

BACKGROUND CONCENTRATIONS OF TRACE ELEMENTS IN SOILS AND ROCKS OF
THE GEORGIA PIEDMONT

by

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(Under the Direction of William P. Miller)

ABSTRACT

Background concentrations of trace elements are unknown for the Georgia Piedmont and are important from both a regulatory and environmental impact standpoint. The purpose of this study was to establish background concentrations for 16 trace elements in surface soils, subsoils, and parent materials of the Georgia Piedmont. Soils (A, B, and C horizons) and parent materials were sampled from remote areas, based on observed and mapped parent material (rock) type (grouped as felsic, mafic, and intermediate), and analyzed for selected major and minor elements. Trace metal content varied little between soil horizons, and mafic soils were clearly higher in a suite of elements (including Cr, Mn, Ni, and V), while felsic rocks were higher in certain heavier elements (Pb and U). Implications are that regulatory levels of trace elements should be referenced to parent rock for a given site.

INDEX WORDS: Background concentrations, Trace elements, Trace metals, Georgia Piedmont, Georgia soils

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CHAPTER 1

INTRODUCTION

Concentrations of trace elements (i.e., any element that is present in relatively small amounts in soils and rock, either natural or anthropogenic) in soil are important to soil scientists not only for environmental purposes, such as quantifying contamination, but also to help solve problems associated with human and plant toxicity. The elements typically studied are Ag, Al, As, Ba, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Mg, Mn, Na, Ni, P, Pb, Sb, Se, Si, Sr, Th, Ti, V, and Zn. These elements are usually described in terms of their total content and availability.

In soil, trace element retention is dependent on several soil characteristics, as well as parent material. Soil characteristics include pH, cation exchange capacity (CEC), particle size distribution, organic matter content, and oxide content. These characteristics cause trace elements to either accumulate in the soil, or leave the soil for other components of the environment. When parent materials have high trace element concentrations, the soils that develop over them have high or even higher trace element concentrations. This is of particular interest to soil pedologists, who try to reconstruct soil formation based on parent materials.

Measuring trace elements accurately is an integral part of collecting data on trace elements. Sampling strategy must be well-planned, with the ultimate goal of finding representative rock and soil types to yield accurate data. Many digestion techniques exist, so it is important to choose the best method available to ensure total digestion. Optimizing laboratory equipment is also essential because trace elements are often near the low limits of analytical detection.

When investigating trace elements in soils it is important to establish background concentrations. Reliable data are also needed because if these data are incorrect, legislators may mistakenly mandate guideline levels lower than are realistically attainable (Davies, 1992). Proper legislation can only be enacted when databases exist with accurate background trace element concentrations of soil. Because of their importance, concentrations of trace elements have been studied in soils of the United States (Holmgren et al., 1993 and Shacklette and Boerngen, 1994), Alaska (Crock et al., 1992), Florida (Chen et al., 1999), Indiana (Esser et al., 1991), Minnesota (Pierce et al., 1982), Missouri (Davies and Wixson, 1985) and South Carolina (Gough et al., 1994). Worldwide, studies have also been conducted in Belgium (De Temmerman et al., 1984), Canada (McKeague and Wolynetz, 1980; Mermut et al., 1996; Soon and Abboud, 1990), India (Malini et al., 1995), Latvia (Mezhals, 1996), Poland (Dudka and Markert, 1992), Scotland (Reaves and Berrow, 1984), and Spain (Tobias et al., 1997).

Trace elements in soils and their background levels are not known for the Piedmont of Georgia. Therefore, this study was conducted to establish background concentrations of trace elements in Piedmont soils and to compare the concentrations in soils to the parent materials the soils developed from.

CHAPTER 2

LITERATURE REVIEW

Definitions of Trace Elements

Trace elements have many names as well as many definitions. Depending on the field of study, trace elements are also known as potentially toxic elements, trace metals, heavy metals, micronutrients, and minor elements. The term “potentially toxic elements” is a recent term, meant to illustrate that while some elements are toxic to humans and plants, not all elements are toxic at all concentrations. In fact, some elements (e.g., Fe) are necessary for life in small amounts (Alloway, 1995).

Definitions of trace elements change between disciplines. For example, chemists define trace elements, or transition metals, as those elements which fall in the center of the periodic table (between Group IIA and IIIA) and exhibit partial d-orbital filling. Other chemical definitions are based on density (greater than 5 g/cm³), atomic weight (greater than that of sodium), and metallic properties. Geologists define trace elements as any element in rocks other than the most abundant eight elements found in the Earth’s crust. Soil fertility experts define trace elements as those elements that are essential to plant growth in small amounts, but toxic to plants at higher concentrations. Toxicologists consider trace elements those elements distributed into the environment by industrial processes that are detrimental to human health or the environment. This definition is not based on abundance in the environment, or density or metallic properties, but solely on the adverse effects of the element in the environment.

Interest in trace elements has increased because of the widespread trace element contamination caused by industrial processing. The manufacture of many goods requires the use of trace elements such as Fe, Al, Cu, Pb, Cd, Ni, Hg, As, and Se, so these elements have become common in industrial wastes and in some cases end up in the environment. The Resource Conservation and Recovery Act (RCRA), enforced by the United States Environmental Protection Agency (EPA), has set mandatory cleanup guidelines for the following trace elements: Ag, As, Ba, Cd, Cr, Hg, Pb, and Se. These eight trace elements are commonly known as the RCRA metals.

Geologists and soils pedologists are interested in trace elements not mentioned above. Titanium is of interest because it can normalize trace element data in soil profile reconstruction, as Ti readily forms insoluble complexes and is not lost during the weathering process (Middelburg et al., 1988). The loss or gain over time of other trace elements in a profile can be analyzed using Ti concentrations as a constant.

In this study, the elements of interest are Si, K, Ti, V, Cr, Mn, Co, Ni, Cu, Zn, As, Cd, Ba, Hg, Pb, and U. Si, Mn, and K are not considered trace elements, but rather major elements in geologic terms. These three elements were chosen for this study as an indication of rock and soil type for classification purposes. Ti and V were chosen for profile reconstruction purposes. The remaining elements were chosen for toxicological and environmental information.

Trace Elements in Plant and Animal Nutrition

Historically, soil scientists have studied trace elements for their effect on plant nutrition and toxicity. A majority of this research was conducted in the 1950's and 1960's. The trace elements (in this case, nutrients) typically studied were those which are essential for normal plant growth and function. Macronutrients (those nutrients needed in large amounts by all plants) include C, H, O, N, P, K, S, Ca, and Mg, although C, H, and O are not usually considered mineral nutrients (Tisdale et

al., 1993). Micronutrients (those nutrients needed by all plants in relatively smaller amounts) include Fe, Zn, Mn, Cu, B, Cl, and Mo (Tisdale et al., 1993). In addition, some micronutrients are needed by only certain plants, including Na, Co, V, Ni, and Si (Tisdale et al., 1993).

Much of the research conducted by soil scientists for fertility purposes has been centered around deficiencies that limit plant growth and the essentiality of trace elements in the plant life cycle. A wide variation in soil content has been noted in soil fertility research.

Certain trace elements are toxic to humans and other animals at elevated concentrations. However, some trace elements are required by humans and other animals for healthy function of the body. The National Research Council provides a list major and trace elements with U.S Recommended Daily Allowances (USRDA) for the following elements: Ca, Cl, Cr, Cu, F, I, Fe, Mg, Mn, Mo, P, K, S, Na, and Zn (Smith and Huyck, 1999). For example, the USRDA for Cr is 50-200 µg, which is required for glucose metabolism, and for Cu is 1.5-3 mg, which is required for respiratory and red blood cell function. In addition, B, Co, Li, Ni, Si, and V are considered important to human health in at least some function (Smith and Huyck, 1999).

Trace Elements in Geologic Materials

The original source of trace elements in soils is the underlying parent material. Trace elements are present in many minerals and ore deposits that make up different rocks and geologic units. Rocks vary widely in trace element content, but certain rocks are higher and lower, in general. The following table (adapted from Kabata-Pendias and Adriano, 1995) shows commonly reported values for trace elements in igneous and metamorphic rocks.

Table 2-1. Concentration of trace elements in igneous and metamorphic rocks

Element	Rock type		
	Felsic (mg/kg)	Intermediate (mg/kg)	Mafic (mg/kg)
V	40 - 90	30 - 100	200 - 250
Cr	4 - 25	15 - 50	170 - 200
Mn	350 - 600	500 - 1200	1200 - 2000
Co	1 - 7	1 - 10	35 - 50
Ni	5 - 15	5 - 55	130 - 160
Cu	15 - 30	15 - 80	60 - 120
Zn	40 - 60	40 - 100	80 - 120
As	1 - 2.6	1 - 2.5	0.6 - 2
Cd	0.09 - 0.2	0.13 - 0.13	0.13 - 0.22
Ba	400 - 850	600 - 1000	250 - 400
Hg	0.08 - 0.08	BDL	BDL
Pb	15 - 25	12 - 15	3 - 8
U	2.5 - 6	1.4 - 3	0.3 - 1

BDL - Below detection limits

Trace element concentrations in rocks are dependent on the trace element concentrations of the rock forming minerals. The following table (adapted from Smith and Huyck, 1999) shows trace elements found in the major rock forming minerals. The minerals are listed in order of stability during weathering (i.e., more easily weathered materials are listed first, the most stable are listed last).

Table 2-2. Trace elements of interest commonly found in rock-forming minerals

Mineral	Elements expressed in range of concentration			
	X%	0.X%	0.0X%	0.00X% or less
Olivine		Mn, Ni	Co, Cr, Ti	Cu, V, Zn
Pyroxene		K, Mn, Ti	Cr, Ni, V	Ba, Co, Cu, Zn
Plagioclase Feldspar	K		Ba, Mn, Ti	Cu, Ni, Pb, V, Zn
Amphibole		K, Mn, Ti	Cr, Ni, V, Zn	Ba, Co, Cu, Pb
Biotite	Ti	Ba, Mn	Cr, Ni, V, Zn	Co, Cu, Pb
Potassium Feldspar		Ba	Ti	Cu, Ni, Pb, V, Zn
Muscovite		Ba, Ti	Cr, Mn, V	Cu
Quartz				Mg, Mn, Ti, Zn

The area of this study is located in the Georgia Piedmont, more precisely the Inner Piedmont, the Charlotte and Slate belts, and Modoc fault zone. Allard and Whitney (1994) have completed a comprehensive review of the geology in this area. In summary, the parent materials found here range from felsic to mafic and are igneous and metamorphic in origin.

A fault separates the Inner Piedmont from the Charlotte and Slate belts. The Inner Piedmont is composed mostly of migmatized biotite gneisses, quartz-muscovite-sillimanite schists, and mica schists. The Charlotte and Slate belts (together called the Carolina terrane) are from the Cambrian period and consist of metamorphosed volcanic and sedimentary rocks. These range from felsic to mafic, and also vary in grade of metamorphism. The rocks in the Inner Piedmont and Carolina terrane were deformed between 425 and 500 million years ago. About 300 million years ago igneous plutons intruded these areas, the most well-known being the Elberton granite. The fault area separating the Carolina terrane from the area south of it is known as the Modoc fault zone (Allard and Whitney, 1994).

Trace Elements in Soils

Trace elements in soils are derived from the weathering of geologic parent materials and tend to be immobile. The concentrations in soils are related to the overlying parent material based on the immobile nature of trace elements. Some transport of trace elements in the A horizon occurs with plant uptake and nutrient cycling. However, trace elements in soils are generally insoluble and exhibit strong adsorption.

The effects of soil characteristics on trace element concentrations in soils have been studied by many soil scientists and have been reviewed by Adriano (1986). In summary, seven factors determine the fate of trace elements in soil: soil pH, CEC, anion exchange capacity (AEC), organic matter content, clay content and type, oxide content and type, and redox

potential. Trace element sorption depends on pH and whether the element occurs in anionic or cationic form. Cation sorption increases with pH showing a steep increase within a small pH range, which is known as the adsorption edge. Sorption of anions shows a maximum when the pH is equal to the pKa of the corresponding acid. This phenomenon is known as the adsorption envelope. A high CEC or AEC allows a soil to hold more cations or anions, respectively, than a soil with a low CEC or AEC. The exchange capacity of a soil is related to other soil properties, such as organic matter, clay, and oxide content. Soil organic matter retains elements both through its exchange capacity and through specific sorption, especially for elements such as Cu, Co, Mn, and B. A soil high in clay has more surface area for elements to adsorb and a higher CEC than a soil low in clay. Also, 2:1 clays usually have a higher CEC than 1:1 clays. Oxides of Fe and Mn have a high affinity for trace elements, and either sorb or occlude the trace elements. Redox potential of a soil can change the solubility of an element. When a soil is reduced, some elements such as Fe, Cd, Ni, and Pb can form insoluble sulfide precipitates. Elements such as Mn and Fe become more soluble under reducing conditions, in the absence of sulfides. All of these factors decide the trace element retention of a soil.

Since parent material is responsible for the lithogenic trace element content of soils, it may be helpful to correlate trace element concentration in soils to parent materials. A database of this information for public use could provide a reliable estimation of the trace element concentration for a specific soil, with knowledge of the parent material in an area and certain soil characteristics as input parameters.

Soil pedologists can perform predictive modeling of soil formation using trace element concentrations in soil and parent material. By comparing the soil and parent material data, using a normalization element, overall soil loss or soil formation can be assessed. Certain elements are

enriched during the weathering of parent material and soil formation, while other elements are lost (Middelburg et al., 1988). It is helpful to quantify the loss and gain of elements when trying to determine the history of a soil.

Soils of the Georgia Piedmont are typically acidic and have well developed argillic horizons. Soils formed over the felsic parent materials are kaolinitic clays while soils formed over the more mafic parent materials often have shrink-swell clays as well. Soil series typically encountered over the felsic parent materials include Cecil, Madison, and Ashlar, which are classified as Kanhapludults and Hapludults. Soil series typically encountered over the mafic parent materials include Iredell, Enon, and Mecklenburg, which are classified as Hapludalfs. Soils encountered during the study typically had sandy loam A horizons, clay or clay loam B horizons, and saprolite that crushes to sandy loam C horizons.

Anthropogenic Trace Element Inputs to Soils

Sources of trace elements in soils are numerous. In nature, trace elements accumulate in the soil during the pedogenic weathering of geologic parent materials. However, humans have added trace elements to soils in many cases. Trace elements are common in industrial goods, as byproducts of the mining industry in mine spoils, as a component of paints and pesticides, and as a constituent of land applied municipal and industrial wastes. In addition, trace elements have been added to soils by spreading inorganic fertilizers, the discharge of atmospheric emissions, and spills and illegal dumping of industrial waste. Because of the extensive use of trace elements in industry and other areas, trace elements have become part of the environment and have likely had a major impact on trace element concentrations in soils in many areas. In the US, some of these additions have been stopped or slowed by environmental regulations. For example, limits set by the EPA require the concentrations of trace elements in biosolids to fall below certain levels before landspreading is

permitted (USEPA, 1993). A lifetime cumulative loading for trace elements is also mandated for soils. Trace element additions to soil through other agricultural amendments have also slowed in some cases. For example, agricultural use of As declined rapidly during the 1970s, greatly reducing the amount of As added to soils (O'Neill, 1995).

At elevated levels, trace elements are harmful to humans. For example, Pb, which is added to gasoline to reduce automobile engine knock, has become widespread in soils. Other additions of Pb to the environment include contamination from Pb paint, smelters, and Pb arsenate, an insecticide. Lead is toxic to humans, especially children, and damages the central nervous system, causing retardation and even death in extreme cases (Ewers and Schlipkötter, 1991).

Trace elements are also of concern in the environment because of their potential to bioaccumulate in the food chain. The well-known Minamata disease, which occurred in Japan, was caused by bioaccumulation of methyl mercury in the fish of Minamata Bay (Ewers and Schlipkötter, 1991). The local people consumed fish that had bioaccumulated the compound. Also in Japan, Itai-Itai disease, a form of Cd poisoning, caused many Japanese to fall ill when they ingested Cd-contaminated rice (Ewers and Schlipkötter, 1991).

Total trace element concentration in soil is often a poor measure of the bioavailability of trace elements. Bioavailability depends on specific soil characteristics, such as organic matter content and pH. Thus, two soils with an identical concentration of a trace element do not necessarily have the same bioavailability of that trace element (Pierzynski, 1998). Bioavailability of trace elements is important because the bioavailable fraction of trace elements is the fraction most likely to harm plants and animals. Remediation strategies for contaminated soils should be aimed at preventing health problems, with the main focus on the availability of trace elements, not on the total concentration of trace elements. For example, if trace elements of concern are strongly sorbed to a

non-mobile fraction of soil, the exposure potential to plants and animal is greatly reduced. For this reason, regulatory controls of trace element concentrations in soils should address bioavailability of trace elements, not total trace element concentrations.

In the case of Cd, sorption densities describe bioavailable trace elements better than total concentrations (Schulte and Beese, 1994). Sorption density takes into account not only Cd chemistry (i.e., bond strength), but the composition of the soil or the possible sorption sites for Cd. Bioavailability can also be measured with plant toxicity or yield testing, where uptake of metals by plants is measured. A test of bioavailability of Zn, Cd, and Pb with soybean (*Glycine max*) found that soil amendments such as lime and manure influence the bioavailability of these trace elements (Pierzynski and Schwab, 1993).

Measurement of Trace Element Background Levels in Soils

Trace element data are collected mostly on polluted or geologically interesting areas, and are scarce in normal or non-polluted areas (Davies, 1992). Uses of background data on non-contaminated soils can be useful for both regulators and soil pedologists. Regulators need reliable data to assure regulations on trace elements are suitable for all areas. Regulations that are too stringent may result in a remediation project that is scientifically or economically infeasible. Regulations that are not stringent enough may result in sites that pose a serious threat to human health and the environment.

It is important to develop a conscientious strategy for sampling soil and parent material, as the reliability of the data depends on the validity of the sampling scheme. Presently, there is no consensus on which technique is best for sampling soils. While many sampling schemes exist (e.g., grid sampling), it is not clear how many samples are necessary to assess soil heterogeneity completely (Davies, 1992). The appropriate tools to use also seem to elude soil scientists

(Davies, 1992). Augers, soil probes, sharpshooters, and shovels are just some of the tools available for sampling. The correct tool often depends on the kind of material that is to be sampled, as well as the trace element of interest. For example, it would be illogical to use a rusty auger for a study on Fe concentrations. In trace element studies, stainless steel tools are typically used to diminish the potential of contamination although carbon steel or Teflon is the best (Ure, 1995).

When sampling trace elements in soil and parent material, it is important to test many sites of each parent material to obtain a representative sample of the parent material and soils forming above it. Soil sampling should be done on residual soils to ensure that the trace elements measured have developed from the weathering of the underlying bedrock. For example, trace elements in alluvial or colluvial soils have the potential to be transported by water or gravity from other parent materials in the area. Road cuts and other areas with exposed parent material are often the best locations for sampling soil and underlying parent material because of their easy access.

Background studies, by definition, require the soils sampled to be unaffected by human activities. In order to assess if the soils have been altered by human activities, historical land use of the area and field observations are often helpful. Field observations include information such as close proximity of abandoned open dumps or agricultural field borders.

Digestion of soil refers to the process of taking soil from solid to solution form. This technique breaks down the crystalline structure of the soil, releasing all trace elements sorbed to the soil particles or incorporated into the soil structure. Because trace element concentrations can only be measured (using inductively coupled plasma mass spectrometry (ICP-MS)) with

solution samples, the soil must be in solution form. Many digestion techniques exist, differing mainly in the type of acid, the type of vessel, and temperature and pressure settings.

There are three common methods to digest soils: a) open vessel or hot plate method, b) closed vessel bomb method, and c) closed vessel microwave method. The amounts and types of acids vary with each method.

Advantages and disadvantages exist for each method. In the open vessel or hot plate method, the soil and acid are heated in a flask on a hot plate. Typically a reflux condenser or watch glass is placed on top of the flask to minimize the sample evaporation. An alternative method involves the intentional evaporation of the sample. In both cases, volatile elements can be lost as no pressure is allowed to build up and volatile elements escape freely into the air. Diaz-Barrientos et al. (1991) found that in open vessel methods the amount of metals measured was significantly lower than the certified levels of the soils. Open vessel digestion has advantages in that strong acid evaporation makes the resulting solution safer to handle, and when the strong acid is hydrofluoric acid the solution has a low salt content in solution following digestion because no boric acid is needed to neutralize the hydrofluoric acid.

Two methods, bomb and microwave, are commonly used for closed vessel digestion. Typically bomb digestion uses a Parr bomb, which is a sealed polytetrafluoroethylene (PTFE or Teflon) vessel designed to withstand high temperatures and pressures when inserted into a stainless steel casing. The bombs are placed in an electric oven to heat, which speeds up digestion time.

Closed vessel microwave digestion also uses Teflon vessels, which are sealed and placed without a casing in a microwave for heating. Commercial microwaves designed for digestion have temperature and pressure sensors that monitor the conditions inside the vessels for optimum

digestion. The microwave vessels are equipped with pressure release valves that open if the pressure becomes too intense.

Both closed vessel methods have significant advantages over the open vessel method because there is no loss of volatile elements and metal contamination of sample from the air is reduced. Higher temperatures and pressures are also achieved with closed vessels and this aids in digestion. Furthermore, since no evaporation is occurring, all the acid is contained in the vessel and for this reason smaller amounts of acids are needed. Microwave digestion has added advantages of decreased digestion time and ease of use. With the exception of As and Mg, acceptable recoveries of metals can be made using the microwave digestion method with hydrofluoric acid (Chen and Ma, 1998).

As with the open vessel method, there are disadvantages to the two closed vessel methods. Sample size must be small to keep the vessel from exploding. The solutions will have a high salt concentration if hydrofluoric acid is used because boric acid must be added to neutralize the hydrofluoric acid.

The acids typically chosen for digestion procedures, either alone or in combination, are hydrofluoric, boric, perchloric, hydrochloric, nitric, and hydrogen peroxide. The amounts and types of acid vary by procedure. Hydrofluoric acid is an extremely strong acid required to dissolve Si in the total digestion of mineral soils. However, this acid cannot obviously be used in glass vessels. Hydrofluoric acid is also a serious threat to human health if spilled. Boric acid neutralizes hydrofluoric acid after digestion, but gives the digest a high salt concentration. Perchloric acid oxidizes the remaining organic matter in soils. Unfortunately, perchloric acid is both dangerous and unpredictable, and can explode occasionally. Hydrochloric acid and nitric acid mixtures (*aqua regia*) provide the necessary oxidizing power and are common substitutes

for perchloric acid. Hydrogen peroxide is also an oxidizing acid commonly used in digestion, especially with high carbon samples. However, Xing and Veneman (1998) found that hydrogen peroxide had no significant effect in microwave digestion of mineral or organic soils, except for analysis of Mn.

Many studies have compared the different methods described above for analysis of specific types of samples. Warren et al. (1990) suggest ignition of soil samples before analysis to burn off the organic matter and to evaporate the water. In a closed vessel microwave system, this keeps pressure down and avoids explosions. Newer microwaves specifically designed for digestion are equipped with pressure sensors that automatically shut down the microwave if pressure inside the vessels reaches becomes excessive. The newer microwaves also reduce the proposed need for ignition of soils.

Ammons et al. (1995) varied the standard microwave digestion technique to increase total digestion of soils and geologic materials containing >45% sand. Incomplete digestion of sands is a common problem, and this results in element concentrations below the actual total levels. Four modifications to the standard digestion procedure were tried: decreasing sample size, decreasing particle size, doubling the amount of acid, and doubling the amount of time in the microwave. None of these modifications improved sand particle digestion. However, adding hydrofluoric acid to the sample 16 h prior to microwave digestion successfully digested all of the soil particles. To date, this method is the most appropriate for the total digestion of soils.

Inductively coupled plasma-mass spectrometry is a common instrument in environmental labs for analysis of digested samples. The most common digestion procedure involves the use of strong acids, which the instrument is designed to handle at a dilution. Inductively coupled plasma-mass spectrometry has many advantages over optical emission or absorption

spectrometry, the most important of which is increased sensitivity. Concentrations as low as nanogram per liter can be measured (Stetzenbach et al., 1994). Inductively coupled plasma-mass spectrometry also allows simultaneous multielement analysis, which saves time and amount of sample required for analysis. Yamasaki (1995) found that reliable analysis of 10 major and over 40 trace elements in soils was possible using strong acid digestion and ICP-MS analysis. Arunachalam et al. (1995) also used ICP-MS to analyze digested soil samples, and found that the analysis was reliable. Alcock (1995) provides a review of other applications of ICP-MS analysis.

Cost is the major disadvantage to ICP-MS analysis. The initial expense of the instrument is so great that many environmental labs cannot afford one. For those labs that can purchase the instrument, high cost is associated with daily operation. For example, the instrument requires high cost argon gas to form the plasma.

Another disadvantage of ICP-MS analysis is interferences. These are well documented for ICP-MS analysis (Evans and Giglio, 1993). However, many of these interferences can be overcome with appropriate quality assurance/quality control programs. Internal standards (an element added to all sample solutions, in known concentrations, which is not previously in the solution) can correct for matrix effects in ICP-MS analysis (Vanhaecke et al., 1992). The internal standard should be close in mass number to the elements of interest in the analysis, so more than one internal standard should be used if a wide range of elements are analyzed (Vanhaecke et al., 1992). The use of internal standards keeps the matrix effects to a minimum by providing an idea of the presence of instrumental drift due to the salt concentrations in the sample solutions.

Statistical analysis of trace element data is problematic due to the non-gaussian distribution of the data and the wide range of data. Methods of statistical analysis have been created to overcome some of these difficulties. When presenting trace element concentration data, it is necessary to include mean values with the range to provide a clear picture of the variation. In addition, mean values are often presented with a range of variability that includes the standard variation of the sample concentrations.

The objectives of this study are to:

- develop a method to collect background trace element concentration data in soils and parent materials,
- describe the distribution of trace elements in soils and parent materials in the Georgia Piedmont, and
- relate the trace element concentrations in parent materials to the overlying soils.

CHAPTER 3

BACKGROUND CONCENTRATIONS OF TRACE ELEMENTS IN THE A AND B HORIZONS OF GEORGIA PIEDMONT SOILS

Introduction

Trace elements are defined as any element that is present in relatively small amounts in soils and rock, either natural or anthropogenic. Background trace element concentrations in soils are generally considered those that are less than 100 mg/kg. Trace elements naturally accumulate in the soil during the pedogenic weathering of geologic parent materials. Trace element concentrations differ between various rock types; therefore, the concentrations differ between the soils that form over the various rocks. Parent materials in the Georgia Piedmont (the study area) range from felsic to mafic and are igneous and metamorphic in origin (Allard and Whitney, 1994). Felsic to intermediate metamorphic rocks predominate Piedmont geology; however, both igneous granite and mafic bodies are occasionally identified. Due to the abundance of different rock types in the study area, a range of concentrations of trace elements is likely to be detected in the Georgia Piedmont.

Quantifying background trace elements in soils is valuable from an environmental regulatory standpoint. Reliable data are needed to determine acceptable regulatory levels in cases of soils affected by industrial processes. The U.S. Environmental Protection Agency (EPA) regulates trace element affected soils by establishing concentration guidelines for risk based studies (e.g., preliminary remediation goals, soil screening values). If the soil is determined to be a human or ecological risk, guidelines for disposal and/or treatment of the soil

(e.g., land-banned rules, universal treatment standards) must be adhered to. Land application of trace element affected wastes are also regulated (e.g., pollutant concentrations, lifetime loading limit).

In addition, some state regulatory bodies have authority to determine further regulatory limits. The State of Georgia, Department of Natural Resources (DNR), Environmental Protection Division (EPD) provides release notification soil concentration limits that require any facility that detects trace elements above the limits to notify the state. The notification process can lead to addition of the facility onto the Georgia Hazardous Site Inventory list, which is the state version of the National Priorities List. In addition, the EPD provides risk reduction standards as cleanup guidelines for determining if soils pose a significant risk for residential and industrial site use. Incorrect trace element data can potentially lead to mandated cleanup guidelines for trace elements in soils that fall below levels that are realistically attainable based on naturally occurring concentrations.

Currently, background concentrations of trace elements in soil are unknown in Georgia. The objective of this study is to determine background concentrations of trace elements in the A and B horizons of Georgia Piedmont soils.

Materials and Methods

The Georgia Piedmont was chosen as the study area because it contains a variety of different rock types. Sample locations were selected to represent the geologic variation of the study area. The individual parent materials were located and identified in the field with thesis maps provided by the University of Georgia, Department of Geology, and confirmed by examination of hand specimens at the sites. Specific locations were forested and judged to be relatively undisturbed, although it is acknowledged that most of the Piedmont has been cultivated

at one time. Three soil profiles were sampled at each sample location, each 5 to 15 meters apart, to assess variation in the field. Samples were collected from the A and B horizons of each profile. In addition, parent material samples were collected when available.

Samples were collected using two different methods, based on field conditions. For sample locations with exposed soil profiles (e.g., road cuts), a sharpshooter was used to remove overburden and eroded topsoil to provide a fresh sampling surface. The samples were collected with a spade directly from the exposed profile. A hand auger was used to sample soils from ground surface locations. All sampling equipment was decontaminated prior to sample collection. Samples were placed for storage in 1-quart freezer bags, identified with labels, and transported to the laboratory for analysis. Upon arrival to the lab, soil samples were air-dried. For each sample location, a composite of the three sub samples from the A and B horizons were passed through a 2mm sieve, then ground with a mortar and pestle.

For each sample, 0.25 grams of soil was placed in a Teflon microwave pressure digestion vessel, to which 2.5 mL of HF was added. The samples were pre-digested for 16 hours to aid in total dissolution (Ammons, et al., 1995). Following pre-digestion, 5 mL of aqua regia (3:1:1 – HCl:HNO₃:ultra pure deionized water) was added to the vessels, the vessels were pressure sealed and heated at 180 C in a CEM digestion microwave oven for 20 minutes (EPA method 3052, modified). The vessels were weighed before and after digestion to ensure no greater than five percent of the sample was lost during the digestion process. After cooling, 25 mL of 5% HBO₃ was added to neutralize the HF. Ultra pure deionized water was added to the vessel to bring the total volume to 100 mL, by weight. The final solution was placed in a polyethylene bottle and stored in a refrigerator to await analysis.

Samples were analyzed on the Perkin Elemer Elan 6000 ICP-MS for Si, K, Ti, V, Cr, Mn, Co, Ni, Cu, Zn, As, Cd, Ba, Hg, Pb, and U. Duplicates, blanks, and standard reference materials (SRMs, obtained from National Institute of Standards and Technology [NIST]) were analyzed to ensure proper method and instrument function.

Results and Discussion

Ten samples of NIST certified SRM 2709 San Joaquin Soil and 15 samples of NIST certified SRM 2711 Montana Soil were analyzed for quality control purposes. The San Joaquin Soil represents background concentrations of trace elements, whereas the Montana Soil has moderately elevated concentrations of trace elements. Both soils were analyzed to provide a concentration range of check samples, both high and low. Table 3-1 presents the results of this analysis along with the instrument limits of detection. Percent recovery and the coefficient of variation are presented for each element.

For most elements, the percent recovery for the SRMs range between 75% and 125% and the coefficient of variation is below 10. However, the percent recoveries for Ni in the Montana Soil and Cd in the San Joaquin Soil fall above and below generally accepted levels, respectively. The source of the elevated recovery for Ni is likely the effect of the deterioration of the Ni cones associated with the ICP-MS. The low recovery of Cd in the San Joaquin Soil is related to the low concentration in this sample, partially due to the dilution required to minimize matrix effects with the ICP-MS. The data associated with both Ni and Cd should be regarded as estimated based on the results of the analysis of the SRMs.

Instrument detection limits are provided as a general indication of instrument performance. Si and Ti are reported as zero because the concentration of both elements in solution, when converted to mg/kg soil, are too small to report accurately.

Table 3-2 presents the average values and ranges of 24 soil samples collected from the A and B horizons of Georgia Piedmont soils. The averages include concentrations of trace elements detected in soils formed over parent materials ranging from felsic to mafic.

The average values and range of values did not differ significantly between the A and B horizons for the trace elements measured. It should be noted that values presented for Cd and Hg are very low and in some cases were observed below instrument detection. For samples that were detected below the instrument detection limit, one half of the instrument detection limit was used to calculate the averages and range of values.

Table 3-3 presents average concentrations of trace elements in surface soils found in the literature for use in comparison to the average Georgia Piedmont values. The comparison data presented in Table 3-3 was adapted from Shacklette and Boerngen (1984) (USGS) and Chen et al. (1999) (Florida soils). The USGS data include trace element concentrations in surface soils across the US, and the Florida data include surface soils only in Florida. In general, the ranges presented in the literature more or less correspond with the ranges measured in this study. Average Florida soil trace element concentrations are considerably lower than Georgia Piedmont soils, which is likely a result of the sandy soils present in Florida. Concentrations of Cd and Hg for both sets of samples are similar and were detected very near the limits of detection of the instrument.

Average trace element concentrations in US soils are more closely related to Georgia Piedmont soils than those found in Florida. The average concentrations are similar between the two sets of data. However, the range of values is consistently greater for the US soils. The larger range of values is likely the effect of the large variation in soil and parent material types observed across the US. Trace element concentrations in soils formed over the felsic and

intermediate parent materials are most closely related to the US soils for all trace elements, with exception of Pb.

Table 3-4 presents regulatory limits for trace elements in soils applicable in Georgia. The limits included in the table are the land application pollutant concentration limits for biosolids, release notification soil concentration limits, and risk reduction standards that indicate if the soil poses a significant risk for residential land use. The land application limits are defined by the EPA and are used to determine the applicability for land application of various biosolid materials. The release notification limits and risk reduction standards are both defined under the Georgia Hazardous Site Response Act for industrial soil contamination.

None of the trace element concentrations detected for any of the soil samples exceed the pollution concentration limits for land application of biosolids. In addition, the average and maximum concentrations for As, Cd, Hg, and Pb do not exceed the release notification concentrations or the risk reduction standards.

The release notification soil concentrations for V, Co, and Ba indicate a maximum concentration, or background, if larger. In the case of V and Ba, the higher end of the range of values exceeds the notification concentration, and the highest concentration of Ba is more than twice the notification concentration. Therefore, when determining if soils in Georgia are above the release notification concentrations, background samples should be collected in the area surrounding the facility, as the potential exists for notification of soils that are naturally above the notification concentrations.

The risk reduction standards were exceeded by either the average or highest concentration for seven of the eleven trace elements regulated. The average concentrations of V, Cr, Co, and Ni in either the A or B horizon exceed the risk reduction standards. The highest

concentration observed was more than eight times the risk reduction standard in the case of Cr. The maximum concentration for Cu, Zn, and Ba exceeded the risk reduction standards, although the average value was below the regulated concentration. In cases where the average background concentration exceeds the risk reduction standards, there is a potential that industrial facilities will be required by Georgia to remediate soils to levels lower than natural background concentrations.

Table 3-5 presents the average concentrations of trace elements in both the A and B horizons sorted by felsic, intermediate, and mafic parent materials. The average concentrations are presented with the range to be used as a measure of variability.

In general, average concentrations of Si, K, Ba, Pb, and U are highest in soils formed over felsic parent materials. Average concentrations of these elements decrease when comparing felsic to intermediate to mafic derived soils. Conversely, Ti, V, Cr, Mn, Co, Ni, Cu, and Zn average concentrations are highest in soils formed over mafic parent materials and average concentrations of these elements decrease when comparing mafic to intermediate to felsic derived soils. Concentrations of Cd and Hg are too close to the instrument detection limits to make any conclusions on concentration differences.

Trace element concentrations in soils vary significantly depending on the parent material the soils developed over. Rocks and soils vary in trace element concentration over a small area in the Georgia Piedmont. It is important for regulators to be aware of these differences when assessing contamination of soils at industrial facilities. For certain trace elements, the release notification limit for the Hazardous Site Inventory is a set concentration, or background, if larger. Industrial facilities would be required to sample background concentrations in an area surrounding the facility to assess the background variation. Based

upon the observed variability of trace elements in soils and parent materials in Georgia, background sample concentrations in any area could potentially misrepresent the background concentration at a specific location. Parent material differences over a short distance could cause the trace element concentrations in soils to be much higher or lower than that of the area of interest.

References

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Table 3-1. Quality control results

Element	NIST SRM 2709 San Joaquin Soil		NIST SRM 2711 Montana Soil		Method detection limit
	Percent recovery	Coefficient	Percent recovery	Coefficient	Units in mg/kg soil
		of variation		of variation	
Si	82	7.8	79	6.9	0.00
K	92	3.8	93	5.4	0.01
Ti	95	2.5	96	4.8	0.00
V	100	3.9	99	8.5	2.16
Cr	84	8.8	124	106.2	7.36
Mn	97	6.7	98	10.2	1.70
Co	105	7.1	118	10.7	0.14
Ni	109	40.7	187	147.0	1.44
Cu	121	15.6	105	6.3	1.04
Zn	107	11.0	107	5.6	4.24
As	114	2.8	100	2.4	1.44
Cd	11	585.6	108	4.5	0.14
Ba	97	2.9	102	2.9	2.00
Hg	122	18.1	127	9.4	0.07
Pb	104	7.8	101	5.5	0.12
U	111	5.0	120	6.3	0.07

Table 3-2. Average background concentrations of trace elements in the A and B horizons

Element	A horizon (mg/kg soil)		B horizon (mg/kg soil)	
	average	range	average	range
Si*	27.0	11.2 - 37.4	22.9	10.2 - 34.3
K*	1.52	0.05 - 4.41	1.30	0.04 - 3.87
Ti*	0.59	0.13 - 4.09	0.52	0.09 - 2.40
V	99.3	16.0 - 308.4	118.2	30.3 - 288.7
Cr	114.2	3.7 - 813.8	182.9	4.0 - 837.6
Mn	426.0	75.3 - 1325.9	380.1	28.2 - 1117.0
Co	18.0	1.0 - 64.7	21.2	3.0 - 81.4
Ni	40.3	1.0 - 178.5	52.8	2.1 - 186.4
Cu	31.8	8.7 - 84.9	44.3	11.7 - 118.2
Zn	75.3	10.2 - 171.2	80.5	22.7 - 132.1
As	5.5	3.5 - 8.6	5.6	3.2 - 9.7
Cd	0.10	0.07 - 0.26	0.08	0.07 - 0.12
Ba	452.0	60.8 - 1351.7	359.0	52.3 - 937.6
Hg	0.07	0.04 - 0.16	0.08	0.04 - 0.19
Pb	27.0	11.5 - 46.5	25.4	4.5 - 66.6
U	2.8	0.5 - 8.5	3.6	0.3 - 7.9

* - designates units are in % dry weight

Table 3-3. Values of selected trace elements in the literature

Element	USGS (mg/kg soil)		Florida soils (mg/kg soil)	
	average	range	average	range
Si*	31	1.6 - 45	NA	NA - NA
K*	1.5	0.005 - 6.3	NA	NA - NA
Ti*	0.29	0.007 - 2	NA	NA - NA
V	80	<7 - 500	NA	NA - NA
Cr	NA	NA - NA	15.9	0.02 - 447
Mn	550	<2 - 7000	48.8	1.4 - 1642
Co	9.1	<3 - 70	NA	NA - NA
Ni	19	<5 - 700	13	0.004 - 375
Cu	25	<1 - 700	6.1	0.1 - 318
Zn	60	<5 - 2900	8.35	0.9 - 169
As	7.2	<0.1 - 97	1.34	0.01 - 50.6
Cd	NA	NA - NA	0.07	0.004 - 2.8
Ba	580	10 - 5000	30.7	1 - 1990
Hg	0.09	<0.01 - 4.6	12.6	0.62 - 430
Pb	19	<10 - 700	11.2	0.18 - 290
U	2.7	0.29 - 11	NA	NA - NA

* - designates units are in % dry weight

NA -- designates no value available

Table 3-4. Regulatory limits for selected trace elements in soil

Element	Pollutant concentration limits for bisolids ¹ (mg/kg dry weight)	Release notification soil concentration limits ² (mg/kg soil)	Risk Reduction Standards Type 1 Soil Criteria ³ (mg/kg soil)
V	--	100/BG	100
Cr	1200	1200	100
Co	--	25/BG	20
Ni	420	420	50
Cu	1500	1500	100
Zn	2800	2800	100
As	41	41	20
Cd	39	39	2
Ba	--	500/BG	1000
Hg	17	17	0.5
Pb	300	400	75

-- designates no value reported

value/BG - designates the indicated concentration, or background, if larger

¹ - land application limits - 40 CFR Part 503, 1993

² - Rules of Georgia DNR, EPD, Chapter 391-3-19 Hazardous Site Response

³ - values that pose no significant risk for residential use - Rules of Georgia DNR, EPD, Chapter 391-3-19.07 Hazardous Site Response

Table 3-5. Concentrations of trace elements in the A and B horizons by parent material

A horizon (mg/kg soil)						
	Felsic		Intermediate		Mafic	
	Average	Range	Average	Range	Average	Range
Si*	30.22	22.93 - 37.41	29.38	22.25 - 33.84	20.16	11.22 - 29.51
K*	2.53	0.36 - 4.41	1.66	0.33 - 3.37	0.17	0.05 - 0.29
Ti*	0.39	0.24 - 0.89	0.35	0.23 - 0.51	1.12	0.13 - 4.09
V	37.40	16.02 - 87.27	67.41	23.09 - 111.26	210.97	77.16 - 308.39
Cr	16.82	3.74 - 32.90	60.13	7.23 - 207.29	367.37	30.91 - 813.79
Mn	319.95	75.32 - 566.28	332.19	100.04 - 957.97	990.03	697.42 - 1325.86
Co	4.60	1.03 - 7.27	11.94	3.06 - 23.21	50.48	27.98 - 64.73
Ni	14.06	1.01 - 44.70	38.57	3.91 - 88.43	85.17	9.25 - 178.47
Cu	20.95	11.96 - 39.27	28.73	8.72 - 57.02	48.13	12.88 - 84.49
Zn	67.44	10.22 - 141.56	56.44	16.80 - 93.34	102.42	57.90 - 171.18
As	5.14	3.84 - 6.26	5.52	4.33 - 7.60	6.03	3.49 - 8.58
Cd	0.11	0.07 - 0.26	0.08	0.07 - 0.18	0.10	0.07 - 0.19
Ba	723.51	157.94 - 1351.72	453.85	175.48 - 846.48	139.44	60.82 - 385.05
Hg	0.07	0.04 - 0.16	0.08	0.04 - 0.14	0.07	0.04 - 0.12
Pb	33.59	17.92 - 46.49	29.61	14.60 - 38.00	15.95	11.54 - 28.85
U	3.56	1.28 - 8.52	3.58	1.13 - 4.97	0.88	0.49 - 1.30
B horizon (mg/kg soil)						
	Felsic		Intermediate		Mafic	
	Average	Range	Average	Range	Average	Range
Si*	25.42	19.30 - 29.47	25.33	19.58 - 34.30	16.99	10.22 - 28.11
K*	2.01	0.30 - 3.87	1.57	0.60 - 2.98	0.15	0.04 - 0.22
Ti*	0.40	0.19 - 0.77	0.44	0.23 - 0.76	0.76	0.09 - 2.40
V	64.47	30.26 - 133.98	102.17	43.54 - 223.10	200.29	85.93 - 288.66
Cr	34.17	3.96 - 56.18	78.68	13.97 - 178.97	486.83	91.11 - 837.63
Mn	214.30	28.22 - 425.47	277.48	99.97 - 671.71	754.96	397.07 - 1117.03
Co	5.96	2.96 - 9.26	13.39	4.91 - 24.35	48.57	19.26 - 81.41
Ni	19.02	5.55 - 49.97	46.77	2.14 - 113.39	117.52	43.56 - 186.39
Cu	26.62	11.67 - 63.51	40.99	13.30 - 70.73	68.77	26.51 - 118.20
Zn	75.08	30.39 - 132.07	80.36	39.22 - 121.88	86.90	40.18 - 130.85
As	5.85	3.97 - 8.95	5.89	3.54 - 9.73	4.86	3.16 - 6.33
Cd	0.08	0.07 - 0.12	0.07	0.07 - 0.08	0.08	0.07 - 0.12
Ba	518.59	146.55 - 937.58	385.02	215.17 - 731.54	143.02	52.32 - 258.22
Hg	0.09	0.04 - 0.18	0.09	0.04 - 0.19	0.07	0.04 - 0.16
Pb	37.32	12.01 - 66.58	28.25	8.07 - 42.54	7.94	4.53 - 11.51
U	5.06	2.03 - 7.90	4.28	1.35 - 6.15	0.92	0.33 - 1.97

* - designates units are in % dry weight

CHAPTER 4
TRACE ELEMENTS IN SOILS AND PARENT MATERIALS OF THE GEORGIA
PIEDMONT

Introduction

Trace elements are defined as any element that is present in relatively small amounts in soils and rock, either natural or anthropogenic. Background trace element concentrations in soils are generally considered those that are less than 100 mg/kg. Trace elements in rocks are defined as any element other than the most abundant eight elements found in the Earth's crust.

The original source of trace elements in soils is the underlying parent material. Trace elements are present in many minerals and ore deposits that make up different rocks and geologic units. Rocks vary widely in trace element content, but certain rocks are higher and lower, in general. Table 4-1 (adapted from Kabata-Pendias and Adriano, 1995) shows commonly reported values for trace elements in igneous and metamorphic rocks.

The area of this study is located in the Georgia Piedmont, more precisely the Inner Piedmont, the Charlotte and Slate belts, and Modoc fault zone. Allard and Whitney (1994) have completed a comprehensive review of the geology in this area. In summary, felsic to intermediate metamorphic rocks predominate Piedmont geology; however, both igneous granite and mafic bodies are occasionally identified.

A fault separates the Inner Piedmont from the Charlotte and Slate belts. The Inner Piedmont is composed mostly of migmatized biotite gneisses, quartz-muscovite-sillimanite schists, and mica schists. The Charlotte and Slate belts (together called the Carolina terrane) are

from the Cambrian period and consist of metamorphosed volcanic and sedimentary rocks. These range from felsic to mafic, and also vary in grade of metamorphism. The rocks in the Inner Piedmont and Carolina terrane were deformed between 425 and 500 million years ago. About 300 million years ago igneous plutons intruded these areas, the most well-known being the Elberton granite. The fault area separating the Carolina terrane from the area south of it is known as the Modoc fault zone (Allard and Whitney, 1994). Due to the abundance of different rock types in the study area, a range of concentrations of trace elements is likely to be detected in the Georgia Piedmont.

Few studies have been conducted directly relating trace element concentrations in soils to trace element concentrations in the underlying parent material. Trace elements are usually studied for purposes of soil profile reconstruction analysis and igneous and metamorphic petrology. Prabhakaran Nair and Cottenie (1971) described a mathematical relationship between soils and underlying parent material that found a reasonable estimation of soil concentrations could be gathered with the analysis of the underlying rock. This mathematical relationship was found to be more accurate for total trace element concentrations, but did not work effectively for acid extractable trace elements. More recently, De Oliveira et al. (2000) studied the relationship between soil magnetic minerals and soil trace elements on various parent materials in Brazil. Higher concentrations were found in soils with higher concentrations of magnetic minerals, which formed over the more mafic parent materials.

The purpose of this study is to describe the concentrations of trace elements in the soils in the Piedmont of Georgia and relate them to the underlying parent materials.

Materials and methods

The Georgia Piedmont was chosen as the study area because it contains a range of different rock types. Sample locations were selected to represent the geologic variation of the study area. The individual parent materials were located and identified in the field with thesis maps provided by the University of Georgia, Department of Geology, and confirmed by examination of rock hand specimens. Three soil profiles were sampled at each sample location, each 5 to 15 meters apart, to assess variation in the field. Samples were collected from the A, B, and C horizons of each profile, where those horizons were present and accessible. In addition, parent material samples were collected when available. Parent material types and sample locations are shown in Table 4-2 and on Figure 4-1.

Soil samples were collected using two different methods, based on field conditions. For sample locations with exposed soil profiles (e.g., road cuts), a sharpshooter was used to remove overburden and eroded topsoil to provide a fresh sampling surface. The samples were collected with a spade directly from the exposed profile. A hand auger was used to sample soils from ground surface locations. Rock samples were collected using a rock hammer. All sampling equipment was decontaminated prior to sample collection. Samples were placed for storage in 1-quart freezer bags, identified with labels, and transported to the laboratory for analysis. Upon arrival to the lab, soil samples were air-dried. For each sample location, a composite of the three sub samples from the A, B, and C horizons were passed through a 2mm sieve, then ground with a mortar and pestle. Rock samples were pulverized using a ball-mill grinder.

For each sample, 0.25 grams of soil or pulverized rock was placed in a Teflon microwave pressure digestion vessel, to which 2.5 mL of HF was added. The samples were pre-digested for 16 hours to aid in total dissolution (Ammons, et. al). Following pre-digestion, 5 mL of aqua

regia (3:1:1 – HCl:HNO₃:ultra pure deionized water) was added to the vessels, the vessels were pressure sealed and heated at 180 C in a CEM digestion microwave oven for 20 minutes (EPA method 3052, modified). The vessels were weighed before and after digestion to ensure no greater than five percent of the sample was lost during the digestion process. After cooling, 25 mL of 5% HBO₃ was added to neutralize the HF. Ultra pure deionized water was added to the vessel to bring the total volume to 100 mL, by weight. The final solution was placed in a polyethylene bottle and stored in a refrigerator to await analysis.

Samples were analyzed on the Perkin Elemer Elan 6000 ICP-MS for Si, K, Ti, V, Cr, Mn, Co, Ni, Cu, Zn, As, Cd, Ba, Hg, Pb, and U. Duplicates, blanks, and standard reference materials (SRMs) were analyzed to ensure proper method and instrument function.

Results and discussion

Average trace element concentrations by parent material are shown in Table 4-3. The average concentration as well as the range are shown for each to show the wide variability of trace element concentrations in the rock samples. Average concentrations vary widely between rock types, although it should be noted that in many cases the range of values between different rock types overlap significantly. Rocks types were placed in felsic, intermediate, and mafic categories based on the Si content of the rocks.

Average values of Si, K, Zn, Ba, and Pb are highest in the felsic rocks and lowest in the mafic rocks. Conversely, average concentrations of Ti, V, Cr, Mn, Co, Ni, Cu, and As are highest in the mafic rocks and lowest in the felsic rocks. The intermediate rocks have the highest average concentration of U and are intermediate in concentration for all other elements. Concentrations of Cd and Hg are too close to the detection limits to make any comparisons of relative concentrations. The trace elements typically observed in the mafic rocks are generally

lighter in atomic weight (e.g., V, Cr, Ni). The heavier elements (e.g., Ba, Pb) are observed in higher concentrations in the felsic parent materials. The trace elements with intermediate atomic weight (e.g., Cu, As) were not significantly different between the felsic and mafic rocks.

Trace element concentrations in rocks are dependent on the trace element concentrations of the rock forming minerals. Table 4-4 (adapted from Smith and Huyck, 1999) shows trace elements found in the major rock forming minerals. The minerals are listed in order of stability during weathering (i.e., more easily weathered materials are listed first, the most stable are listed last).

The felsic parent materials in the Georgia Piedmont (granites, tonalite, and quartzite) are primarily composed of quartz and plagioclase, with varying parts of biotite and other minerals (Allard and Whitney, 1994). The high silica content of quartz and increased amount plagioclase are the source of the high percentages of Si, K, Ba, Pb, and Zn compared to that of the intermediate and mafic rocks.

The mafic parent materials (gabbros, serpentinite, schist) are composed of varying parts of olivine, pyroxene, amphiboles, hornblende, and biotite. These minerals are the primary source of Ti, V, Cr, Mn, Co, Ni, and Cu.

High concentrations of trace elements are also present in certain minerals and may account for a larger portion of trace element concentrations in certain cases. For example, Pb is found in large amounts in both galena and some feldspars (Plumlee, 1999).

Table 4-5 shows the average concentrations of trace elements in the A, B, and C horizons and the underlying parent materials. The soil horizons are separated into groups based upon the parent material (felsic, intermediate, and mafic).

The average concentrations in Table 4-5 were used to compute enrichment ratios (ER) between the soil and parent materials. The ER is defined as the trace element concentration in soil divided by the concentration in rock for each element. An ER of 1 would mean an equal concentration of a trace element in the soil and rock. Saprolite that has not weathered much from the parent material would likely exhibit the same concentrations of trace elements as the underlying parent material, and would likely have an ER of 1. Soils that have lost trace elements from the profile would have an ER less than 1. Table 4-6 shows the ER for each element for the A, B, and C horizons.

The ER for Si is greater than 1 in the A horizon because the sandy topsoil increased the Si measured. The ER for K is low for the A, B, and C horizons because K is soluble and moves relatively quickly through a soil profile. Ti is highly immobile in soil due to the formation of titanium oxides and has an ER greater than 1 in the A, B, and C horizons. V, Cr, Mn, Ni, Cu, and Zn have an ER less than 1 in the A horizon, with increasing ERs in the B and C horizons. These elements are likely involved in nutrient cycling or uptake by plants and animals. As has an ER much greater than 1 in the A and B horizons. As is immobile in the acid soils of Georgia and does not move readily through the soil profile. In addition, anthropogenic influence may have historically increased As concentrations in the soil profile. The ER for Cd is highest in the A horizon due to either atmospheric deposition or increased organic matter holding the Cd in the A horizon. Ba behaves as a mobile cation in soils due to low ionic potential and therefore has an ER less than one. Co and Hg have ERs near 1 in all soil horizons so are neither accumulated or lost over time. Pb and U are immobile and have accumulated in the soil profile.

Trace element concentrations in soils are highly dependent on the trace element concentrations in the parent materials in which they formed. Trace element concentrations vary

widely in rocks, and are derived from the rock forming minerals. When measuring trace elements in soils, it is important to consider not only soil properties, but more importantly the underlying parent materials.

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Table 4-1. Concentration of trace elements in igneous and metamorphic rocks

Element	Rock type		
	Felsic (mg/kg)	Intermediate (mg/kg)	Mafic (mg/kg)
V	40 - 90	30 - 100	200 - 250
Cr	4 - 25	15 - 50	170 - 200
Mn	350 - 600	500 - 1200	1200 - 2000
Co	1 - 7	1 - 10	35 - 50
Ni	5 - 15	5 - 55	130 - 160
Cu	15 - 30	15 - 80	60 - 120
Zn	40 - 60	40 - 100	80 - 120
As	1 - 2.6	1 - 2.5	0.6 - 2
Cd	0.09 - 0.2	0.13 - 0.13	0.13 - 0.22
Ba	400 - 850	600 - 1000	250 - 400
Hg	0.08 - 0.08	BDL	BDL
Pb	15 - 25	12 - 15	3 - 8
U	2.5 - 6	1.4 - 3	0.3 - 1

BDL - Below detection limits

Table 4-2. Parent material type and location

Rock type	Sample location	Rock sample description	Latitude	Longitude
Felsic	1	quartzite	33° 52' 50"	83° 6' 27"
	6	elberton granite	34° 1' 48"	83° 0' 24"
	9	elberton granite	34° 0' 53"	83° 1' 31"
	10	elberton granite	34° 1' 0"	82° 58' 0"
	15	metatonalite	34° 0' 44"	82° 52' 20"
	22	danburg granite	33° 57' 13"	82° 37' 46"
	23	siloam granite	33° 17' 0"	82° 55' 49"
	24	panola granite	33° 38' 15"	84° 10' 29"
Intermediate	2	granite gneiss	34° 5' 6"	83° 6' 18"
	3	sillimanite-quartz-sericite-schist	34° 4' 29"	83° 1' 1"
	4	cal-silicate schist assemblage	34° 7' 18"	83° 3' 19"
	5	gneiss schist amphibolite assemblage	34° 5' 20"	83° 2' 57"
	7	undifferentiated gneiss/schist	34° 2' 29"	83° 0' 14"
	8	augite hornblende gneiss	34° 2' 45"	83° 0' 16"
	11	migmatic gneiss	34° 5' 30"	82° 58' 59"
	16	metaquartz diorite	34° 0' 19"	82° 49' 58"
25	lithonia gneiss	33° 50' 54"	83° 53' 41"	
Mafic	12	gabbro	34° 1' 27"	82° 41' 16"
	13	serpentine	34° 3' 59"	82° 42' 7"
	14	coarse grained metagabbro/metapyroxene	34° 1' 55"	82° 45' 20"
	17	chlorite schist	33° 20' 36"	83° 4' 56"
	19	metagabbro	34° 2' 48"	84° 29' 41"
	20	gladesville gabbro	33° 13' 16"	83° 44' 35"
	21	metagabbroic-dioritic rock	34° 0' 13"	82° 48' 29"

Table 4-3. Trace element concentrations by parent material

Element	All parent materials		Felsic	
	Average	Range	Average	Range
Si*	24.40	13.82 - 32.99	29.46	25.86 - 32.99
K*	2.57	0.04 - 6.14	4.23	3.20 - 5.02
Ti*	0.43	0.04 - 1.54	0.24	0.06 - 0.65
V	118.15	11.71 - 403.07	34.05	11.71 - 90.23
Cr	183.17	25.81 - 715.08	55.58	25.81 - 85.13
Mn	579.46	23.07 - 1686.79	242.11	23.07 - 527.84
Co	19.75	0.85 - 72.04	3.41	0.85 - 7.29
Ni	60.60	1.91 - 261.89	3.84	1.91 - 5.55
Cu	37.39	2.34 - 140.27	16.29	5.84 - 26.28
Zn	88.15	11.68 - 162.72	95.94	13.50 - 162.72
As	3.26	2.34 - 5.30	3.13	2.69 - 3.79
Cd	0.07	0.07 - 0.07	0.07	0.07 - 0.07
Ba	588.19	16.90 - 3326.25	874.83	46.89 - 2189.61
Hg	0.07	0.04 - 0.21	0.08	0.04 - 0.21
Pb	20.50	2.39 - 76.46	33.14	3.38 - 52.49
U	2.00	0.04 - 8.65	2.17	0.84 - 4.02

Element	Intermediate		Mafic	
	Average	Range	Average	Range
Si*	25.75	20.44 - 32.43	16.89	13.82 - 20.61
K*	2.94	0.07 - 6.14	0.21	0.04 - 0.57
Ti*	0.41	0.04 - 0.94	0.67	0.07 - 1.54
V	108.21	15.06 - 230.45	227.04	92.49 - 403.07
Cr	147.35	55.05 - 321.63	375.06	95.66 - 715.08
Mn	551.10	68.28 - 1686.79	1001.48	683.92 - 1385.12
Co	9.45	0.99 - 30.46	51.68	36.49 - 72.04
Ni	19.15	2.81 - 53.46	134.49	56.04 - 261.89
Cu	29.84	2.34 - 86.41	71.20	8.07 - 140.27
Zn	86.71	37.41 - 124.24	82.04	11.68 - 121.41
As	3.17	2.67 - 4.18	3.54	2.34 - 5.30
Cd	0.07	0.07 - 0.07	0.07	0.07 - 0.07
Ba	711.02	70.88 - 3326.25	102.67	16.90 - 257.76
Hg	0.07	0.04 - 0.21	0.07	0.04 - 0.20
Pb	19.98	4.69 - 76.46	4.43	2.39 - 7.39
U	2.98	1.17 - 8.65	0.53	0.04 - 2.35

* - designates units are in % dry weight

Table 4-4. Trace elements of interest commonly found in rock-forming minerals

Mineral	Elements expressed in range of concentration			
	X%	0.X%	0.0X%	0.00X% or less
Olivine		Ni, Mn	Cr, Ti, Co	Zn, V, Cu
Pyroxene		Ti, Mn, K	Cr, V, Ni	Cu, Co, Zn, Ba
Plagioclase Feldspar	K		Ba, Ti, Mn	V, Zn, Ni, Pb, Cu
Amphibole		Ti, K, Mn	Zn, Cr, V, Ni	Ba, Cu, Co, Pb
Biotite	Ti	Ba, Mn	Zn, V, Cr, Ni	Cu, Co, Pb
Potassium Feldspar		Ba	Ti	Pb, V, Zn, Ni, Cu, Zn
Muscovite		Ti, Ba	Cr, Mn, V	Cu
Quartz				Mg, Ti, Mn, Zn

Table 4-5. Average concentrations of trace elements in soils and parent material

A horizon (mg/kg soil)						
	Felsic		Intermediate		Mafic	
	Average	Range	Average	Range	Average	Range
Si*	30.22	22.93 - 37.41	29.38	22.25 - 33.84	20.16	11.22 - 29.51
K*	2.53	0.36 - 4.41	1.66	0.33 - 3.37	0.17	0.05 - 0.29
Ti*	0.39	0.24 - 0.89	0.35	0.23 - 0.51	1.12	0.13 - 4.09
V	37.40	16.02 - 87.27	67.41	23.09 - 111.26	210.97	77.16 - 308.39
Cr	16.82	3.74 - 32.90	60.13	7.23 - 207.29	367.37	30.91 - 813.79
Mn	319.95	75.32 - 566.28	332.19	100.04 - 957.97	990.03	697.42 - 1325.86
Co	4.60	1.03 - 7.27	11.94	3.06 - 23.21	50.48	27.98 - 64.73
Ni	14.06	1.01 - 44.70	38.57	3.91 - 88.43	85.17	9.25 - 178.47
Cu	20.95	11.96 - 39.27	28.73	8.72 - 57.02	48.13	12.88 - 84.49
Zn	67.44	10.22 - 141.56	56.44	16.80 - 93.34	102.42	57.90 - 171.18
As	5.14	3.84 - 6.26	5.52	4.33 - 7.60	6.03	3.49 - 8.58
Cd	0.11	0.07 - 0.26	0.08	0.07 - 0.18	0.10	0.07 - 0.19
Ba	723.51	157.94 - 1351.72	453.85	175.48 - 846.48	139.44	60.82 - 385.05
Hg	0.07	0.04 - 0.16	0.08	0.04 - 0.14	0.07	0.04 - 0.12
Pb	33.59	17.92 - 46.49	29.61	14.60 - 38.00	15.95	11.54 - 28.85
U	3.56	1.28 - 8.52	3.58	1.13 - 4.97	0.88	0.49 - 1.30
B horizon (mg/kg soil)						
	Felsic		Intermediate		Mafic	
	Average	Range	Average	Range	Average	Range
Si*	25.42	19.30 - 29.47	25.33	19.58 - 34.30	16.99	10.22 - 28.11
K*	2.01	0.30 - 3.87	1.57	0.60 - 2.98	0.15	0.04 - 0.22
Ti*	0.40	0.19 - 0.77	0.44	0.23 - 0.76	0.76	0.09 - 2.40
V	64.47	30.26 - 133.98	102.17	43.54 - 223.10	200.29	85.93 - 288.66
Cr	34.17	3.96 - 56.18	78.68	13.97 - 178.97	486.83	91.11 - 837.63
Mn	214.30	28.22 - 425.47	277.48	99.97 - 671.71	754.96	397.07 - 1117.03
Co	5.96	2.96 - 9.26	13.39	4.91 - 24.35	48.57	19.26 - 81.41
Ni	19.02	5.55 - 49.97	46.77	2.14 - 113.39	117.52	43.56 - 186.39
Cu	26.62	11.67 - 63.51	40.99	13.30 - 70.73	68.77	26.51 - 118.20
Zn	75.08	30.39 - 132.07	80.36	39.22 - 121.88	86.90	40.18 - 130.85
As	5.85	3.97 - 8.95	5.89	3.54 - 9.73	4.86	3.16 - 6.33
Cd	0.08	0.07 - 0.12	0.07	0.07 - 0.08	0.08	0.07 - 0.12
Ba	518.59	146.55 - 937.58	385.02	215.17 - 731.54	143.02	52.32 - 258.22
Hg	0.09	0.04 - 0.18	0.09	0.04 - 0.19	0.07	0.04 - 0.16
Pb	37.32	12.01 - 66.58	28.25	8.07 - 42.54	7.94	4.53 - 11.51
U	5.06	2.03 - 7.90	4.28	1.35 - 6.15	0.92	0.33 - 1.97

Table 4-5. Continued

	C horizon (mg/kg soil)					
	Felsic		Intermediate		Mafic	
	Average	Range	Average	Range	Average	Range
Si*	26.38	22.67 - 32.16	24.83	19.47 - 29.32	17.49	10.08 - 21.69
K*	2.84	0.07 - 3.96	1.75	0.93 - 3.26	0.12	0.03 - 0.36
Ti*	0.40	0.12 - 0.71	0.42	0.19 - 0.87	0.59	0.06 - 2.52
V	63.57	27.16 - 102.25	101.63	31.49 - 263.44	167.05	55.64 - 280.03
Cr	27.93	3.68 - 79.11	112.71	23.82 - 236.05	356.61	18.32 - 778.66
Mn	248.48	13.43 - 477.76	368.76	75.89 - 770.00	835.03	598.34 - 1003.07
Co	5.69	2.96 - 9.83	22.28	4.63 - 62.25	40.55	12.75 - 84.06
Ni	25.13	5.67 - 72.80	82.97	37.01 - 170.86	133.93	21.99 - 319.92
Cu	26.63	12.44 - 62.31	37.66	24.23 - 73.00	56.20	17.80 - 130.14
Zn	83.77	40.35 - 149.65	96.45	58.29 - 158.07	87.24	44.93 - 134.54
As	4.34	2.39 - 6.05	4.28	3.07 - 6.12	3.21	2.21 - 4.94
Cd	0.08	0.07 - 0.11	0.07	0.07 - 0.09	0.08	0.07 - 0.15
Ba	671.64	87.44 - 1732.14	552.57	134.01 - 1111.79	100.78	23.85 - 257.55
Hg	0.05	0.04 - 0.16	0.07	0.04 - 0.14	0.05	0.04 - 0.12
Pb	51.45	17.23 - 122.42	28.92	7.22 - 50.74	7.57	3.18 - 12.96
U	5.28	1.29 - 11.13	4.10	1.36 - 6.55	0.39	0.02 - 0.86
	Rock (mg/kg)					
	Felsic		Intermediate		Mafic	
	Average	Range	Average	Range	Average	Range
Si*	29.46	25.86 - 32.99	25.75	20.44 - 32.43	16.89	13.82 - 20.61
K*	4.23	3.20 - 5.02	2.94	0.07 - 6.14	0.21	0.04 - 0.57
Ti*	0.24	0.06 - 0.65	0.41	0.04 - 0.94	0.67	0.07 - 1.54
V	34.05	11.71 - 90.23	108.21	15.06 - 230.45	227.04	92.49 - 403.07
Cr	55.58	25.81 - 85.13	147.35	55.05 - 321.63	375.06	95.66 - 715.08
Mn	242.11	23.07 - 527.84	551.10	68.28 - 1686.79	1001.48	683.92 - 1385.12
Co	3.41	0.85 - 7.29	9.45	0.99 - 30.46	51.68	36.49 - 72.04
Ni	3.84	1.91 - 5.55	19.15	2.81 - 53.46	134.49	56.04 - 261.89
Cu	16.29	5.84 - 26.28	29.84	2.34 - 86.41	71.20	8.07 - 140.27
Zn	95.94	13.50 - 162.72	86.71	37.41 - 124.24	82.04	11.68 - 121.41
As	3.13	2.69 - 3.79	3.17	2.67 - 4.18	3.54	2.34 - 5.30
Cd	0.07	0.07 - 0.07	0.07	0.07 - 0.07	0.07	0.07 - 0.07
Ba	874.83	46.89 - 2189.61	711.02	70.88 - 3326.25	102.67	16.90 - 257.76
Hg	0.08	0.04 - 0.21	0.07	0.04 - 0.21	0.07	0.04 - 0.20
Pb	33.14	3.38 - 52.49	19.98	4.69 - 76.46	4.43	2.39 - 7.39
U	2.17	0.84 - 4.02	2.98	1.17 - 8.65	0.53	0.04 - 2.35

* - designates units are in % dry weight

Table 4-6. Enrichment ratios for all parent material types

Element	A to R	B to R	C to R
Si*	1.11	0.94	0.95
K*	0.59	0.51	0.64
Ti*	1.37	1.20	1.08
V	0.84	1.00	0.91
Cr	0.62	1.00	0.85
Mn	0.74	0.66	0.80
Co	0.91	1.07	1.12
Ni	0.66	0.87	1.25
Cu	0.85	1.18	1.06
Zn	0.83	0.91	1.01
As	1.70	1.71	1.22
Cd	1.36	1.11	1.11
Ba	0.77	0.61	0.78
Hg	0.98	1.13	0.82
Pb	1.31	1.24	1.48
U	1.40	1.78	1.69

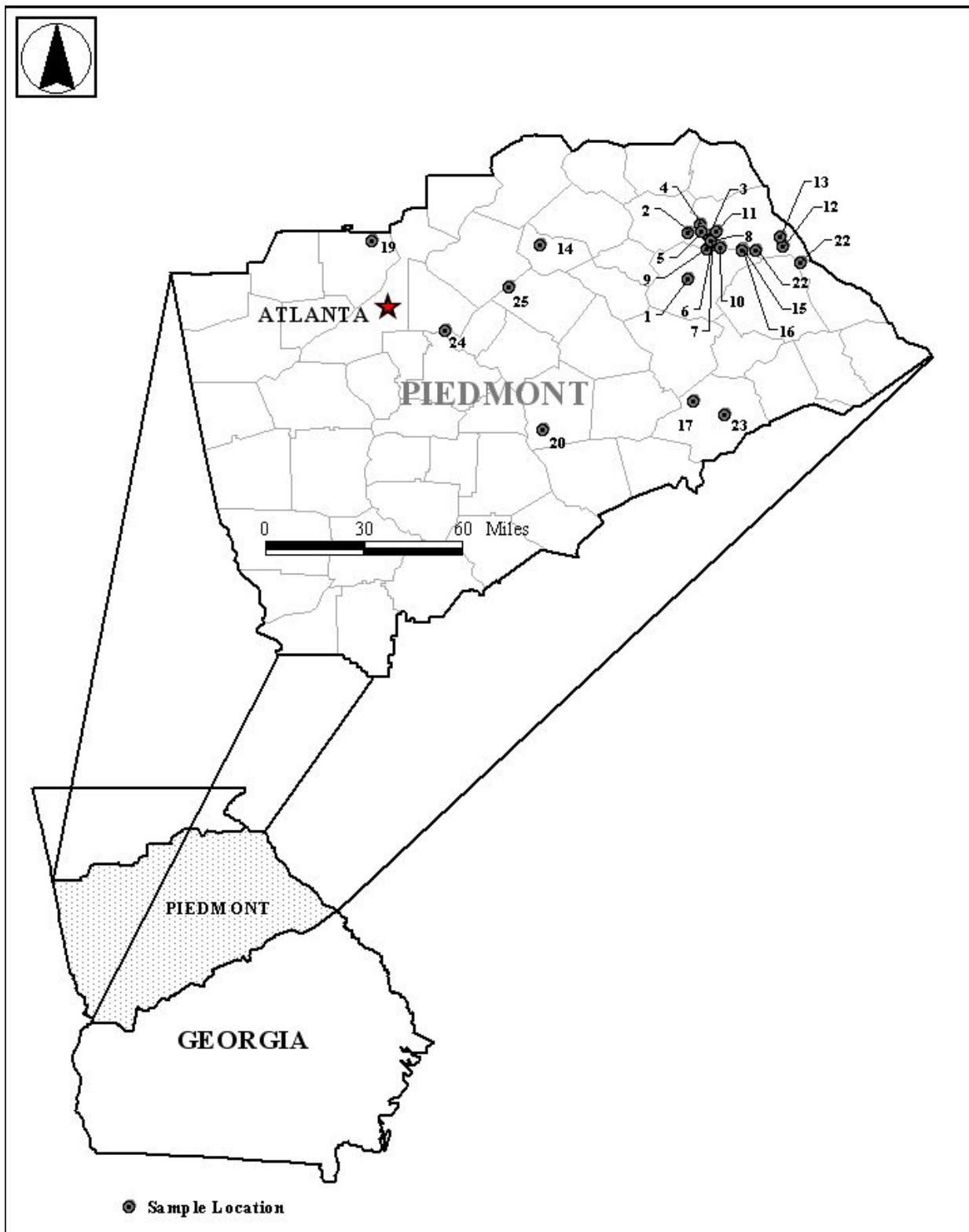


Figure 1. Sample Location Map

CHAPTER 5

CONCLUSIONS

Background concentrations of trace elements were previously unknown for the Georgia Piedmont. The purpose of this study was to establish background concentrations for 16 trace elements in surface soils, subsoils, and parent materials of the Georgia Piedmont. Soils and parent materials were systematically sampled, prepared, and analyzed for the following trace elements: Si, K, Ti, V, Cr, Mn, Co, Ni, Cu, Zn, As, Cd, Ba, Hg, Pb, and U. A comparison of the results of the analysis to studies conducted in Florida, the United States, and world-wide show wide variation in trace element concentrations in soils. Georgia concentrations were higher than those reported in Florida, although ranges of values indicated Georgia soils are comparable to those in the continuous US. Mafic parent rocks showed consistently elevated levels of a suite of trace elements (Cr, Mn, Co, V) in all soil horizons sampled, while felsic rocks were higher in Pb, U, and Ba. Intermediate rocks weathered to soils with trace elements contents in between these extremes.

Trace element concentrations in soils were compared to regulatory limits for trace elements in soils applicable in Georgia. The regulatory criteria included the land application pollutant concentration limits for biosolids, release notification soil concentration limits, and risk reduction standards that indicate if the soil poses a significant risk for residential land use. The risk reduction standards were exceeded by either the average or highest concentration for seven of the eleven trace elements regulated. In areas where the average background concentration exceeds the risk reduction standards, there is a potential that industrial facilities will be required by regulators to remediate soils to levels lower than natural background concentrations.

Trace element concentrations in soils vary significantly depending on the parent material the soils developed over. Rocks and soils vary in trace element concentration over a small area in the Georgia Piedmont. It is important for regulators to be aware of these differences when assessing contamination of soils at industrial facilities. For certain trace elements, the release notification limit for the Hazardous Site Inventory is a set concentration, or background, if larger. Industrial facilities would be required to sample background concentrations in an area surrounding the facility to assess the background variation. Based upon the observed variability of trace elements in soils and parent materials in Georgia, background sample concentrations in any area could potentially misrepresent the background concentration at a specific location. Parent material differences over a short distance could cause the trace element concentrations in soils to be much higher or lower than that of the area of interest.

Trace element concentrations vary widely in rocks, and are derived from the rock forming minerals. When measuring trace elements in soils, it is important to consider not only soil properties, but more importantly the underlying parent materials.

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APPENDIX A

SITE LOCATION DESCRIPTIONS

Site 1

Parent material: Quartzite

Location: 33° 52' 50"N, 83° 6' 27"W

Directions: From the junction of Highway 78 and Highway 22 in Lexington, take Highway 22 north. Turn right at the first unpaved road, travel south down the road. Samples were collected from the road cut on the eastern side of the road, north of Trouble Creek.

Landscape position: Side slope

Soil description: Cecil sandy loam. A horizon – brown sandy loam, B horizon – clay, C horizon – coarse sandy loam saprolyte.

Site 2

Parent material: Granite gneiss

Location: 34° 5' 6"N, 83° 6' 18"W

Directions: From Highway 72 in Comer, travel east on Highway 72. Turn right (north) on New Hope Church Road toward Paoli. Site is located near the intersection of New Hope Church Road and Fork Creek. Travel by foot west from the road along Fork Creek. Samples collected with hand auger on the south side of the river. Rocks collected from outcrop.

Landscape position: Head slope. Slope approximately 2%.

Soil description: Madison sandy clay loam. A horizon – sandy loam, B horizon – clay, C horizon – micacious clay loam

Site 3

Parent material: Sillimanite-quartz-sericite-schist

Location: 34° 4' 29"N, 83° 1' 1"W

Directions: From Highway 72 in Carlton, go east on Highway 72. Turn left (north) immediately before reaching the Broad River. Travel approximately 0.75 miles along road. Samples collected from road cut along the north side of the road.

Landscape position: Side slope

Soil description: Madison sandy loam. A horizon – granular sandy loam, B horizon – blocky clay loam, C horizon – massive sand.

Site 4

Parent material: Cal-silicate schist assemblage

Location: 34° 7' 18"N, 83° 3' 19"W

Directions: From Highway 72 in Comer, travel east to New Hope Church Road. Travel north on New Hope Church Road. In Paoli, go right at the Y-intersection. Continue north to T-intersection. Turn right. Sampled south of Vineyard Creek on the north side of the road.

Samples collected with hand auger above the road cut.

Landscape position: Back slope

Soil description: Cecil sandy loam. A horizon – granular sandy loam, B horizon – blocky clay, C horizon – loose sand.

Site 5

Parent material: Gneiss schist amphibolite assemblage

Location: 34° 5' 20"N, 83° 2' 57"W

Directions: From Highway 72 in Comer, travel east on Highway 72. Turn left (north) on New Hope Church Road. Turn right on Paoli New Town Road in Paoli. Turn left on Osley Mill Road (north) and drive to Holly Creek. Sampled on north side of the road, just south of Holly Creek.

Sampled from road cut.

Landscape position: Side slope.

Soil description: Pacolet sandy loam. A horizon – sandy loam, B horizon – clay, C horizon – sandy loam.

Site 6

Parent material: Elberton granite

Location: 34° 1' 48"N, 83° 0' 24"W

Directions: From Highway 72 in Carlton, take Sandy Cross Road south. Cross the South Fork Broad River and turn into dirt parking area. Sample location is approximately 0.2 miles east of the parking area. Samples collected with a hand auger. Rock sampled near river.

Landscape position: Side slope

Soil description: Ashlar sandy loam. A horizon – sandy loam, B horizon – sandy loam, C horizon – sandy loam.

Site 7

Parent material: undifferentiated gneiss/schist

Location: 34° 2' 29"N, 83° 0' 14"W

Directions: From Highway 72 in Carlton, take Sandy Cross Road south. Turn left (east) onto the first road (unnamed road) that connects Sandy Cross Road and Berkley Road. Sampled south of the intersection of Fork Creek and the unnamed road, immediately south of the power line right of way.

Landscape position: Head slope

Soil description: Grover sandy loam. A horizon – sandy loam, B horizon – sandy clay loam, C horizon – sandy loam.

Site 8

Parent material: Augite hornblende gneiss

Location: 34° 2' 45"N, 83° 0' 16"W

Directions: From Highway 72 in Carlton, take Sandy Cross Road south. Turn left (east) onto the first road (unnamed road) that connects Sandy Cross Road and Berkley Road. Sampled south of the intersection of Fork Creek and the unnamed road, north of the power line right of way.

Landscape position: Side slope.

Soil description: Pacolet sandy loam. A horizon – sandy clay loam, B horizon – clay, C horizon – sandy loam.

Site 9

Parent material: Elberton granite

Location: 34° 0' 53"N, 83° 1' 31"W

Directions: From Highway 72 in Carlton, take Sandy Cross Road south. Turn right (west) onto North Point Peter Road. Take third left onto unnamed road. Sampled approximately 0.25 miles west down the road, on the south side of the road. Samples collected with hand auger

Landscape position: Side slope

Soil description: Cecil sandy loam. A horizon – sandy loam, B horizon – clay, C horizon – sandy loam

Site 10

Parent material: Elberton granite

Location: 34° 1' 0"N, 82° 58' 0"W

Directions: From Highway 72 in Carlton, take Sandy Cross Road south. Take first left after crossing the Broad River. Turn right (south) onto Milstone Church Road. Pass a circle and quarry road, then take the next left onto an unnamed road. Sampled 0.4 miles from the turn on the south side of the road.

Landscape position: Head slope, 0-2% slope.

Soil description: Appling or Cecil sandy loam. A horizon – sandy loam, B horizon – clay, C horizon – sandy loam

Site 11

Parent material: Migmatic gneiss

Location: 34° 5' 30"N, 82° 58' 59"W

Directions: From Highway 72 in Carlton, drive east to Oglesby. Turn left (north) at intersection in Oglesby. Take the first left onto an unnamed road. Sampled east of Dove Creek on south side of road.

Landscape position: Shoulder

Soil description: Madison sandy loam. A horizon – sandy loam, B horizon – clay, C horizon – sandy loam.

Site 12

Parent material: Gabbro

Location: 34° 1' 27"N, 82° 41' 16"W

Directions: Drive east out of Elberton on Highway 72. Turn right onto Highway 79. Turn right onto Balchin Road. Sampled north of the power line right of way along dirt road.

Landscape position: Upland flat

Soil description: Iredell sandy loam. A horizon – sandy loam, B horizon – clay, C horizon – clay loam.

Site 13

Parent material: Serpentinite

Location: 34° 3' 59"N, 82° 42' 7"W

Directions: Drive east from Elberton on Highway 72. Turn left at the Elberton boat ramp.

Sampled north of the boat parking lot along the road. Samples collected with a hand auger.

Landscape position: River terrace, upland flat. 1% slope

Soil description: Iredell sandy loam. A horizon – sandy loam, B horizon – clay (shrink/swell),
BC horizon – clay loam.

Site 14

Parent material: coarse grained metagabbro/metapyroxene

Location: 34° 1' 55"N, 82° 45' 20"W

Directions: From Fortsonia, travel east on Flatwoods road. Turn left (north) after crossing
Wahachee Creek. Sampled south of Wahachee Creek on the east side of the road at the T-
intersection with a dirt road.

Landscape position: Hill slope, 4% slope

Soil description: Iredell sandy loam. A horizon – sandy loam, B horizon – blocky clay, C
horizon – clay loam.

Site 15

Parent material: Metatonalite

Location: 34° 0' 44"N, 82° 52' 20"W

Directions: Drive south on Highway 77 from Elberton. Turn left after crossing Falling Creek.

Sampled along the road north of the T-intersection with a dirt road.

Landscape position: Back slope, 3% slope

Soil description: Cecil sandy loam. A horizon – sandy loam, B horizon – clay, C horizon – sandy loam.

Site 16

Parent material: Metaquartz diorite

Location: 34° 0' 19"N, 82° 49' 58"W

Directions: Drive south on Highway 77 from Elberton. Turn left after crossing Falling Creek.

Sampled on the north side of the road, west of the Y-intersection.

Landscape position: Back slope, 4% slope.

Soil description: Cecil sandy loam. A horizon – sandy loam, B horizon – sandy clay, C horizon – sandy loam.

Site 17

Parent material: Chlorite schist

Location: 33° 20' 36"N, 83° 4' 56"W

Directions: Located northwest of Shoulderbone at the intersection of Highway 16 and Veazy Road.

Landscape position: Upland flat

Soil description: A horizon – sandy loam, B horizon – clay, C horizon – loamy sand.

Site 19

Parent material: Metagabbro

Location: 34° 2' 48"N, 84° 29' 41"W

Directions: From Noonday, take Shallowford Road east to Shallowford Baptist Church.

Sampled west of the parking area with hand auger.

Landscape position: Side slope

Soil description: Iredell sandy loam. A horizon – sandy loam, B horizon – blocky clay, C horizon – clay loam.

Site 20

Parent material: Gladesville gabbro

Location: 33° 13' 16"N, 83° 44' 35"W

Directions: Travel north from Gladesville on Highway 83. At the Gladesville Lookout Tower, take a right (east) into the large quarry. Sampled on the southeast side of the quarry along the dirt road.

Landscape position: Side slope

Soil description: Iredell sandy loam. A horizon – sandy loam, B horizon – blocky clay, C horizon – clay loam.

Site 21

Parent material: Metagabbroic-dioritic rock

Location: 34° 0' 13"N, 82° 48' 29"W

Directions: Drive east out of Fortsonia on Flatwoods Road. Sampled from east side of Falling Creek on the north side of the road.

Landscape position: Side slope

Soil description: Ashlar sandy loam. A horizon – sandy loam, B horizon – sandy loam, C horizon – sandy loam.

Site 22

Parent material: Danburg granite

Location: 33° 57' 13"N, 82° 37' 46"W

Directions: Travel north on Highway 79 from Beulah. Sampled north of Pistol Creek.

Landscape position: Side slope

Soil description: Cecil sandy loam. A horizon – sandy loam, B horizon – clay, C horizon – sandy loam

Site 23

Parent material: Siloam granite

Location: 33° 17' 0"N, 82° 55' 49"W

Directions: Drive east from Sparta on Highway 16. At Granite Hill, turn right (south) and drive to the large quarry. Sampled south of the quarry.

Landscape position: Side slope

Soil description: Cecil sandy loam. A horizon – sandy loam, B horizon – clay, C horizon – sandy loam

Site 24

Parent material: Panola granite

Location: 33° 38' 15"N, 84° 10' 29"W

Directions: From Panola Mountain State Park, take the hiking trail to the overlook. From the overlook, walk down to the base of the outcrop.

Landscape position: Side slope

Soil description: Madison sandy loam. A horizon – sandy loam, B horizon – clay, C horizon – sandy loam

Site 25

Parent material: Lithonia gneiss

Location: 33° 50' 54"N, 83° 53' 41"W

Directions: Go north from the intersection of Highway 78 and Highway 8. Sampled along Big Flat Creek.

Landscape position: Toe slope, 6-10% slope

Soil description: Madison sandy loam. A horizon – sandy loam, B horizon – clay, C horizon – sandy loam

APPENDIX B

CONCENTRATION OF ELEMENTS BY SITE

Si concentration data

Rock type	Sample location	Rock sample description	A	B	C	R
Felsic						
	1	quartzite	31.39	27.22	32.16	32.99
	6	elberton granite	26.39	29.47	31.25	29.71
	9	elberton granite	28.56	27.95	29.63	31.33
	10	elberton granite	30.82	19.60	25.25	29.03
	15	metatonalite	35.39	23.82	23.35	30.04
	22	danburg granite	28.87	26.55	23.85	27.25
	23	siloam granite	37.41	29.44	22.67	25.86
	24	panola granite	22.93	19.30	22.86	29.49
Intermediate						
	2	granite gneiss	32.04	26.59	24.03	30.14
	3	sillimanite-quartz-sericite-schist	33.02	22.79	25.02	20.83
	4	cal-silicate schist assemblage	25.26	19.58	25.61	20.44
	5	gneiss schist amphibolite assemblage	28.99	25.69	29.32	29.26
	7	undifferentiated gneiss/schist	32.71	21.87	19.47	20.73
	8	augite hornblende gneiss	33.84	34.30	27.05	21.61
	11	migmatic gneiss	22.25	21.87	20.61	26.84
	16	metaquartz diorite	29.69	28.81	27.48	32.43
	25	lithonia gneiss	26.64	26.49	ND	29.49
Mafic						
	12	gabbro	11.22	10.22	10.08	16.95
	13	serpentinite	29.51	28.11	20.24	20.61
	14	coarse grained metagabbro/metapyroxene	16.59	15.50	16.56	16.06
	17	chlorite schist	20.27	12.59	16.96	13.82
	19	metagabbro	22.93	21.05	21.69	16.80
	20	gladesville gabbro	19.80	15.02	17.15	17.69
	21	metagabbroic-dioritic rock	20.81	16.44	19.76	16.28

Notes:

ND - Not Determined

--all units in % Si

K concentration data

Rock type	Sample location	Rock sample description	A	B	C	R
Felsic						
	1	quartzite	2.15	1.11	3.11	3.50
	6	elberton granite	2.02	2.55	3.44	5.02
	9	elberton granite	3.76	3.87	3.96	4.52
	10	elberton granite	4.00	1.91	3.90	4.73
	15	metatonalite	0.36	0.70	1.39	3.20
	22	danburg granite	4.41	3.57	3.50	4.16
	23	siloam granite	0.81	0.30	0.07	4.47
	24	panola granite	2.73	2.08	3.33	4.25
Intermediate						
	2	granite gneiss	2.46	2.25	2.55	1.75
	3	sillimanite-quartz-sericite-schist	1.85	1.73	1.85	4.81
	4	cal-silicate schist assemblage	1.17	1.20	1.10	4.73
	5	gneiss schist amphibolite assemblage	2.01	1.87	2.92	3.75
	7	undifferentiated gneiss/schist	0.66	0.98	1.01	0.34
	8	augite hornblende gneiss	1.69	1.28	1.15	0.07
	11	migmatic gneiss	1.43	1.28	0.93	6.14
	16	metaquartz diorite	0.33	0.60	0.95	0.60
	25	lithonia gneiss	3.37	2.98	3.26	4.25
Mafic						
	12	gabbro	0.10	0.09	0.09	0.34
	13	serpentinite	0.21	0.46	0.36	0.57
	14	coarse grained metagabbro/metapyroxene	0.05	0.06	0.03	0.05
	17	chlorite schist	0.15	0.04	0.04	0.19
	19	metagabbro	0.18	0.22	0.18	0.13
	20	gladesville gabbro	0.21	0.08	0.04	0.15
	21	metagabbroic-dioritic rock	0.29	0.13	0.12	0.04

Notes:

--all units in % K

Ti concentration data

Rock type	Sample location	Rock sample description	A	B	C	R
Felsic						
	1	quartzite	0.34	0.31	0.56	0.17
	6	elberton granite	0.24	0.19	0.12	0.06
	9	elberton granite	0.26	0.29	0.28	0.24
	10	elberton granite	0.37	0.35	0.33	0.30
	15	metatonalite	0.25	0.35	0.28	0.10
	22	danburg granite	0.45	0.43	0.52	0.28
	23	siloam granite	0.34	0.48	0.41	0.65
	24	panola granite	0.89	0.77	0.71	0.17
Intermediate						
	2	granite gneiss	0.38	0.51	0.59	0.45
	3	sillimanite-quartz-sericite-schist	0.51	0.48	0.23	0.94
	4	cal-silicate schist assemblage	0.34	0.38	0.34	0.74
	5	gneiss schist amphibolite assemblage	0.44	0.43	0.20	0.21
	7	undifferentiated gneiss/schist	0.23	0.76	0.87	0.38
	8	augite hornblende gneiss	0.32	0.26	0.36	0.49
	11	migmatic gneiss	0.45	0.59	0.56	0.24
	16	metaquartz diorite	0.23	0.23	0.19	0.04
	25	lithonia gneiss	0.24	0.32	ND	0.17
Mafic						
	12	gabbro	4.09	2.40	2.52	1.54
	13	serpentinite	0.24	0.42	0.36	0.64
	14	coarse grained metagabbro/metapyroxene	0.26	0.26	0.14	0.08
	17	chlorite schist	1.12	0.93	0.54	1.20
	19	metagabbro	0.67	0.45	0.24	0.11
	20	gladesville gabbro	1.33	0.78	0.27	1.08
	21	metagabbroic-dioritic rock	0.13	0.09	0.06	0.07

Notes:

ND - Not Determined

--all units in % Ti

V concentration data

Rock type	Sample location	Rock sample description	A	B	C	R
Felsic						
	1	quartzite	31.12	55.12	84.85	34.16
	6	elberton granite	35.90	36.73	34.16	11.71
	9	elberton granite	26.20	30.26	27.16	30.72
	10	elberton granite	18.09	73.42	44.98	33.51
	15	metatonalite	26.40	64.50	45.49	17.61
	22	danburg granite	58.23	66.81	70.39	38.08
	23	siloam granite	16.02	54.97	102.25	90.23
	24	panola granite	87.27	133.98	99.24	16.42
Intermediate						
	2	granite gneiss	50.39	90.25	105.93	82.46
	3	sillimanite-quartz-sericite-schist	111.26	120.64	51.74	228.19
	4	cal-silicate schist assemblage	73.58	108.64	62.07	230.45
	5	gneiss schist amphibolite assemblage	68.09	78.17	31.49	49.78
	7	undifferentiated gneiss/schist	51.82	223.10	263.44	192.22
	8	augite horneblende gneiss	38.84	48.64	61.30	126.29
	11	migmatic gneiss	89.53	131.18	96.20	33.04
	16	metaquartz diorite	100.12	75.32	54.09	15.06
	25	lithonia gneiss	23.09	43.54	188.43	16.42
Mafic						
	12	gabbro	272.47	277.31	280.03	403.07
	13	serpentine	127.59	147.47	189.85	252.23
	14	coarse grained metagabbro/metapyroxene	277.43	288.66	234.41	152.75
	17	chlorite schist	124.55	198.62	169.08	229.43
	19	metagabbro	289.20	194.59	106.14	138.06
	20	gladesville gabbro	308.39	209.45	134.22	321.23
	21	metagabbroic-dioritic rock	77.16	85.93	55.64	92.49

Notes:

--all units in mg/kg soil V

Cr concentration data

Rock type	Sample location	Rock sample description	A	B	C	R
Felsic						
	1	quartzite	12.79	48.86	21.27	49.34
	6	elberton granite	15.27	34.06	79.11	56.19
	9	elberton granite	3.74	3.96	3.68	65.44
	10	elberton granite	27.19	42.11	3.68	25.81
	15	metatonalite	32.90	56.18	30.22	79.80
	22	danburg granite	16.21	13.24	10.78	85.13
	23	siloam granite	8.36	39.73	57.79	27.88
	24	panola granite	18.08	35.24	16.95	55.05
Intermediate						
	2	granite gneiss	39.27	159.73	115.83	100.35
	3	sillimanite-quartz-sericite-schist	104.90	136.32	88.57	160.28
	4	cal-silicate schist assemblage	53.60	77.25	190.78	189.56
	5	gneiss schist amphibolite assemblage	44.81	46.56	25.00	75.65
	7	undifferentiated gneiss/schist	16.26	13.97	30.61	321.63
	8	augite horneblende gneiss	30.33	20.55	23.82	274.60
	11	migmatic gneiss	37.48	56.29	106.96	57.98
	16	metaquartz diorite	207.29	178.97	196.75	91.03
	25	lithonia gneiss	7.23	18.48	236.05	55.05
Mafic						
	12	gabbro	30.91	347.85	18.32	449.80
	13	serpentine	ND	658.20	353.88	382.64
	14	coarse grained metagabbro/metapyroxene	176.66	255.29	230.53	331.60
	17	chlorite schist	627.13	837.63	778.66	391.64
	19	metagabbro	188.36	91.11	30.96	258.99
	20	gladesville gabbro	ND	527.65	545.56	95.66
	21	metagabbroic-dioritic rock	813.79	690.06	538.39	715.08

Notes:

ND - Not Determined

--all units in mg/kg soil Cr

Mn concentration data

Sample			A	B	C	R
Rock type	location	Rock sample description				
Felsic						
	1	quartzite	316.31	120.99	21.25	23.07
	6	elberton granite	566.28	335.91	334.43	226.15
	9	elberton granite	257.29	425.47	172.04	234.64
	10	elberton granite	164.67	96.83	118.71	183.47
	15	metatonalite	339.27	243.57	452.94	158.57
	22	danburg granite	365.79	220.67	397.27	370.13
	23	siloam granite	75.32	28.22	13.43	527.84
	24	panola granite	474.62	242.70	477.76	213.02
Intermediate						
	2	granite gneiss	376.35	307.34	392.46	1259.89
	3	sillimanite-quartz-sericite-schist	295.01	238.02	161.77	170.49
	4	cal-silicate schist assemblage	100.04	99.97	75.89	91.71
	5	gneiss schist amphibolite assemblage	224.08	134.22	458.28	80.13
	7	undifferentiated gneiss/schist	199.88	671.71	770.00	1686.79
	8	augite hornblende gneiss	371.75	234.37	409.81	1199.46
	11	migmatic gneiss	204.39	132.85	344.13	190.08
	16	metaquartz diorite	957.97	461.03	514.66	68.28
	25	lithonia gneiss	260.20	217.83	191.88	213.02
Mafic						
	12	gabbro	ND	808.70	699.55	1385.12
	13	serpentinite	697.42	397.07	949.90	1041.34
	14	coarse grained metagabbro/metapyroxene	ND	ND	826.33	720.50
	17	chlorite schist	ND	931.54	914.67	898.53
	19	metagabbro	1325.86	656.52	853.33	992.28
	20	gladesville gabbro	ND	1117.03	1003.07	1288.65
	21	metagabbroic-dioritic rock	946.81	618.90	598.34	683.92

Notes:

ND - Not Determined

--all units in mg/kg soil Mn

Co concentration data

Rock type	Sample location	Rock sample description	A	B	C	R
Felsic						
	1	quartzite	6.71	5.08	2.96	1.32
	6	elberton granite	5.20	5.43	3.76	0.85
	9	elberton granite	5.38	5.56	4.59	3.81
	10	elberton granite	2.05	6.81	3.97	4.61
	15	metatonalite	3.70	5.82	9.00	1.11
	22	danburg granite	5.50	6.77	8.20	5.85
	23	siloam granite	1.03	2.96	3.22	7.29
	24	panola granite	7.27	9.26	9.83	2.43
Intermediate						
	2	granite gneiss	13.57	21.08	23.89	9.12
	3	sillimanite-quartz-sericite-schist	23.21	10.11	7.68	5.19
	4	cal-silicate schist assemblage	5.29	7.15	5.49	2.35
	5	gneiss schist amphibolite assemblage	7.73	7.08	4.63	0.99
	7	undifferentiated gneiss/schist	6.24	24.35	26.06	30.46
	8	augite hornblende gneiss	17.09	10.86	12.61	23.57
	11	migmatic gneiss	10.84	12.76	36.72	8.99
	16	metaquartz diorite	20.39	22.24	21.17	1.93
	25	lithonia gneiss	3.06	4.91	62.25	2.43
Mafic						
	12	gabbro	27.98	28.99	17.84	72.04
	13	serpentinite	32.70	19.26	32.03	36.49
	14	coarse grained metagabbro/metapyroxene	64.73	51.71	50.20	68.75
	17	chlorite schist	ND	81.41	84.06	44.96
	19	metagabbro	62.71	34.91	12.75	51.13
	20	gladesville gabbro	ND	71.13	44.49	43.58
	21	metagabbroic-dioritic rock	64.28	52.61	42.46	44.83

Notes:

ND - Not Determined

--all units in mg/kg soil Co

Ni concentration data

Rock type	Sample location	Rock sample description	A	B	C	R
Felsic						
	1	quartzite	13.28	49.97	15.05	ND
	6	elberton granite	12.93	16.96	72.80	ND
	9	elberton granite	44.70	10.39	8.56	5.31
	10	elberton granite	15.88	28.14	ND	5.55
	15	metatonalite	7.78	15.06	41.99	2.58
	22	danburg granite	9.74	5.55	6.49	1.91
	23	siloam granite	1.01	11.99	25.37	ND
	24	panola granite	7.13	14.12	5.67	ND
Intermediate						
	2	granite gneiss	34.83	113.39	64.19	11.22
	3	sillimanite-quartz-sericite-schist	88.43	65.83	90.28	6.16
	4	cal-silicate schist assemblage	35.14	54.13	170.86	7.33
	5	gneiss schist amphibolite assemblage	29.32	32.42	37.01	ND
	7	undifferentiated gneiss/schist	10.22	19.24	48.89	53.46
	8	augite hornblende gneiss	17.39	20.54	23.66	34.28
	11	migmatic gneiss	60.71	2.14	82.09	18.82
	16	metaquartz diorite	67.18	103.18	146.77	2.81
	25	lithonia gneiss	3.91	10.06	ND	ND
Mafic						
	12	gabbro	9.25	119.31	ND	261.89
	13	serpentine	123.29	153.74	125.93	117.09
	14	coarse grained metagabbro/metapyroxene	56.79	84.60	70.69	83.19
	17	chlorite schist	ND	ND	ND	182.69
	19	metagabbro	58.08	43.56	21.99	110.28
	20	gladesville gabbro	ND	ND	319.92	56.04
	21	metagabbroic-dioritic rock	178.47	186.39	131.13	130.24

Notes:

ND - Not Determined

--all units in mg/kg soil Ni

Cu concentration data

Rock type	Sample location	Rock sample description	A	B	C	R
Felsic						
	1	quartzite	16.62	23.52	20.56	5.84
	6	elberton granite	39.27	63.51	62.31	26.28
	9	elberton granite	15.23	20.69	12.44	23.86
	10	elberton granite	14.65	20.91	13.78	14.04
	15	metatonalite	11.96	26.23	33.89	12.18
	22	danburg granite	28.31	11.67	16.61	18.32
	23	siloam granite	26.43	13.22	30.43	14.62
	24	panola granite	15.16	33.19	22.98	15.21
Intermediate						
	2	granite gneiss	29.00	45.51	40.93	19.51
	3	sillimanite-quartz-sericite-schist	57.02	51.02	25.49	86.41
	4	cal-silicate schist assemblage	25.52	38.07	45.99	53.32
	5	gneiss schist amphibolite assemblage	28.81	27.62	24.55	15.59
	7	undifferentiated gneiss/schist	29.65	70.73	73.00	2.34
	8	augite hornblende gneiss	19.13	20.28	24.23	53.24
	11	migmatic gneiss	39.91	59.52	42.33	12.69
	16	metaquartz diorite	20.83	42.83	24.76	10.27
	25	lithonia gneiss	8.72	13.30	ND	15.21
Mafic						
	12	gabbro	70.37	56.35	54.46	117.50
	13	serpentine	23.87	82.74	85.95	88.14
	14	coarse grained metagabbro/metapyroxene	84.49	118.20	130.14	111.03
	17	chlorite schist	41.56	80.14	35.44	22.33
	19	metagabbro	73.24	75.47	44.47	8.07
	20	gladesville gabbro	30.49	42.00	17.80	140.27
	21	metagabbroic-dioritic rock	12.88	26.51	25.11	11.05

Notes:

ND - Not Determined

--all units in mg/kg soil Cu

Zn concentration data

Rock type	Sample location	Rock sample description	A	B	C	R
Felsic						
	1	quartzite	35.91	53.99	49.95	45.92
	6	elberton granite	141.56	109.35	85.66	13.50
	9	elberton granite	57.36	34.71	55.92	133.48
	10	elberton granite	48.25	111.49	112.94	162.72
	15	metatonalite	44.28	90.67	95.46	ND
	22	danburg granite	62.89	37.97	80.25	72.83
	23	siloam granite	10.22	30.39	40.35	147.18
	24	panola granite	139.06	132.07	149.65	ND
Intermediate						
	2	granite gneiss	68.87	83.29	112.58	78.61
	3	sillimanite-quartz-sericite-schist	93.34	87.51	58.29	119.00
	4	cal-silicate schist assemblage	56.54	95.05	77.61	74.87
	5	gneiss schist amphibolite assemblage	68.44	118.07	96.66	37.41
	7	undifferentiated gneiss/schist	16.80	121.88	123.40	97.22
	8	augite hornblende gneiss	57.72	50.87	72.87	124.24
	11	migmatic gneiss	78.19	104.70	158.07	75.60
	16	metaquartz diorite	48.15	22.70	72.15	ND
	25	lithonia gneiss	19.94	39.22	ND	ND
Mafic						
	12	gabbro	171.18	122.08	97.21	113.45
	13	serpentine	57.90	66.04	81.09	99.76
	14	coarse grained metagabbro/metapyroxene	66.85	70.14	64.61	11.68
	17	chlorite schist	145.15	130.85	134.54	70.85
	19	metagabbro	74.26	92.81	81.72	75.10
	20	gladesville gabbro	121.61	86.19	106.61	121.41
	21	metagabbroic-dioritic rock	79.99	40.18	44.93	ND

Notes:

ND - Not Determined

--all units in mg/kg soil Zn

As concentration data

Rock type	Sample location	Rock sample description	A	B	C	R
Felsic						
	1	quartzite	5.56	6.72	3.27	2.73
	6	elberton granite	6.17	4.83	3.86	3.58
	9	elberton granite	6.02	4.44	4.20	3.08
	10	elberton granite	4.81	8.21	5.57	3.28
	15	metatonalite	3.84	4.38	2.39	2.69
	22	danburg granite	4.08	3.97	3.61	3.16
	23	siloam granite	4.43	5.31	6.05	3.79
	24	panola granite	6.26	8.95	5.73	2.70
Intermediate						
	2	granite gneiss	4.55	4.89	3.65	3.47
	3	sillimanite-quartz-sericite-schist	4.96	5.24	3.88	3.08
	4	cal-silicate schist assemblage	7.60	9.73	4.79	4.18
	5	gneiss schist amphibolite assemblage	6.20	4.93	4.01	2.88
	7	undifferentiated gneiss/schist	5.45	4.21	3.40	3.25
	8	augite hornblende gneiss	5.71	6.38	5.35	3.30
	11	migmatic gneiss	6.04	7.30	6.12	2.67
	16	metaquartz diorite	4.84	3.54	3.07	3.01
	25	lithonia gneiss	4.33	6.78	ND	2.70
Mafic						
	12	gabbro	6.56	6.33	4.94	5.30
	13	serpentinite	7.34	5.03	3.36	4.38
	14	coarse grained metagabbro/metapyroxene	4.77	4.08	2.57	4.49
	17	chlorite schist	5.22	4.87	2.85	2.48
	19	metagabbro	6.23	5.39	3.04	2.45
	20	gladesville gabbro	8.58	5.15	3.46	3.32
	21	metagabbroic-dioritic rock	3.49	3.16	2.21	2.34

Notes:

ND - Not Determined

--all units in mg/kg soil As

Cd concentration data

Rock type	Sample location	Rock sample description	A	B	C	R
Felsic						
	1	quartzite	0.07	0.07	0.07	0.07
	6	elberton granite	0.26	0.11	0.10	0.07
	9	elberton granite	0.16	0.12	0.11	0.07
	10	elberton granite	0.08	0.07	0.07	0.07
	15	metatonalite	0.07	0.07	0.07	0.07
	22	danburg granite	0.07	0.07	0.07	0.07
	23	siloam granite	0.07	0.07	0.07	0.07
	24	panola granite	0.07	0.07	0.07	0.07
Intermediate						
	2	granite gneiss	0.07	0.07	0.07	0.07
	3	sillimanite-quartz-sericite-schist	0.07	0.07	0.07	0.07
	4	cal-silicate schist assemblage	0.07	0.07	0.07	0.07
	5	gneiss schist amphibolite assemblage	0.07	0.07	0.07	0.07
	7	undifferentiated gneiss/schist	0.09	0.08	0.07	0.07
	8	augite hornblende gneiss	0.18	0.07	0.07	0.07
	11	migmatic gneiss	0.07	0.07	0.07	0.07
	16	metaquartz diorite	0.07	0.07	0.09	0.07
	25	lithonia gneiss	0.07	0.07	ND	0.07
Mafic						
	12	gabbro	0.09	0.10	0.07	0.07
	13	serpentinite	0.10	0.07	0.07	0.07
	14	coarse grained metagabbro/metapyroxene	0.07	0.07	0.07	0.07
	17	chlorite schist	0.19	0.12	0.15	0.07
	19	metagabbro	0.07	0.07	0.07	0.07
	20	gladesville gabbro	0.09	0.07	0.07	0.07
	21	metagabbroic-dioritic rock	0.07	0.07	0.07	0.07

Notes:

ND - Not Determined

--all units in mg/kg soil Cd

Ba concentration data

Rock type	Sample location	Rock sample description	A	B	C	R
Felsic						
	1	quartzite	557.91	230.02	87.44	46.89
	6	elberton granite	780.80	649.55	711.14	804.79
	9	elberton granite	930.63	937.58	839.36	892.89
	10	elberton granite	901.13	488.34	621.59	941.67
	15	metatonalite	157.94	237.56	513.55	471.49
	22	danburg granite	896.33	800.96	776.06	1157.86
	23	siloam granite	211.64	146.55	91.86	2189.61
	24	panola granite	1351.72	658.16	1732.14	493.45
Intermediate						
	2	granite gneiss	827.79	731.54	978.50	247.03
	3	sillimanite-quartz-sericite-schist	846.48	453.67	682.82	509.10
	4	cal-silicate schist assemblage	213.97	215.17	134.01	702.54
	5	gneiss schist amphibolite assemblage	345.81	332.27	497.40	394.24
	7	undifferentiated gneiss/schist	241.47	254.24	254.05	70.88
	8	augite hornblende gneiss	461.98	290.23	506.72	97.63
	11	migmatic gneiss	512.78	474.65	414.91	3326.25
	16	metaquartz diorite	175.48	268.24	392.95	558.06
	25	lithonia gneiss	458.83	445.22	1111.79	493.45
Mafic						
	12	gabbro	70.32	52.32	54.55	115.87
	13	serpentinite	86.73	218.61	257.55	236.40
	14	coarse grained metagabbro/metapyroxene	60.82	103.95	23.85	16.90
	17	chlorite schist	88.75	60.86	37.15	30.42
	19	metagabbro	124.30	177.07	116.39	41.80
	20	gladesville gabbro	385.05	130.09	147.70	257.76
	21	metagabbroic-dioritic rock	160.09	258.22	68.29	19.57

Notes:

--all units in mg/kg soil Ba

Hg concentration data

Rock type	Sample location	Rock sample description	A	B	C	R
Felsic						
	1	quartzite	0.16	0.18	0.11	0.04
	6	elberton granite	0.09	0.10	0.07	0.04
	9	elberton granite	0.08	0.09	0.05	0.07
	10	elberton granite	0.10	0.09	0.04	0.04
	15	metatonalite	0.04	0.06	0.06	0.08
	22	danburg granite	0.06	0.11	0.05	0.09
	23	siloam granite	0.04	0.04	0.04	0.07
	24	panola granite	0.04	0.10	0.04	0.21
Intermediate						
	2	granite gneiss	0.12	0.12	0.14	0.04
	3	sillimanite-quartz-sericite-schist	0.07	0.11	0.04	0.10
	4	cal-silicate schist assemblage	0.14	0.19	0.08	0.04
	5	gneiss schist amphibolite assemblage	0.06	0.04	0.04	0.04
	7	undifferentiated gneiss/schist	0.09	0.04	0.06	0.04
	8	augite hornblende gneiss	0.09	0.06	0.06	0.04
	11	migmatic gneiss	0.06	0.09	0.04	0.04
	16	metaquartz diorite	0.04	0.07	0.13	0.15
	25	lithonia gneiss	0.06	0.05	ND	0.21
Mafic						
	12	gabbro	0.08	0.04	0.04	0.09
	13	serpentinite	0.04	0.16	0.05	0.20
	14	coarse grained metagabbro/metapyroxene	0.04	0.04	0.04	0.07
	17	chlorite schist	0.12	0.11	0.15	0.04
	19	metagabbro	0.09	0.09	0.04	0.04
	20	gladesville gabbro	0.06	0.04	0.04	0.04
	21	metagabbroic-dioritic rock	0.04	0.04	0.04	0.04

Notes:

ND - Not Determined

--all units in mg/kg soil Hg

Pb concentration data

Rock type	Sample location	Rock sample description	A	B	C	R
Felsic						
	1	quartzite	34.69	27.84	53.42	52.49
	6	elberton granite	37.36	66.58	122.42	51.45
	9	elberton granite	39.86	39.62	35.28	37.13
	10	elberton granite	33.87	37.31	48.31	38.19
	15	metatonalite	17.92	12.01	17.23	3.38
	22	danburg granite	39.56	36.97	37.87	25.02
	23	siloam granite	18.99	31.85	45.76	36.50
	24	panola granite	46.49	46.41	51.28	20.94
Intermediate						
	2	granite gneiss	38.00	37.08	35.89	11.94
	3	sillimanite-quartz-sericite-schist	37.59	42.54	38.54	10.52
	4	cal-silicate schist assemblage	25.33	29.68	27.88	23.05
	5	gneiss schist amphibolite assemblage	33.98	35.47	50.74	11.51
	7	undifferentiated gneiss/schist	14.60	8.07	7.22	4.69
	8	augite hornblende gneiss	28.67	20.55	18.02	9.42
	11	migmatic gneiss	33.72	35.66	39.91	76.46
	16	metaquartz diorite	23.63	16.84	13.19	11.28
	25	lithonia gneiss	30.97	28.38	ND	20.94
Mafic						
	12	gabbro	11.80	6.24	4.84	3.88
	13	serpentinite	15.64	10.04	12.96	7.39
	14	coarse grained metagabbro/metapyroxene	11.54	4.53	11.83	2.39
	17	chlorite schist	13.70	7.69	4.91	4.56
	19	metagabbro	14.54	11.51	10.97	3.25
	20	gladesville gabbro	28.85	9.10	3.18	5.13
	21	metagabbroic-dioritic rock	15.59	6.42	4.29	ND

Notes:

ND - Not Determined

--all units in mg/kg soil Pb

U concentration data

Rock type	Sample location	Rock sample description	A	B	C	R
Felsic						
	1	quartzite	4.67	4.85	1.95	1.12
	6	elberton granite	3.66	5.65	4.90	3.60
	9	elberton granite	2.97	3.73	3.08	4.02
	10	elberton granite	1.99	5.11	4.70	1.76
	15	metatonalite	1.28	2.03	1.29	0.84
	22	danburg granite	8.52	7.90	8.83	2.78
	23	siloam granite	3.48	7.23	11.13	1.69
	24	panola granite	1.94	3.94	6.34	1.55
Intermediate						
	2	granite gneiss	3.93	5.81	6.55	1.90
	3	sillimanite-quartz-sericite-schist	4.22	5.88	2.73	4.51
	4	cal-silicate schist assemblage	4.97	6.15	5.30	8.65
	5	gneiss schist amphibolite assemblage	4.96	5.26	5.81	1.18
	7	undifferentiated gneiss/schist	1.72	2.16	2.32	1.17
	8	augite hornblende gneiss	4.19	3.04	4.28	4.08
	11	migmatic gneiss	3.41	3.41	4.44	2.62
	16	metaquartz diorite	1.13	1.35	1.36	1.20
	25	lithonia gneiss	3.74	5.45	ND	1.55
Mafic						
	12	gabbro	1.30	1.09	0.86	0.32
	13	serpentine	0.98	1.97	0.74	2.35
	14	coarse grained metagabbro/metapyroxene	0.49	0.33	0.02	0.04
	17	chlorite schist	0.88	0.98	0.32	0.86
	19	metagabbro	0.90	1.07	0.41	0.04
	20	gladesville gabbro	1.05	0.61	0.17	0.10
	21	metagabbroic-dioritic rock	0.56	0.39	0.24	0.04

Notes:

ND - Not Determined

--all units in mg/kg soil U