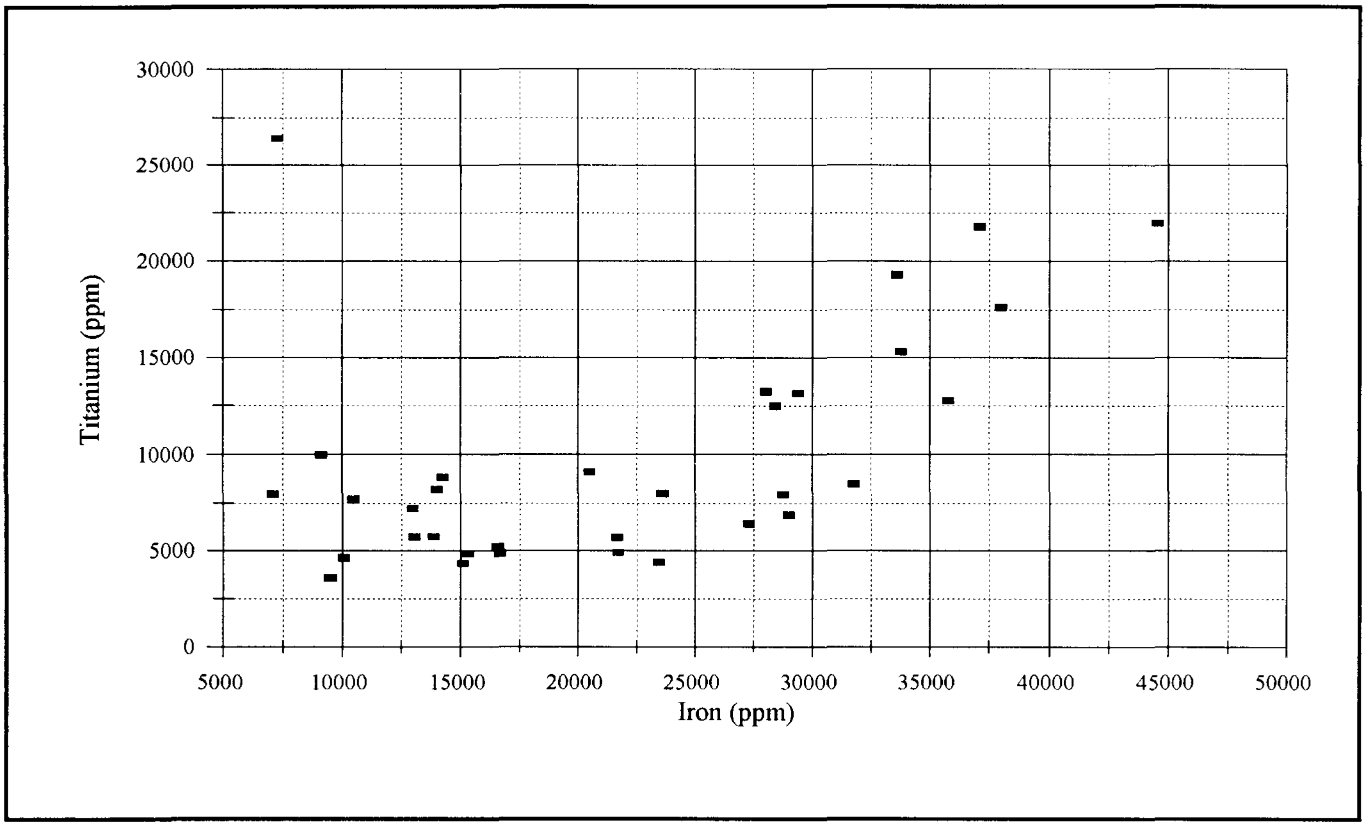

Figure 33. Variation of titanium with iron. A plot of average compositions per rock unit.

rocks. Median concentrations are 400 ppm in limestones and 4,600 ppm in shales (Levinson, 1974).

As in the Oconee River Basin study (Cocker, 1996b) and the Chattahoochee River Basin study (Cocker, 1998), titanium shows a strong correlation with iron (Table 14 and Fig. 33). Titanium may be present as iron-titanium oxides such as ilmenite, hematite, leucoxene or magnetite.

## *Vanadium (V)*

Studies indicate 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 (Edwards and others, 1995). 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).

Rock units with the lowest vanadium (Table 12) include: *Nu* - undifferentiated Neogene (20 ppm), *Pcn* - Clayton, Porters Creek and Nanafalia Formations (30 ppm), *Ptu* - Tuscahoma Sand (30 ppm), *Pnf* - Nanafalia Formation (30.8 ppm), *q1* - quartzite (30.8 ppm), *Kr* - Ripley Formation (33.2 ppm), *Os* - Suwanee Limestone (33.9 ppm), *Eu* - undifferentiated Eocene (34.0 ppm), *Kt* - Tuscaloosa Formation (34.6 ppm), *Qal* - alluvium (36.0 ppm), *Kcbe* - Cusseta, Blufftown and Eutaw Formations (36.7 ppm), and *Kp* - Providence Sand (38.6 ppm). Nearly all NURE samples from Coastal Plain sediments contain very low amounts of vanadium. Low vanadium concentrations in sandy units of the Coastal Plain (unpublished Georgia Geologic Survey map) are coincident with a region with low pH streams (Fig. 11).

Average vanadium concentration in the Flint River Basin is 53.7 ppm with a maximum of 290 ppm and a minimum of 10 ppm. Rock units with the highest vanadium (Table 12) include: *gr1b* - porphyritic granite (93.3 ppm), *Kb* - Blufftown Formation (90 ppm), *mm2* - hornblende gneiss (87.5 ppm), *bg1* - biotite gneiss (84.3 ppm), *pa2* - sillimanite schist (84.2 ppm), and *pa1* - aluminous schist (80 ppm). Highest vanadium concentrations occur in Coweta (290 ppm) and Fayette (290 ppm) Counties. Areas of high vanadium (generally greater than 100 ppm vanadium) include the Uchee terrane in Talbot, Taylor, Upson and Crawford Counties associated with *bg1* - biotite gneiss (Fig. A-4). In Coweta County high vanadium is associated with pa2 - sillimanite schist (Fig. A-8), in Meriwether County high vanadium is associated with *pms3a* - mica schist (Fig. A-7), and in Fayette County it is associated with *pms1* - mica schist (Fig. A-7).

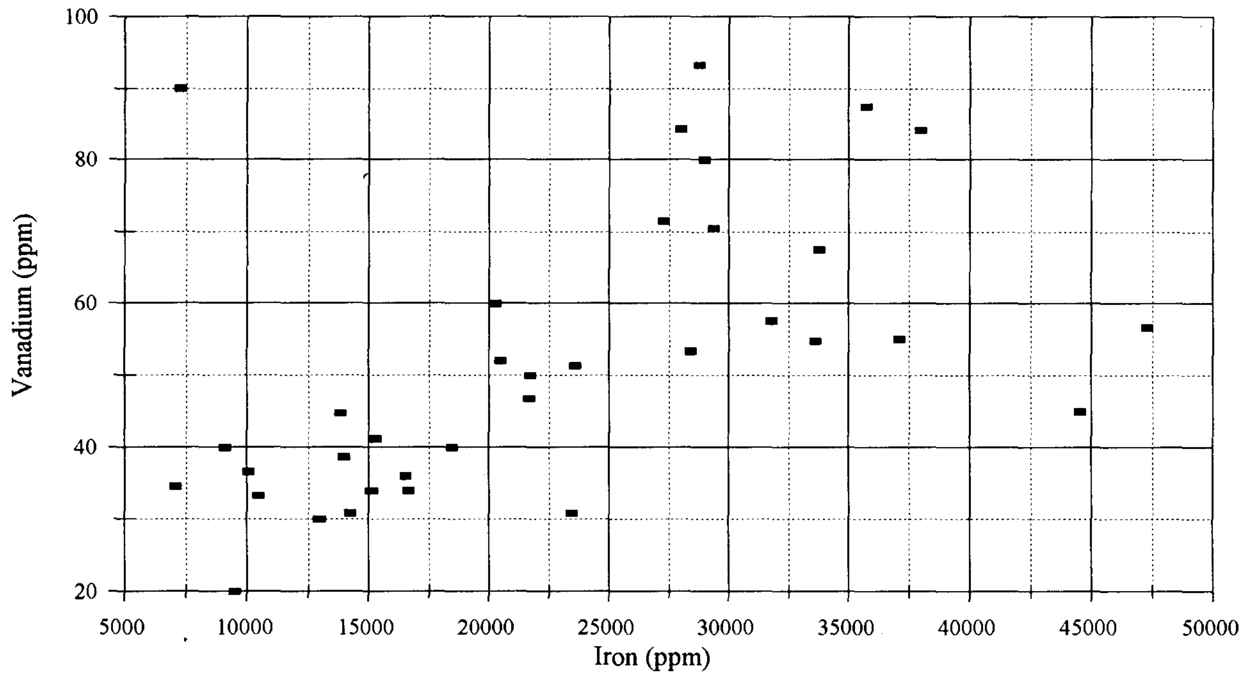

Figure 34. Variation of vanadium with iron. A plot of average compositions per rock unit.

The vanadium-iron-titanium-manganese association (Table 14), which has been discussed earlier, is illustrated by a plot of vanadium versus iron (Fig. 34), and the similar spatial distribution of titanium (unpublished Georgia Geologic Survey map) and iron (Fig. 27).

The median crustal abundance of vanadium (Table 7) is significantly higher in mafic rocks (250 ppm) and shales (130 ppm) (Rose and others, 1979) than in other rock types. This relation is in agreement with high vanadium in shales and amphibolitic rocks from the NURE sediment data, and may help identify sediments derived from mafic rocks and shales.

## GEOCHEMICAL STATISTICS

Basic statistics were computed for each element for all samples in the Flint River Basin, and all samples within various rock units within the Flint River Basin. Previous studies of the Oconee and Chattahoochee River Basins indicated that stream sediment geochemistry and stream hydrogeochemistry are strongly influenced by the mineralogy of the associated rock units (Cocker, 1996b, 1998).

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 10 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. Table 10 also shows the percentage of sample sites that are found within each rock unit in the Flint River Basin. Rock units that had no sample sites are indicated by zero sample sites. The percentage of total samples indicates the contribution of each rock unit to the overall geochemistry of the Flint River Basin. The number of sample sites may indicate the degree of confidence of the data from each rock unit. A greater degree of confidence may be expected in the geochemistry for rock units *Ec, Eo, Eo-Os, Eu, Kc, Kp, Kr, Kt, Os, Pnf, bg1, fg3, gg1, gg4, gr1, mm4, pa2, pms1, pms3a,* and *q1* than for rock units such as *Kb, Kcbe, Ke, Nu, Pcn, Ptu, Qal, Qas, fg1, gr1b, gr4, mm2, mm5, pa1, pms3,* and *um* (Table 10). Average values were calculated for all sample sites that are within each rock unit (Table 12).

Average concentrations of the various metals in the more common rock types in the earth's crust (Table 7) provide a standard for comparison with NURE data. Table 7 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.

**Table 13. Correlation coefficients for all stream sediment and stream samples.**

| | Temp | pH | Alkalinity | Conductivity | Ag | Al | Ba | Be | Co | Cr | Cu |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | 1.0000 | | | | | | | | | | |
| pH | -0.1482 | 1.0000 | | | | | | | | | |
| Alkalinity | 0.0836 | 0.4804 | 1.0000 | | | | | | | | |
| Conductivity | -0.0412 | 0.4577 | 0.8557 | 1.0000 | | | | | | | |
| Ag | -0.0456 | -0.0586 | 0.0021 | -0.0019 | 1.0000 | | | | | | |
| Al | -0.0328 | 0.2344 | 0.1160 | 0.1893 | 0.0418 | 1.0000 | | | | | |
| Ba | -0.0394 | 0.0506 | -0.0096 | -0.0627 | 0.0357 | 0.4131 | 1.0000 | | | | |
| Be | 0.0713 | 0.1905 | 0.0835 | 0.0537 | -0.0895 | 0.3634 | 0.1359 | 1.0000 | | | |
| Co | -0.0112 | 0.0421 | 0.2168 | 0.1277 | 0.0368 | 0.3664 | 0.1972 | 0.3003 | 1.0000 | | |
| Cr | -0.0580 | 0.0543 | -0.0276 | 0.0176 | -0.0258 | 0.0784 | 0.0798 | -0.0769 | -0.0712 | 1.0000 | |
| Cu | -0.0071 | -0.0050 | 0.1570 | 0.1296 | 0.4837 | 0.3705 | 0.1068 | 0.2678 | 0.4914 | 0.0057 | 1.000 |
| Fe | -0.0226 | 0.2094 | 0.0782 | 0.1397 | 0.1033 | 0.5002 | 0.1092 | 0.2692 | 0.3921 | 0.1258 | 0.2554 |
| K | 0.0245 | 0.1631 | 0.0991 | 0.0829 | -0.0253 | 0.2962 | 0.0207 | 0.2065 | -0.1258 | -0.0959 | -0.0922 |
| Mg | 0.0927 | 0.2250 | 0.1467 | 0.0947 | -0.0495 | 0.0649 | -0.0513 | 0.2045 | 0.1896 | -0.0557 | 0.2037 |
| Mn | -0.0793 | 0.2926 | 0.0742 | 0.1268 | 0.0406 | 0.3662 | 0.1018 | 0.1778 | 0.6263 | -0.0641 | 0.2156 |
| Na | -0.1732 | 0.3400 | 0.1729 | 0.1985 | 0.0531 | 0.3202 | -0.0444 | 0.0246 | 0.1495 | 0.1033 | 0.0792 |
| Ni | -0.0607 | -0.1062 | 0.0179 | 0.0006 | 0.0923 | 0.3363 | 0.2622 | 0.0637 | 0.4888 | 0.0663 | 0.3920 |
| Pb | 0.0801 | -0.1754 | 0.0505 | -0.0132 | 0.2272 | 0.4481 | 0.0333 | 0.2477 | 0.4706 | -0.0273 | 0.5260 |
| Sc | -0.0878 | 0.1267 | 0.0512 | 0.1492 | -0.0385 | 0.5832 | 0.1564 | 0.2938 | 0.3365 | 0.1690 | 0.2935 |
| Ti | -0.1049 | 0.1955 | 0.0089 | 0.0670 | -0.0714 | 0.0849 | 0.0585 | 0.1367 | 0.1624 | 0.0396 | 0.0501 |
| V | -0.0431 | 0.2060 | 0.1065 | 0.1411 | -0.0575 | 0.4917 | 0.0560 | 0.1913 | 0.3760 | 0.1868 | 0.2531 |
| Zn | -0.0468 | -0.0364 | 0.1306 | 0.1026 | 0.3696 | 0.4259 | 0.1805 | 0.1510 | 0.4789 | 0.1131 | 0.6942 |

| | Fe | K | Mg | Mn | Na | Ni | Pb | Sc | Ti | V | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fe | 1.0000 | | | | | | | | | | |
| K | -0.1549 | 1.0000 | | | | | | | | | |
| Mg | 0.2506 | 0.1139 | 1.0000 | | | | | | | | |
| Mn | 0.5051 | -0.0356 | 0.0811 | 1.0000 | | | | | | | |
| Na | 0.1212 | 0.1773 | 0.0621 | 0.3196 | 1.0000 | | | | | | |
| Ni | 0.2240 | -0.1266 | 0.0112 | 0.3175 | 0.0580 | 1.0000 | | | | | |
| Pb | 0.2510 | 0.0046 | -0.0600 | 0.4489 | 0.0286 | 0.3958 | 1.0000 | | | | |
| Sc | 0.6716 | -0.1217 | 0.2023 | 0.3561 | 0.1807 | 0.2332 | 0.2522 | 1.0000 | | | |
| Ti | 0.5146 | -0.0220 | 0.3353 | 0.4520 | 0.0596 | 0.0194 | 0.0639 | 0.4451 | 1.0000 | | |
| V | 0.7182 | -0.1848 | 0.3496 | 0.4884 | 0.1924 | 0.2470 | 0.1766 | 0.5917 | 0.5637 | 1.0000 | |
| Zn | 0.1869 | -0.1242 | 0.1124 | 0.1410 | 0.2528 | 0.3190 | 0.5010 | 0.3076 | 0.0164 | 0.2108 | 1.0000 |

## Table 14. Correlation coefficients by rock unit.

| | Temp | pH | Alkalinity | Conductivity | Ag | Al | Ba | Be | Co | Cr | Cu |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | 1.0000 | | | | | | | | | | |
| pH | -0.0837 | 1.0000 | | | | | | | | | |
| Alkalinity | 0.1453 | 0.5193 | 1.0000 | | | | | | | | |
| Conductivity | -0.2890 | 0.5392 | 0.7360 | 1.0000 | | | | | | | |
| Ag | 0.1304 | -0.2081 | 0.0318 | -0.0060 | 1.0000 | | | | | | |
| Al | -0.2049 | 0.6616 | 0.1774 | 0.4959 | -0.1516 | 1.0000 | | | | | |
| Ba | 0.1254 | 0.4499 | 0.0465 | 0.1067 | 0.4128 | 0.4500 | 1.0000 | | | | |
| Be | 0.4510 | 0.5940 | 0.1447 | 0.1004 | -0.4519 | 0.4598 | 0.1965 | 1.0000 | | | |
| Co | 0.1170 | 0.6400 | 0.1908 | 0.2795 | -0.3770 | 0.5710 | 0.1873 | 0.6156 | 1.0000 | | |
| Cr | -0.5325 | -0.0118 | -0.4246 | -0.1292 | -0.4409 | 0.3038 | 0.0311 | -0.2019 | 0.1970 | 1.0000 | |
| Cu | 0.4443 | 0.3725 | 0.1844 | 0.1542 | 0.2058 | 0.4198 | 0.1997 | 0.4994 | 0.6248 | -0.2813 | 1.000 |
| Fe | -0.2617 | 0.6863 | 0.1768 | 0.3493 | -0.1388 | 0.6549 | 0.3749 | 0.2650 | 0.4521 | 0.1691 | 0.3362 |
| K | 0.2285 | 0.4614 | -0.1231 | 0.0091 | -0.5135 | 0.6192 | 0.4980 | 0.6152 | 0.3879 | 0.2960 | 0.0136 |
| Mg | 0.0355 | 0.5394 | -0.1253 | 0.0804 | -0.1548 | 0.7469 | 0.2837 | 0.0591 | 0.3477 | 0.5440 | 0.0911 |
| Mn | -0.2962 | 0.5840 | 0.1332 | 0.4717 | -0.2916 | 0.6948 | 0.3866 | 0.2584 | 0.6618 | 0.3162 | 0.2790 |
| Na | -0.3705 | 0.4278 | 0.0546 | 0.2998 | -0.2768 | 0.5936 | 0.1255 | -0.0554 | 0.1095 | 0.5881 | -0.0407 |
| Ni | -0.0953 | 0.1767 | -0.0136 | 0.0075 | 0.5021 | 0.1270 | 0.6924 | -0.1232 | 0.2500 | -0.1298 | 0.3288 |
| Pb | 0.2619 | -0.3029 | 0.3303 | 0.2251 | -0.1459 | -0.3300 | -0.4235 | -0.1063 | 0.0207 | -0.2197 | 0.1204 |
| Sc | -0.3770 | 0.1286 | -0.2430 | 0.0886 | -0.1872 | 0.4064 | 0.3721 | 0.4719 | 0.4772 | 0.4292 | 0.2859 |
| Ti | -0.3894 | 0.1149 | -0.3493 | -0.2207 | -0.3509 | 0.0856 | 0.5658 | 0.5063 | 0.5266 | 0.4514 | 0.0340 |
| V | -0.2865 | 0.2845 | -0.0303 | 0.1727 | -0.1592 | 0.5111 | 0.3242 | 0.4376 | 0.7717 | 0.2717 | 0.4798 |
| Zn | 0.4082 | 0.1280 | 0.4980 | 0.3075 | 0.2386 | -0.0271 | -0.0889 | 0.1822 | 0.3138 | -0.3234 | 0.6509 |

| | Fe | K | Mg | Mn | Na | Ni | Pb | Sc | Ti | V | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fe | 1.0000 | | | | | | | | | | |
| K | 0.1541 | 1.0000 | | | | | | | | | |
| Mg | 0.5865 | 0.3890 | 1.0000 | | | | | | | | |
| Mn | 0.6828 | 0.3105 | 0.3872 | 1.0000 | | | | | | | |
| Na | 0.3429 | 0.3301 | 0.3291 | 0.4908 | 1.0000 | | | | | | |
| Ni | 0.2728 | -0.1424 | 0.0021 | 0.4337 | -0.1424 | 1.0000 | | | | | |
| Pb | -0.0448 | -0.2197 | -0.4065 | 0.0317 | -0.1728 | -0.1695 | 1.0000 | | | | |
| Sc | 0.4523 | 0.4485 | 0.7159 | 0.4874 | 0.4982 | 0.1153 | -0.1538 | 1.0000 | | | |
| Ti | 0.4185 | 0.4310 | 0.4851 | 0.4615 | 0.3491 | 0.6224 | -0.2007 | 0.6336 | 1.0000 | | |
| V | 0.5767 | 0.3317 | 0.7215 | 0.6502 | 0.5494 | 0.4753 | 0.0645 | 0.7605 | 0.6075 | 1.0000 | |
| Zn | 0.0694 | -0.1948 | -0.1768 | -0.1863 | -0.1838 | -0.0176 | 0.2761 | -0.0197 | -0.3543 | 0.1263 | 1.0000 |

**Table 15. Ranking of correlation coefficients for all stream sediment and stream samples.**

| | |
|---|---|
| Temperature | below 0.3000 |
| pH | alkalinity (0.4804), conductivity (0.5392) |
| Alkalinity | conductivity (0.8557), pH (0.4804) |
| Conductivity | alkalinity (0.8557), pH (0.4577) |
| Ag | Cu (0.4837), Zn (0.3696) |
| Al | Sc (0.5832), Fe (0.5002), V (0.4917), Pb (0.4481), Zn (0.4259), Ba (0.4131), Cu (0.3705), Co (0.3664), Ni (0.3663), Mn (0.3662), Be (0.3634), Na (0.3202) |
| Ba | Al (0.4131) |
| Be | Al (0.3634), Co (0.3003) |
| Co | Mn (0.6263), Cu (0.6248), Ni (0.4888), Zn (0.4789), Pb (0.4706), Fe (0.3921), V (0.3760), Al (0.3664), Be (0.3003) |
| Cr | below 0.3000 |
| Cu | Co (0.6248), Zn (0.5542), Pb (0.5260), Ag (0.4837), Ni (0.4914), Al (0.3705) |
| Fe | V (0.7182), Sc (0.6716), Ti (0.5146), Mn (0.5051), Al (0.5002), Co (0.3921) |
| K | below 0.3000 |
| Mg | V (0.3496), Ti (0.3353) |
| Mn | Co (0.6263), Fe (0.5051), V (0.4884), Ti (0.4520), Pb (0.4489), Al (0.3662), Sc (0.3561), Na (0.3196), Ni (0.3175) |
| Na | Mn (0.3196) |
| Ni | Co (0.4888), Pb (0.3958), Cu (0.3920), Al (0.3363), Zn (0.3190 ), Mn (0.3175) |
| Pb | Cu (0.5260), Zn (0.5010), Co (0.4706), Mn (0.4489), Al (0.4481 ), Ni (0.3958) |
| Sc | Fe (0.6716), V (0.5917), Al (0.5832), Ti (0.4451), Co (0.3365), Zn (0.3076) |
| Ti | V (0.5637), Sc (0.4451), Mn (0.4520), Sc (0.4451), Zn (0.3076) |
| V | Fe (0.7182), Sc (0.5917), Ti (0.5637), Al (0.4917), Mn (0.4484), Co (0.3760), Mg (0.3496) |
| Zn | Cu (0.6942), Pb (0.5010), Co (0.4789), Al (0.4529), Ag (0.3696), Ni (0.3190) |

**Table 16. Ranking of correlation coefficients for samples by rock unit.**

| | |
|---|---|
| Temperature | Be (0.4510), Cu (0.4443), Zn (0.4228), Cr (-0.5325) |
| pH | Fe (0.6863), Al (0.6616), Co (0.6400), Be (0.5940), Mn (0.5840), Mg (0.5394), conductivity (0.5392), alkalinity (0.5193), K (0.4614), Ba (0.4499) |
| Alkalinity | Conductivity (0.7360), Zn (0.5354), pH (0.5193) |
| Conductivity | Alkalinity (0.7360), pH (0.5392), Mn (0.4717) |
| Ag | Ni (0.5021), K (-0.05135) |
| Al | Mg (0.7469), Mn (0.6948), pH (0.6616), Fe (0.6549), K (0.6192), Na (0.5936), Co (0.5710), V (0.5511), Ba (0.4500) |
| Ba | Ni (0.6924), K (0.4980), Ti (0.4656), Al (0.4500), pH (0.4499), Ag (0.4128) |
| Be | Co (0.6156), K (0.6152), pH (0.5940), Cu (0.4994), Al (0.4598), Ag (-0.4519) |
| Co | V (0.7419), Mn (0.6618), pH (0.6400), Cu (0.6248), Be (0.6156), Al (0.5710), Ti (0.4803), Fe (0.4521) |
| Cr | Na (0.5881), Mg (0.5440), Ti (0.5044), temperature (-0.5325), Ag (-0.4409), alkalinity (-0.4246) |
| Cu | Co (0.6248), Zn (0.5542), Be (0.4994), V (0.4583), temperature (0.4443), Al (0.4198) |
| Fe | pH (0.6863), Mn (0.6828), Al (0.6549), Mg (0.5865), V (0.5330), Ti (0.5031), Sc (0.4710), Co (0.4521) |
| K | Al (0.6192), Be (0.6152), Ba (0.4980), pH (0.4614), Ag (-0.5135) |
| Mg | Al (0.7469), V (0.5983), Fe (0.5865), Sc (0.5779), Cr (0.5440), pH (0.5394), Pb (-0.4065) |
| Mn | Al (0.6948), Fe (0.6828), V (0.6796), Co (0.6618), pH (0.5840), Na (0.4908), conductivity (0.4717), Ni (0.4337) |
| Na | Al (0.5936), Cr (0.5881), Mn (0.4908), pH (0.4278), V (0.4069) |
| Ni | Ba (0.6924), Ti (0.5134), Ag (0.5021), Mn (0.4337) |
| Pb | Ba (-0.4235), Mg (-0.4065) |
| Sc | Ti (0.6485), V (0.6090), Mg (0.5779), Fe (0.4710), Al (0.4258) |
| Ti | Sc (0.6485), V (0.5231), Ni (0.5134), Cr (0.5044), Fe (0.5031), Co (0.4803), Ba (0.4656), temperature (-0.4468) |
| V | Co (0.7419), Mn (0.6796), Sc (0.6090), Mg (0.5983), Al (0.5511), Fe (0.5330), Ti (0.5231), Cu (0.4583), Na (0.4069) |
| Zn | Cu (0.5542), alkalinity (0.5354), temperature (0.4228) |

Correlation coefficients were calculated to provide a basin-wide picture of the more prominent geochemical relations (Table 13). Correlation coefficients were also calculated for samples grouped by rock unit (Table 14). Intra-group correlations aid in assessing effects of geologic 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 modify otherwise strong correlation coefficients. Variations in mineralogy may generate a low correlation coefficient between metals derived from the same source rock.

Strongest correlations (Tables 13, 14) are those in the conductivity-alkalinity-pH group (or association), the aluminum-cobalt-iron-manganese-magnesium-sodium-scandium-vanadium-pH group and the zinc-copper group. In the conductivity-alkalinity-pH group coefficients range from 0.5193 to 0.7360. In the aluminum-cobalt-iron-manganese-magnesium-sodium-scandium-vanadium-pH group coefficients range from 0.4064 to 0.7717. The associations in this group suggests the presence of manganese- and vanadium-bearing iron oxides such as magnetite, sodic plagioclase (sodium and aluminum), and amphiboles (iron, magnesium, scandium, aluminum). Inclusion of cobalt with this group rather than with other base metals may be the result of adsorption of cobalt on manganese oxides. Titanium shows a moderate correlation with most elements in this group.

In the zinc-copper group, the correlation coefficient is 0.6509. Base-metal associations that include copper, cobalt, nickel, and zinc have been observed in both the Chattahoochee and Oconee River Basins and may reflect the presence of base-metal-bearing sulfides (Cocker, 1996b, 1998). Although base-metal sulfide mineralization is poorly documented in this part of Georgia, the fairly good correlation between copper and zinc may reflect some undetected mineralization of that type. The low number of base-metal analyses and non-random distribution (concentration of analyses in several counties) may also influence the degree of correlation among base-metals.

Alkalinity, pH and conductivity are regionally associated with tectonostratigraphic terranes and locally with individual rock units. This association appears to be similar to that observed further to the east in the Oconee River Basin (Cocker, 1996b). Correlation coefficients of pH with alkalinity and conductivity are 0.5193 and 0.5392, respectively. The stronger association in this group is between alkalinity and conductivity with a correlation coefficient of 0.7360.

Two associations are suggested between the more felsic components. 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 natural occurrence. 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 0.4064 to 0.5936 and may reflect the presence of sodic plagioclase. A good correlation of beryllium with potassium that was noted in the Oconee River Basin (Cocker, 1996b) is also present in the Flint River Basin.

Correlation of chromium with sodium, magnesium and titanium is suggested by the data in Table 13. This suite of elements may reflect the presence of chromium in ultramafic or mafic rocks. The small number of these rock types in the Flint River Basin does not favor a more rigorous interpretation.

Correlation coefficients for all NURE stream sediment and stream samples (Table 13) indicate that the strongest associations are an alkalinity-conductivity-pH group, a copper-lead-zinc-cobalt-nickel-silver-aluminum group, and an iron-titanium-vanadium-manganese-scandium group. These are somewhat different from the associations discussed above. The base-metal association is more prominent than observed in the within-rock unit correlations and may indicate that any base-metal mineralization in the Flint River Basin is independent of rock type.

## CONTAMINATION

Contamination, as discussed in this report, concerns effects contemporaneous with the period of collection of the NURE samples (1976 to 1978). Stream sediments probably have a wide range in age. Significant, recent sedimentation probably occurred in the streams of the Flint 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) to identify those 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 Flint River Basin included: mining, sewage, "dumps", farming, urban, and other industrial activity. Activities noted as "dumps" in the NURE databases may include a wide 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 660 stream sediment and stream sample sites in the Flint River Basin, farming was noted for 330, waste disposal sites were indicated for 8, other industrial for 3, and urban, sewage and mining for 2 sites each (Fig. 35). Although all other sample sites in the Flint River Basin are considered "non-contaminated", 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 quantitative impact of such sources on geochemical results may be difficult to demonstrate. However, the analytical results may qualitatively show that some activities have contributed to anomalous hydrogeochemical or geochemical analytical results. The large number of sites that may have been affected by farming - exactly half of all the sample sites in the Flint River Basin - also increases the difficulty of assessing the impact of farming on stream sediment and stream geochemistry.

Several sites in the Flint River Basin appear to have been affected by contamination as noted by the observations in the NURE data sets and by proximity to urban centers. Average geochemistry for urban, sewage and waste disposal sites (Table 17) appear to be abnormally higher or, in some instances, lower than what might be natural. Average pH of urban sites was 5.6, beryllium was 1.00 ppm, copper was 10 ppm, manganese was 2,525 ppm, nickel was 10 ppm, phosphorous was 900 ppm, and lead was 18 ppm. At waste disposal sites,

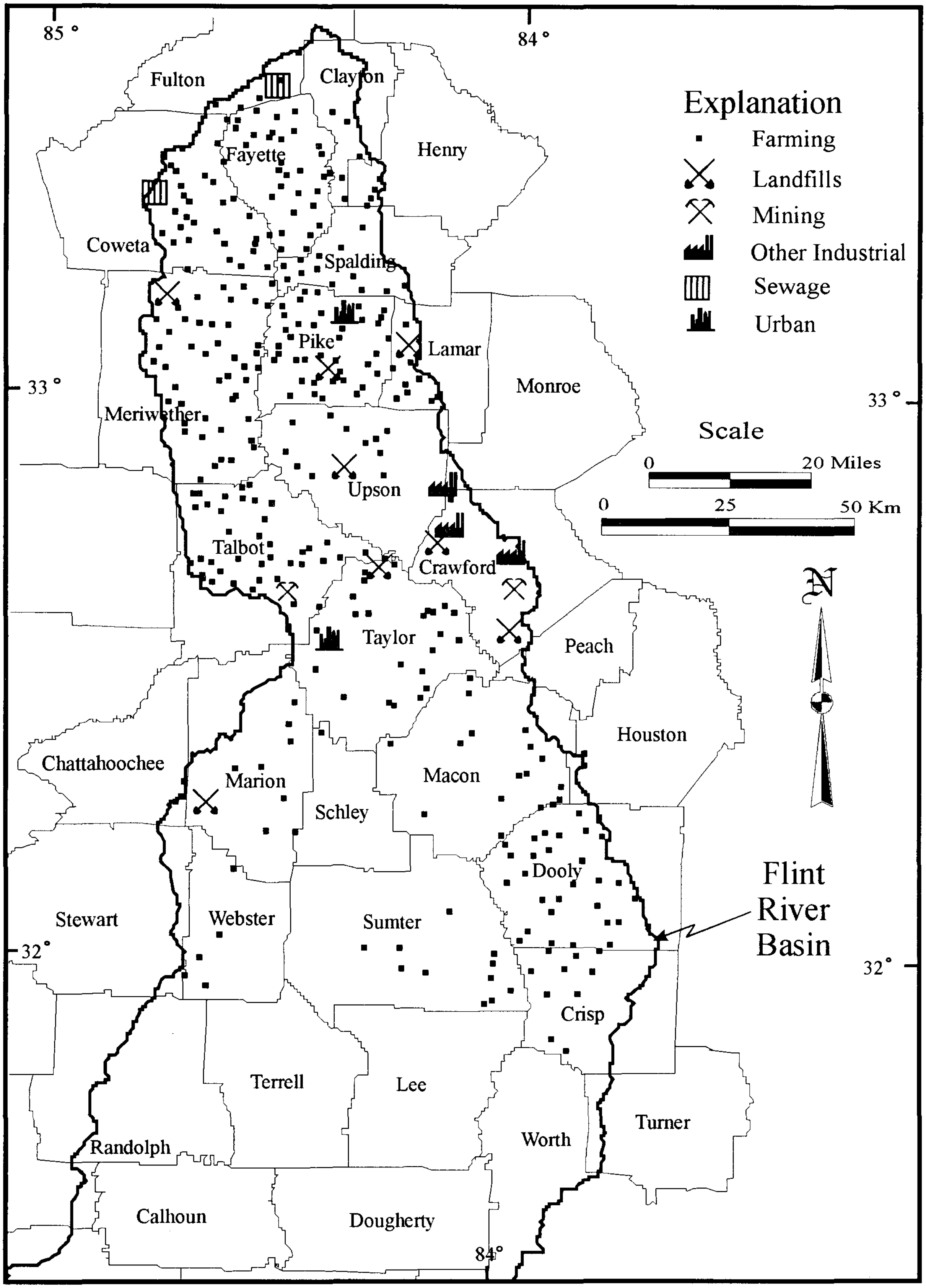

Figure 35. Contamination sources in the Flint River Basin.
Sources as noted during the 1976-1978 NURE sampling period.

**Table 17. Average geochemistry for analyses potentially influenced by nearby anthropogenic activities.**

| Activity | Other Industrial | Urban | Farming | Dumps | Sewage | Mining |
|---|---|---|---|---|---|---|
| Number | 3 | 2 | 330 | 8 | 2 | 2 |
| Temperature | 19 | 20 | 21 | 21 | 23 | 22 |
| pH | 6.9 | 5.6 | 6.6 | 6.7 | 6.9 | 6.1 |
| Alkalinity | 0.46 | 0.26 | 0.29 | 0.32 | 0.74 | 0.13 |
| Conductivity | 63 | 29 | 45 | 57 | 161 | 20 |
| Ag | 0.30 | 0.30 | 0.26 | 0.30 | 0.20 | 0.30 |
| Al | 37,300 | 26,450 | 31,200 | 27,483 | 46,150 | 19,600 |
| Ba | 26.5 | 19.0 | 45.1 | 23.7 |  | 13.0 |
| Be | 0.40 | 1.00 | 0.86 | 0.53 | 0.30 | 0.50 |
| Co | 6.3 | 5.0 | 5.9 | 0.53 | 0.30 | 0.50 |
| Cr | 4.0 | 3.0 | 3.4 | 3.0 | 3.0 | 3.0 |
| Cu | 3 | 10 | 5 | 15 | 5 | 4 |
| Fe | 26,100 | 20,900 | 26,656 | 27,825 | 22,350 | 10,550 |
| K | 4,000 | 9,000 | 14,088 | 7,667 | 24,000 | 4,000 |
| Mg | 1,050 | 900 | 1,463 | 1,500 | 1,300 | 900 |
| Mn | 653 | 2,525 | 944 | 558 | 920 |  |
| Na | 3,533 | 1,400 | 2,444 | 1,267 | 1,600 |  |
| Ni | 8 | 10 | 5 | 7 | 3 | 3 |
| P |  | 900 | 383 | 333 | 10 | 500 |
| Pb | 5 | 18 | 7 | 10 | 5 | 5 |
| Sc | 8 | 5 | 6 | 6 | 7 | 3 |
| Ti | 8,833 | 8,900 | 11,677 | 13,325 | 17,300 |  |
| V | 73 | 55 | 59 | 45 | 100 |  |
| Zn | 32 | 25 | 17 | 34 | 33 | 35 |

average cobalt was 7.8 ppm, copper was 15 ppm, and lead was 10 ppm. At sewage sites average alkalinity was 0.74 meq/L, conductivity was 161 micromhos/ cm, aluminum was 46,150 ppm, potassium was 24,000 ppm, phosphorous was 10 ppm, and vanadium was 100 ppm. At these two sites, the low phosphorous suggests that removal of phosphorous from treated water has been exceptional. However, high conductivities and alkalinities suggest high concentrations of dissolved solids are in the water. High aluminum, potassium, and vanadium in the stream sediments suggests suspended solids may also be unusually high.

Two urban sites had unusually high conductivities of 360 and 485 micromhos/cm 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 first site and 0.06 meq/L at 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) are lower than average for the basin. These samples were not analyzed for heavy metals. These samples are located by the GIS to be within the Cretaceous Tuscaloosa Formation. Average stream water geochemical values for the Tuscaloosa Formation are similar to those recorded at the "other industrial" sites. Although average aluminum, iron, manganese, sodium and vanadium values are also low in the Tuscaloosa Formation, stream sediments at these two sites contain lower values for these metals.

Additional potential sources of stream sediment and stream contamination that could not be addressed through the NURE stream sediment and stream 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. Within the Flint River Basin, during the first half of the twentieth century, arsenic was used extensively as a pesticide against the boll weevil. Road grading with mine wastes is probably not a major source of contamination in Georgia because of a lack of major metal mine workings.

A recently published summary of water quality in the combined Chattahoochee-Flint-Apalachicola River Basin suggest heavy metals are now present in river and stream sediments. Frick and others (1998) report two-fold enrichment of arsenic, copper, lead, and zinc over background and eight-fold enrichment of mercury and lead in the major tributaries of the Flint River Basin. Sediments collected below Albany showed sixteen-fold enrichment in mercury, and an eight-fold enrichment in copper and lead over background values (Frick and others, 1998). That study also indicated that trace-element scores for 41 of the 48 sites in the Chattahoochee-Flint-Apalachicola River Basin were enriched relative to background concentrations of these elements (arsenic, cadmium, copper, chromium, lead, nickel, and zinc). Frick and others (1998) suggest that much of the trace-element contaminants may be derived by atmospheric pathways. The greatest number of facilities that were within a 300 mile radius of Albany that released metals to the atmosphere include: metal products, chemicals, lumber and wood, electronics, rubber and plastics, and food preparation. That report does not indicate the relative contribution of each of these facility types, however. A general comparison of the data in that study with the NURE data suggests that trace-elements have been introduced into the Chattahoochee-Flint-Apalachicola River Basin since the NURE samples were collected. Direct comparison of these two studies may be limited if different sediment size fractions were sampled.

## 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 hydrogeochemistry of the Flint River. Spatial distributions of these data were analyzed using a computer-based Geographical Information System to define the background geochemistry and hydrogeochemistry of the Flint River Basin. Regional geology and local geology are the principal factors that control geochemistry and hydrogeochemistry within Flint River Basin streams.

The Flint River Basin is underlain with metamorphic and igneous rocks in the Piedmont physiographic province and sedimentary rocks and sediments in the Coastal Plain physiographic province. In contrast with the previously documented Oconee and Chattahoochee River Basins (Cocker, 1996b; 1998), most of the Flint River Basin (approximately 76 percent) is located within the Coastal Plain. The Coastal Plain is dominated by carbonate rocks and sediments which underlie approximately 42 percent of the basin. Most of the clastic sediments (sands and clays) are Cretaceous and are found in the northern part of the Coastal Plain near the Fall Line. Within the Piedmont, mica schist, biotite gneiss, and granite gneiss are the dominant rock types.

Major regional factors controlling distribution of metals within the Flint River Basin are differences between rocks of the Piedmont versus the Coastal Plain and between rocks of tectonostratigraphic terranes within the Piedmont. Chemical and physical differences between carbonate rocks and clastic rocks in the Coastal Plain strongly influence the composition of stream and river water and the resulting parameters such as pH, conductivity and alkalinity. Major terranes in the Piedmont include the Inner Piedmont, Pine Mountain, and Uchee terranes. These terranes are separated by major fault zones commonly containing mylonitic rocks. Most of the metamorphic rocks within the Flint River Basin are of intermediate to high metamorphic grade.

Mining of sediment-hosted kaolin, palygorskite, sand, sand and gravel, bauxite, limonite and limestone is present in various parts of the Coastal Plain province. Kaolin deposits are found in the Paleocene Nanafalia Formation in the Springvale and Andersonville districts. Bauxite is also found in these districts and was formed by extreme weathering and desilicification of the kaolin deposits. Palygorskite deposits are found in upper Oligocene and Miocene sediments in the southernmost part of the Flint River Basin. "Brown iron ore" (limonite) deposits formed as residual deposits from extreme weathering of carbonate rocks in the Paleocene Nanafalia Formation and Oligocene age sediments in Stewart, Quitman, Pulaski, Dooly and Houston Counties. Industrial sand is processed from Cretaceous and early Tertiary sandy sediments. Sand and gravel deposits are located in stream and river alluvium. Limestone is mined for agricultural lime, aggregate, and lime for Portland cement. None of these deposit types are known to contain heavy metals, although no detailed geochemical studies are available for these deposits. Pegmatites were mined in the Piedmont during the early part of the 1900's; except for beryllium, no other heavy metals are known to be concentrated in these deposits. Little is known geochemically of the other deposit types discussed earlier in this report.

Regional differences in stream pH, conductivity, and alkalinity are related to the geology of the Flint River Basin. In the Inner Piedmont terrane, streams generally have higher alkalinities, conductivities and somewhat higher 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 somewhat higher pH. Streams within the Coastal Plain that are spatially associated with sandy and clayey sediments have distinctly lower pH, conductivities and alkalinities than those streams which are spatially associated with calcareous sediments. The lowest stream pH occurs in streams spatially associated with Cretaceous sandy sediments near the Fall Line. High permeability, non-reactive compositions (e.g., quartz sand and clay), and perhaps higher amounts of decaying carbonaceous matter contribute to lower pH, conductivity and alkalinity of streams associated with non-calcareous Coastal Plain sediments. Further to the south, Paleocene, Eocene, Oligocene, and Miocene carbonate rocks underlie much of the basin, and alkalinities, conductivities and pH of streams are higher than in the northern part of the Coastal Plain. Carbonate rocks buffer rain and surface water by raising pH and alkalinity. Carbonate rocks also contribute dissolved solids to streams, as measured by higher alkalinities and conductivities. Concentrations of silica, iron, calcium, magnesium, potassium, bicarbonate, and pH could all be influenced by lithogeochemistry of dominant rock units in different parts of the Flint River Basin (Cherry, 1961; Couch and others, 1996).

Anomalously high iron, manganese, and vanadium appear to be associated with "brown iron ore" (limonite) deposits in the Coastal Plain. Although not analyzed in this part of the Coastal Plain, anomalous heavy metals may be found in stream sediments and streams in these areas.

Statistical analyses of NURE data suggest several element associations: 1) aluminum-cobalt-iron-magnesium-manganese-scandium-sodium-titanium-vanadium; 2) copper-nickel-cobalt-zinc-lead; 3) barium-potassium-aluminum; and 4) sodium-scandium-aluminum. The first association may be related to iron-magnesium mafic silicates, iron-titanium oxides, and sodic feldspars and reflect the distribution of mafic metavolcanic and metaplutonic rocks. Base-metal sulfides as disseminated or vein mineralization may be the explanation for the second association. The barium-potassium-aluminum association may be related to granitic plutons. A sodium-scandium-aluminum relation 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. Similar relations have been described in the Oconee and Chattahoochee River Basins (Cocker, 1996b; 1998).

Anthropogenic-related contamination may locally affect stream and river hydrogeochemistry. NURE data examined in this report were not collected to document anthropogenic effects on stream and river sediment geochemistry. Nearby human activities may have affected stream pH, conductivity and alkalinity and the beryllium, copper, cobalt, lead and manganese content of stream sediments in the NURE database. Activities which appear to have affected the geochemistry of streams and stream sediments include: urban, sewage and waste disposal sites. Watersheds with dominantly urban land-use contributed the largest yield of lead, zinc, copper, arsenic, phosphorous, nitrogen and organic carbon to the Chattahooochee River (Faye and others, 1980) and similar results may be expected in the Flint River Basin. In the Chattahoochee River Basin study, suspended sediment yields were also greatest in urban areas perhaps because of stream-channel erosion. 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). Stream sedimentation related to poor agricultural practices in the 1800's and early 1900's (Trimble, 1969) is evident in the Oconee and Chattahoochee River Basins (Cocker, 1996b; 1998) and has probably occurred to some extent in the northern part of the Flint River Basin. Additional down cutting by streams and rivers has caused remobilization of that recent sedimentation.

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# APPENDIX A

## GENERAL GEOLOGY

### Introduction

The geology discussed in this report is based principally on the Geologic Map of Georgia. Additional important sources include: Atkins and Lineback (1992), Higgins and Atkins (1981), Huddlestun (1988, 1993), Hetrick (1990a, b), and Reinhardt and others (1980, 1986). Rock units on the Geologic Map of Georgia are principally defined by the dominant lithology and secondarily by less abundant lithologies.

The Flint River Basin is located within the Piedmont and the Coastal Plain physiographic provinces (Fig. 9) which are described in the section on geomorphology. The Piedmont province, which constitutes approximately 24 percent of the Flint River Basin, is underlain by crystalline metamorphic and igneous rocks (Figs. A-2, A-3, A-4, A-5, A-6, A-7, A-8, A-9). Most of the basin, approximately 76 percent, is in the Coastal Plain province which is underlain by sedimentary strata (Figs. A-10, A-11, A-12, A-13, A-14, A-15, A-16). Because of significant differences in chemical composition, porosity, permeability, and origin of different rock units within the Piedmont and Coastal Plain, these rock units and stream sediments derived from these rock units significantly influence stream hydrogeochemistry. Lithologic map units which occur within the Flint River Basin are listed in Table 1.

Within the Piedmont, mica schists, biotite gneisses, and granitic rocks are the more common rock types (Table 1). Schistose rocks (Fig. A-7, A-8) cover approximately 10 percent, and quartzites (Fig. A-6) occupy approximately 1 percent of the Flint River Basin. Less than 1 percent of the Flint River Basin is occupied by ultramafic rock units (Fig. A-2). 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 Flint River Basin is approximately 11:1. 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, this ratio may only be viewed as a generalization. Cataclastic rocks (Fig. A-9) are depicted as covering approximately 0.1 percent of the basin.

Coastal Plain sediments are present over 76 percent of the Flint River Basin. Eleven of the fourteen most widespread rock units are found in the Coastal Plain (Table 1). Approximately 28 percent of the Flint River Basin is underlain by sandy and clayey sediments that are mainly Cretaceous (Fig. A-10) and Paleocene (Fig. A-11) in age. These sediments are located mainly in the northern part of the Coastal Plain near the Fall Line. Carbonate rocks of the Ocala Limestone (*Eo* and *Eo-Os* or Ocala Group), as depicted on the Geologic Map of Georgia, are the most widespread rocks in the Flint River Basin and represent approximately 42 percent of the exposed rocks. This limestone and several other carbonate rocks that are mainly Eocene, Oligocene and Miocene (Figs. A-12, A-13, A-14) exert a strong influence on the hydrogeochemistry of the surface water and ground water particularly in the southern half of the Flint River Basin. Other Coastal Plain sediments include Quaternary alluvium (*Qal*) that was mapped over approximately 3 percent of the Flint River Basin (Fig. A-16), and Quaternary aeolian sand deposits (*Qas*) that were mapped over 0.02 percent of the basin.

### Crystalline Rocks

#### *Intrusive Rocks*

Included in this group are rock bodies that are clearly intrusive in nature such as the map units "granite undifferentiated" (*gr1*), "porphyritic granite" (*gr1b*), "granite/biotite gneiss/amphibolite" (*gr3*), "charnockite" (*gr4*), and diabase intrusions. Also included are ultramafic rocks (*um*) that may in some cases, be intrusive, and in other cases, may be tectonic slices. Not included here are rock units that are probably intrusive, but are listed as metamorphosed rocks. Principal candidates include granite gneisses and perhaps some amphibolitic bodies. The ratio of felsic igneous rocks to mafic igneous rocks is approximately 5 to 1.

**Granites:** Granites, which include *gr1, gr1b, gr3,* and *gr4*, occupy approximately 5 percent of the Flint River Basin in Georgia. The largest masses of granite are several bodies of undifferentiated granite (*gr1*) in southern Fayette, Spalding, Pike, and Meriwether Counties (Fig. A-2). These are a continuation of the granite bodies noted in Troup, Talbot and Harris Counties in the Chattahoochee River Basin (Cocker, 1998) and are predominantly 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). These granites cover approximately 3 percent of the Flint River Basin. A small mass of the granite *gr3* is found in northeastern Coweta County. Two bodies of porphyritic granite (*gr1b*) in Coweta and Fayette Counties are the northeastern continuation of the Palmetto granite in the Chattahoochee River Basin. Charnockite, represented by four masses of *gr4* in Talbot, and Upson Counties, is a continuation of a group of charnockite bodies noted in Harris County in the Chattahoochee River Basin (Cocker, 1998). Charnockite represents less than 1 percent of the Flint River Basin.

**Ultramafic Rocks:** Two small bodies of ultramafic rock units (*um*) in Table 1 and on the Geologic Map of Georgia are found in Fayette County and in Crawford County (Fig. A-2). Most of these rock units are small in size and as a group represent less than 0.01 percent of the Flint River Basin. Ultramafic rocks may be metaperidotites, serpentinites, or metadunites. These rock units may be igneous intrusions or remnants of oceanic crust tectonically emplaced along crustal sutures. Ultramafic rocks in the Flint River Basin generally consist of serpentine, talc, actinolite, carbonates, magnetite, chromite, and sulfides (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.

**Diabase Intrusions:** Diabase dikes are scattered throughout the Georgia Piedmont and the Flint River Basin. More persistent dikes are depicted on the Geologic Map of Georgia. 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 one to several feet in width, and may extend for ten's of miles in a northwest-southeast direction. A set of four en-echelon dike segments that extends from the vicinity of Talbotton to Newnan is referred as the Talbotton diabase dikes. These dikes are up to 300 feet wide and could locally affect stream hydrogeochemistry. Concentrations of copper (142 to 162 ppm), nickel (53 to 65 ppm), zinc (109 to 124 ppm) and iron as $Fe2O3$ (14.5 to 15.53 weight percent) are relatively high in these dikes (Milla and Ragland, 1992).

## *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). Further information regarding the presence of metamorphosed mafic volcanic rocks in the Flint River Basin is included in a following section on amphibolites.

**Granitic Gneisses:** Granitic gneisses, rock types *gg1* - granitic gneiss undifferentiated and *gg4* - granite gneiss/amphibolite in Table 1, are most common in Upson, Fayette, and Clayton Counties (Fig. A-3). These rock units may include metamorphosed granodiorites, granodiorite gneisses, two-mica gneisses and migmatites as well as minor amphibolitic gneisses. Although they represent less than 3 percent of the Flint River Basin, local concentrations of granitic gneisses may affect nearby stream sediment geochemistry and hydrogeochemistry. Being relatively impermeable to ground water, granitic masses may do little to buffer the pH of precipitation, and contribute a relatively minor amount of dissolved solids to affect conductivity and alkalinity.

Undifferentiated granite gneiss *(gg1)* is found principally as a large mass in Upson County with lesser amounts in Lamar, Pike, and Talbot Counties (Fig. A-3). Granite gneiss (*gg4*) is located in southeastern Fulton, northern Fayette, and western Clayton Counties (Fig. A-3).

**Intermediate (Biotite) Gneisses:** Intermediate or biotite gneisses (Fig. A-4) include the rock units *fg1* - biotite gneiss/feldspathic biotite gneiss, *fg3* - biotitic gneiss/mica schist/amphibolite, and *bg1* - biotite gneiss (Table 1) on the Geologic Map of Georgia. These rocks represent nearly 5 percent of the Flint River Basin. Biotite gneiss/feldspathic biotite gneiss (*fg1*) is found in eastern Pike and western Lamar Counties (Fig. A-4). The biotite gneiss (*fg3*) is represented principally by a large mass in Fayette, Clayton, Henry, and Spalding Counties (Fig. A-4).

Biotite gneiss (*bg1*) is the second most abundant crystalline rock type (approximately 9 percent) in the Flint River Basin, and is found principally in the southernmost part of the Piedmont. The largest mass extends from Crawford through Upson and Taylor and into Talbot County (Fig. A-4). Additional smaller masses are found in northern Talbot and southeastern Meriwether Counties.

**Amphibolites and Amphibolite Gneisses:** Amphibolites, amphibolitic gneisses and schists are represented by units *mm1* -amphibolite, *mm2* - hornblende gneiss, *mm3* - hornblende gneiss/amphibolite, *mm4* - hornblende gneiss/amphibolite/ granite gneiss, *mm5* - hornblende-biotite gneiss/amphibolite and *mm9* - amphibolite/mica schist/biotitic gneiss (Table 1) on the Geologic Map of Georgia. These rock units represent approximately 2 percent of the Flint River Basin. Amphibolites may also be present in units such as *fg3* - biotitic gneiss/mica schist/amphibolite, *gg4* - granite gneiss/ amphibolite, and *pms3a* - mica schist/gneiss/amphibolite (Table 1). Amphibolitic rocks are generally concentrated in the northern and southern parts of the Piedmont in the Flint River Basin (Fig. A-5).

Hornblende gneiss *(mm4)* is the most abundant amphibolitic rock type and is represented by an elongate body that extends from Muscogee County through Harris County and into Talbot County (Fig. A-5). These amphibolitic rocks may be the Phenix City Gneiss of the Uchee terrane. Hornblende gneiss *(mm2)* is represented principally by three bodies in Coweta, Fayette, Clayton, and Meriwether Counties. Scattered small masses of the amphibolite *(mm1)* are found in Fulton, Coweta, and Meriwether County. Only one small occurrence of the hornblende gneiss *(mm3)* is found in Talbot County (Fig. A-5). A moderately-sized mass of the amphibolite *(mm9)* is found in Fulton and Coweta Counties. A moderately sized mass of hornblende-biotite gneiss *(mm5)* is located in northeastern Fayette County and adjacent Clayton County.

Amphibolitic rocks are commonly interpreted to be metamorphosed mafic volcanic rocks. 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 flow through metavolcanic rocks.

## *Metasedimentary Rocks*

Metasedimentary rock units shown on the Geologic Map of Georgia include aluminous schists, mica schists and quartzites. These metasedimentary rocks constitute approximately 44 percent of the crystalline rocks of the Piedmont in the Flint River Basin with various mica schists making up the bulk of these rocks. The dominance of mica schists in this part of Georgia is compatible with the disposition of metasediments as discussed in Cocker (1998). A northeast to southwest decrease in sediment size, as suggested in Cocker (1998), is compatible with a southwesterly prograding clastic wedge extending across northwestern Georgia into Alabama during the Cambrian and Ordovician (Thomas and Neathery, 1980). The Pine Mountain terrane is geologically distinct from the Inner Piedmont and Blue Ridge terranes to the north, which may explain the abundance of quartzites in the Pine Mountain terrane.

**Quartzites:** Quartzites are represented by the rock unit *q1* (Table 1). The quartzite *q1* is found in the Pine Mountain terrane and holds up the sinuous ridges known as Pine Mountain. Numerous large folds have repeated this unit which can be found in Meriwether, Talbot, Upson, Pike, and Lamar Counties (Fig. A-6).

**Schists:** Mica schists, which include the rock units *pms1* - mica schist, *pms3* - mica schist/gneiss, and *pms3a* - mica schist/gneiss/amphibolite (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 schist *(pms3a)* is the third most abundant (approximately 8 percent) rock type in the Flint River Basin which is quite similar to its presence (approximately 8 percent) in the adjacent Chattahoochee River Basin (Cocker, 1998). The largest concentration of this rock type is depicted as one large mass extending from Coweta and southern Fayette Counties to Talbot and Upson Counties (Fig. A-7). This is a continuation of the mica schist noted in the Chattahoochee River Basin in Troup, Harris, Talbot, and Meriwether Counties. Mapped occurrences of the mica schist *(pms1)* are found principally in Fayette County and also in Pike and Upson County. The mica schist *(pms3)* is located mainly in Talbot County (Fig. A-7) and is the extension of the unit noted in Harris County in the Chattahoochee River Basin.

Aluminous schists *(pa1* and *pa2)* are located in two parts of the Flint River Basin (Fig. A-8). The aluminous schist *(pa1)* is located in southern Fulton County and is part of the same unit noted in the Chattahoochee River Basin (Cocker, 1998). Also, the sillimanite schist *(pa2)* in eastern Coweta County is part of the same unit noted in the Chattahoochee River Basin (Cocker, 1998). A large mass of this rock type extends across Pike and Lamar Counties. Aluminous schists may represent concentrations of more aluminous sediments such as kaolinitic clays or perhaps alteration clays associated with hydrothermal activity. The association of most of the mapped aluminous schists with rocks of sedimentary origin suggests that the aluminous schists may also be sedimentary.

## *Mylonite and Flinty Crush Rock*

Mylonites and flinty crush rock represent annealed or silicified zones of intense faulting or shearing. Mylonites, represented by *c1*, are found in two parts of the Flint River Basin (Fig. A-9). Mylonites in Pike and Meriwhether Counties mark the traces of the Towaliga fault zone, and mylonites in Upson County may mark the extension of the Bartlett's Ferry fault. Flinty crush rock *(c2)* is essentially a silicified breccia with silica having replaced most if not all of the breccia fragments and the matrix. One occurrence of flinty crush rock is found in Talbot County and is along strike of another flinty crush rock zone noted in the Chattahoochee River Basin (Cocker, 1998). These occurrences are generally subparallel to the strike of the Goat Rock fault. Other masses of unmapped flinty crush rock have been noted by the author in the Flint River Basin (Cocker, unpublished field notes).

## Structural Geology and Tectonic Terranes

Within the Flint River Basin, three tectonostratigraphic terranes are currently recognized: the Inner Piedmont, Pine Mountain terrane, and Uchee terranes (Fig. A-1). 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 Inner Piedmont terrane is separated from the Pine Mountain terrane (Fig. A-1) by the Towaliga fault zone (Williams, 1978). The Goat Rock fault zone separates the Pine Mountain terrane from the Uchee terrane. Tectonostratigraphic terranes, most crystalline rock units and major faults in the Georgia Piedmont as depicted on the Geologic Map of Georgia, strike approximately N 45° E and define the regional tectonic fabric. Mesozoic mafic igneous dikes (diabase) cut across the main regional fabric in a northwest to southeast direction. A few post tectonic granitic intrusions may also cut across the regional tectonic fabric, but without a preferred orientation.

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; Nelson and others, 1987; Higgins and others, 1988; Nelson, 1988; Nelson and others, 1990). Boundaries between these thrust sheets are either poorly defined or concealed (Nelson and others, 1987). Although effects of these thrust sheets are presently difficult to define, the three major tectonostratigraphic terranes noted above appear to affect the basin's composition. Each of these terranes contains metasedimentary, metavolcanic, and granitic rocks. Differences in composition and volumes of these rock units, as well as metamorphic and structural development, influence regional geochemistry and hydrogeochemistry in the Piedmont of the Flint River Basin.

Major geologic structures determine the spatial distribution of rock units within a 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 the Towaliga and Goat Rock faults are generally not mineralized, secondary structures related to these faults may be important hosts to metal mineralization.

Within the Flint River Basin, traces of major faults (Fig. A-1) that extend through the basin are marked by intensely sheared cataclastic rocks (Fig. A-9). The Towaliga fault zone (Fig. A-1) is 4.5 to 6 miles wide and consists of blastomylonite, porphyroblastic blastomylonite, mylonite, mylonite gneiss, mylonite schist, mylonite quartzite, micro breccia (Fig. A-9), and slices of the Pine Mountain metasedimentary rocks (Thomas and Neathery, 1980). The Goat Rock fault zone (Fig. A-1) 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.

## Coastal Plain Strata

The Coastal Plain within the Flint River Basin contains sixteen rock units that include Late Cretaceous to Miocene strata as well as Quaternary alluvium. Average dips are low, on the order of 30 to 50 feet per mile to the southeast. Map patterns of these strata are generally in the form of southwardly pointed V's resulting from the geometry of their southeasterly dip and the gradient of the Flint River. Intricate dendritic map patterns are developed for the Cretaceous and Paleocene strata in the northern part of the Coastal Plain (Figs. A-10, A-11). Sandy and clayey strata are dominant in the Cretaceous rocks, and calcareous rock units are more abundant in younger strata. Paleocene to middle Eocene rocks are mixed carbonate rocks and clastic rocks. Late Eocene and Oligocene rocks are dominantly carbonates. Miocene rocks are a mixture of dolostones and clastic sediments.

More recent geologic mapping and stratigraphic analyses of the Georgia Coastal Plain by Huddlestun (1988, 1993), and Hetrick (1990a,b) have redefined the stratigraphy and distribution of sedimentary formations in Georgia's Coastal Plain. Studies by Reinhardt and Donovan (1986) and Reinhardt and others (1980) focused on older sediments of the Cretaceous and Paleocene. The Flint River Basin lies along an axis of varied and rapidly changing depositional environments between the Gulf of Mexico and the Atlantic Ocean. Depositional conditions changed rapidly from east to west and north to south from the Cretaceous and into the Miocene (Reinhardt and Donovan, 1986; Reinhardt and others, 1980). In general, continental to near-shore marine depositional environments are dominant toward the east and north in the Coastal Plain. More marine depositional environments are found to the west, to the south and down-dip. Depositional environments strongly affected the composition of the sediments and thereby affect the composition of the stream sediments and stream water that flows through them.

### Cretaceous

Cretaceous sediments occupy approximately 11 percent of the Flint River Basin (Fig. A-11). Most of these sediments are located in Chattahoochee, Stewart, Marion, Webster, Schley, Macon, Taylor, Crawford, and Peach Counties. Map units include the Tuscaloosa Formation (*Kt*), the Eutaw Formation (*Ke*), the Blufftown Formation (*Kb*), the Cusseta Sand (*Kc*), the Ripley Formation (*Kr*), and the Providence Sand (*Kp*). Cretaceous sediments form a wide band that narrows to the northeast across the Flint River Basin. East of the Flint River, the Blufftown Formation, Eutaw Formation, and Cusseta Sand are undivided on the State Geologic Map coverage. Average dips are low, on the order of 30 to 50 feet per mile to the southeast. The dendritic drainage pattern and the low dips strongly influence the outcrop patterns of these sediments. Most of the sediments are composed of micaceous, feldspathic, quartzose sand.

The lowermost unit, the Tuscaloosa Formation (*Kt*) lies directly on crystalline basement rocks of the Piedmont. 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 correspond 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). The Tuscaloosa Formation (*Kt*) consists of generally reddish-brown, micaceous, feldspathic, massive, non-marine clayey sand and sandy clays (Lukett, 1979). Kaolinitic lenses 5 to 10 feet thick and up to 50 feet across are common (Eargle, 1955). This unit is considerably thinner in the Flint River Basin with thicknesses of only 60 to 80 feet (Lukett, 1979) as compared to an average of 250 feet in the Chattahoochee River Basin.

The Eutaw Formation (*Ke*) is composed of two units. The basal unit is a coarse-grained, feldspathic, quartzose sand. This unit ranges in thickness from 18 feet to 40 feet near the Chattahoochee River. The upper unit consists of micaceous, carbonaceous, silty sand, sandy silt and silty sandy clay. Thickness of this unit is 75 to 100 feet near the Chattahoochee River. The Eutaw Formation changes from marine in the Chattahoochee River area to non-marine east of the Flint River (Eargle, 1955; Lukett, 1979). Analysis by Frazier (1982) suggests that Eutaw strata were deposited in a barrier-island complex that formed in a transgressive regime.

Overlying the Eutaw Formation is the Blufftown Formation (*Kb*) which consists of a lower unit of coarse-grained quartzose sand overlain by sandy, carbonaceous, highly micaceous clay. In the vicinity of the Flint River, the Blufftown Formation is thin and discontinuous. Environment of deposition changes from marine to a marsh environment from the Chattahoochee to the Flint River (Lukett, 1979). The Cusseta Sand (*Kc*) is the third most abundant Cretaceous lithology exposed over approximately 2 percent of the basin. This unit lies on top of the Blufftown Formation and consists of a basal, thin, friable, coarse-grained, ferruginous sandstone overlain by fine to coarse-grained, cross-bedded sands. Kaolinitic clays and sandy clays occur in two beds near the top and near the lower part of the formation. Depositional environment of the Cusseta Sand in much of the Flint River Basin is fluvial; to the west the formation becomes marginal marine (Lukett, 1979). The Ripley Formation (*Kr*) consists of ferruginous, sandy clay overlain by micaceous, silty, sandy clay, and micaceous sand (Lukett, 1979). Environment of deposition is marine. The Providence Sand (*Kp*) consists of a basal coarse-grained, ferruginous sandstone overlain by sand, clayey sand and sandy clays with a few kaolinitic lenses (Lukett, 1979). Environment of deposition is thought to be fluvial in the Flint River area and changes to shallow marine to the west (Lukett, 1979). Hetrick (1996) noted that the Providence Formation is 40 to 110 feet thick near the Flint River. Strike and dips were measured as N47°E and 30 feet per mile to the southeast (Hetrick, 1996). Saturated, permeable sands in the Providence Sand constitute the Providence aquifer, an important aquifer in the upper part of the Coastal Plain (McFadden and Perriello, 1983).Together, the Providence Sand and the Blufftown Formation cover approximately 60 percent of the outcrop area of Cretaceous sediments in the Flint River Basin. The dominance of sandy sediments in the Cretaceous section should have a strong impact on stream sediment composition, and stream and ground water hydrogeochemistry.

### Paleocene

Paleocene age sediments occupy less than 4 percent of the Flint River Basin (Fig. A-11). Most Paleocene sediments are found in Calhoun, Randolph, Terrell, Stewart, Webster, Schley, Sumter, and Macon Counties in the west central part of the Flint River Basin. Paleocene sediments include the Clayton Formation (*Pc*), the Porters Creek Formation (*Pcn*), the Nanafalia Formation (*Pnf*), and the Tuscahoma Formation (*Ptu*).

Near the Chattahoochee River, 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 (Cocker, 1998). Near the Flint River, the Clayton Formation is much thinner and consists of argillaceous, sandy, fossiliferous limestone (Lukett, 1979), or according to Hetrick (1996) silty to finely sandy, dense clay, fine-to medium-grained sand. Depositional environment is believed to be shallow water marine (Lukett, 1979). 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. Heavy metal content of the iron oxides is unknown. 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 Periello, 1983).

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). Environment of deposition is thought to be marine (Lukett, 1979). Nonmarine updip facies of the Nanafalia Formation (*Pnf*) consist of highly micaceous, carbonaceous sand with some kaolinitic clay. Lukett (1979) indicated that these sands were fluvial in origin. Bauxites were mined from this unit in the Eufaula district in Alabama, and the Andersonville and Springvale districts in Georgia (Fig. 5). Marine portions of this formation are highly micaceous, carbonaceous silt and fine sand. Marine sediments are located to the west and south of the Eufaula bauxite district in Alabama (Clarke, 1992). The Nanafalia Formation (*Pnf*) is located mainly in Macon, Sumter, Schley and Webster Counties (Fig. A-11). Lukett (1979) referred to the bauxitic sands as the Gravel Creek Sand. Lenses of bauxitic-kaolinitc clay are up to 20 feet thick and may be greater than a hundred feet wide. The Tuscahoma Formation (*Ptu*) is mainly composed of interlaminated clay, silty clay, and fine quartzose sand. Highly glauconitic, coarse-grained sand is found at the base of this formation. Thicknesses range from 90 to 153 feet in the Chattahoochee River area. In the Flint River area, the Tuscahoma Formation is thin and discontinuous (Lukett, 1979). Environment of deposition is believed to be marginal marine marsh (Lukett, 1979). The Tuscahoma Formation is found principally in Randolph, Calhoun, Terrell, Webster, and Sumter Counties (Fig. A-11).

## *Eocene*

Eocene strata as depicted on the Geologic Map of Georgia include undifferentiated Claiborne (*Ec*), the Ocala Limestone (*Eo*), and the Twiggs Clay (*Etw*), and these units cover 32.72 percent of the Flint River Basin (Fig. A-12). Undifferentiated Eocene-Oligocene residuum (*Eo-Os*) covers an additional 12.68 percent of the basin. Eocene and undifferentiated Eocene-Oligocene sediments cover most of the lower half of the basin extending from Seminole County to Crawford County. Recent geologic studies suggest that much of the sediments mapped as undifferentiated residuum are Oligocene rather than Eocene in age (Huddlestun, 1993). Also, Eocene stratigraphy was redefined with establishment of the Claiborne and Ocala Groups.

Middle Eocene rocks of the Claiborne Group include the Lisbon and Tallahatta Formations. The Tallahatta Formation is also included in the undifferentiated Eocene (*Eu*). The Tallahatta Formation overlies the Paleocene rocks and consists of fine to coarse sand, sandy, cherty, clay or marl, and dense, massive, sandy, fossiliferous limestone (Herrick and Vorhis, 1963). This formation is also described as a reddish-brown clayey sand with lesser amounts of gravel. Down-dip the formation consists of relatively clean sands with thin clay interbeds. Depositional environment for the Tallahatta Formation in this area is believed to be a low energy fluvial regime (Lukett, 1979). The Lisbon Formation consists of interbedded, fine to coarse fossiliferous sand, silty, micaceous, glauconitic, locally cherty clay or marl, and occasional beds of sandy, glauconitic limestone (Herrick and Vorhis, 1963). The Tallahatta Formation and the lower part of the Lisbon Formation host the Claiborne aquifer.

Upper Eocene strata consist of the Ocala Group and may constitute the largest portion (approximately 30 percent) of the Eocene sediments. These strata extend from Early and Seminole Counties northeastward to Dooly County. In central Georgia, the Ocala Group consists of the lower Tivola Limestone (equivalent to the Ocala Limestone (*Eo*)) and the upper Ocmulgee Formation separated by the Twiggs Clay Member of the Dry Branch Formation (Huddlestun and Hetrick, 1986). The Tivola Limestone is generally a fine to coarse, bioclastic limestone with subordinate montmorillonite, kaolinite, illite, glauconite, disseminated pyrite, and quartz sand. The Twiggs Clay (*Etw*) consists of arkosic sands interbedded with glauconitic, locally fuller's earth, fossiliferous clay or marl and locally fossiliferous limestone (Herrick and Vorhis, 1963). Sediments of the Ocmulgee Formation consist of a glauconitic, calcareous clay to an argillaceous, glauconitic, granular limestone. Undifferentiated Eocene and Oligocene residuum (*Eo-Os*) which covers nearly 13 percent of the Flint River Basin is included with the Upper Eocene strata. Spatial disposition of this residuum (*Eo-Os*) favors inclusion of this unit with the Ocala Group (*Eo*). Recent studies by Huddlestun (1988) include much of the area shown as *Eo* and *Eo-Os* on the Geologic Map of Georgia as Oligocene in age. The Floridan aquifer system is hosted by the Ocala Group as well as Oligocene and Miocene age sediments discussed below.

## *Oligocene*

The Geologic Map of Georgia show Oligocene and Miocene-age sedimentary rocks occurring along the southeastern edge of the Flint River Basin (Figs. A-13, A-14). These rocks underlie a cuesta that marks the edge between the Fort Valley Plateau and the Tifton Upland topographic divisions, which are discussed in a earlier section on land surfaces. The Suwanee Limestone (*Os*) occupies approximately 6 percent of the Flint River Basin and extends from Decatur County northeastward to Houston County.

A revision of the lithostratigraphy of Oligocene age rocks by Huddlestun (1993) has added a number of geologic units not shown on the Geologic Map of Georgia. Details concerning the distribution of these units are lacking on the page-sized maps in Huddlestun's (1993) work. As noted above, rock units that have been previously included as Eocene (*Eo* and *Eo-Os)* are included as Oligocene.

Oligocene rock units in the Flint River Basin are in the eastern Gulf of Mexico continental shelf association (Huddlestun, 1993). These units include the Marianna Limestone of the Vicksburg Group, undifferentiated residuum, the Ochlockonee Formation, Wolf Pit Dolostone, Okapilco Limestone, and Bridgeboro Limestone. The Marianna Limestone is described as an unconsolidated, massive to thick -bedded, very fine- to fine-grained limestone. Undifferentiated residuum (*Eo-Os*) consists of variably sandy clay, inclusions or blocks of chert, and ironstone and has been referred to, in the past as the Flint River Formation. Along the western edge of the Gulf Trough, which is a major structural feature (Fig. A-15) that has influenced deposition during the Oligocene and Miocene, is the calcarenitic coralline Okapilco Limestone. Also along the western edge of the Gulf Trough in the Flint River Basin is the Bridgeboro Limestone. This unit is a rhodolithic limestone in a bioclastic calcarenite (Huddlestun, 1993). Within the Gulf Trough are the Ochlockonee Formation, a variably dolomitic, somewhat argillaceous limestone, and the Wolf Pit Dolostone, a sucrosic dolostone.

### *Miocene*

Miocene rock units include the Hawthorne Formation (*Mh*), the Muccosukee Formation (*Nm*), and undifferentiated Neogene (*Nu*). The Hawthorne Formation is mapped as a narrow band extending from Decatur County into Mitchell County (Fig. A-14). The Miccosukee Formation is also shown extending from Decatur County into Mitchell County along the southeastern edge of the Flint River Basin. Miocene-age sediments north of mid-Decatur County are shown on the Geologic Map of Georgia as undifferentiated Neogene (*Nu*). The undifferentiated Neogene may include sedimentary rocks that may belong to the Hawthorne Miccosukee Formations. Together these three units occupy approximately 5 percent of the Flint River Basin. If the undifferentiated Neogene were to be subdivided based on exposures further south, the Hawthorne Formation may be expected to cover approximately 1 percent of the basin and the Muccosukee Formation approximately 4 percent.

Several stratigraphic nomenclature changes postdate the coverage of the Geologic Map of Georgia. Huddlestun (1988) elevates the Hawthorne Formation and younger sediments to the Hawthorne Group. In the Hawthorne Group argillaceous sand and clay are the dominant lithologies. Dolomite is the characteristic carbonate mineral. Clays of the Hawthorne Group may contain a large component of palygorskite and sepiolite. Hawthorne Group sediments are dominantly shallow-water, marine, continental shelf deposits. Chert, siliceous claystone, and diatomaceous sediments are locally common. Phosphatic sediments are more abundant further to the east (Huddlestun, 1988).

### *Quaternary*

Quaternary age stream alluvium and stream terrace deposits (*Qal*, Fig. A-16) cover approximately 3 percent of the Flint River Basin in Georgia on the Geologic Map of Georgia. A significant portion of the alluvial deposits are found in the northern part of the Coastal Plain in Crawford, Taylor and Macon Counties. Some of these deposits may actually be Tertiary in age (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). A small deposit of aeolian sand (*Qas*) was mapped in eastern Dougherty County (Fig. A-17). Some of these deposits could be sources of sand and gravel for aggregate or industrial sand.

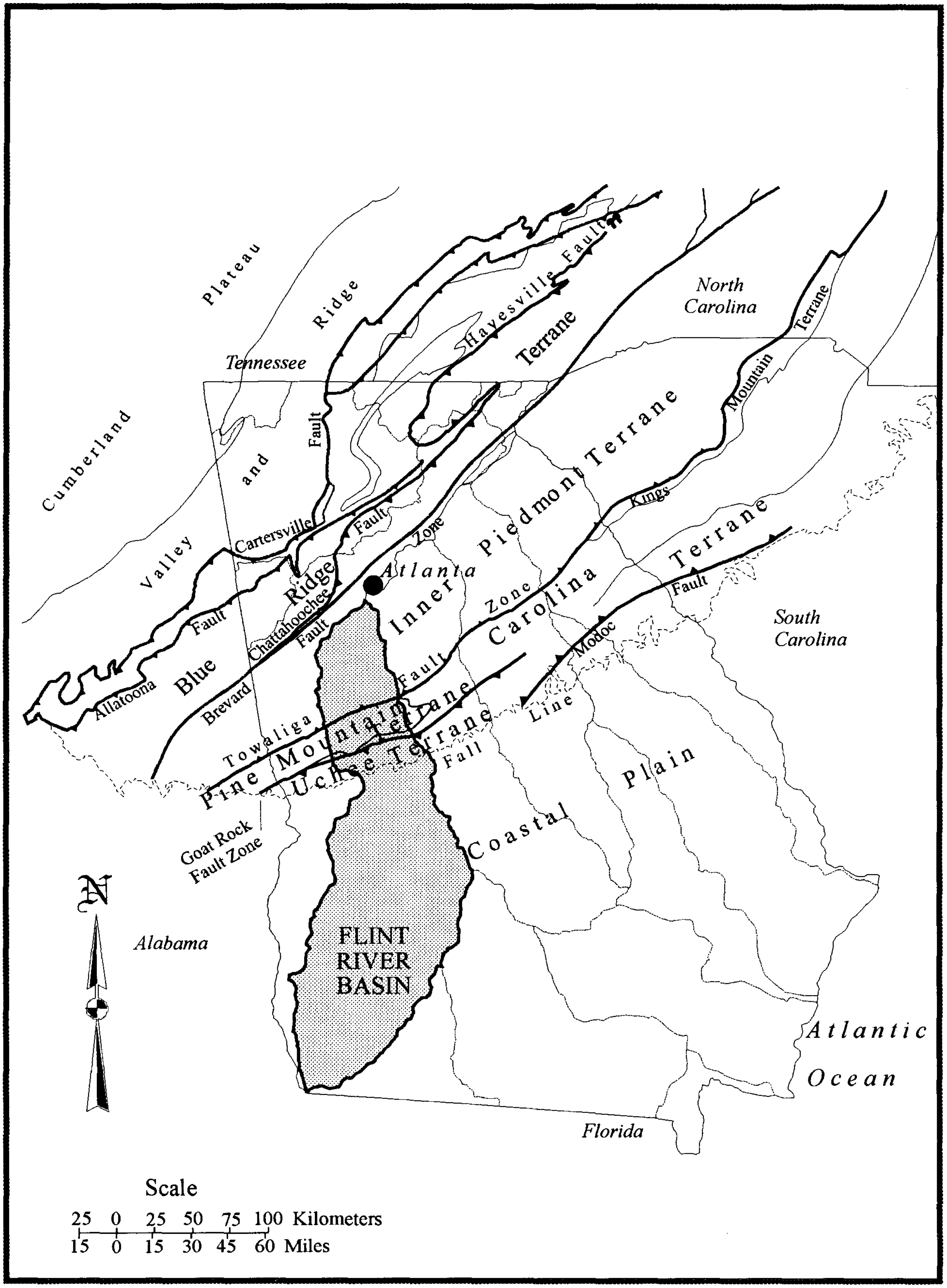

Figure A-1. Tectonic terranes and major fault structures. (Modified after Williams, 1978).

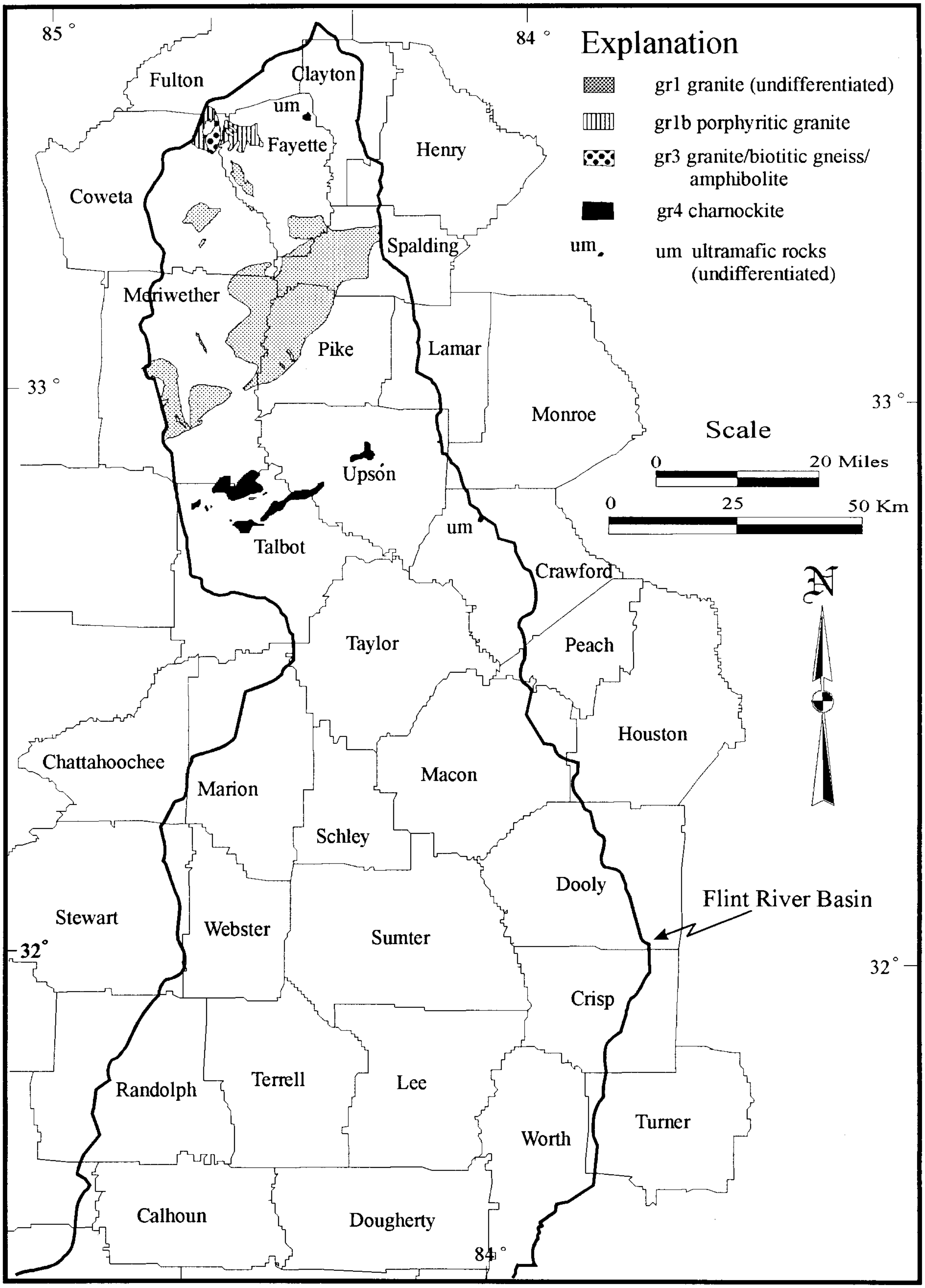

Figure A-2. Granites and ultramafic rocks.

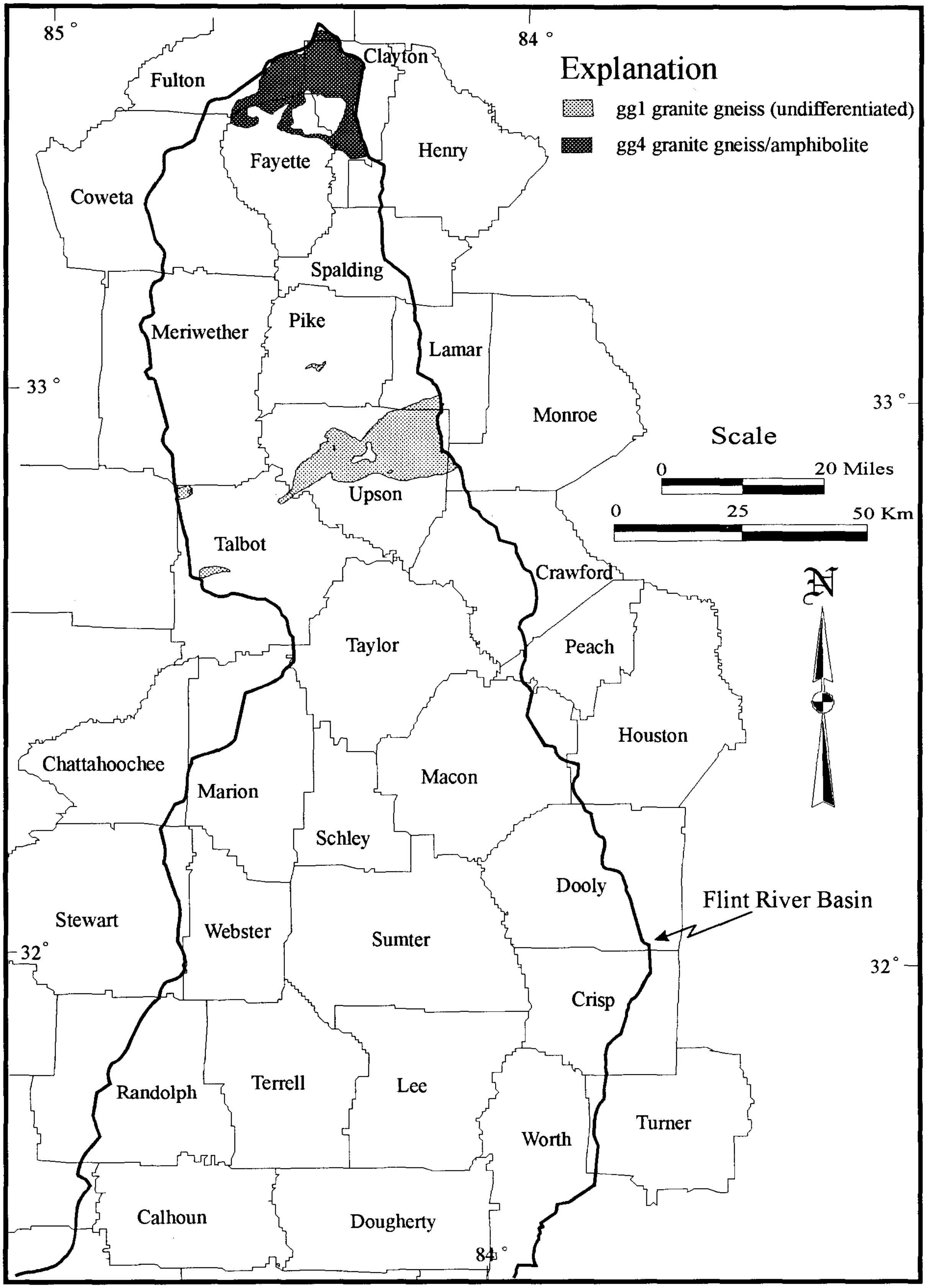

Figure A-3. Granitic gneiss.

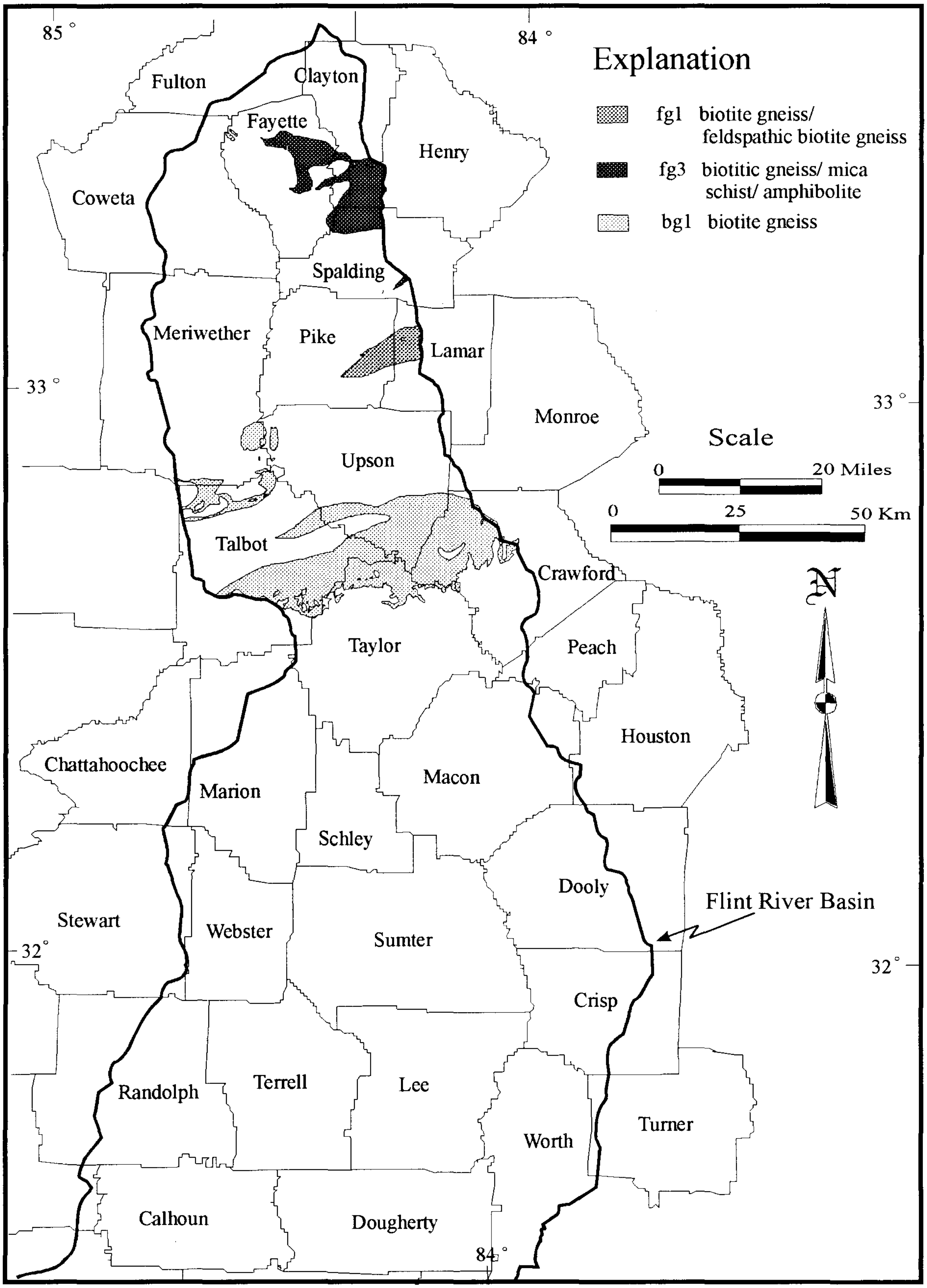

Figure A-4. Biotite gneiss.

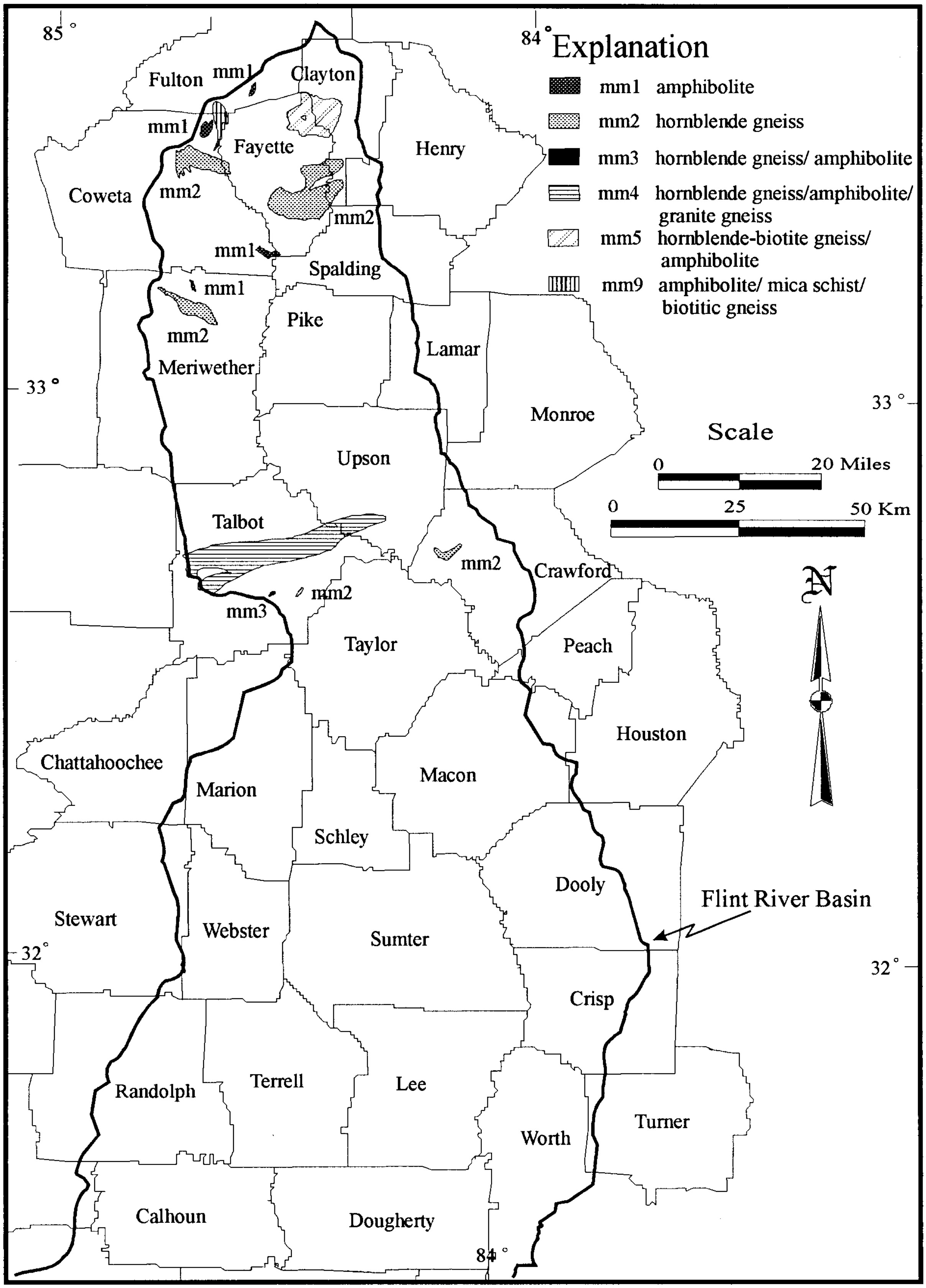

Figure A-5. Amphibolitic rocks.

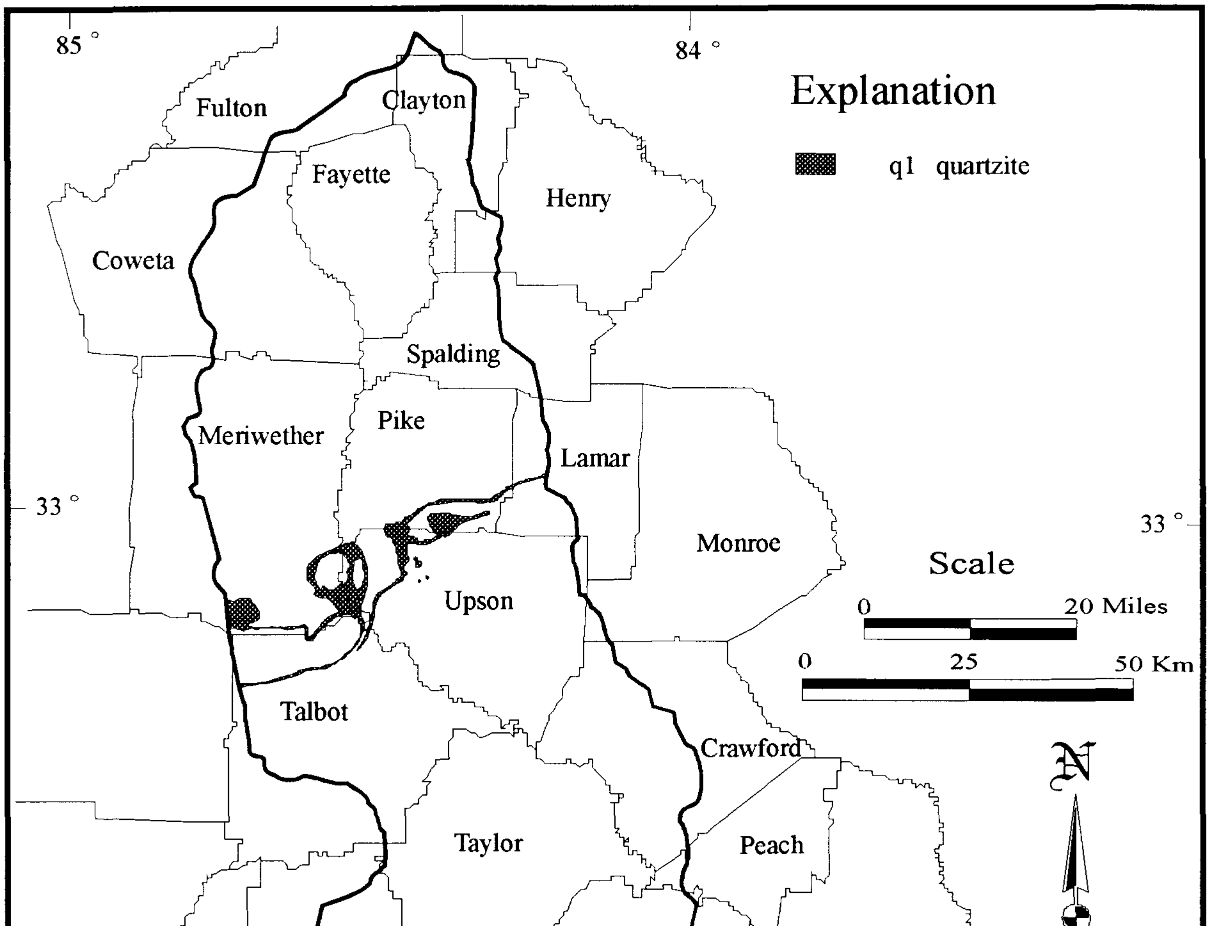

Figure A-6. Quartzites.

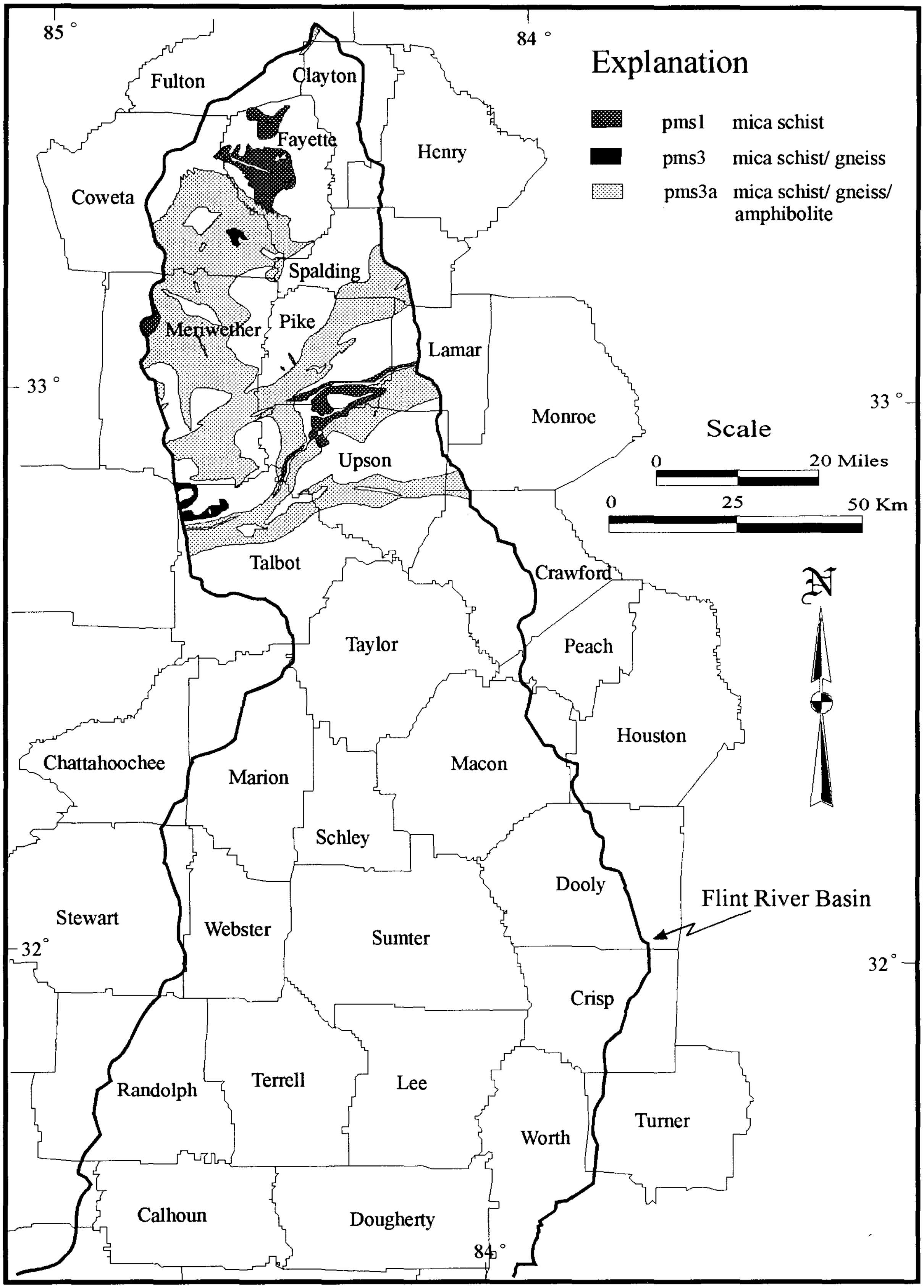

Figure A-7. Mica schists.

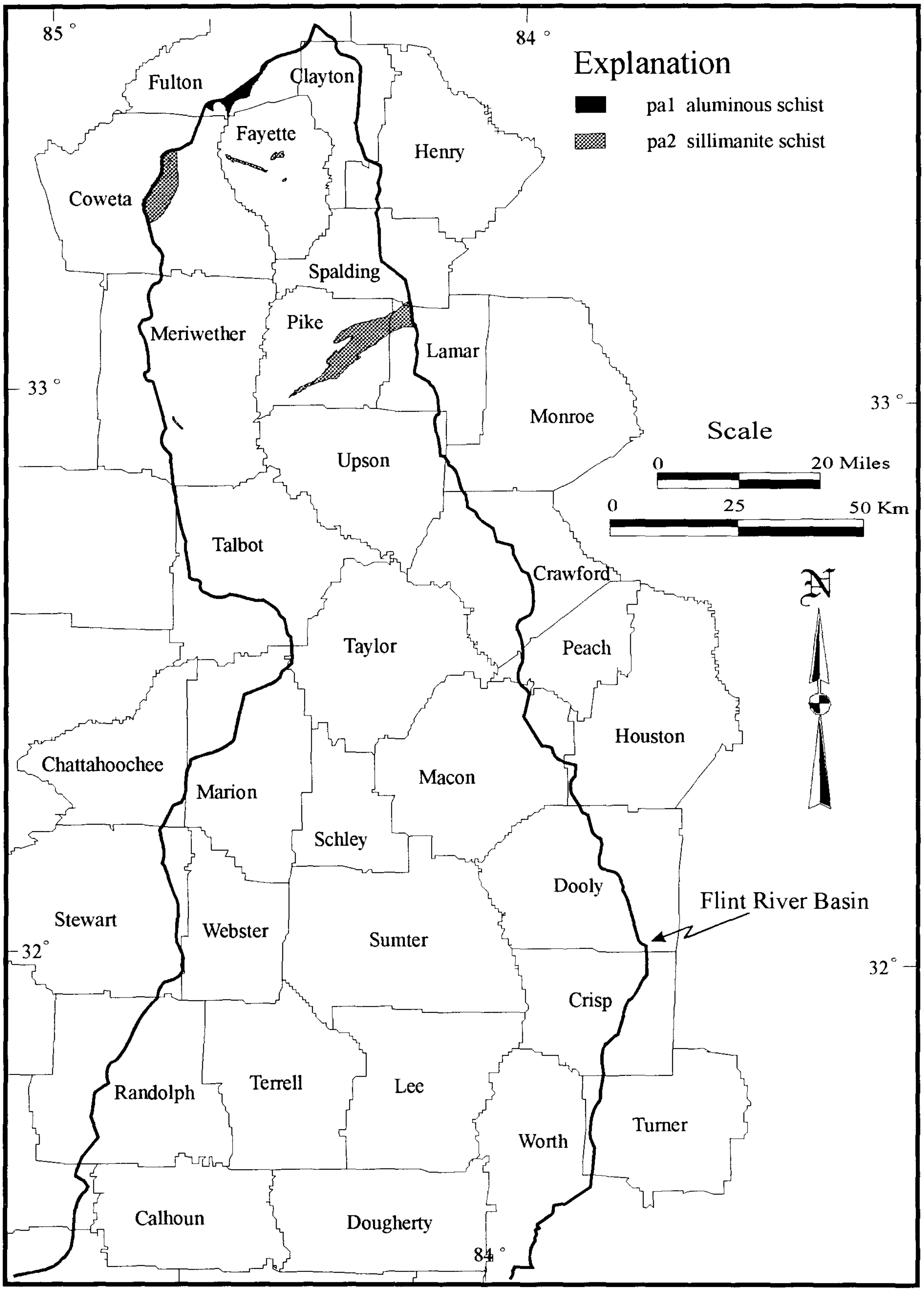

Figure A-8. Aluminous schists.

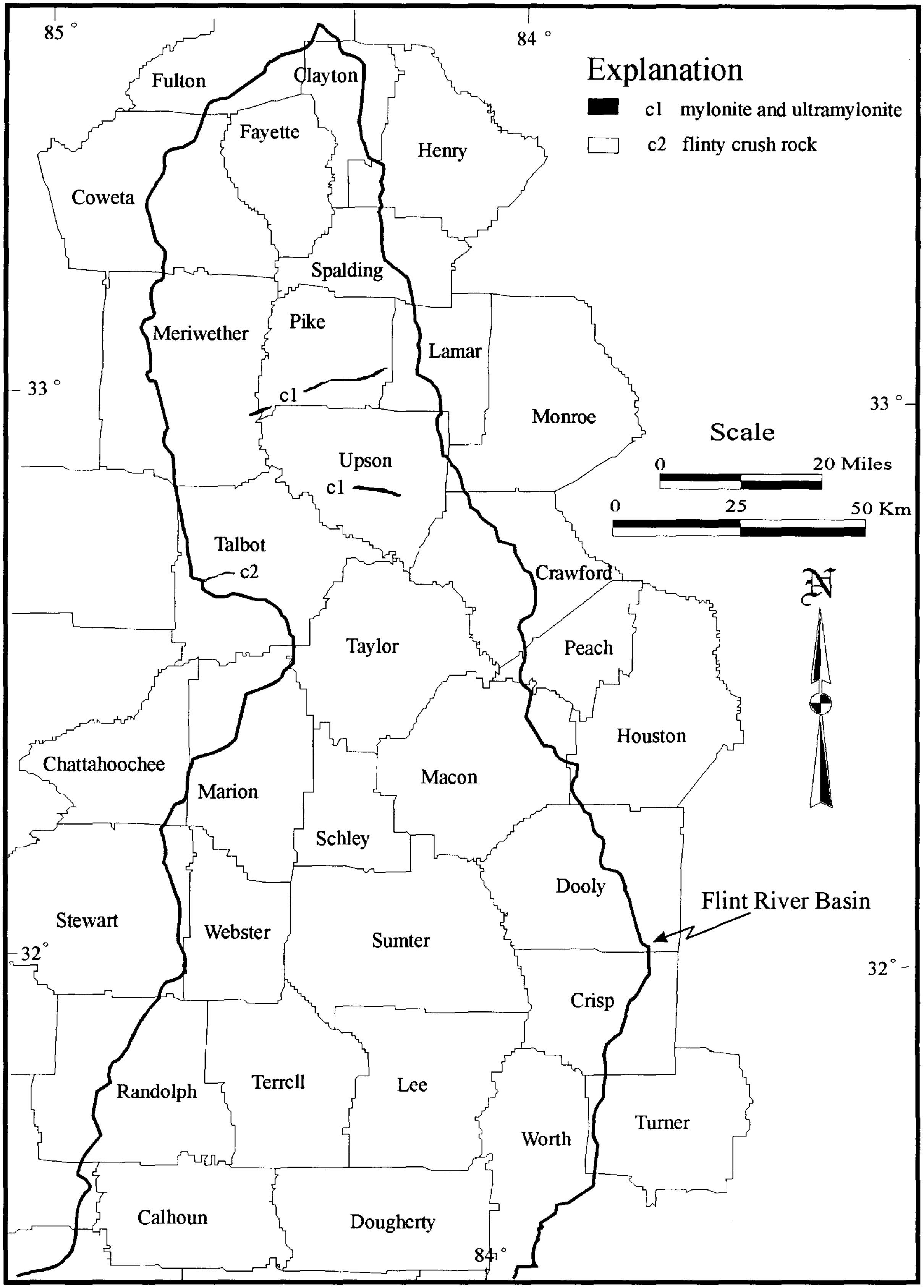

Figure A-9. Mylonites and flinty crush rock.

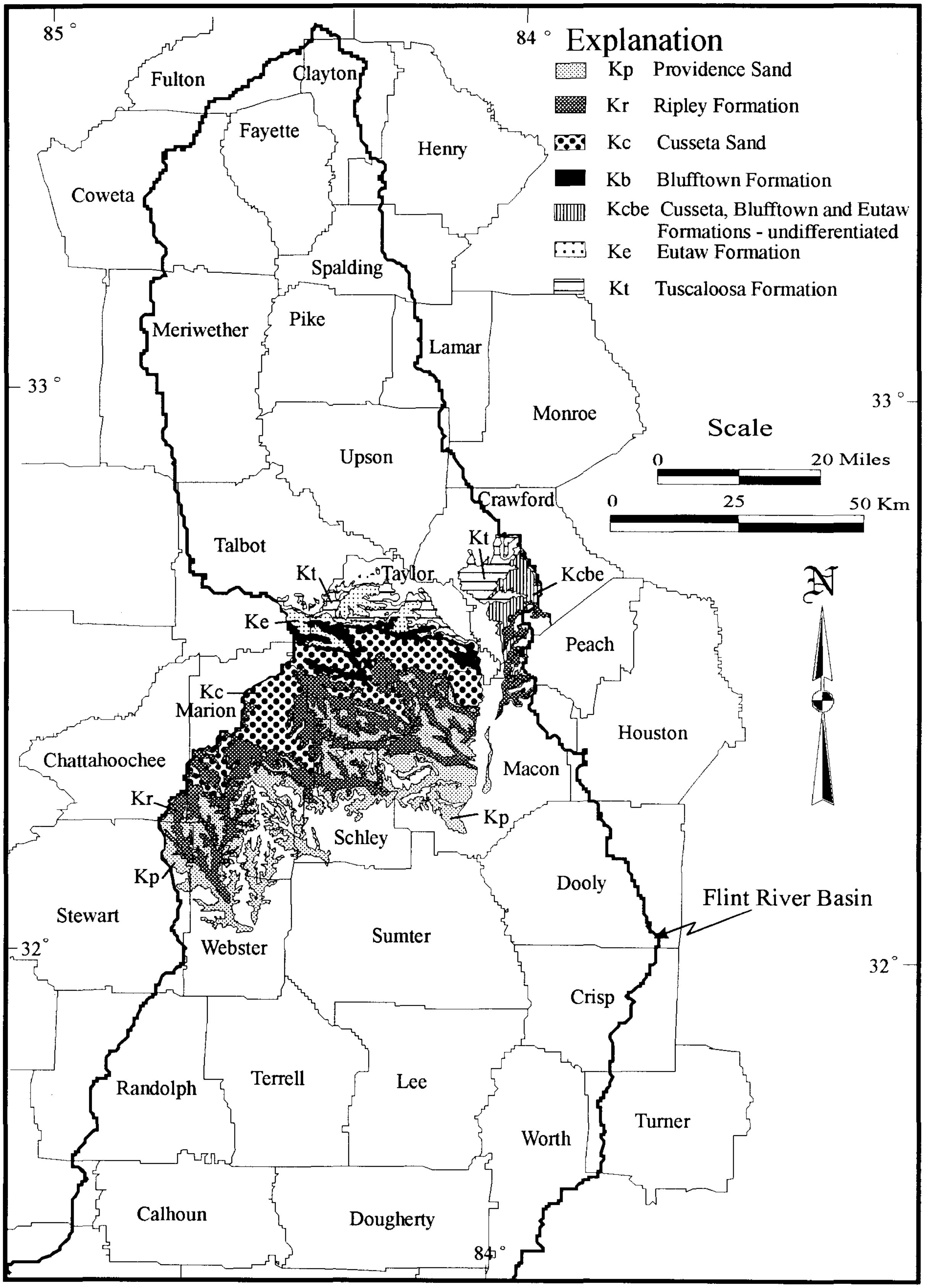

Figure A-10. Cretaceous sedimentary units.

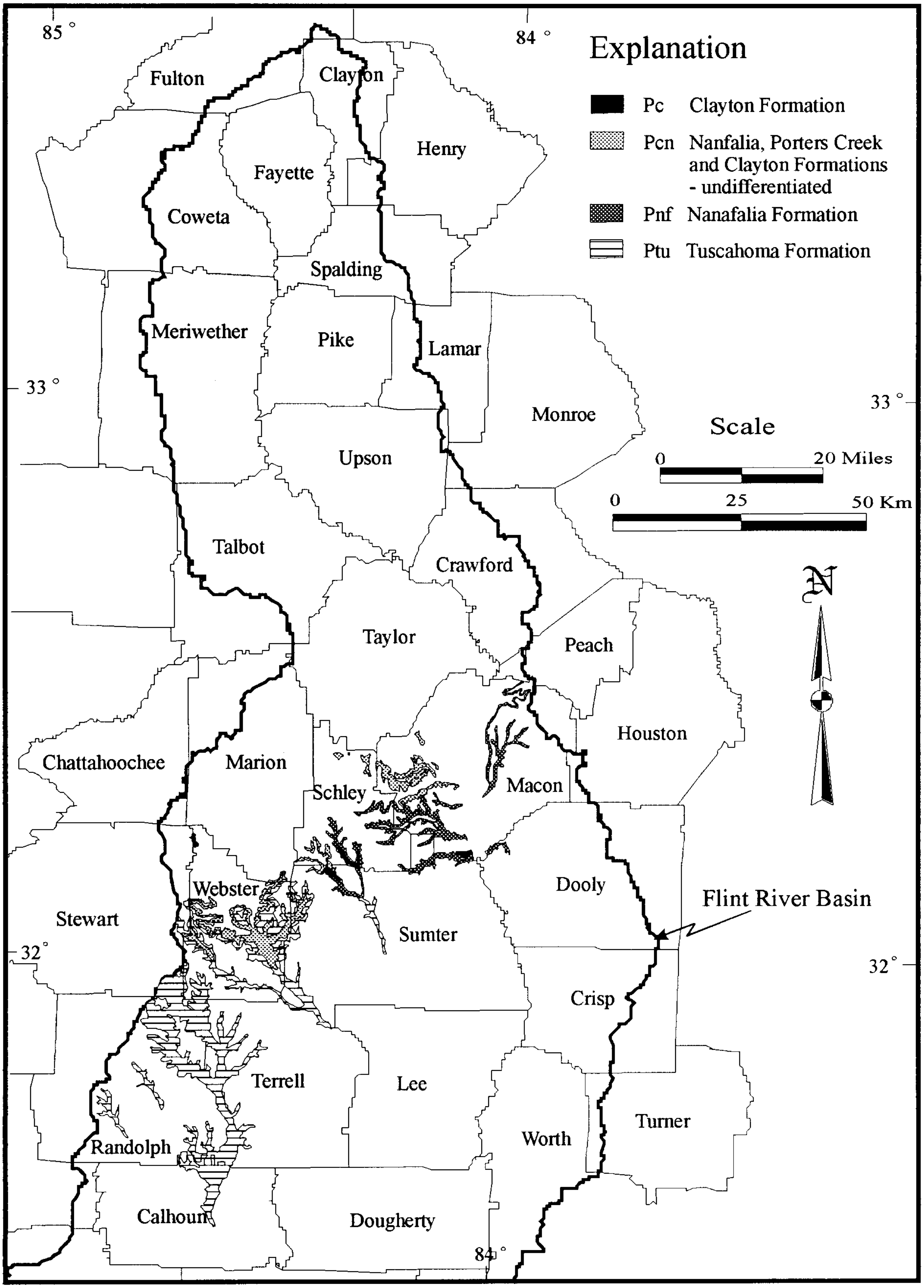

Figure A-11. Paleocene sedimentary units.

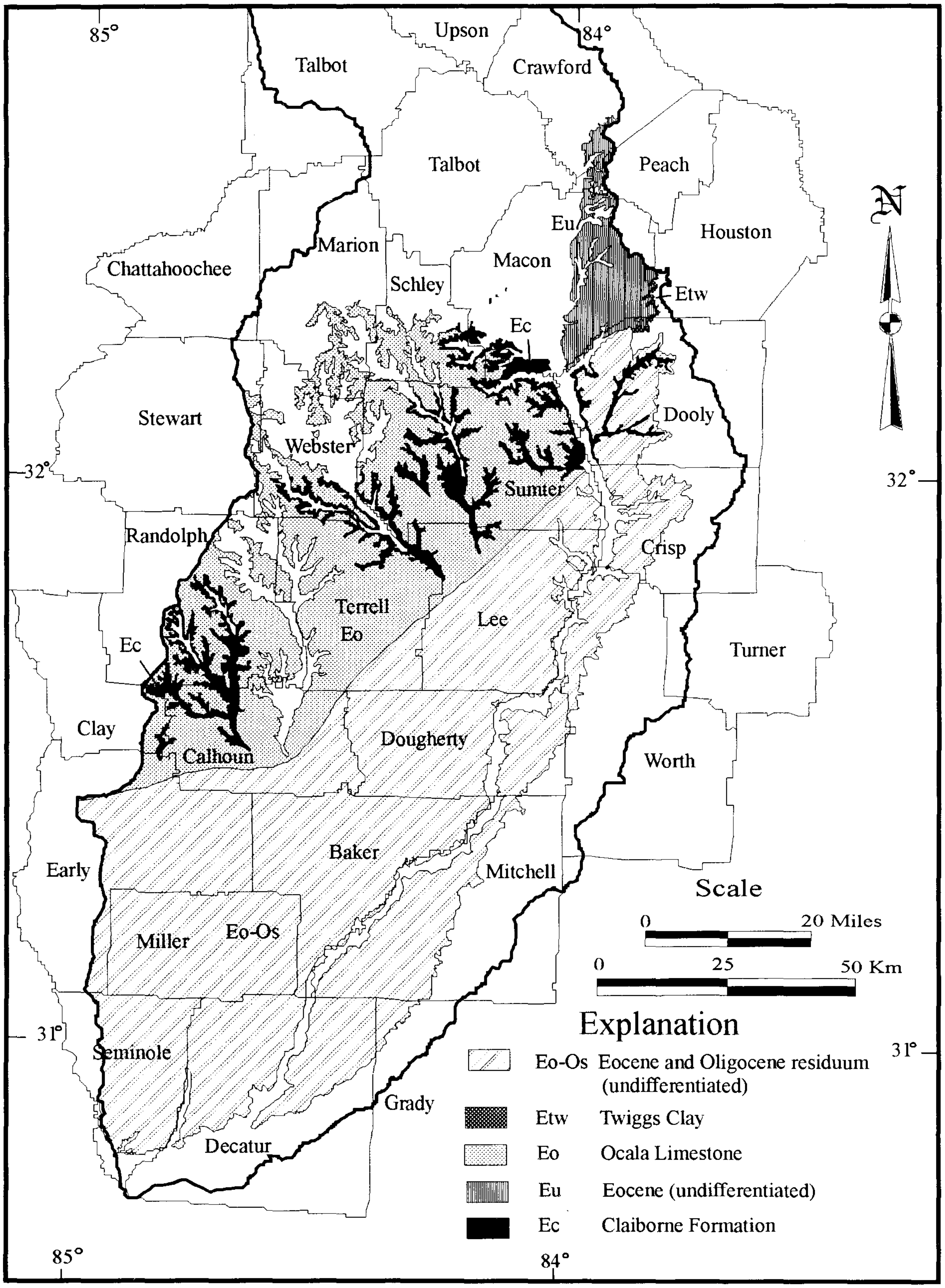

Figure A-12. Eocene sedimentary units.

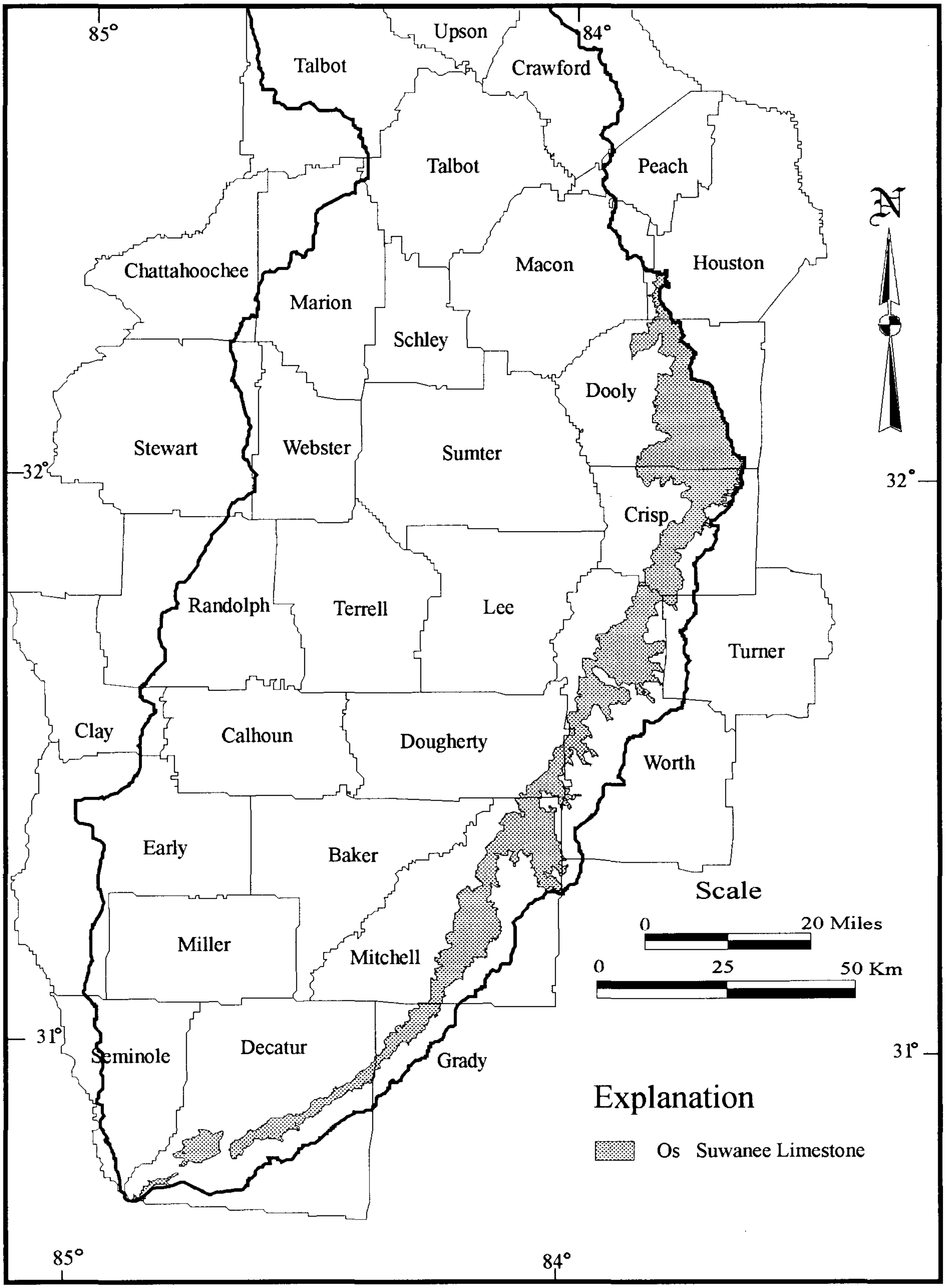

Figure A-13. Oligocene sedimentary units.

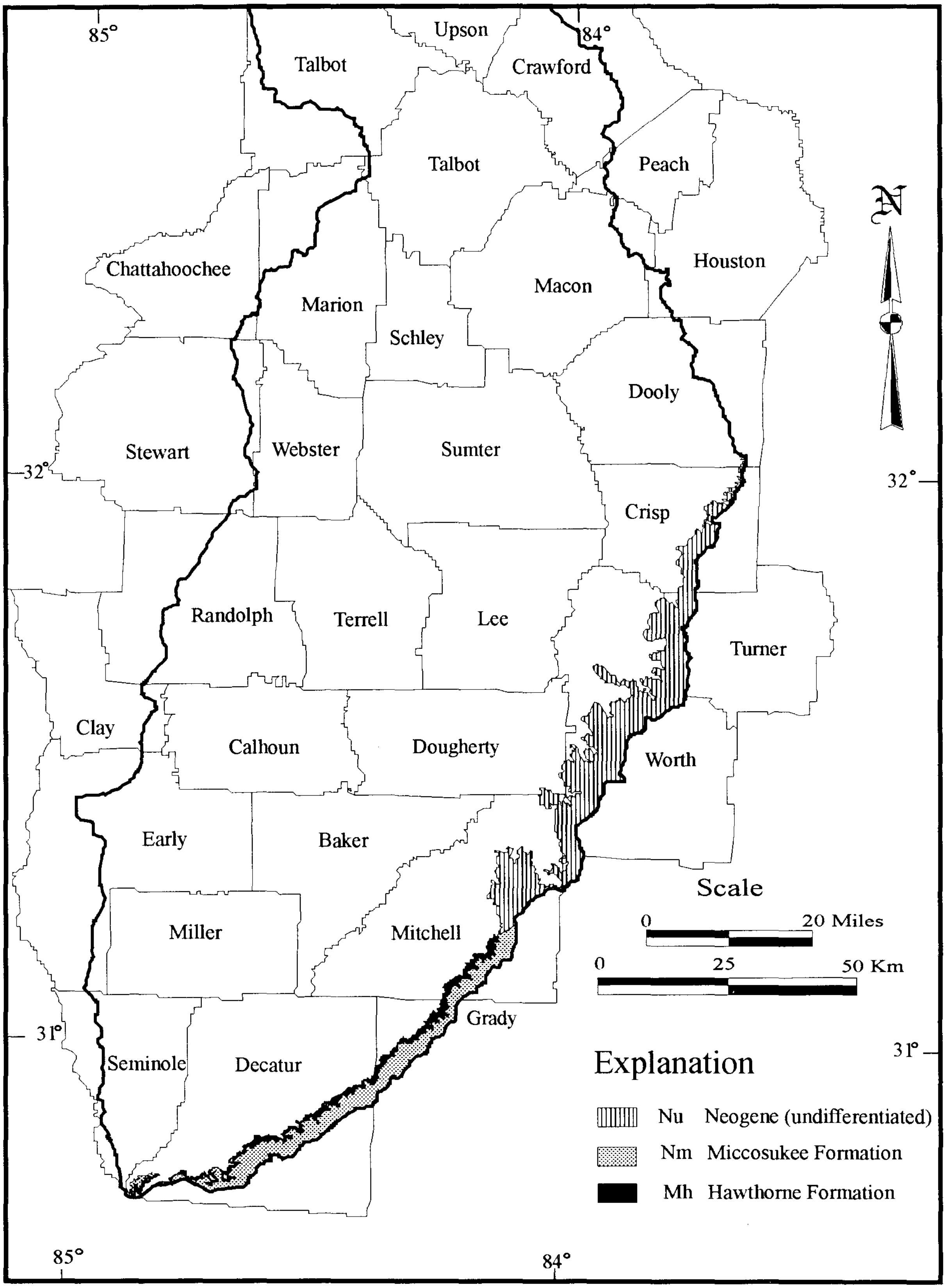

Figure A-14. Miocene sedimentary units.

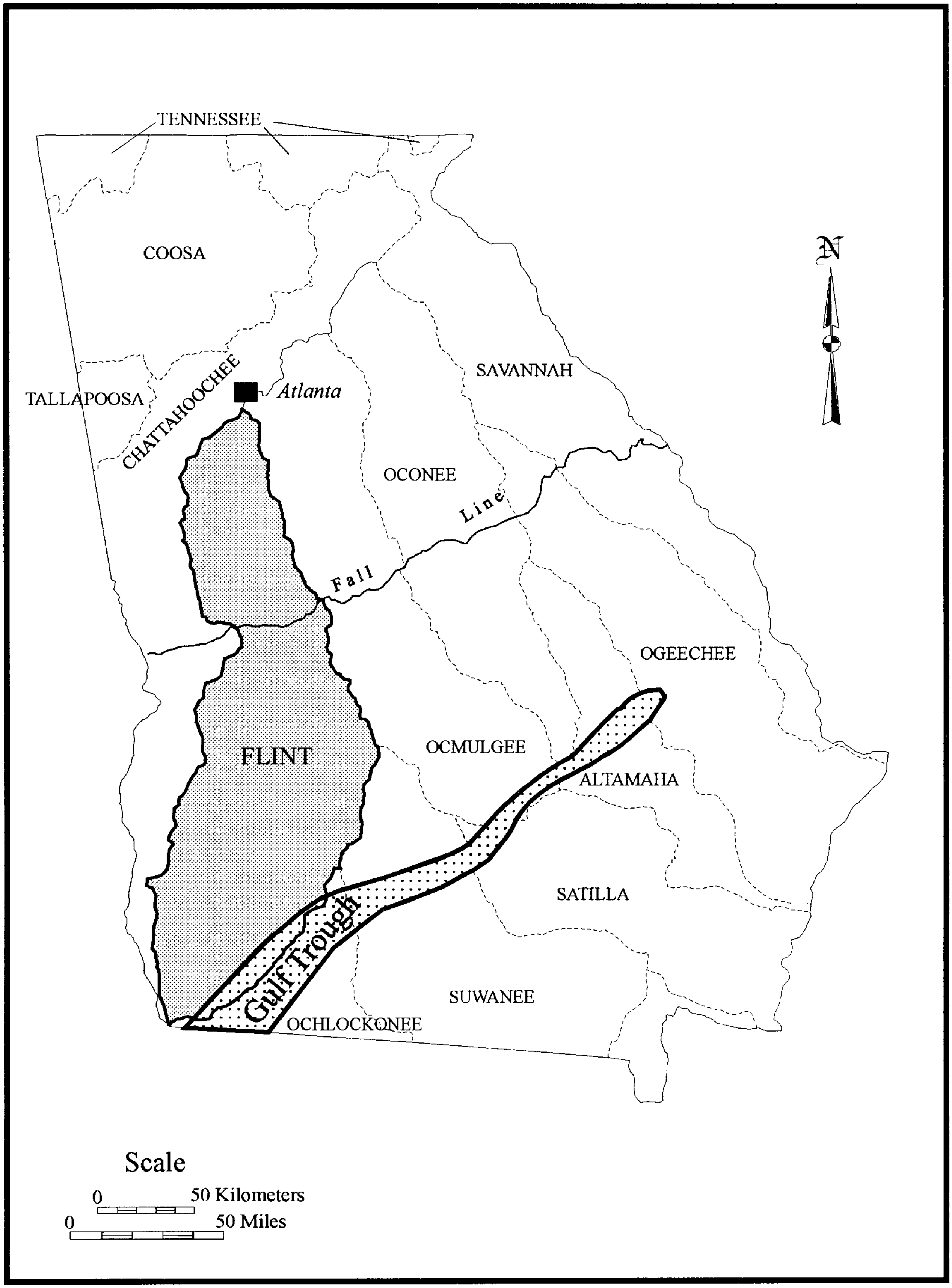

Figure A-15. Disposition of the Gulf Trough in Georgia. (Modified from Huddlestun, 1993).

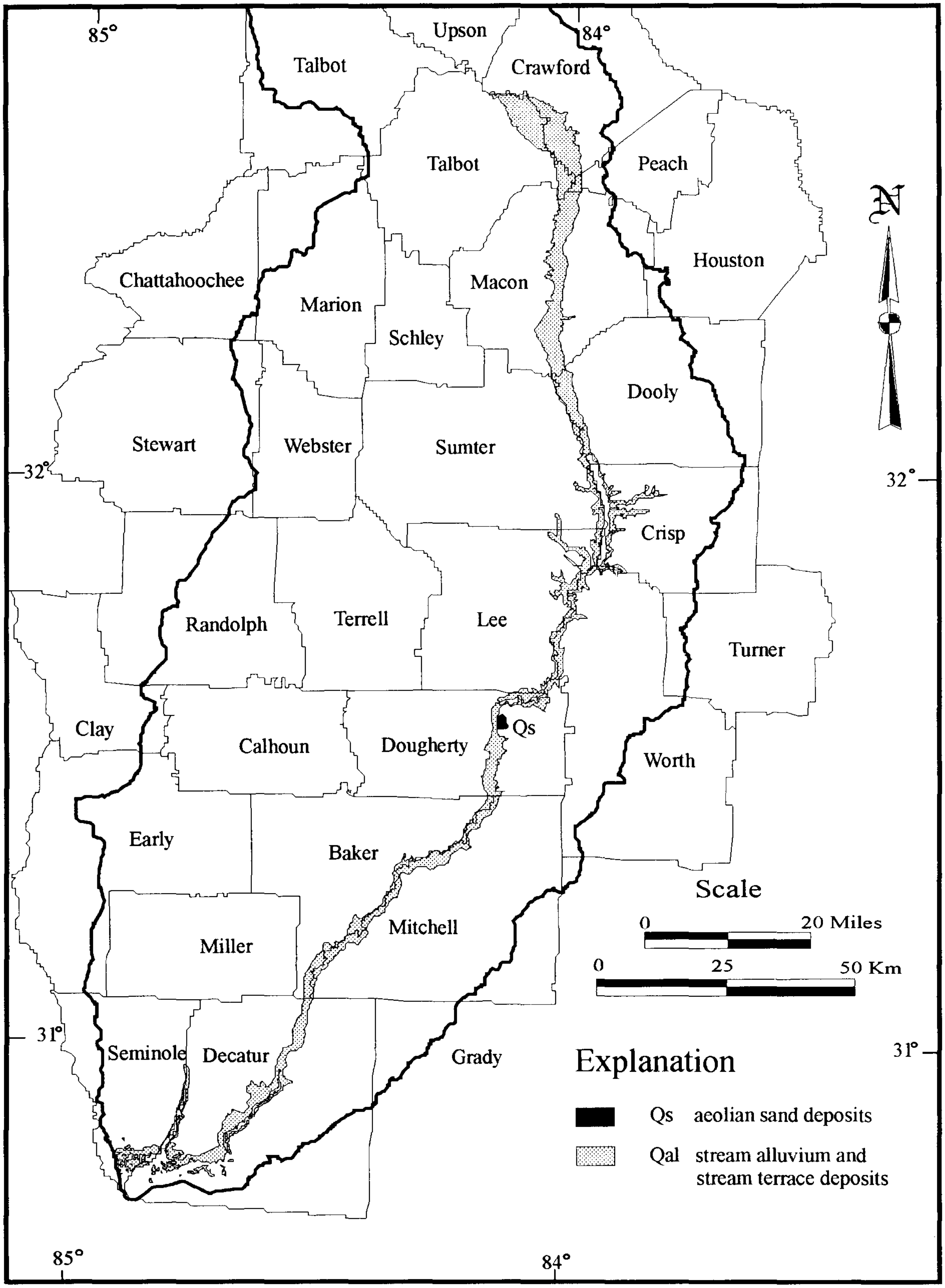

Figure A-16. Quaternary sedimentary units.

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