STONE QUARRIES AND SOURCING IN THE CAROLINA SLATE BELT

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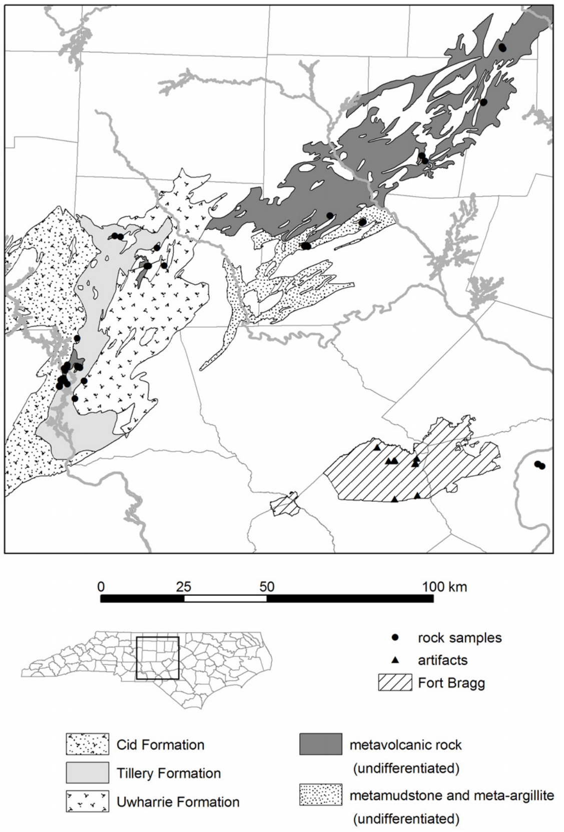

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In memory of J. Robert Butler

Abstract

Decades of archaeological work on Fort Bragg have revealed thousands of prehistoric sites that were inhabited by Indian peoples before the arrival of the Europeans. It is believed that many of these sites were temporary camps occupied by hunters and gatherers whose territories extended far beyond the boundaries of the modern fort. Thus, understanding the archaeology of Fort Bragg requires that these sites be placed in a larger geographical framework.

One way that modern archaeologists can trace the movements of ancient hunter-gatherers is through geological and geochemical studies that identify the sources of the raw materials used to make the artifacts found at archaeological sites. Such "sourcing" or "provenance" studies have the potential to delineate the territories over which hunter-gatherers traveled in the course of their yearly round of activities.

With these considerations in mind, the present study was designed to achieve two main objectives: (*a*) to evaluate the effectiveness of a range of mineralogical and chemical techniques for "fingerprinting" potential sources of raw materials, and (*b*) to apply these techniques in determining the sources of ancient stone tools found at Fort Bragg.

As a first step, 71 rock samples were collected from 12 different *quarry zones*, which were believed to be likely sources from which the prehistoric inhabitants of Fort Bragg obtained their stone; 11 of these quarry zones were located in the Piedmont (specifically in the Carolina Slate Belt), and one was located in the Coastal Plain. In addition, nine artifacts were selected from archaeological sites on Fort Bragg; all were Savannah River Stemmed points dating to the Late Archaic period (ca. 3000–1000 BC). The mineralogical and chemical composition of these 80 samples was then determined using five different techniques: petrography, neutron activation analysis (NAA), neodymium-isotope analysis, x-ray fluorescence (XRF), and inductively coupled plasma mass spectrometry (ICP-MS).

Petrographic analysis, supplemented by XRF, revealed that each quarry zone was marked by a distinctive suite of metavolcanic and/or metasedimentary rocks. A more general distinction was also seen between the northern and southern portions of the study area. The northern zones contained a mixture of metavolcanic and metasedimentary rocks and showed lower degrees of metamorphism. The southern zones were dominated by metavolcanic rocks and showed higher degrees of metamorphism. Of the nine artifacts examined, only two could be confidently matched with particular quarry zones. The rest could only be tentatively assigned to quarry zones or not assigned at all.

The study of elemental composition based on NAA revealed eight chemical groups among the quarry samples. When the elemental composition of the nine artifacts was compared to these groups, the results suggested that seven came from quarry zones in the southern Uwharrie Mountains. The assignment of the other two artifacts was unclear.

The analysis of neodymium (Nd) isotopes, supplemented by rare-earth elements as measured by ICP-MS, also revealed some interesting patterns. Different quarry zones were marked by distinctive, yet sometimes overlapping, ranges of Nd-isotope ratios. Even more interesting was a general trend of increase in the value of this ratio as one moves from south to north along the Carolina Slate Belt. This trend appears to be very consistent for the metavolcanic rocks and less so for the metasedimentary rocks. Based on these isotope ratios and the rare-earth data, one artifact was confidently assigned to the Orange County zone in the northern portion of the study

area, four were assigned to the Uwharrie Mountains in the southern portion of the study area, and four were left unassigned.

When the results of these studies were compared, we found that each provided useful information, but that there were significant discrepancies among the assignments of artifacts to geological sources made by different researchers using different lines of evidence. Indeed, there was not a single case in which all three lines of evidence produced exactly the same assignment. This illustrates the need to look at *all* the lines of evidence together in making such assignments. The most reliable interpretations came from a synthetic approach that considered and weighed the different lines of evidence together. Based on this approach, we were able to conclude with some confidence that two artifacts came from the northern portion of the study area (including one from the Orange County zone), three came from the Uwharrie Mountains in the southern portion of the study area, and two may have come from the Uwharrie Mountains or even farther south. Two artifacts remained unassigned.

Based on this pilot study, we now have a much better understanding of the relative utility of the different techniques for sourcing artifacts from Fort Bragg. The two most useful techniques proved to be petrography and Nd-isotope analysis, although the elemental data (NAA, XRF, and ICP-MS) were also very helpful in certain cases. Nd-isotope analysis has the additional advantage of producing reliable results with very small samples of rock, which makes it particularly valuable for sourcing artifacts nondestructively.

We also now have a somewhat better idea of how ancient people moved over the landscape, at least for Late Archaic times, when the artifacts in our study were manufactured and used. The artifact assignments just described suggest that Late Archaic inhabitants of Fort Bragg utilized a number of quarries scattered over a wide area. Before being discarded, the artifacts had been carried over the linear distance between Fort Bragg and the Carolina Slate Belt quarries, minimally some 70–80 km. Given the non-linear patterns of movement often seen among hunter-gatherers, the actual distances involved may well have been over 200 km.

We recommend further studies of quarries in the Carolinas and artifacts from Fort Bragg. Additional quarries in the Piedmont should be sampled in order to refine our understanding of their chemical fingerprints and to answer some of the questions raised by this pilot study. It is especially important, for example, to sample areas south of the Uwharrie Mountains in order to see if the north-south trend in Nd ratios continues in this direction. We also need to learn more about the composition of rocks from the Coastal Plain. The sample of Fort Bragg artifacts should also be expanded to include both a wider variety of materials and periods other than the Late Archaic.

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Preface

The research presented in this volume was prompted by two simple questions: Where did the ancient inhabitants of Fort Bragg come from, and how did they move over the landscape? As our knowledge of prehistoric settlements on Fort Bragg grew, it became increasingly clear that these sites could not be understood in isolation. Rather, many seemed to be temporary camps of people whose territories extended far beyond the bounds of the present-day military base. The only way to reconstruct these ancient territories archaeologically would be to trace the movements of the artifacts that these people carried with them. This objective could best be accomplished by linking the artifacts to their geological sources — that is, by "fingerprinting" the raw materials from which the artifacts were made and matching the fingerprints with particular outcrops of stone. The methods were well established; yet very few such studies had ever been done in the Carolinas.

It was clear from the outset that our questions could only be answered by a collaborative project involving both geologists and archaeologists. The archaeological impetus for this project was provided by Jeff Irwin and Chris Moore. A number of scholars were then recruited for their geological and geochemical skills: Skip Stoddard for his knowledge of petrography and local rocks, Brent Miller and Drew Coleman for their expertise in isotope geochemistry, and Mike Glascock and Jeff Speakman for their expertise in element geochemistry and archaeological sourcing. Vin Steponaitis and John Rogers were brought in to provide additional perspectives and to help design and coordinate the research. Once the work was underway, Theresa McReynolds joined the team in order to help edit and produce the report.

The analysis of archaeological and geological samples took place over a period of two years at three different laboratories, each working independently. The petrography was done by Skip Stoddard at North Carolina State University; neutron activation, x-ray fluorescence, and inductively coupled plasma mass spectrometry were carried out by Mike Glascock, Jeff Speakman, and their colleagues at the University of Missouri in Columbia; and the neodymium-isotope analysis was done by Brent Miller and Drew Coleman at the University of North Carolina at Chapel Hill. The results were then discussed and compared by the research group as a whole, a fruitful process that led to the synthetic conclusions presented in Chapter 7.

Needless to say, many other individuals provided crucial help in bringing this project to a successful conclusion. Wayne Boyko, Tad Britt, and Paul Webb provided leadership, administrative support, and constructive oversight, without which this project would never have gotten off the ground and kept moving. Tim Brown shared his computer expertise at many points along the way. Mary Ayers, Randy Daniel, Steve Davis, Mike Harmon, Brett Riggs, and Ken Robinson provided archaeological advice and assisted greatly in identifying and collecting samples. Dolores Hall and John Mintz helped in working with the North Carolina site files. And many avocational archaeologists — among them Robert Graham, Mark McCravey, and Joe Moylan — shared their knowledge of quarry sites throughout the Carolina Slate Belt. To all these colleagues and friends, we express our sincere gratitude.

Chapter 1

Introduction

Jeffrey D. Irwin and Vincas P. Steponaitis

The archaeology of prehistoric hunter-gatherers in the Sandhills of North Carolina requires a fundamental understanding of how stone from the Appalachian Piedmont was acquired and utilized by prehistoric peoples. A significant body of data on thousands of archaeological sites or isolates continues to accumulate through the management of cultural resources at Fort Bragg, an Army installation of some 65,000 ha in the Sandhills. Stone tools and debris made from Piedmont material, particularly from the Carolina Slate Belt, constitute a large percentage of these assemblages, elevating questions of how prehistoric groups provisioned themselves with tool stone and organized stone-based technology to the fore of research. Stone from the Carolina Slate Belt was procured, used, and transported over hundreds of kilometers throughout the record of human history extending from the Paleoindian to Late Woodland periods. This study is intended to establish a scientific process for determining the original provenance of such artifacts, that is, for connecting the artifacts to their original geological sources.

This study has two primary objectives: first, to evaluate chemical and mineralogical techniques for differentiating quarries, and second, to apply these techniques in determining the sources of stone tools from Fort Bragg. Systematic characterization of stone samples from known quarries is a necessary first step before the basic problem of source differentiation can be addressed. The bulk of the analyses reported here are directed towards characterizing quarries in the Carolina Slate Belt and exploring ways to distinguish those quarries. The second question of sourcing artifacts is addressed through a case study using artifacts from Fort Bragg.

While studies of volcanic rock and Carolina Slate Belt materials exist, previous studies have been relatively limited in geographical scale and methodological scope. Our project was therefore designed to move beyond these limitations by sampling a broader range of quarries and using a greater variety of analytical techniques. In the present study, three lines of compositional evidence were brought to bear on the problem of distinguishing quarries. The mineralogy of all samples was assessed through petrographic analysis of thin sections. In addition, elemental composition was measured using neutron activation analysis, x-ray fluorescence, and inductively coupled plasma mass spectrometry. Finally, neodymium isotope ratios were measured with a mass spectrometer. Using this range of methods allowed us to assess their relative efficacy in determining geological sources. It also allowed us to identify these sources with greater precision and confidence than could be achieved with any single method by itself.

Although our immediate focus is to identify the sources of stone used in making tools, this study is ultimately driven by research questions about the adaptations and social organization of prehistoric people. Assuming direct procurement of stone by hunter-gatherers who used or moved through the Sandhills, knowledge of tool-stone sources will ultimately facilitate modeling of the “mobility scale” (Binford 1979:261) or territorial mobility (Kelly 1992) of hunter-gatherer settlement systems. Modeling of stone procurement and conveyance from within the Carolina Slate Belt should allow for refinement of existing settlement models (e.g., Anderson and Hanson 1988; Daniel 1994b, 1998), if not construction of new ones (Irwin and Moore 2003; Moore and Irwin 2002, 2004). By recognizing patterns of movement across the landscape, we may detect evidence of the settlement range or "foraging territories" (Jones et al. 2003) formed by mobile groups. Furthermore, by characterizing and sourcing tool stone, we may eventually gain knowledge of how raw material selection and treatment relate to concepts of the relative costs of procurement, raw material quality or reliability, and curation—issues integral to technological organization (Andrefsky 1994; Bamforth 1986, 1991).

The implications of this study for North Carolina archaeology are significant. Most fundamentally, identifying the sources of tool stone creates a context for interpreting artifacts recovered through archaeological investigations. Current identification of Carolina Slate Belt material at the artifact level is generic. The ability to source lithic artifacts more precisely would make use of a significant body of data that is otherwise restricted to functional meaning. By allowing issues of mobility, territory, and technological organization to be addressed regionally, tool-stone provenance research will enable the modeling of ancient cultural practices and adaptations as well as a more informed evaluation of archaeological resources.

Archaeology of Fort Bragg

Our perspective on prehistoric mobility and technology originates from a seemingly marginal region. Located in the interior Coastal Plain of North Carolina, the Sandhills mark an ancient coastal dune environment that is characterized by dissected hilly topography, longleaf pine and wiregrass forest, and acidic, arid sands along ridges and side slopes. The Sandhills have been referred to historically as the "Pine Barrens," "Pine Plains," even the "Sahara of the Carolinas," pejorative terms reflecting the nutrient-poor soils and low resource abundance of the area. Despite this reputation, the unique Sandhills area was persistently used throughout prehistory, as indicated by the presence of thousands of prehistoric sites and isolated artifacts on Fort Bragg.

Archaeological survey (e.g., Benson 1998; Clement et al. 1997; Idol and Becker 2001; Ruggiero 2003) and site excavation reports (Benson 2000; Ollendorf 1999; Idol and Pullins 2001) consistently reveal an archaeological landscape with lithic and ceramic artifacts distributed across all but the highest elevated ridges of Fort Bragg. These artifacts represent limited-duration occupations and specialized activities related to hunting and gathering throughout prehistory. The low density and often low diversity of artifacts relate to fairly high mobility and small group size. As Cable and Cantley (2005:391) describe, "most sites in the region are composed of a complex and redundant array of special purpose camps, extraction loci, single nuclear family and small multiple family short-term residences." Archaeological sites range in size from a few square meters to over 3 hectares, though most sites contain unrelated, temporally disjunctive components. While artifact distributions are sparse at the landscape or site level, isolated activity areas, most commonly debris from lithic reduction episodes or the discarded remains of broken pots, can produce dense artifact concentrations with hundreds of artifacts per square meter (Benson 2000:644; Cable and Cantley 2005:396).

Archaeological sites in the Sandhills often contain stone tools or debitage made of rocks found in the Carolina Slate Belt (Figure 1.1). Artifact surfaces are often weathered, which makes the characteristics of the underlying, unaltered stone difficult to see. Even when unaltered

Figure 1.1. Selected diagnostic hafted bifaces, metavolcanic material, Fort Bragg.

surfaces are visible, the macroscopic distinctions among metavolcanic rocks are often subtle. These factors, combined with archaeologists' lack of geological training, make specific rock types hard to identify. What Abbott (2003) terms the "identification problem" has resulted in predominant use of the term "metavolcanic" as an inclusive category for material from the Slate Belt (e.g., Braley 1989; King 1992; Trinkley et al. 1996a).

Some archaeologists working at Fort Bragg have addressed variability in metavolcanic material, identifying rocks such as rhyolite and argillite "where possible" (Ollendorf 1999) or subdividing the metavolcanic category into "unidentified metavolcanic, general rhyolite, and . . . fine grained rhyolites" (Idol and Becker 2001:37). Following Daniel and Butler's (1996) work and his own 1,600-ha survey in the Uwharrie Mountains, Benson (2000) expanded on the previously defined Uwharrie-Mountain rock types, adding several categories of rhyolitic tuffs in a Fort Bragg survey. In recent years emphasis has been placed on key attributes, particularly the occurrence of flow banding and phenocrysts (e.g., Culpepper et al. 2000; Cable and Cantley 2005; Ruggiero and Grunden 2005). Given historic attention on the southern Uwharrie Mountains, there was little need to refine stone identification since the proximity of quarries precludes meaningful analysis of mobility patterns relative to stone procurement. Recent attempts to capture variation in metavolcanic material, whether at the classificatory or attribute level, are geared towards differentiating individual components or activity areas at the intrasite level (Benson 2000; Cable and Cantley 2005). Indeed, attribute-based sorting is particularly important for analysis of the number and kinds of cores being reduced at a site.

It is assumed here that most metavolcanic materials appearing archaeologically on Fort Bragg were procured in the Carolina Slate Belt and imported as flake blanks or preforms. There is substantial, albeit indirect, evidence for this supposition in the form of metavolcanic debitage. Lithic assemblages on Fort Bragg are typically dominated by flakes reflecting late-stage biface thinning. Of 15,858 pieces of metavolcanic debitage cataloged in the Fort Bragg database, 87% are classified as late-reduction, biface-thinning flakes. Metavolcanic flakes tend to be less than 2-3 cm in maximum length (see site descriptions in Idol and Pullins 2001; Cable and Cantley 2005:Table 120) and lack cortex, revealing an emphasis on reduction of prepared cores or bifaces. Additionally, among tool classes, metavolcanic material appears most frequently in projectile points. Most points dating from the Early Archaic through the Early Woodland periods are made of metavolcanic stone (Benson 2000; Culpepper et al. 2000). With the exception of prepared biface preforms, core technology in the Sandhills is based predominantly on quartz (Brannan and Irwin 2005).

Several examples of lithic caches found in or around the Sandhills reveal the likely form of transported material. The senior author has observed six caches (all but one collected by amateurs) of metavolcanic material. Cached material includes porphyritic and aphyric metavolcanic or metasedimentary stone, and the artifacts include flake blanks as well as biface preforms (Figure 1.2). Most of these caches contain 20 or more artifacts.

Given a persistent hunting and gathering economy and residential mobility throughout most of prehistory in the Sandhills, it is reasonable to assume direct acquisition and embedded procurement within a certain mobility scale. The maximum linear distance between the Sandhills region and quarry groups sampled in this study is roughly 130 km, while many quarries are roughly 70-80 km away. While metavolcanic stone is nonlocal, the Carolina Slate Belt is certainly within the range of annual mobility practiced by modern hunter-gatherers (Kelly 1995), and so direct procurement is a reasonable assumption (Meltzer 1989). If trade in stone occurred prehistorically in the region, it probably was most important in the Middle and Late Woodland periods, when trade and long-distance contacts were evidenced in the sand burial mounds of the southern coast (Irwin 2004; Irwin et al. 1999; MacCord 1966). Indeed, metavolcanic material may have been at its most exotic when groups associated with Hanover pottery were largely confined to the Coastal Plain and were relying heavily on quartz for arrow points (Culpepper et al. 2000; Ruggiero 2003).

The possibility for local procurement of metavolcanic material redeposited or exposed by rivers in the Coastal Plain is considered real, but minor. The occasional presence of cortex on metavolcanic debris or metavolcanic cobbles or cobble fragments on Fort Bragg has led some to suggest local procurement (Benson 2000; Idol 2005; Cable and Cantley 2005). Cortex may indeed reflect reduction of locally available stream cobbles, though it should be noted that cortex must be distinguished from weathering rinds common on quarry samples. Metavolcanic cobbles (e.g., Benson 2000) found on Fort Bragg are rare and tend to be of extremely poor quality. Recent excavations along the Cape Fear River have produced evidence of local procurement and use of material occurring as float in the ancient terraces along the north side of the river near Fayetteville (Kenneth Robinson, personal communication 2001). Similar materials were included in this study.

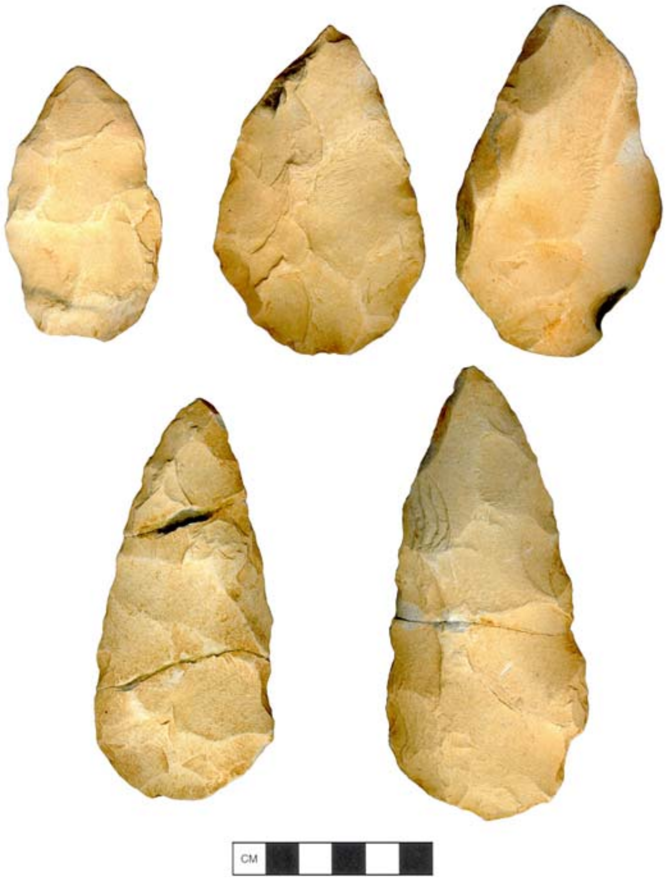

Figure 1.2. A blank and biface cache, metavolcanic material, Fort Bragg.

Sourcing Metavolcanic Rocks

This study is unique in its multidisciplinary application to a broad range within the Slate Belt, but the individual components of the tripartite methodological scheme utilized in this study (petrography, trace element analysis, isotope analysis) are not without precedent.

Although rocks of the Carolina Slate Belt have interested geologists for many years, a geoarchaeological approach to individual formations and outcrops is relatively new. The pioneering work was conducted by Daniel and Butler (1996), who documented quarry sites in the Uwharrie Mountains and characterized quarry samples macroscopically and petrographically. Daniel and Butler found important differences in groundmass texture and mineral composition upon which the current study expands. Beyond their study, however, the use of petrography in this region has been limited. Petrographic analysis is critical to understanding differences among stone raw materials and evaluating the credibility of associations based on other evidence. Hermes et al. (2001:927) note the importance of combining petrography with chemistry to distinguish among felsite, chert, and argillite as well as "varieties of look-alike felsite."

Geochemical studies of volcanic rocks have become especially important in the past two decades in southwestern regions of North America, where Jones et al. (1997:1) note that "source provenance studies of obsidian artefacts have become almost routine." In addition to obsidian, volcanic rocks such as andesite, dacite, and silicified rhyolite have been characterized using x-ray fluorescence (Dello-Russo 2004; Jones et al. 1997). In eastern North America, Bondar (2001) utilized neutron activation analysis to study metarhyolite samples from several eastern states, including North Carolina. Hermes et al. (2001) combine geochemical and petrographic analyses to evaluate the sources of rhyolites in New England. Despite the general similarity in raw material and the geochemical approach, these previous attempts to source volcanic stone vary in the techniques employed, the number of elements utilized, the statistical treatment of data, and the success of their results. The methodology remains in a formative stage and methods must be tailored to research questions and regional conditions.

Sourcing with neodymium-isotope ratios was pioneered in New England by Brady and Coleman (2000). Following previous attempts to source felsites using trace element and petrographic analyses (Hermes and Ritchie 1997), Brady and Coleman (2000:3) developed their isotopic technique to permit sourcing of artifacts to "a particular ash or lava flow within a quarry." Brady and Coleman found neodymium-isotope ratios to be an effective tool for confirming or refining previous sourcing conclusions based on visual, mineralogical, and trace-element data.

Research Design

The present study was conducted in two phases. In Phase 1, our goal was to characterize the compositional variation of quarries and evaluate potential for discrimination of metavolcanic rocks that would have been used by the prehistoric inhabitants of the Fort Bragg area. We collected 50 rock samples from 19 quarry sites in the North Carolina Piedmont and one site in the Coastal Plain. These samples were characterized by means of petrographic analysis (to provide data on mineralogy), neutron activation analysis (to provide data on a wide range of major and trace elements), and conventional mass spectrometry (to measure neodymium isotope ratios). In Phase 2, the study was expanded to include an additional 30 samples—21 rock fragments from quarries and 9 artifacts from Fort Bragg—bringing the total to 80. The new samples were studied using the same three techniques as in Phase 1. In addition, all 80 samples were examined with two more techniques: x-ray fluorescence spectrometry (to provide data on the lighter major elements that cannot be detected with neutron activation) and inductively coupled plasma mass spectrometry (to provide data on all the rare-earth elements).

For the purposes of sampling and analysis, our rock specimens were grouped into *quarry zones* based on considerations of geography, geology, and sample size. Ideally, each zone was defined to encompass quarries that formed a discrete geographical cluster, corresponded to a single geological formation (or mapped rock unit), and together produced at least six samples. The 12 zones so defined were named as follows: Uwharries Eastern, Uwharries Western, Uwharries Southern, Uwharries Southeastern, Uwharries Asheboro, Chatham Pittsboro, Chatham Silk Hope, Chatham Siler City, Orange County, Durham County, Person County, and Cumberland County (Figure 1.3, Table 1.1). In the end, two of these zones deviated from our ideal criteria. Only four samples were collected from the Chatham Siler City zone, primarily because the original quarries targeted in this area could not be relocated, and the Uwharries Asheboro zone combined samples from two different, but closely related, geological formations.

In order to directly assess the ability of our techniques to match artifacts with geological sources, the Phase 2 samples also included nine projectile points from sites on Fort Bragg. These

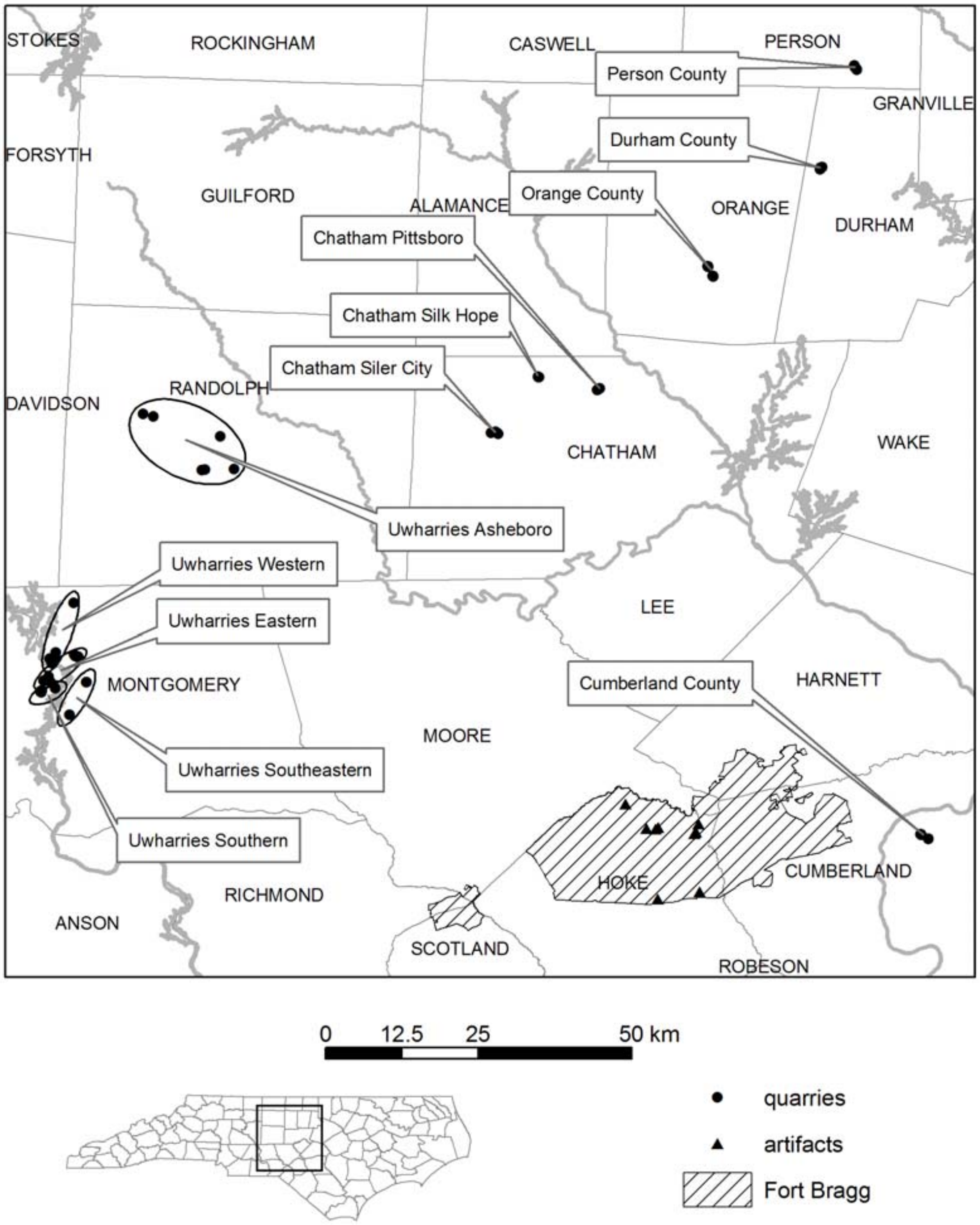

Figure 1.3. The geographic distribution of quarries, quarry zones, and artifacts used in this study.

artifacts were chosen according to three criteria. First, all were made of metavolcanic rock visually consistent with the quarry samples. Second, all belonged to a single type associated with a discrete chronological period, specifically Savannah River Stemmed points made in Late Archaic times (ca. 3000-1000 BC). And third, all were large enough to produce enough material for the various analytical techniques employed.

For the sake of consistency and clarity, our rock and artifact specimens are individually designated throughout this volume with numbers having the prefix “FBL” (for Fort Bragg lithics). Specimens FBL001 through FBL050 were analyzed in Phase 1; specimens FBL051 through FBL080 were added in Phase 2. All specimens are described in detail in Appendix A.

Table 1.1. Distribution of Quarry Samples, Phases 1 and 2.

Sample Category: Quarry Zone or Locality	Geologic Formation[a]	Mapped Rock Type[b]	Phase 1[c] (n)	Phase 2[d] (n)
Quarry samples:				
Uwharries Eastern	Tillery	felsic metavolcanic rock	7	0
Uwharries Western	Cid	felsic metavolcanic rock, mafic metavolcanic rock	7	0
Uwharries Southern	Tillery	felsic metavolcanic rock, metamudstone and meta-argillite	5	0
Uwharries Asheboro	Tillery, Uwharrie	felsic metavolcanic rock, mafic metavolcanic rock, metamudstone and meta-argillite	5	1
Uwharries Southeastern	Uwharrie	felsic metavolcanic rock	2	4
Chatham Pittsboro		metamudstone and meta-argillite	4	2
Chatham Silk Hope		intermediate metavolcanic rock	4	2
Chatham Siler City		metamudstone and meta-argillite	4	0
Orange County		felsic metavolcanic rock, metamorphosed gabbro and diorite[e]	0	6
Durham County		felsic metavolcanic rock	4	2
Person County		felsic metavolcanic rock	4	2
Cumberland County			4	2
Artifact samples:				
Fort Bragg			0	9
			50	30

[a] This column contains entries only for quarries that fall within named geological formations (North Carolina Geological Survey 1985).

[b] For quarry samples, this column contains the dominant rock type as indicated on the state geologic map (North Carolina Geological Survey 1985).

[c] Specimens FBL001-FBL050.

[d] Specimens FBL051-FBL080.

[e] Although one of the quarries in this zone is mapped in the "metamorphosed gabbro and diorite" unit (North Carolina Geological Survey 1985), the results of our analyses suggest that the sampled rocks are actually felsic metavolcanics, the discrepancy being the result of a mapping error.

The geological background, the quarry reconnaissance, and the analytical results of this study are described in the pages that follow. In Chapter 2, John Rogers provides a general overview of the geology of the Carolina Slate Belt and surrounding regions. Chapter 3, by Jeffrey Irwin and Christopher Moore, describes the quarries from which the rock samples were obtained, as well as the artifacts from Fort Bragg that were used in this study. Chapters 4-6 report on the various characterization studies that were done on these items: Edward Stoddard describes the petrography, Michael Glascock and Robert Speakman present and analyze the element data, and Drew Coleman and Brent Miller discuss the neodymium isotope geochemistry. Chapter 7 presents the overall conclusions, in which Vincas Steponaitis, Jeffrey Irwin, and John Rogers synthesize the results, evaluate the methods, and point to directions for future research. Finally, details of the analytical methods and all the raw data are gathered in a series of appendices at the end.

Chapter 2

The Carolina Slate Belt

John J. W. Rogers

The hilly Piedmont of North Carolina separates the flat Coastal Plain and Triassic-Jurassic rift basins from the mountainous Blue Ridge and Appalachians (Figure 2.1). The Coastal Plain consists of Mesozoic-Cenozoic sediments developed on the subsiding continental margin as the North Atlantic Ocean became wider, and the Triassic-Jurassic rift basins are filled mostly by sedimentary debris washed into rifts formed during the initial stages of opening of the Atlantic Ocean. The Raleigh Belt and Eastern Slate Belt (see alternative terminology in Hibbard et al. 2002) contain rocks similar to those of the Piedmont. These suites, however, are exposed mostly east of the Triassic-Jurassic basins, and their connection with the Piedmont is unclear. This study does not include the rift basins, whose rocks are unsuitable for manufacturing artifacts, and also omits the Raleigh and Eastern Slate belts.

The Piedmont can be divided into eastern and western areas dominated by two very different rock suites. The eastern part, the focus of this study, is the Carolina Slate Belt, and the western part is known as the Inner Piedmont. Some geologists group the Carolina Slate Belt and Inner Piedmont as a Carolina Terrane, but others restrict the term Carolina Terrane to include only the Carolina Slate Belt. Information about the Carolina Slate Belt and other terranes in a large region east of the Appalachians referred to as the "Carolina Zone" is in Hibbard et al. (2002).

The Carolina Slate Belt consists mostly of rocks originally deposited on or near the earth's surface by volcanic eruption and sedimentation (North Carolina Geological Survey 1985). This area is referred to as the Carolina Slate Belt because low-grade metamorphism has given many of the rocks a slaty cleavage. The area is cut in several places by coarse-grained intrusive rocks, generally termed granites, that are relatively undeformed because they apparently intruded following the metamorphism that affected the sedimentary and volcanic rocks.

The Inner Piedmont mostly contains metamorphosed intrusive rocks that now occur as various types of gneiss. This area is eliminated from the present study, partly because of its greater distance from Fort Bragg, but mostly because the rocks in it are unsatisfactory for making stone tools.

The entire Piedmont is underlain at a depth of about 20 km by a zone that strongly reflects seismic waves. This zone is generally regarded as a fault or series of faults along which the upper block, including the exposed part of the Piedmont, moved westward over a suite of almost completely unknown rocks. The fault may bend upward to the west and come to the surface as one of the numerous thrusts in the Appalachian Mountains, although exact correlation of any of these faults eastward under the Piedmont has thus far been impossible.

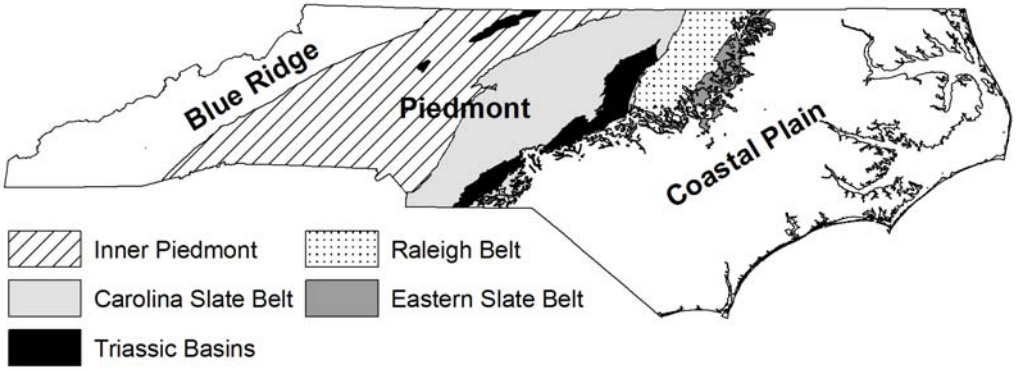

Figure 2.1. Major geologic regions of North Carolina (Rogers 1999; North Carolina Geological Survey 1998).

Ancient History

A very few of the sedimentary rocks of the Carolina Slate Belt in South Carolina contain fossils of Cambrian age (about 500 million years old). They are referred to as "Gondwanan" because they resemble Cambrian fossils found in the southern continents rather than those in North America. These fossils and those in other blocks along the eastern edge of North America show that a series of terranes (known as "Avalonian") were close to the western margin of South America 500 million years ago and moved to collide ("dock") with eastern North America at a later time.

Several questions about the docking of the Carolina Slate Belt are unresolved. One is whether the Carolina Slate Belt was an independent block or whether it was fused with the Inner Piedmont to form a larger Carolina Terrane before docking. A further question is the time at which docking occurred. Metamorphism presumably occurred during collision, but the post-metamorphic granites are about 300 million years old and presumably were emplaced after docking. The 20-km-deep fault zone beneath the Piedmont probably developed during western movement of the Carolina Terrane, although that cannot be proven.

The Carolina Slate Belt contains two rock suites: the Uwharrie Mountains contain rocks referred to as either the Uwharrie suite or the Albemarle suite (Figure 2.2); the Virgilina suite comprises the rest of the Carolina Slate Belt outside of the Uwharrie Mountains. Both suites probably began to form while the Carolina Slate Belt was near South America and continued to develop as the terrane moved across the intervening ocean basin to North America (Harris and Glover 1988; Rogers 1999). Rocks of the Uwharrie suite appear to have been deposited in a rift in a microcontinent that may already have separated from South America before the internal rifting occurred. Rocks of the Virgilina suite probably developed as a primitive island arc on oceanic lithosphere. Virgilina rocks are slightly older than Uwharrie rocks, and the time and mechanism of joining of the Virgilina and Uwharrie suites is uncertain.

Rock Types

Very little of the rock in the Carolina Slate Belt consists of sediment eroded from continental land masses. Rather, development primarily in an ocean basin caused the generation of silicic

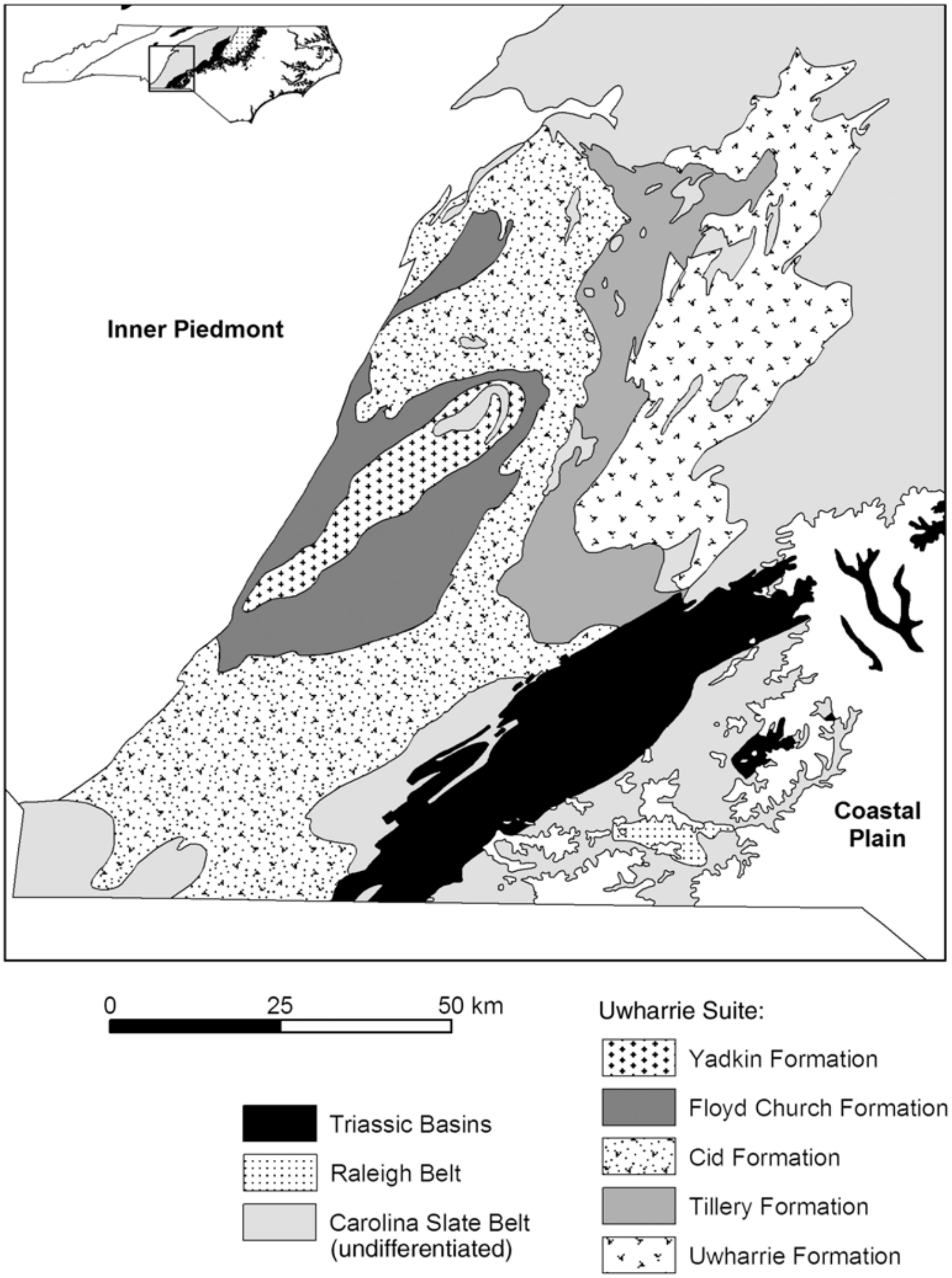

Figure 2.2. Geologic features in the vicinity of the Uwharrie Mountains (North Carolina Geological Survey 1998). The named formations in the right-hand column of the legend comprise the Uwharrie suite.

volcanic rocks that are high in sodium (Na) and low in potassium (K). Consequently, the volcanic rocks of the Carolina Slate Belt consist mostly of quartz and plagioclase and contain very little K-feldspar. An official geologic term for these rocks is “dacite,” but older geological and all archaeological literature refers to them as “rhyolite.” The term “felsite,” which includes any high-silica volcanic rock, is also sometimes used.

A small proportion of the rocks of the Carolina Slate Belt are low-silica basalts whose origin is unclear. They are useful for bowls and bannerstones but are too soft to be used for stone tools and are not considered in this report.

Dacitic volcanism in the Carolina Slate Belt generated rocks deposited by an enormous variety of processes. The resulting diversity of rock types is best displayed in the well-exposed Uwharries region, and similar processes undoubtedly formed all of the other volcanic and sedimentary rocks in areas of the Carolina Slate Belt where exposures are poor.

Most rocks were formed by consolidation of fragments blown out of volcanoes. These fragments include a few broken pieces of crystals but mostly consist of glass formed by rapid cooling of liquid blobs. Angular glass fragments are referred to as "shards."

Fine-grained ash accumulations are called "tuff" and include rocks formed by at least three different processes. One such process is consolidation of steam-saturated ash clouds, which travel at speeds up to 100 km/hour at temperatures of higher than 600°C. Thick ash clouds retain so much heat that the interiors may remelt ("vitrify") after consolidation to form thinly layered rocks that are very hard. The black rock at the quarry site at Morrow Mountain probably formed from a thick ash cloud. Another process by which tuff forms is through accumulation, either on land or in water, of ash blown through the air. Tuffs formed in this way are finely layered, but because they accumulate after cooling they do not become vitrified. They are probably useful as stone tools only after metamorphism or some other secondary process. Finally, a third process resulting in the formation of tuff is the accumulation of ash and larger fragments moved by water or wind. Sedimentary rocks formed through this process are hard enough to be used for tools only after metamorphism or other secondary processes.

Rocks formed from liquid flows are rare. They contain various proportions of quartz and plagioclase phenocrysts, and some show a crude flow banding.

All of the rocks in the Carolina Slate Belt have undergone low-grade metamorphism that converted most of their original minerals except quartz to lower-temperature assemblages. Metamorphic minerals commonly include chlorite, epidote, stilpnomelane, and smaller amounts of numerous other minerals (with at least one occurrence of the rare mineral piedmontite).

Stratigraphy

Stratigraphic relationships have been determined for the Uwharrie suite in the Uwharrie Mountains but are virtually unknown elsewhere in the Carolina Slate Belt. Even in the Uwharries, stratigraphic thicknesses are uncertain because the base of the sequence is unexposed, an unknown amount of rock has been eroded from the top, and deformation obscures relationships within the exposed section. This discussion follows the stratigraphy proposed by Milton (1984; cf. North Carolina Geological Survey 1998).

The lowermost unit in the Uwharrie Mountains is the Uwharrie Formation, a sequence of silicic flow and volcaniclastic rocks. The Uwharrie Formation is overlain by the Tillery Formation, consisting mostly of planar-laminated silicic siltstones and mudstones that may represent the distal parts of turbidites that episodically filled the Uwharrie basin. The Cid Formation, above the Tillery, appears to have been deposited in comparatively shallow water. It consists largely of silicic debris in beds 10-40 cm thick, with cross stratification in the lower part and thin laminations toward the top. The Flat Swamp member of the Cid Formation is distinguishable by its assemblage of silicic flows and ignimbrites. The Floyd Church Formation, above the Cid, consists almost wholly of mudstones whose clay contents give rocks a higher K content than is found in other rocks in the Uwharrie suite. The uppermost unit is the Yadkin Formation, which consists of poorly sorted sandstones that include abundant grains of basaltic rocks. One distinguishable unit of the Yadkin Formation is the Badin greenstone, which contains a few basaltic flow rocks but consists mostly of sand- and silt-sized grains of basaltic rock. The Morrow Mountain ignimbrite and the identical rocks of Tater Top Mountain may be the same age as the Yadkin Formation, but their stratigraphic position is unclear because they may represent the deposits of volcanoes that were injected through an unknown sequence of other rocks in the Uwharrie Mountains.

Ages of Uwharrie rocks are poorly constrained. All of them are probably younger than 600 million years, and discovery of the Ediacaran fossil *Pteridium* in the Floyd Church Formation suggests that most deposition in the North Carolina part of the Carolina Slate Belt occurred before the end of the Proterozoic.

Topography and Human History

The Piedmont in North Carolina is about 200 m higher than in South Carolina and Virginia. This high elevation results from the Cape Fear Arch, an uplift that trends roughly along the Cape Fear River and continues on a linear trend through the Piedmont into the Appalachians. Drill cores and geophysical studies in the Coastal Plain show that the Arch has been an uplift for at least the past 250 million years, and studies of modern river patterns show that the Arch has risen nearly one half meter since human habitation began some 12,000 years ago (Rogers 1999).

The high elevation in North Carolina causes rivers to flow either north or south from the Piedmont rather than directly eastward (Figure 2.3). Only two rivers with tributaries in the interior of the Piedmont (Cape Fear and Neuse) remain wholly within North Carolina until they reach the Atlantic Ocean. Two other systems (Yadkin and Catawba) flow into South Carolina, and one river system (Dan) flows north into Virginia before it turns south in the Coastal Plain to reach the ocean in North Carolina.

The high elevation in North Carolina prevented the establishment of a simple fall line between the Piedmont and Coastal Plain. The fall line is easily seen in Virginia and South Carolina, where the cities of Richmond and Columbia are built along it. North Carolina,

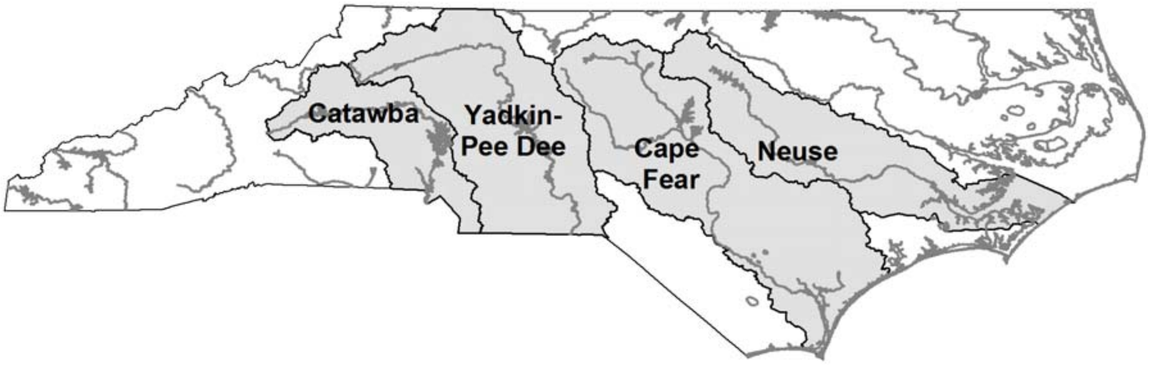

Figure 2.3. North Carolina rivers and drainage basins mentioned in the text (United States Department of Agriculture 1998).

however, has a broad fall zone more than 100 km wide over which rivers lose about 200 m of elevation. This difference in fall zones explains why river transportation by all types of ships is possible across the entire Coastal Plain to the Piedmont in both South Carolina and Virginia, but even powered vessels can get no farther upstream than Fayetteville in North Carolina.

The greater elevation and lack of fall line in North Carolina has had a profound effect on human history (Rogers 1999). The inability of people in the North Carolina Piedmont to communicate freely with the Coastal Plain led to isolation of early Piedmont inhabitants. Most early settlers in the Piedmont arrived by wagon roads through Virginia instead of from coastal North Carolina. Until the development of railroads in the 1800s, Piedmont inhabitants traded with the ports of Richmond and Charleston instead of with North Carolina ports. In colonial time, the isolation caused numerous rebellions, including the activities of the Regulators shortly before the American Revolution.

Because the headwaters of the Cape Fear and Neuse River basins are at high elevations, these rivers and their tributaries have cut deeply incised valleys. Floodplains would have been narrow or absent during most of human history, except during the eighteenth through early twentieth centuries when widespread deforestation accompanying the development of farms allowed the valleys to be temporarily choked by runoff debris. The lack of floodplains causes even modern highways to follow routes between rivers instead of along the rivers.

It is not known whether the high elevation of the North Carolina Piedmont and the lack of floodplains along its rivers affected transportation in prehistoric times. Without pack animals or wheeled vehicles, people walking along trails may have crossed between the Piedmont and the Coastal Plain just as easily as they would have walked within either the Piedmont or the Coastal Plain. An indirect indication of this possibility is that the Cherokee trading path led through the Appalachians in North Carolina, where they are the highest, whereas colonial wagon roads passed through lower parts of the mountains in Virginia or Georgia.

Comparison of the stone tools at Fort Bragg with rocks at quarry sites in the North Carolina Piedmont will help resolve the question of whether prehistoric groups crossed the fall zone consistently. If they did, then it should be possible to correlate Fort Bragg projectile points with specific quarries in the Piedmont. An absence of correlation may suggest that people traveled farther north or south along the Coastal Plain looking for more accessible quarry sources.

Chapter 3

Quarries and Artifacts

Christopher R. Moore and Jeffrey D. Irwin

Prior to developing a sampling scheme, an effort was made to identify and map all known quarries in the Carolina Slate Belt. Site files at the North Carolina Office of State Archaeology (OSA) were reviewed, and additional information was obtained from amateur archaeologists. The resulting information was compiled into a database (Appendix B). While many quarries were identified in areas of intensive archaeological survey (i.e., the Uwharrie National Forest and Morrow Mountain State Park), the database includes isolated quarries and workshops in Alamance, Anson, Chatham, Davidson, Durham, Orange, and Union counties. Archaeological surveys by Abbott (1987), Cooper and Hanchette (1977), Benson (1999), Daniel and Butler (1991, 1996), Hargrove (1989), Millis (2003), and others have recorded numerous metavolcanic and metasedimentary quarry sites in the Carolina Slate Belt. It should be noted that dense concentrations of recorded quarry sites within the Uwharrie National Forest are in many cases simply the most visible expressions of a single quarry complex (e.g., the Wolf Den and Shingle Trap Mountain areas) and as such represent the prehistoric exploitation of a single expansive stone resource area (e.g., Cooper and Hanchette 1977; Benson 1999). In all, over 100 quarries and limited-use extraction sites were identified (Figure 3.1). This compilation served as the baseline from which our sample locations were selected.

Below we describe the sites that produced our rock samples and how these samples were collected. We also describe the artifacts from sites at Fort Bragg that were selected for comparison to the quarry samples.

Quarry Sites

A total of 71 rock samples from 25 quarries or possible source locations were examined in this study (Table 3.1; Figures 3.2-3.3; Appendix A). While the majority of sample locations are recorded archaeological quarries, a few simply represent local geological deposits. Quarries were sampled from Montgomery, Randolph, and Stanly counties in the Uwharrie Mountains and from Chatham, Orange, Durham, and Person counties outside of the Uwharries. Additional samples were taken from a source near Fayetteville in Cumberland County.

As mentioned in Chapter 1, sites were grouped into quarry zones according to spatial proximity and geologic characteristics. Individual quarry sites are here described under the heading of the zone to which they were assigned. Descriptions include information about terrain, sample provenience, rock exposures, geologic formation, and the nature of each sample.

Many of the samples from the Uwharrie Mountains (Figure 3.4) were originally collected by Randolph Daniel and Robert Butler during the early 1990s as part of Daniel's dissertation

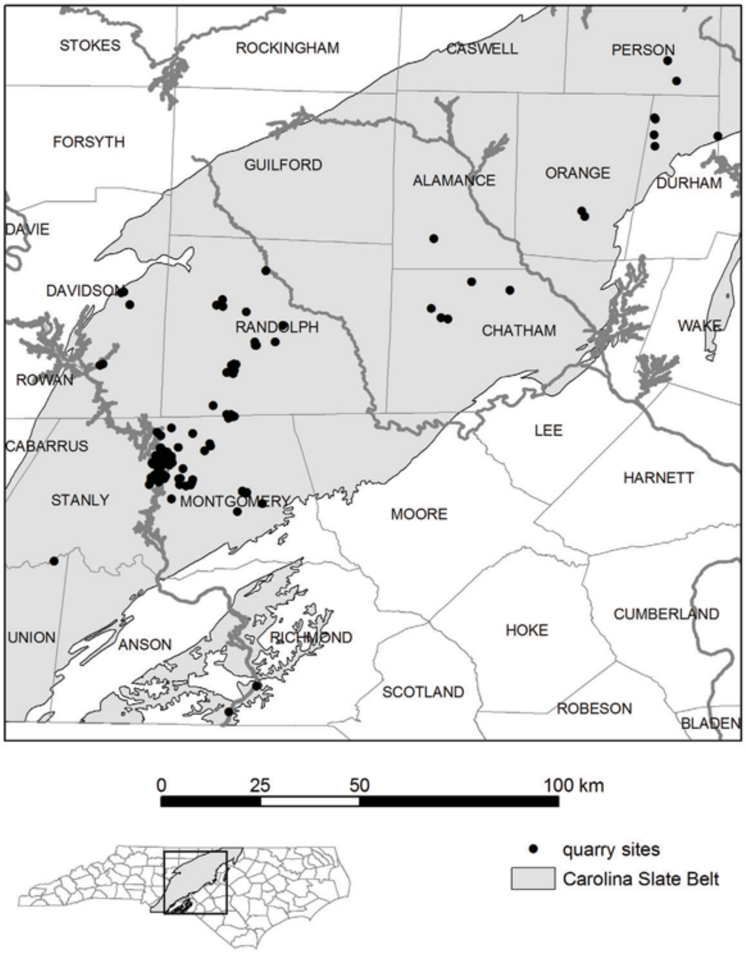

Figure 3.1. Recorded quarry sites in the Carolina Slate Belt of North Carolina.

research (Daniel and Butler 1996). These rock samples are now curated at the Research Laboratories of Archaeology (RLA), University of North Carolina at Chapel Hill. Additional quarry samples were obtained during several field trips to quarry locations throughout the Carolina Slate Belt in 2002 and 2003. Participants in these trips included Christopher Moore, Jeffrey Irwin, Edward Stoddard, Brent Miller, Randolph Daniel, and Michael Harmon. Many of the new quarries in this study were brought to our attention by other archaeologists, both professional and amateur.

Uwharries Southeastern

The Uwharries Southeastern zone contains the Horse Trough Mountain and Lick Mountain quarries (Figure B.1). These quarries are located on the eastern side of the Yadkin-Pee Dee River in the Uwharrie National Forest and are part of the Uwharrie Formation.

The Horse Trough site was selected on the advice of Harmon, who recalled earlier visits to the site and suggested its potential as a quarry. Two samples (FBL025-FBL026) were collected from the southern portion of the ridge in the general vicinity of two recorded nonquarry archaeological sites (31Mg378 and 31Mg379). Because Horse Trough Mountain is forested and

Table 3.1. Quarry Samples Used in the Present Study.

Quarry Zone:			UTM^a		Field	North Carolina Geologic Map^b		
Sample	Site Number	Site Name	Northing	Easting	Description	Code	Description	Formation
Uwharries Southeastern:								
FBL025	31Mg378/379	Horse Trough Mountain	3908577	586311	dacite	CZfv$_1$	felsic metavolcanic rock	Uwharrie
FBL026	31Mg378/379	Horse Trough Mountain	3908577	586311	dacite	CZfv$_1$	felsic metavolcanic rock	Uwharrie
FBL051	31Mg222	USS Ranger Quarry	3913923	588488	dacite	CZfv$_1$	felsic metavolcanic rock	Uwharrie
FBL052	31Mg222	USS Ranger Quarry	3913923	588488	dacite	CZfv$_1$	felsic metavolcanic rock	Uwharrie
FBL053	31Mg222	USS Ranger Quarry	3913923	588488	dacite	CZfv$_1$	felsic metavolcanic rock	Uwharrie
FBL054	31Mg222	USS Ranger Quarry	3913923	588488	dacite	CZfv$_1$	felsic metavolcanic rock	Uwharrie
Uwharries Southern:								
FBL015	31St18	Morrow Mountain	3912209	582492	felsite	CZfv	felsic metavolcanic rock	Tillery
FBL016	31St64	Tater Top Mountain	3912917	584354	felsite	CZmd$_1$	metamudstone and meta-argillite	Tillery
FBL017	31St18	Morrow Mountain	3912252	582362	felsite	CZfv	felsic metavolcanic rock	Tillery
FBL018	31St18	Morrow Mountain	3912421	582459	felsite	CZfv	felsic metavolcanic rock	Tillery
FBL019	31St18	Morrow Mountain	3912560	582554	felsite	CZfv	felsic metavolcanic rock	Tillery
Uwharries Eastern:								
FBL001	31Mg554	Shingle Trap Mountain	3917872	587452	dacite	CZfv	felsic metavolcanic rock	Tillery
FBL002	31Mg554	Shingle Trap Mountain	3918056	587342	dacite	CZfv	felsic metavolcanic rock	Tillery
FBL003	31Mg554	Shingle Trap Mountain	3918363	586781	dacite	CZfv	felsic metavolcanic rock	Tillery
FBL004	31Mg554	Shingle Trap Mountain	3918121	586929	dacite	CZfv	felsic metavolcanic rock	Tillery
FBL005	31St68	Sugarloaf West	3914124	582758	dacite	CZfv	felsic metavolcanic rock	Tillery
FBL006	31St66	Sugarloaf Mountain	3913852	583741	dacite	CZfv	felsic metavolcanic rock	Tillery
FBL007	31St67	Hattaway Mountain	3914765	583453	dacite	CZfv	felsic metavolcanic rock	Tillery
Uwharries Western:								
FBL008		Falls Dam	3916984	583805	andesite	CZfv	felsic metavolcanic rock	Cid
FBL009	31Mg639	Wolf Den 639	3918067	584251	andesite	CZfv	felsic metavolcanic rock	Cid
FBL010	31Mg639	Wolf Den 639	3917939	584300	andesite	CZfv	felsic metavolcanic rock	Cid
FBL011	31Mg117	Wolf Den 117	3918742	584316	andesite	CZfv	felsic metavolcanic rock	Cid
FBL012	31Mg117	Wolf Den 117	3918742	584316	andesite/latite	CZfv	felsic metavolcanic rock	Cid
FBL013	31Mg640	Wolf Den 640	3917723	583542	andesite	CZfv^c	felsic metavolcanic rock	Cid
FBL014	31Mg641		3926732	586632	andesite/latite	CZmv$_1$	mafic metavolcanic rock	Cid

Table 3.1. Quarry Samples Used in the Present Study (continued).

Quarry Zone:			UTM[a]		Field	North Carolina Geologic Map[b]		
Sample	Site Number	Site Name	Northing	Easting	Description	Code	Description	Formation
Uwharries Asheboro:								
FBL020	31Rd37		3948533	603523	tuff	CZmv	mafic metavolcanic rock	Uwharrie
FBL021	31Rd1201	Carraway Mountain	3957237	596949	dacite/andesite	$CZmd_1$	metamudstone and meta-argillite	Tillery
FBL022	31Rd1202	Tater Head Mountain	3957598	595573	dacite/andesite	CZfv	felsic metavolcanic rock	Tillery
FBL023		Dave's Mountain	3954020	605891	dacite	$CZfv_1$	felsic metavolcanic rock	Uwharrie
FBL024	31Rd37		3948601	603912	tuff	CZmv	mafic metavolcanic rock	Uwharrie
FBL055	31Rd1350	Northhampton Rd. Quarry	3948745	607738	dacite	$CZfv_1$	felsic metavolcanic rock	Uwharrie
Chatham Pittsboro:								
FBL027	31Ch729	Joe Moylan Quarry	3962336	655804	mudstone	CZmd	metamudstone and meta-argillite	
FBL028	31Ch729	Joe Moylan Quarry	3962336	655804	mudstone	CZmd	metamudstone and meta-argillite	
FBL029	31CH729	Joe Moylan Quarry	3962336	655804	siltstone	CZmd	metamudstone and meta-argillite	
FBL030	31Ch729	Joe Moylan Quarry	3962336	655804	fine sandstone	CZmd	metamudstone and meta-argillite	
FBL056	31Ch729	Joe Moylan Quarry	3962589	656168	mudstone	CZmd	metamudstone and meta-argillite	
FBL057	31Ch729	Joe Moylan Quarry	3962454	655975	mudstone	CZmd	metamudstone and meta-argillite	
Chatham Siler City:								
FBL035		Rocky River 1	3955002	642790	mud/siltstone	CZmd	metamudstone and meta-argillite	
FBL036		Rocky River 2	3955158	642626	dacite	CZmd	metamudstone and meta-argillite	
FBL037		Rocky River 3	3955297	642445	mudstone	CZmd	metamudstone and meta-argillite	
FBL038	31Ch427	31Ch427	3955164	641835	sandstone	CZmd	metamudstone and meta-argillite	
Chatham Silk Hope:								
FBL031	31Ch741	Chestnut Hill Quarry	3964340	647964	dacite/rhyodacite	CZiv[d]	intermediate metavolcanic rock	
FBL032	31Ch741	Chestnut Hill Quarry	3964340	647964	lithic tuff	CZiv[d]	intermediate metavolcanic rock	
FBL033	31Ch741	Chestnut Hill Quarry	3964340	647964	dacite	CZiv[d]	intermediate metavolcanic rock	
FBL034	31Ch741	Chestnut Hill Quarry	3964340	647964	lithic tuff	CZiv[d]	intermediate metavolcanic rock	
FBL058	31Ch741	Chestnut Hill Quarry	3964275	648050	lithic tuff	CZiv	intermediate metavolcanic rock	
FBL059	31Ch741	Chestnut Hill Quarry	3964353	647937	lithic tuff	CZiv[d]	intermediate metavolcanic rock	
Orange County:								
FBL060	31Or564	Bald Mountain Quarry	3982716	670171	dacite	CZfv	felsic metavolcanic rock	
FBL061	31Or564	Bald Mountain Quarry	3982672	670133	dacite	CZfv	felsic metavolcanic rock	

Table 3.1. Quarry Samples Used in the Present Study (continued).

Quarry Zone:			UTM[a]		Field	North Carolina Geologic Map[b]		
Sample	Site Number	Site Name	Northing	Easting	Description	Code	Description	Formation
FBL062	31Or564	Bald Mountain Quarry	3982816	670076	dacite	CZfv	felsic metavolcanic rock	
FBL063	31Or549		3981131	670883	dacite	PzZg[d]	metamorphosed gabbro and diorite	
FBL064	31Or549		3981195	670815	dacite	PzZg[d]	metamorphosed gabbro and diorite	
FBL065	31Or549		3981171	670810	dacite	PzZg[d]	metamorphosed gabbro and diorite	
Durham County:								
FBL047	31Dh703	Cains Chapel Quarry	3999181	684723	dacite	CZfv	felsic metavolcanic rock	
FBL048	31Dh703	Cains Chapel Quarry	3999181	684723	sandstone	CZfv	felsic metavolcanic rock	
FBL049	31Dh703	Cains Chapel Quarry	3999181	684723	sandstone	CZfv	felsic metavolcanic rock	
FBL050	31Dh703	Cains Chapel Quarry	3999181	684723	tuff	CZfv	felsic metavolcanic rock	
FBL066	31Dh703	Cains Chapel Quarry	3998905	684667	dacite	CZfv	felsic metavolcanic rock	
FBL067	31Dh703	Cains Chapel Quarry	3999235	684872	sandstone	CZfv	felsic metavolcanic rock	
Person County:								
FBL043	31Pr115	Powerline Quarry	4015567	688965	mudstone?	CZfv	felsic metavolcanic rock	
FBL044	31Pr115	Powerline Quarry	4015567	688965	tuff	CZfv	felsic metavolcanic rock	
FBL045	31Pr115	Powerline Quarry	4015567	688965	mudstone	CZfv	felsic metavolcanic rock	
FBL046	31Pr115	Powerline Quarry	4015567	688965	sandstone	CZfv	felsic metavolcanic rock	
FBL068	31Pr115	Powerline Quarry	4015213	689130	siltstone	CZfv	felsic metavolcanic rock	
FBL069	31Pr115	Powerline Quarry	4015889	688827	siltstone	CZfv	felsic metavolcanic rock	
Cumberland County:								
FBL039	31Cd400		3890907	700336	aplite			
FBL040	31Cd400		3890907	700336	basalt			
FBL041	31Cd400		3890907	700336	diorite			
FBL042	31Cd424		3890818	700408	tuff?			
FBL070	31Cd402		3890184	701416	greenstone			
FBL071	31Cd424		3890818	700408	metagabbro			

[a] NAD 1927 datum.

[b] North Carolina Geological Survey (1985).

[c] Near contact with $CZmv_1$ (mafic metavolcanic rock).

[d] Near contact with CZfv (felsic metavolcanic rock).

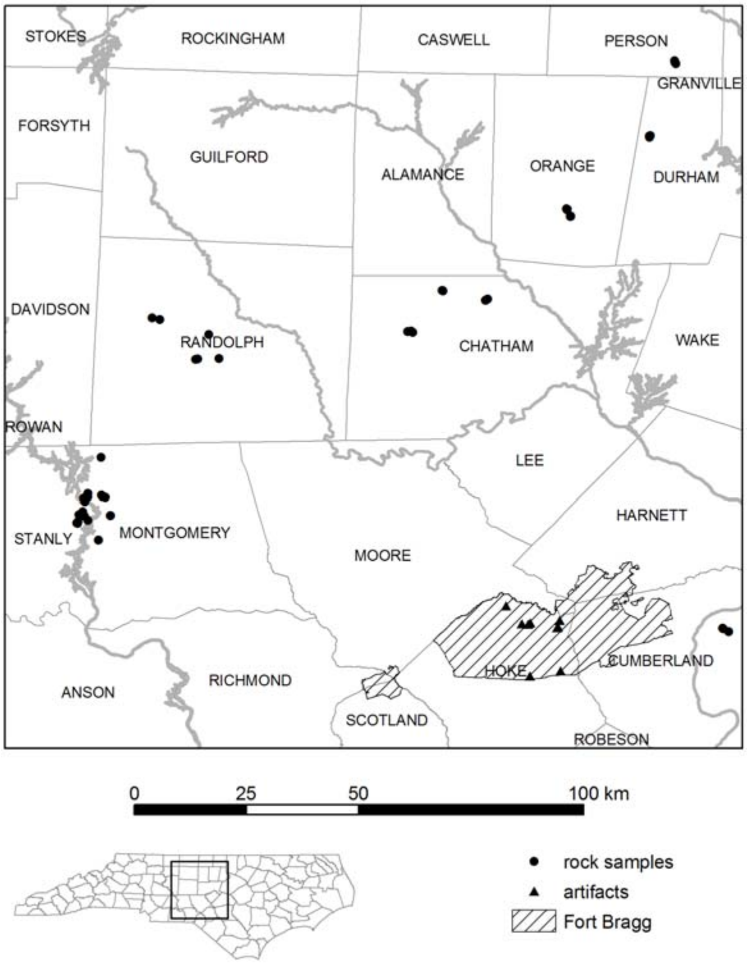

Figure 3.2. Sample locations mapped by county.

most areas were covered in dense leaf litter, identifying potential areas of quarrying was difficult. Actual evidence of quarry debris was rare. Several areas of boulder outcrops and float were observed, and several large rocks appeared to have large flake scars. Some possible quarry debris was observed around the bases of trees. The material is a coarse-grained metadacite. This site was probably minimally used prehistorically, although a more intensive survey of the mountain may reveal areas with denser debris.

Four samples from Lick Mountain were collected from the general vicinity of a quarry site, 31Mg222, first recorded by Peter Cooper in 1977. The samples were taken from the summit of a hill just west of Lick Mountain proper. Quarry debris was lightly scattered along the ridge and around the bases of trees (Figure 3.5). Low density suggests minor use of this source prehistorically. Boulder outcrop and float were also observed. Samples include actual quarry debris consisting of large primary reduction flakes (FBL051-FBL052) and bedrock taken from outcrop in the immediate vicinity of the site (FBL053-FBL054). Like the Horse Trough specimens, these rocks are coarse-grained metadacite.

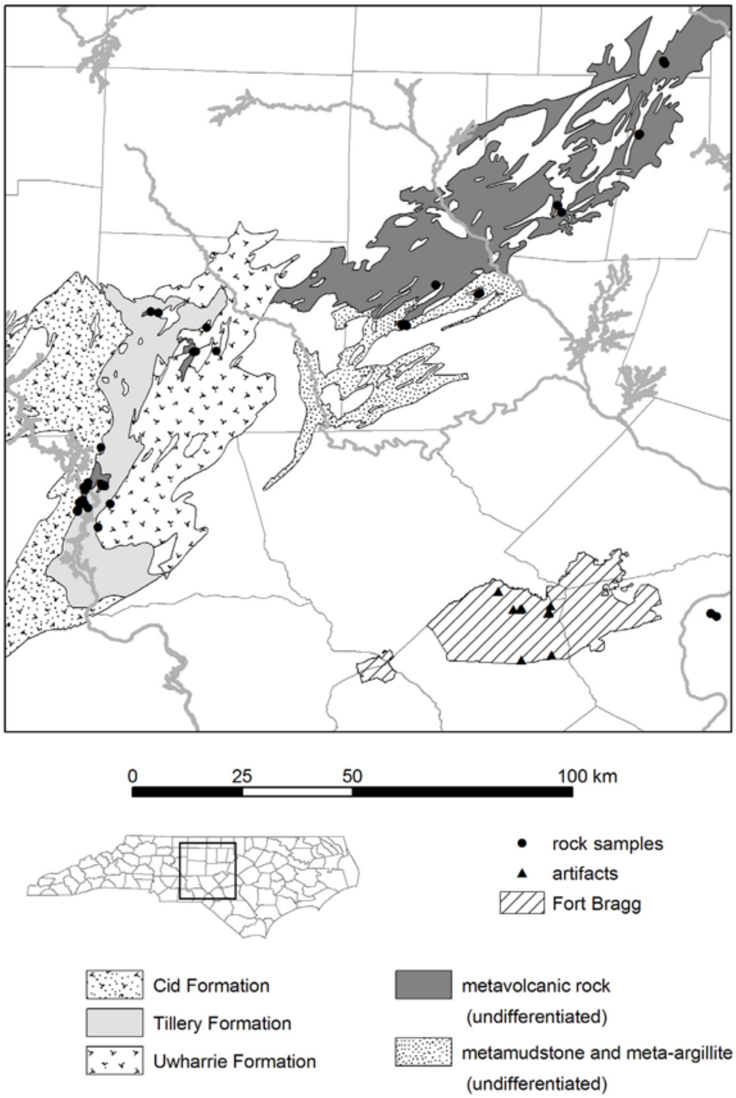

Figure 3.3. Sample locations mapped by geologic formation.

Uwharries Southern

The Uwharries Southern zone is represented by five samples collected by Daniel and Butler (1996:13-15) directly from Morrow Mountain and Tater Top Mountain (Figure B.2). This quarry zone corresponds to Daniel and Butler's "Morrow Mountain rhyolite." While Tater Top Mountain is a minor quarry site, Morrow Mountain is known as one of the largest and most intensively used quarry sites in North Carolina. Morrow Mountain stone is considered to be of very high quality for tool manufacture. It is fine-grained and aphyric and is the only sampled stone exhibiting flow banding. Daniel and Butler describe the stone from Tater Top as having a blocky fracture. Both quarries are part of the Tillery Formation and are the only known quarry sites in the area that produce nonporphyritic felsite.

The samples, which include one specimen from Tater Top Mountain (FBL016) and four specimens from Morrow Mountain (FBL015, FBL017-FBL019), consist of both quarry flakes

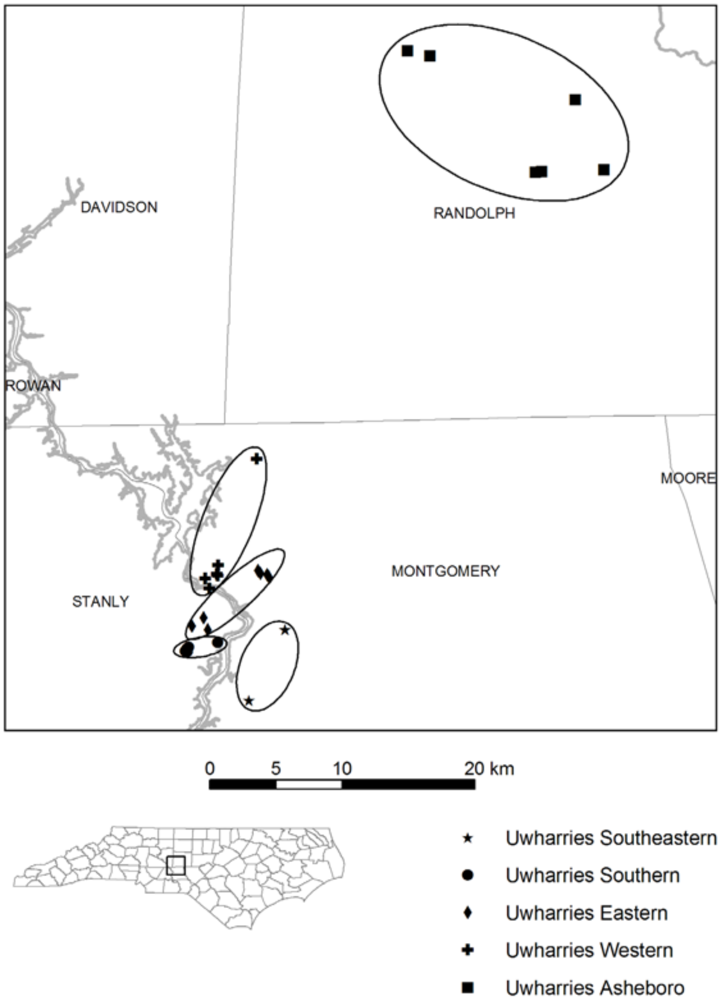

Figure 3.4. Quarry zones and sample locations in the Uwharrie Mountains.

and bedrock. A number of these were obtained from an erosional gully near the top of Morrow Mountain on the southeastern slope (Figure 3.6; also see Daniel and Butler 1996:Figure 8).

Uwharries Eastern

Four other quarries within the Tillery Formation constitute the Uwharries Eastern zone (Figure B.3). These quarries include Hattaway Mountain (FBL007), Sugarloaf Mountain (FBL006), an unnamed peak in Morrow Mountain State Park just west of Sugarloaf Mountain (FBL005), and Shingle Trap Mountain in the Uwharrie National Forest (FBL001-FBL004). Daniel and Butler observed localized but abundant quarry debris at Hattaway Mountain, an "extensive mountain-top quarry" at Sugarloaf Mountain, low density debris and minor use at the unnamed peak (St68), and a major quarry with continuous distribution of debris along the summit at Shingle Trap (1996:20-22). Quarries in this zone yield a porphyritic dacite which is exposed along the mountain ridges and is consistent with Daniel and Butler's (1996:20) "Sugarloaf Mountain rhyolite." This material was generally available for use by prehistoric inhabitants but was apparently less desirable than the felsite from Morrow Mountain.

Figure 3.5. Jeffrey Irwin collecting quarry debris on Lick Mountain in the general vicinity of site 31Mg222, Uwharries Southeastern zone.

With the exception of two samples from Shingle Trap Mountain, all samples from this zone were collected by Daniel and Butler. Two Shingle Trap samples were collected in 2002 (FBL002, FBL004). These correspond to the general locations of Daniel and Butler's samples HD18a and HD18b (FBL001 and FBL003, respectively).

Uwharries Western

The Uwharries Western zone consists of quarries within the Cid Formation. These quarries are included in Daniel and Butler's (1996:16-19) "Wolf Den rhyolite" and are represented by seven samples of meta-andesite and metalatite from three areas (Figure B.4). All but two of the samples were collected by Daniel and Butler.

Five Uwharries Western samples come from three sites (31Mg639, 31Mg117, and 31Mg640) in the Wolf Den Mountain area, which is just north and east of the Yadkin-Pee Dee River and just west of Shingle Trap Mountain. Two samples were collected in 2002 (FBL010 and FBL012), and the other three samples were acquired from the Daniel and Butler collections (FBL009, FBL011, and FBL013). Quarry debris density varies considerably from location to location at the Wolf Den sites, with heavy concentrations visible in areas of significant ground disturbance and erosion (Figure 3.7). Daniel and Butler (1996:16-19) observed abundant debris and small boulders at 31Mg117; small outcrops and cores, chunks, and flakes at 31Mg639; and thin scattering of debris at 31Mg640.

Figure 3.6. Dense quarry debris from erosional gulley on Morrow Mountain, Uwharries Southern zone. The scale bar in the lower right corner of the image is approximately 10 cm long.

Another Uwharries Western sample was collected by Daniel and Butler further south along the Yadkin-Pee Dee River in the vicinity of Falls Dam (FBL008). This sample comes from outcrop and may not be associated with an actual quarry site (Randolph Daniel, personal communication 2002). No attempt was made to relocate the outcrop.

The final sample was collected by Daniel and Butler from site 31Mg641 (FBL014). This quarry is located east of Badin Lake and just north of Eldorado near Highway 109. Daniel and Butler (1996:18) describe the site as “larger but less intensively used than Wolf Den.” No attempt was made to revisit the site, which is now on private property.

Uwharries Asheboro

This zone consists of four quarries and one possible quarry (Dave’s Mountain) in the vicinity of Asheboro (Figure B.5). Three of the sites from this zone fall within the Uwharrie Formation.

Figure 3.7. Brent Miller collecting samples on Wolf Den Mountain, Uwharries Western zone. Note the outcrop and the surrounding quarry debris on the ground surface.

These include 31Rd1350 along Northhampton Road in southern Asheboro (FBL055), 31Rd37 just southwest of Asheboro (FBL020, FBL024), and Dave's Mountain in northern Asheboro (FBL023). Two Uwharries Asheboro quarries fall within the Tillery Formation. These quarries occur in a group of mountains just west and north of Asheboro and include 31Rd1201 just west of Caraway Mountain (FBL021) and 31Rd1202 at Tater Head Mountain (FBL022). Except for FBL055, all Uwharries Asheboro samples were collected by Daniel and Butler (1996:27-29; note that their sites Rd852, Rd854, and Rd855 are equivalent to our sites 31Rd1350, 31Rd1201, and 31Rd1202, respectively).

Stoddard and Moore collected sample FBL055 in 2003 in a wooded area along Northhampton Road in the vicinity of 31Rd1350. This sample was taken directly from a rock outcrop (Figure 3.8). This wooded site has extensive outcrop exposures and a light scatter of large quarry debris. Daniel and Butler (1996:28-29) observed "worked outcrops" at 31Rd1350; they found a "minor amount of debris" consisting of light gray, sugary, crystal-lithic metatuff.

Site 31Rd37 is located in an area with extensive development and ground disturbance that may have obliterated the original quarry site. A revisit to the site did not reveal any significant quarry debris along the highway or in other accessible areas. Samples FBL020 and FBL024 are Daniel and Butler's (1996:27-28) "metarhyolite."

Sample FBL023 is from Dave's Mountain on the northern edge of the Uwharrie Mountains. This mountain was sampled by Daniel and Butler (1996:30-31) and considered to be an unlikely quarry, although significant modern development precluded adequate survey. Daniel and Butler describe the stone as dense plagioclase porphyritic rhyolite with a blocky fracture. No attempt was made to revisit the site since it is in an area of Asheboro that is heavily developed.

Figure 3.8. Edward Stoddard collecting outcrop sample (FBL055) at site 31Rd1350, Uwharries Asheboro zone.

Attempts to relocate the 31Rd1201 and 31Rd1202 quarries were made by Stoddard and Moore in 2003. Small amounts of quarry debris were found at 31Rd1201, consistent with the minor quarry status attributed by Daniel and Butler (1996:29; their site Rd854). More extensive outcrop and artifact debris was observed at 31Rd1202, which Daniel and Butler (1996:30; their site Rd855) describe as "the most intensively quarried source" in the Asheboro area. Both quarries are composed primarily of dacite, although the quarry debris observed by Stoddard and Moore at each site appeared visually distinctive.

Chatham Pittsboro

This zone is represented by six samples taken from a single large quarry, 31Ch729, in north-central Chatham County (Figures 3.9, B.6). This extensive site is the largest known quarry in the county and has clusters of moderate and dense quarry debris scattered over several hundred meters of a ridge crosscut by a small stream (Figure 3.10). The site was recorded by amateur archaeologist Joseph Moylan and is now part of a large residential development. Dense quarry debris is scattered on both sides of a residential road, and quarry debris is being used to landscape yards (Figure 3.11). Phase 1 samples (FBL027-FBL030) were taken from a central location within the residential development. Phase 2 samples were taken with more precise GPS provenience. Sample FBL056 is a piece of quarry debris taken from the northeastern portion of the site. Sample FBL057 is from a float boulder along the main road into the quarry, close to the Long Branch tributary.

The Chatham Pittsboro quarry appears distinct from the Uwharries quarries in that the rock is primarily a very fine-grained, nonporphyritic metasedimentary material. Many larger rocks and

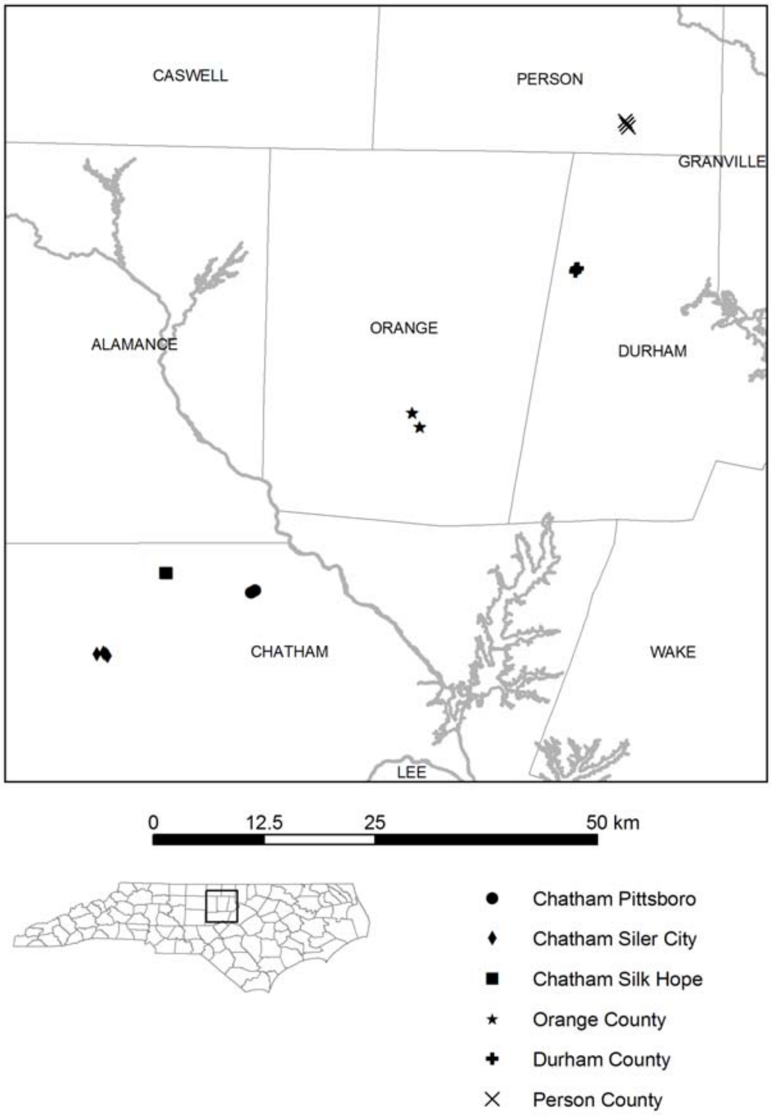

Figure 3.9. Quarry zones and sample locations in the northern portion of the study area.

outcrops observed at the site have clear sedimentary bedding (Figure 3.12). This massive, parallel bedding with differential textures across layers is distinct from the flow banding seen in Morrow Mountain material, but it may not always be visible in flakes and bifaces. The rocks themselves show a range of colors and textures. Most of the worked pieces are extremely fine-grained and bluish-gray to greenish-gray or black in color.

Chatham Siler City

The Chatham Siler City zone is represented by four samples collected near two sites reported to be quarry or quarry workshop locations (Figure B.7). FBL038 was taken from the vicinity of 31Ch427, a quarry site identified during a cultural resources survey for the US 421 bypass

Figure 3.10. Quarry debris at site 31Ch729, Chatham Pittsboro zone.

Figure 3.11. Quarry debris used for landscaping near site 31Ch729, Chatham Pittsboro zone.

Figure 3.12. Rock with parallel bedding still visible, Chatham Pittsboro zone.

around Siler City (Baker 1980; Cable and Mueller 1980). This large site was originally an agricultural field on a hilltop with a localized outcrop of small boulders of andesite porphyry. A revisit revealed that the site had recently been destroyed by development. Sample FBL038 was taken from the general site area, although it does not appear to match the rock type seen in 1980.

An attempt was also made by Stoddard and Moore to find 31Ch578 along the Rocky River. Although the site was not relocated, samples of metavolcanic rocks were taken from several places on both the west and east side of the river (FBL035, FBL036, FBL037). The samples represent float (FBL035, FBL037) and outcrop (FBL036) from the Rocky River and its surrounding terraces, just east of Siler City.

Samples from this zone included three metasedimentary rocks and a single example of dacite. This is a heterogeneous group with little known prehistoric utilization.

Chatham Silk Hope

This zone is represented by six samples taken from a single quarry site in north-central Chatham county (Figure B.8). The site was identified by Robert Graham and is known as Chestnut Hill (31Ch741). The known extent of the quarry site is restricted to a small hill with a few large trees and a dirt road leading to and around the side of the quarry. Dense flake debris was observed covering large portions of the hill and a graded dirt road that runs up the hill. Quarry debris was also visible around trees and other areas of disturbed ground (Figure 3.13).

Figure 3.13. Eroded roadbed and dense quarry debris at site 31Ch741, Chatham Silk Hope zone.

Phase 1 samples FBL031-FBL034 have general provenience from the quarry. Phase 2 samples FBL058 and FBL059 were collected by Stoddard and Moore, and their exact locations were recorded using a GPS unit.

Although Chestnut Hill is just a few kilometers east of 31Ch427 (in the Chatham Siler City zone), the material is unique. Described by Stoddard as lithic tuff and dacite, the rocks from Chestnut Hill are often dark purple or blue in color, although hues of red are also prevalent. Quarry debris containing fragments of rock within the overall groundmass are common. The debris varies in density from moderate to heavy and covers the entire hill and slope. Although variability within the quarry is quite high, the Chestnut Hill material is as visually distinct as anything observed at any other quarry.

Orange County

This zone consists of six samples taken from two quarries in Orange County (Figure B.9). An archaeological survey by Heather Millis (2003) located one potential quarry or quarry workshop area (31Or549), and local resident Mary Ayers located the second, larger quarry on Bald Mountain (31Or564), immediately to the north of the first. The Bald Mountain quarry sits on a large hill located on the edge of Duke Forest. The hill is heavily wooded and contains large outcrop “fins” and boulder float surrounded by areas of light to moderate quarry debris. Dense leaf litter covers the ground at both quarry sites, although it is clear from the amount of visible quarry debris that Bald Mountain is the more intensively used of the two quarries (Figure 3.14).

Figure 3.14. Quarry debris seen through dense leaf litter at the Bald Mountain quarry, Orange County zone.

The potential for other quarry sites in this part of Orange County seems high, but reconnaissance of other hilltops within Duke Forest did not reveal more such sites.

Samples collected from the Bald Mountain quarry were taken from outcrop or large float boulders (FBL060-FBL062). Samples from 31Or549 also only included outcrop or boulder exposures rather than actual quarry flakes (FBL063-FBL065; Figure 3.15).

The material at both Bald Mountain and 31Or549 is a plagioclase-quartz porphyritic metavolcanic rock. While generally similar to porphyritic material from the Uhwarries zones, Orange County material shows a much higher phenocryst density.

Durham County

The Durham County zone is represented by six samples taken from a single large quarry site (31Dh703) in northwest Durham County (Figure B.10). Amateur archaeologist Joseph Moylan found this quarry. The rock from this quarry is spread out over a large ridge south of St. Mary's Road and immediately across from Cain's Chapel Church. The extent of the quarry is unknown, but it is potentially expansive, consisting of multiple quarry loci and outcrops along hills and ridges in the vicinity. Quarry debris is dense in places, with disturbed ground and tree throws revealing thick flake concentrations (Figure 3.16).

Phase 1 samples FBL047-FBL050 were taken from the slope near St. Mary's Road and further south on the ridge. These samples include both quarry flakes and float. Phase 2 samples FBL066 and FBL067 were collected by Miller, Stoddard, and Moore on a return visit in 2003. Samples were taken from a cleared area under a power line that crosses the quarry and from a large boulder in the woods near St. Mary's Road between two houses (Figure 3.17). The Phase 2

Figure 3.15. Brent Miller and Edward Stoddard collecting outcrop sample (FBL065) at site 31Or549, Orange County zone.

Figure 3.16. Dense quarry debris in upturned tree roots at site 31Dh703, Durham County zone.

samples were plotted precisely using a GPS unit; both rock outcrop (FBL067) and actual quarry debris (FBL066) were obtained.

The quarry debris includes a mix of crystal-lithic lapilli tuffs and tuffaceous sandstones, with some material resembling rocks from 31Ch729 (Chatham Pittsboro zone) and 31Pr115 (Person County zone).

Person County

The Person County zone is represented by six samples from a single quarry (31Pr115) (Figure B.11). This quarry was also identified by Joseph Moylan and is spread out over several small hills connected by a power line clearing. Quarry debris is lightly scattered along virtually the entire power line corridor, but it is concentrated in areas where the road intersects ridge tops (Figure 3.18). Heaviest flake debris concentrations are along the slope in eroded gullies and on the ridge in the vicinity of FBL069.

Phase 1 samples FBL043-FBL046 were collected primarily from areas along the road closest to the highest ridge. These samples lack precise GPS coordinates and consist of both quarry debris and float. Phase 2 samples FBL068 and FBL069 were collected by Miller, Stoddard, and Moore during a visit in 2003 and were precisely provenienced using a GPS unit. Phase 2 samples include both outcrop (FBL068) and float (FBL069). The float sample comes from an area of moderate quarry debris and consists of very fine-grained material that appears to have been flaked but may also reflect natural breakage. The outcrop sample comes from what appeared to be a vein of fractured, fine-grained material eroding out of the power line roadbed in an area with only light quarry debris evident.

The stone is highly variable in quality and includes both metamudstone and metasiltstone. Very little evidence of geologic outcrops was observed at the site, although large chunks of material exist as float within the eroded gullies.

Cumberland County

This zone is represented by six float samples of cobbles found near prehistoric sites along a relict coastal plain terrace of the Cape Fear River (Figure B.12). These rocks were presumably transported from their original sources by the Cape Fear, which contains numerous cobble and small boulder deposits of mixed metavolcanic and metasedimentary rocks washed or rafted down the river over millions of years (Thieme and Moore 2001). Although none of the Cumberland County samples come from quarry sites, the local abundance of cobble metavolcanics and proximity to Fort Bragg prompted their inclusion in this study.

Samples were selected for this study based on information from Kenneth Robinson and examination of local collections. In archaeological investigations, Robinson had encountered a coarse-grained greenstone occurring as cobbles and artifacts (Robinson 2005; Robinson and Terrell 2005a, 2005b). Local collections examined by the authors revealed the use of similar material near the river, particularly for large bifaces, axes, grinding stones, and nutting stones. Phase 1 samples FBL039-FBL042 are natural cobbles found by Robinson in his archaeological excavations at sites 31Cd400 and 31Cd424. Phase 2 samples FBL070 and FBL071 were collected by Moore and Irwin from the vicinity of 31Cd402 and 31Cd424 and were provenienced with the use of a GPS unit.

Figure 3.17. Boulder from which sample FBL067 was taken, Durham County zone.

Figure 3.18. Dense quarry debris on largest ridge at site 31Pr115 (near FBL069), Person County zone.

Petrographically a heterogeneous group, the Cumberland County samples were classified in the field as basalt, diorite, tuff(?), greenstone, metagabbro, and aplite. The last (FBL039) is a highly distinctive rock, white in color, that is either absent or very rare in local float deposits.

Artifacts

Nine artifacts were selected from different sites on Fort Bragg to be tested in the same fashion as the quarry samples (FBL072-FBL080; Table 3.2; Figures 3.19-3.20). In general, the sites from which these artifacts originated can be broadly characterized as ephemeral occupations or special activity loci typical of Sandhills archaeology. Most are multi-component, having been visited or occupied multiple times throughout prehistory. All of the sites represent upland settings along hills, ridges, or ridge noses overlooking or nearby small streams and seepage springs (Figure B.13).

Most sites were initially recorded in surveys involving limited surface collection of exposed areas across the installation (e.g., firebreak roads, drop zones). Some of the artifacts were found during large-scale surveys that included surface collection and/or systematic shovel testing, but FBL077 is the only specimen with a subsurface provenience. Five sites that were initially documented in a survey were revisited in subsequent survey or testing work. Artifact FBL080 was collected by an amateur archaeologist and is simply associated with a stream drainage.

Except for the few isolated finds, the tools were recovered with other artifacts, including stone tools, debitage, and/or pottery. In only one case, however, can a sampled artifact be reliably associated with other artifacts based on the context of recovery (FBL077).

The nine artifacts selected for study are all Savannah River Stemmed points, which date to the Late Archaic period (ca. 3000-1000 BC). These artifacts are large hafted bifaces with square stems and long triangular blades (Coe 1964). They range from 70 to 170 mm in length and 35 to 70 mm in width. They are similar to other Late Archaic bifaces of the Broadspear tradition that

Table 3.2. Fort Bragg Artifact Samples.

		UTM[a]			
Sample	Site	Northing	Easting	Rock Type	Artifact Type
FBL072	31Hk100	3890370	670080	dacite	Savannah River Stemmed point
FBL073	31Hk148	3890600	670270	dacite	Savannah River Stemmed point
FBL074	31Hk173	3891970	670560	dacite	Savannah River Stemmed point
FBL075	31Hk182	3891290	665200	andesite	Savannah River Stemmed point
FBL076	31Hk224	3895060	660730	tuff/siltstone	Savannah River Stemmed point
FBL077	31Hk737	3891053	664850	siltstone	Savannah River Stemmed point
FBL078	31Hk999	3880860	670910	dacite	Savannah River Stemmed point
FBL079	31Hk1408	3879599	665320	dacite	Savannah River Stemmed point
FBL080	Flat Creek	3891062	663638	dacite	Savannah River Stemmed point

[a] NAD 1927 datum.

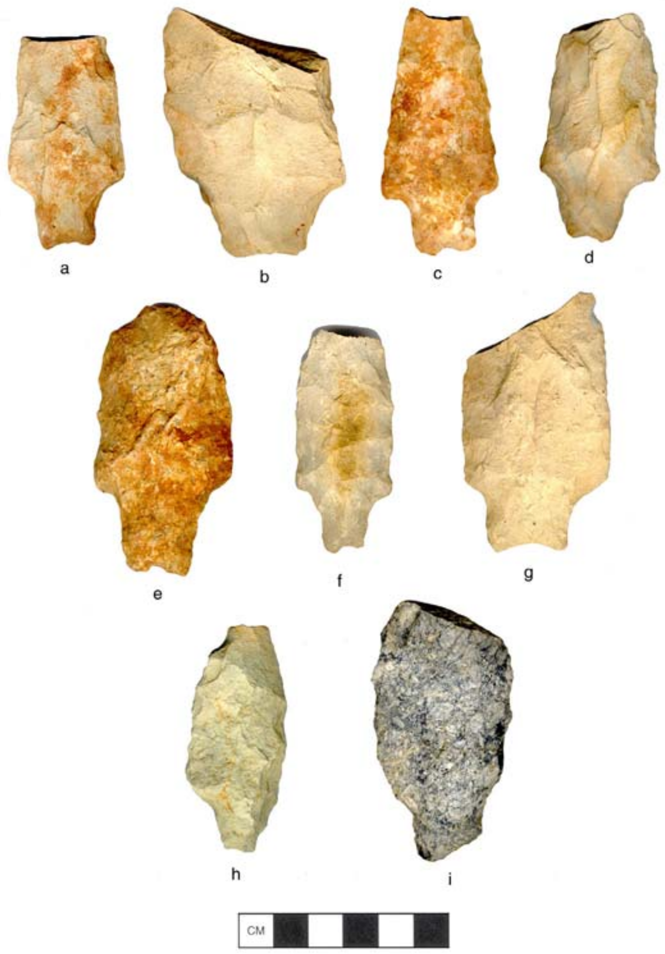

Figure 3.19. Artifacts used in this study, all Savannah River Stemmed points: a, FBL072; b, FBL080; c, FBL077; d, FBL076; e, FBL073; f, FBL079; g, FBL074; h, FBL075; and i, FBL078.

are often followed chronologically by smaller stemmed bifaces. Inferred functions for Savannah River Stemmed bifaces have included projectile points (spears or darts) and knives (Claflin 1931; Coe 1964; House and Ballenger 1976).

All of the bifaces are broken with transverse fractures occurring in the distal half or near the midsection of the blade. Four of these breaks are at oblique angles to the blade's long axis, and four are roughly perpendicular. Three bifaces exhibit step fractures while the others are amputations (Crabtree 1982). Fractures likely resulted from use of these bifaces as knives or projectiles. Artifact FBL073 was bifacially reworked after the blade fracture and may have served as a scraper prior to discard. Most of the bifaces exhibit some degree of asymmetry in the blade and shoulders that likely resulted from differential use and resharpening of blade edges.

Prior to thin-sectioning and geochemical analysis, multiple cast reproductions were made of each artifact, photographs were taken, and attribute and metric data were recorded (Appendix A). Only the distal portions (from the mid-blade to the fracture point) of the bifaces were utilized for petrography and geochemistry, preserving all or most of the diagnostic basal portions. A brief description of each artifact and its context is presented below.

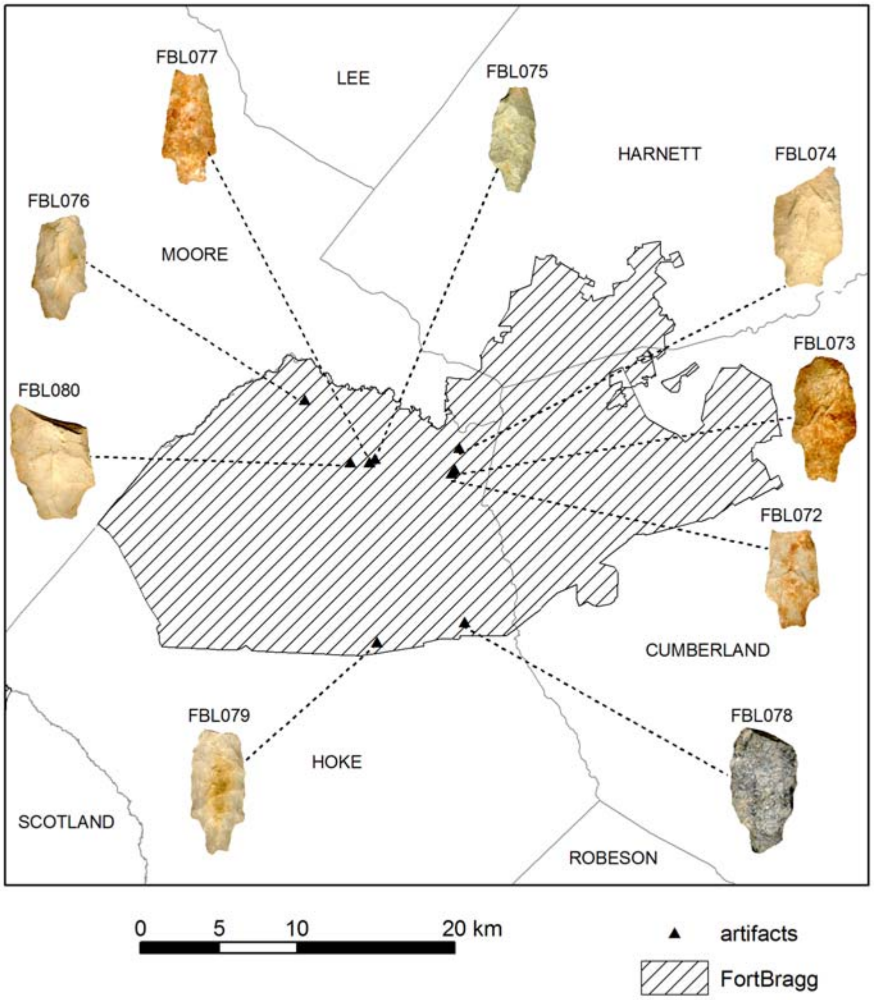

Figure 3.20. Artifact locations on Fort Bragg.

FBL072

FBL072 is a small Savannah River Stemmed biface with a roughly square stem and slightly concave base. Among the more symmetrical specimens, it has oblique or “raised” shoulders of similar width and fairly straight blade margins. The biface has a plano-convex cross-section influenced by a resistant longitudinal ridge on one blade face. The blade exhibits random percussion flaking with some retouch along the edges. The distal portion of the blade exhibits a transverse fracture. The material was identified in hand specimen as aphyric metavolcanic stone with a pale to moderate yellowish-brown patina and was considered generally similar to aphyric Carolina Slate Belt quarry samples.

This artifact was found at site 31HK100, located in the northern portion of Sicily Drop Zone on a flat, broad interfluvial landform. During the initial surface collection, Early Archaic, Middle Archaic, and Late Archaic bifaces were found along with debitage, three blades, and a Woodland sherd (Loftfield 1979). Subsequent survey produced additional debitage and a Middle Archaic biface (Trinkley et al. 1996b).

FBL073

This large Savannah River Stemmed biface has a long square stem and slightly concave base. The shoulders are asymmetrical, with one oblique and one with a shallow notch. The stem is well formed through retouch along the edges, but the blade is only roughly shaped through random percussion, and one margin is incurvate while the other is excurvate. The blade has a biconvex cross-section. The biface was broken in the distal portion and subsequently reworked bifacially. The material was identified in hand specimen as quartz and plagioclase porphyritic metavolcanic stone with a dark-yellowish-orange patina. It was considered generally similar to Carolina Slate Belt samples.

FBL073 was recovered from site 31HK148 in the central portion of Sicily Drop Zone on a ridge nose between two first-order streams. The Savannah River Stemmed biface was collected along with a Middle Archaic biface (Guilford type), a retouched flake, and debitage (Loftfield 1979). Subsequent survey by Trinkley et al. (1996b) produced additional debitage, undiagnostic hafted bifaces, and a Woodland sherd.

FBL074

This artifact is a large Savannah River Stemmed biface with a square stem, concave base, and oblique shoulders that are slightly asymmetrical. The blade is thin and biconvex, nearly flattened, and appears to have been shaped through random percussion with retouch along the margins. The blade edges are roughly straight, tapering towards the tip. The biface has a transverse break just beyond the midsection. In hand specimen, the material was identified as quartz and plagioclase porphyritic stone with a thin, light-bluish-gray patina. It was considered generally similar to Carolina Slate Belt samples.

This artifact comes from site 31HK173 in the northeastern area of Sicily Drop Zone along the edge of a flat interfluvial ridge overlooking the Jumping Run Creek drainage. In the initial survey, this biface was collected along with three scrapers (including an end scraper), a core, bifaces, and debitage (Loftfield 1979). Subsequent survey produced debitage, a biface fragment, and a scraper (Trinkley et al. 1996b).

FBL075

A Savannah River Stemmed type assignment is questionable for this artifact. It has a small, narrow stem, is poorly made, and exhibits great asymmetry. One half of the biface has a shoulder at an oblique angle to the stem while the other half lacks a stem-to-blade transition. The latter blade margin has been reduced or thinned to a maximum extent, terminating at a thick longitudinal ridge, which contributes to a plano-convex cross-section. The opposite blade edge is only roughly shaped through random percussion. The distal tip is removed. The material is a coarse-grained, aphyric metavolcanic material with a patinated grayish-green color. It was originally selected because it resembled the material sampled from Cumberland County.

This artifact was found at site 31HK182, located in northwestern Normandy Drop Zone on the north slope of a hill. The biface was collected along with another biface, a scraper, and debitage (Loftfield 1979). Subsequent survey, primarily surface collection, produced a quartz debitage scatter, a biface, biface fragments, and a Woodland sherd (Braley 2000).

FBL076

This small Savannah River Stemmed biface has a square stem, slightly concave base, and distinct but asymmetrical shoulders. A small, relatively reduced shoulder lies at the base of the incurvate blade margin, while a more pronounced shoulder occurs on the opposite, excurvate blade edge. The blade exhibits percussion flaking and minimal retouch, primarily unifacial. The distal portion has a transverse break at an oblique angle to the blade. It has a relatively thick biconvex cross-section influenced by a longitudinal ridge along one face. The material was identified in hand specimen as aphyric metavolcanic stone, lightly weathered yellowish gray and grayish orange, and thought to be generally similar to Carolina Slate Belt samples.

FBL076 was an isolated find recorded as site 31HK224. It was located on a hilltop at the headwaters of an unnamed tributary of the Lower Little River (Loftfield 1979). A subsequent survey recovered no additional materials in this particular area (Ruggerio 2005).

FBL077

This Savannah River Stemmed biface is beautifully made, small, and has a square stem and slightly bifurcated base. The shoulders show only minor asymmetry and are roughly perpendicular to the stem. The thick biconvex blade has symmetrical, straight edges and exhibits random percussion flaking with minimal retouch. The biface has a transverse snap towards the distal end. The material was identified in hand specimen as aphyric metavolcanic material with a grayish-orange patina. It was considered generally similar to Carolina Slate Belt samples.

The artifact was recovered from site 31HK737, which is located along a distinct ridge toe adjacent to a seepage spring just west of Salerno Drop Zone. The initial survey (Idol 1999) and subsequent testing (Irwin 1999) along the low ridge revealed evidence of several occupations dating to the Middle Archaic (Guilford), Late Archaic, and Woodland periods. FBL077 was recovered in a test unit along the center of the ridge with no apparent overlap of Woodland or Middle Archaic deposits. The test unit also yielded debitage and several tools including a retouched flake, a utilized flake, at least five biface fragments, and a freehand core. Assuming contemporaneity of these deposits, the fairly substantial and diverse range of discarded tools and debitage suggests at least a temporary residential camp.

FBL078

This specimen is a large, poorly crafted or early-stage Savannah River Stemmed biface. The original stem was likely square, but one basal corner has been removed and the stem subsequently retouched. The biface has weak, oblique shoulders and excurvate blade margins. It exhibits random percussion flaking with little or no retouch. The cross-section is biconvex, and the biface has a transverse fracture near the midsection in the distal half of the blade. In hand specimen the material was identified as a possible breccia with a light-bluish-gray patina. It was selected for its unusual appearance and possible similarity to the Chatham Silk Hope quarry samples.

FBL078 was an isolated find recorded as 31HK999 on St. Mere Eglise Drop Zone in a flat upland area in the Puppy Creek drainage (Braley 2000).

FBL079

This slim, small Savannah River Stemmed biface has a slender, square stem and slightly concave base. The shoulders are distinct and roughly perpendicular to the stem, and the blade is symmetrical with gently excurvate margins. Percussion flaking appears to be collateral. This well-made biface has a biconvex cross-section and was snapped towards the distal end. The material was identified as plagioclase porphyritic metavolcanic stone, weathered with a yellowish-gray to grayish-orange patina, and thought to be generally similar to Carolina Slate Belt samples.

The artifact was recovered during a surface collection at site 31HK1408 on an upland flat between Nicholson Creek and McDuffy Creek drainages. Only a few flakes were found with it.

FBL080

The final specimen is a large Savannah River Stemmed biface with a short, square base and a broad blade. One shoulder is pronounced while the other is smaller and less notable as the stem transitions to an excurvate blade. The opposing blade edge that ascends from the distinct shoulder is incurvate, perhaps indicative of a knife function. This biface has a transverse oblique fracture near the biface midsection. The material was identified in hand specimen as aphyric metavolcanic stone with a grayish-orange patina. It was considered generally similar to Carolina Slate Belt samples.

FBL080 was collected around 1960 in the vicinity of Flat Creek by Col. Howard MacCord. A more exact provenience is not known, nor is it known if this biface was associated with other artifacts at the time of discovery.

Acknowledgments

We wish to thank Dolores Hall and John Mintz for their help in navigating the state site files while compiling the quarry database. We also wish to thank Skip Stoddard and Brent Miller for their assistance in collecting field specimens during many repeated visits to quarry locations as well as for their insight into the geology of the region. Thanks are also due to Joseph Moylan, Robert Graham, Mary Ayers, Lawrence Abbott, Ken Robinson, Randy Daniel, Matt Jorgenson, and other professional and amateur archaeologists who shared their knowledge of quarry sites included in this study.

Chapter 4

Petrography

Edward F. Stoddard

A petrographic study was taken in order to help determine the sources of lithic artifacts found at archaeological sites on Fort Bragg. In the first phase of the study, known and suspected archaeological quarry sites in the central Piedmont of North Carolina were visited. From each quarry, hand specimens were collected and petrographic thin sections were examined in an attempt to establish a basis for distinguishing among the quarries. If material from each quarry was sufficiently distinctive, then quarry sources could potentially be matched with Fort Bragg lithic artifacts. Seventy-one samples from 12 quarry zones were examined (Table 4.1). Thirty-one of these samples are from five quarry zones in the Uwharrie Mountains region; 20 of these were collected and described previously by Daniel and Butler (1996). Forty specimens were collected from seven additional quarry zones in Chatham, Durham, Person, Orange, and Cumberland Counties.

All quarries are within the Carolina Terrane, except the Cumberland County quarry, which occurs in younger sedimentary material derived primarily from Carolina Terrane outcrops. Rocks include both metavolcanic and metasedimentary types. Compositionally, most metavolcanic rocks are dacitic and include flows, tuffs, breccias, and porphyries. Metasedimentary rocks are metamudstone and fine metasandstone.

The Uwharrie quarries are divided into five zones: Eastern, Western, Southern, Asheboro, and Southeastern. The divisions are based primarily on macroscopic petrography and follow the results of Daniel and Butler (1996); the Uwharries Southeastern zone was added in this study. Each of the Uwharrie quarry zones represents three to six individual quarries in relatively close proximity. Rock specimens are all various felsic metavolcanic rocks, but zones may be distinguished based upon mineralogy and texture. These quarries sample the Tillery, Cid and Uwharrie Formations (Stromquist and Sundelius 1969).

The remaining quarries include three from Chatham County (Chatham Pittsboro, Chatham Silk Hope, and Chatham Siler City) and one each from Orange, Person, Durham, and Cumberland Counties. Rocks from the Chatham Pittsboro, Durham, and Person quarries are dominantly fine-grained metasedimentary rocks. The Chatham Silk Hope and Orange County quarries are metaigneous. The Cumberland County quarry is from a deposit of alluvial cobbles, and the Chatham Siler City quarry is a mixture of metasedimentary and metavolcanic types.

In the second phase of the study, thin sections were prepared from nine Late Archaic Savannah River points collected on Fort Bragg (Table 4.2). These artifact thin sections were examined for the purpose of comparison with the quarry samples. All nine artifacts appear to have been fashioned from rocks belonging to the Carolina Terrane. Two are interpreted as metasedimentary and the remaining seven are metaigneous rocks.

Geological Setting

All quarry sites except Cumberland County occur in outcrop. Geologically, these outcrops belong to the Carolina Slate Belt, which is part of the Carolina Terrane. The Carolina Terrane is the largest of several suprastructural fault-bounded crustal blocks that had a common volcanic-arc origin and may be grouped as the Carolina Zone (Hibbard et al. 2002). In North Carolina, two additional terranes within the Carolina Zone are the Spring Hope Terrane and the Roanoke Rapids Terrane. These lie to the east of the study area and were not sampled, but they contain rocks similar to those in the Carolina Terrane and therefore may also have been a source of lithic material. Traditionally, these eastern terranes have been referred to as the Eastern Slate Belt. Rocks in all terranes of the Carolina Zone are thought to have formed in association with a volcanic arc between 670 and 450 million years ago – during the Late Proterozoic and Early Paleozoic (Butler and Secor 1991; Hibbard et al. 2002).

Within the Carolina Terrane, three stratigraphic sequences are the Albemarle, Virgilina, and Cary sequences. In this study, the five Uwharries quarries lie within the Albemarle sequence, while the Person, Durham, Orange, and Chatham County quarries are within the Virgilina sequence (Hibbard et al. 2002). Uwharrie quarry samples are from the Tillery, Cid, and Uwharrie Formations (Stromquist and Sundelius 1969). Some samples from the Virgilina sequence quarries may be from the Hyco or Aaron Formations (Harris and Glover 1988), but most are from regions that lack detailed mapping and for which a stratigraphic sequence has not been firmly established (Green et al. 1982).

The Cumberland County quarry actually consists of cobbles and boulders that have been transported from their outcrop regions and deposited as alluvial material, perhaps associated with the Cape Fear River. Not surprisingly, this quarry consists of specimens that do not seem to have a common origin. Although the river mainly drains the Carolina Terrane region, and most of the samples clearly come from the Carolina Terrane, one of them is from a much younger (Late Paleozoic) body of granite and has not been metamorphosed (FBL039).

Petrographic Criteria for Characterizing Specimens

With a sole exception, all specimens examined in this study, including the artifacts, are characterized by a combination of primary and secondary minerals and features. Primary minerals and features are those crystallized or acquired during the initial formation of the rock; secondary ones form as a result of subsequent alteration, deformation, or metamorphism. Samples from most of the quarry sites may be distinguished on the basis of their specific combination of primary and secondary minerals and primary and secondary features.

Primary Igneous Minerals and Features

Rocks examined are either metaigneous or metasedimentary. The metaigneous rocks originated as pyroclastic volcanic deposits, or less commonly, lava flows or shallow subvolcanic plutons. Primary igneous minerals are those that crystallized in a magma chamber prior to eruption or complete solidification. These minerals are generally larger than minerals forming later, and are called phenocrysts. The mineral type, shape, size, and relative abundance of phenocrysts are important primary criteria for characterizing these specimens. Common

Table 4.1. Rock Samples Examined, with Selected Normative Values and Classification.

Quarry Zone:	Normative Values				IUGS Field/	IUGS	
Sample	An%	Q/QAP	A/QAP	P/QAP	Petrographic Name	Normative Name	TAS Name
Uwharries Eastern:							
FBL001	0.0	26.5	21.8	51.7	dacite	dacite	rhyolite
FBL002	0.0	27.2	21.1	51.7	dacite	dacite	rhyolite
FBL003	4.5	30.3	24.0	45.7	dacite	dacite/rhyodacite	rhyolite
FBL004	0.0	25.8	15.4	58.8	dacite	dacite	rhyolite
FBL005	0.0	29.3	18.3	52.4	dacite	dacite	rhyolite
FBL006	0.0	28.1	14.3	57.6	dacite	dacite	rhyolite
FBL007	0.0	36.2	25.0	38.8	dacite	rhyodacite	rhyolite
Uwharries Western:							
FBL008	0.0	36.2	16.8	47.1	andesite	dacite	rhyolite
FBL009	0.0	34.8	20.7	44.5	andesite	dacite	rhyolite
FBL010	0.0	36.1	14.0	50.0	andesite	dacite	rhyolite
FBL011	1.5	29.3	18.4	52.2	andesite	dacite	rhyolite
FBL012	0.0	24.5	17.0	58.5	andesite/latite	dacite	rhyolite
FBL013	0.0	31.6	9.9	58.6	andesite	dacite	rhyolite
FBL014	9.5	23.1	20.0	56.9	andesite/latite	dacite	rhyolite
Uwharries Southern:							
FBL015	0.0	29.2	17.2	53.6	felsite	dacite	rhyolite
FBL016	0.0	26.2	24.3	49.5	felsite	dacite	rhyolite
FBL017	0.0	29.7	19.5	50.8	felsite	dacite	rhyolite
FBL018	0.0	29.4	19.9	50.7	felsite	dacite	rhyolite
FBL019	0.0	32.3	15.0	52.6	felsite	dacite	rhyolite
Uwharries Asheboro:							
FBL020	23.4	41.3	15.9	42.7	tuff	dacite	rhyolite
FBL021	2.5	31.2	17.4	51.4	dacite/andesite	dacite	rhyolite
FBL022	15.2	38.0	16.4	45.6	dacite/andesite	dacite	rhyolite
FBL023	12.0	42.7	8.3	48.9	dacite	dacite	rhyolite
FBL024	7.0	36.3	4.6	59.1	tuff	dacite	rhyolite
FBL055	0.0	29.9	11.6	58.5	dacite	dacite	rhyolite
Uwharries Southeastern:							
FBL025	0.4	33.2	26.8	40.0	dacite	rhyodacite	rhyolite
FBL026	0.0	30.0	23.8	46.2	dacite	dacite	rhyolite
FBL051	1.9	40.6	21.0	38.4	dacite	rhyodacite	-
FBL052	0.0	62.5	16.6	20.9	dacite	-	-
FBL053	2.5	37.5	21.5	41.0	dacite	dacite	rhyolite
FBL054	4.1	59.6	23.5	16.9	dacite	rhyodacite	-
Chatham Pittsboro:							
FBL027	11.3	47.1	28.3	24.6	mudstone	rhyodacite	-
FBL028	39.4	35.2	56.4	8.4	mudstone	alkali feldspar rhyolite	rhyolite
FBL029	14.0	43.1	29.4	27.5	siltstone	rhyodacite	rhyolite
FBL030	10.0	31.8	9.2	59.0	fine sandstone	dacite	rhyolite
FBL056	27.2	54.0	40.5	5.4	mudstone	alkali feldspar rhyolite	-
FBL057	0.0	25.2	22.6	52.2	mudstone	dacite	rhyolite
Chatham Silk Hope:							
FBL031	0.0	29.2	27.2	43.5	dacite/rhyodacite	rhyodacite	rhyolite
FBL032	0.0	24.3	21.6	54.1	lithic tuff	dacite	rhyolite
FBL033	0.0	25.9	26.5	47.5	dacite	rhyodacite	rhyolite
FBL034	0.0	27.6	25.0	47.5	lithic tuff	dacite/rhyodacite	rhyolite
FBL058	0.0	28.1	26.3	45.7	lithic tuff	rhyodacite	rhyolite
FBL059	5.1	27.0	34.9	38.1	lithic tuff	rhyodacite	rhyolite

Table 4.1. Rock Samples Examined, with Selected Normative Values and Classification (continued).

Quarry Zone:	Normative Values				IUGS Field/ Petrographic Name	IUGS Normative Name	TAS Name
Sample	An%	Q/QAP	A/QAP	P/QAP			
Orange County:							
FBL060	0.0	28.6	21.5	49.9	dacite	dacite	rhyolite
FBL061	0.0	26.3	21.6	52.1	dacite	dacite	rhyolite
FBL062	0.0	27.3	21.7	50.9	dacite	dacite	rhyolite
FBL063	0.0	30.8	22.4	46.8	dacite	dacite	rhyolite
FBL064	5.7	32.4	24.6	43.0	dacite	rhyodacite	rhyolite
FBL065	0.0	25.4	22.8	51.8	dacite	dacite	rhyolite
Durham County:							
FBL047	0.0	28.3	7.5	64.1	dacite	dacite	rhyolite
FBL048	0.0	9.1	0.3	90.6	sandstone	andesite/basalt	trachyte
FBL049	0.0	18.0	8.0	73.9	sandstone	andesite/basalt	rhyolite
FBL050	0.0	18.2	4.8	77.0	tuff	andesite/basalt	rhyolite
FBL066	2.5	19.0	3.5	77.5	dacite	andesite/basalt	rhyolite
FBL067	14.8	11.2	8.8	80.0	sandstone	andesite/basalt	trachydacite
Person County:							
FBL043	0.4	3.0	6.9	90.1	mudstone?	andesite/basalt	trachyte
FBL044	0.0	30.6	3.6	65.8	tuff	dacite	rhyolite
FBL045	3.2	17.2	7.2	75.5	mudstone	andesite/basalt	rhyolite
FBL046	2.4	42.2	6.9	50.9	sandstone	dacite	rhyolite
FBL068	0.0	34.8	2.0	63.2	siltstone	dacite	rhyolite
FBL069	0.0	23.4	17.6	59.0	siltstone	dacite	rhyolite
Chatham Siler City:							
FBL035	22.7	24.8	23.8	51.4	mud/siltstone	dacite	dacite
FBL036	0.0	12.9	21.7	65.5	dacite	andesite/basalt	rhyolite
FBL037	62.8	29.9	31.7	38.4	mudstone	rhyodacite	dacite
FBL038	13.3	0.0	24.0	76.0	sandstone	andesite/basalt	trachyandesite
Cumberland County:							
FBL039	0.6	31.6	28.5	39.9	aplite	rhyodacite	rhyolite
FBL040	32.8	0.0	5.1	94.9	basalt	andesite/basalt	basaltic trachyandesite
FBL041	13.9	2.3	11.1	86.6	diorite	andesite/basalt	basaltic trachyandesite
FBL042	45.2	0.0	13.0	87.0	tuff?	andesite/basalt	trachybasalt
FBL070	60.3	0.0	3.4	96.6	greenstone	andesite/basalt	basalt
FBL071	59.9	0.0	9.6	90.4	metagabbro	andesite/basalt	basalt

phenocryst mineral types are plagioclase feldspar and quartz; alkali feldspar phenocrysts are extremely rare in this study and throughout the Carolina Zone. In a few specimens, there exists indirect evidence that phenocrysts of amphibole or pyroxene were formerly present; they have been replaced by secondary minerals.

Other primary igneous features include flow banding, spherulites, glass shards, amygdules, and fragmental (pyroclastic) texture (McBirney 1993; Vernon 2004). Flow banding is suggested by parallel alignment of plagioclase grains or other elongate features, or by layer-variable concentrations of tiny mineral grains, devitrification features, or fluid inclusions in extremely fine-grained (aphyric or glassy) rocks. Spherulites are round (spherical) features in some very fine-grained felsic volcanic rocks. They consist of radially oriented needle-shaped microcrystals of feldspar and quartz that nucleated from a common point at the center. They are thought to form soon after solidification of glassy rocks, and therefore represent a mechanism of devitrification. Glass shards are thin V- or Y-shaped fragments of glass, believed to form as a

Table 4.2. Fort Bragg Artifacts Examined, with Selected Normative Values and Classification.

		Normative Values				IUGS Field/	IUGS	
Sample	Site	An%	Q/QAP	A/QAP	P/QAP	Petrographic Name	Normative Name	TAS Name
FBL072	31Hk100	0.0	30.6	11.2	58.2	dacite	dacite	rhyolite
FBL073	31Hk148	0.0	25.8	14.9	59.3	dacite	dacite	rhyolite
FBL074	31Hk173	0.0	24.2	22.1	53.7	dacite	dacite	rhyolite
FBL075	31Hk182	23.3	16.9	11.1	72.1	andesite	andesite/basalt	dacite
FBL076	31Hk224	0.0	27.3	13.0	59.8	tuff/siltstone	dacite	rhyolite
FBL077	31Hk737	0.0	31.9	11.2	56.9	siltstone	dacite	rhyolite
FBL078	31Hk999	3.2	30.5	14.3	55.2	dacite	dacite	rhyolite
FBL079	31Hk1408	6.6	22.9	26.0	51.1	dacite	dacite	rhyolite
FBL080	Flat Creek	0.0	28.2	16.9	54.9	dacite	dacite	rhyolite

result of rapid vesiculation of rising magma immediately prior to eruption, followed by fragmentation of the porous rock (pumice). The shards then represent the solidified glass walls that separated adjacent gas bubbles. Amygdules represent vesicles (gas bubbles) in a volcanic rock that are later filled in by secondary minerals. This typically occurs soon after cooling of a volcanic rock, and so is included as a primary feature.

Pyroclastic material (tephra) is categorized according to its size, into ash (< 2 mm), lapilli (2-64 mm) and blocks and bombs (> 64 mm). Many felsic pyroclastic rocks consist largely of pumice lapilli. Where tephra accumulates on the surface following a volcanic eruption, it may be consolidated by compaction and welding due to volcanic heat and pressure from the overlying material, or by cementation. A volcanic rock formed by such processes is called tuff (dominantly ash), lapilli tuff (ash and lapilli), or, if it includes larger fragments, tuff breccia or agglomerate. Loose pyroclastic material may be eroded, transported, and redeposited by sedimentary processes, as in tuffaceous sandstone.

Primary Sedimentary Features

Primary sedimentary features include clastic texture, where clasts and corresponding rock names may be classified according to size and composition, as in feldspathic sandstone or quartz siltstone. Deposition from water is indicated by parallel bedding planes or laminae (essentially very thin and cyclic beds). More specialized sedimentary structures may be indicative of water depth, current velocity and direction, and/or stratigraphic younging direction. Such features include graded bedding, ripple marks, and cross bedding. In a couple of specimens, small ovoid features may be trace fossils, possibly fecal pellets.

Metamorphic Minerals

Rocks originally formed in one environment and later held in a different environment tend to change in an attempt to seek equilibrium with the new conditions. Volcanic rocks initially equilibrate at very high temperatures (magmatic, 800-1100°C) and low pressures (surface or near-surface). Sedimentary rocks form in a low-temperature and low-pressure environment at the surface of the earth. Rocks formed in the volcanic arc(s) of the Carolina Terrane during the late Proterozoic and early Paleozoic were later buried under many kilometers of rock during tectonic plate collisions in the middle and late Paleozoic. Under these new conditions of pressure and temperature some primary minerals became chemically unstable and reacted to produce new stable minerals. To the geologist, the particular minerals produced in this manner indicate the general conditions of the metamorphism, or metamorphic grade. Geologists have grouped metamorphic rocks, based upon the types of metamorphic minerals they contain, into several metamorphic facies, each of which denotes a general range of pressure and temperature conditions. Rocks of the Carolina Terrane contain minerals and other features indicative of the greenschist facies, corresponding roughly to 4-10 kbar and 300-500°C. This is a relatively low to moderate grade of metamorphism, and therefore many (perhaps most) of the primary igneous or sedimentary characteristics are preserved as relict features.

Metamorphic minerals in this study include all of the most common greenschist facies minerals, including white mica (muscovite), chlorite, epidote/clinozoisite, albite (Na-plagioclase), actinolite, titanite (also known as sphene), pyrite, and calcite. Less common greenschist facies metamorphic minerals identified include biotite (both green and brown varieties in different specimens), stilpnomelane, (Mn/Ca-rich) garnet, and piedmontite. Because the growth of metamorphic minerals is also a function of the rock's overall composition, the absence of a particular mineral does not necessarily imply a different facies or conditions. For example, actinolite is typical of metamorphosed basalt in the greenschist facies, but is not found in metamorphosed mudstone. However, the presence of biotite in the Carolina Terrane is limited to the southern and western half of the terrane (approximately the Uwharries), and indicates that metamorphic temperatures (and possibly pressures) there were somewhat higher than in the northern and eastern portions (Butler 1991; North Carolina Geological Survey 1985).

Other Secondary Features

Locally, pervasive alteration has affected phenocryst minerals. This process may be a metamorphic event, or it may have begun during or shortly after the igneous rock cooled (deuteric alteration) and then been accentuated during metamorphism. One feature that may have formed in this manner is the progressive replacement of plagioclase by clinozoisite, a process known as saussuritization. Because clinozoisite is a Ca-Al-silicate mineral, this implies that the original plagioclase contained enough Ca to produce the feature. Trachyte and rhyolite typically have low-Ca plagioclase, whereas dacite, andesite, and basalt have plagioclase with increasingly higher Ca content. Sericitization is an analogous process whereby K- and Na-rich feldspar is replaced by fine-grained mica. These processes imply the presence of warm aqueous fluid. One possible mechanism for chemical alteration is by interaction of newly formed volcanic rocks with magmatically warmed seawater (e.g., Butler and Ragland 1969).

Small clusters or clots of associated metamorphic minerals occur in some of the metavolcanic rocks. Because the specific mineral types tend to occur in roughly constant proportions, it appears that they have replaced a primary mineral or minerals. Some clusters have a rounded or ovoid shape and are interpreted as metamorphosed amygdules, that is, the secondary minerals that filled in a vesicle shortly after cooling of the volcanic rock were later converted to a greenschist-facies assemblage (cf. Fodor et al. 1981). In instances where a primary mineral such as a phenocryst is completely replaced, but its original shape and size are preserved, the new mineral is said to be a pseudomorph of the original mineral.

Veins of epidote, calcite, or quartz occur in a few samples. These features did not form from magma, but precipitated out of an H_2O- and CO_2-rich fluid that accompanied the greenschist facies metamorphism. Features indicative of tectonic stress are locally present but sparse. They include microfaults, where primary layers are offset, and also slaty cleavage, a rock fabric characterized by the parallel growth of tiny metamorphic minerals, usually sheet silicates such as white mica, biotite, or chlorite. The slaty cleavage defines a planar direction that is typically parallel to axial planes of large folds in the region, thus indicating the approximate direction of maximum tectonic stress during deformation.

Rock Names

Choosing a name for most rocks in the Carolina Terrane is no simple matter. If asked whether any particular rock sample from the region is igneous, sedimentary, or metamorphic, perhaps the most correct answer is simply "Yes!" Merely consider that many of these rocks consist of material that was originally erupted from a volcano, then perhaps reworked by sedimentary processes, and then subsequently metamorphosed. It is therefore no wonder that there is some confusion and disagreement surrounding the names of these rocks. In this study, three different classifications are applied and their results may be compared: IUGS based upon phenocrysts (and secondarily rock color), TAS based on bulk chemistry, and IUGS based upon normative minerals.

Igneous rock classification is generally based upon the widely accepted IUGS system (Streckeisen 1976, 1978; LeMaitre 1989). For felsic and intermediate rocks, the name is determined by the normalized percentages of quartz, alkali feldspar, and plagioclase (QAP), referring to a triangular QAP classification diagram (Figure 4.1).

The QAP classification procedure is straightforward for coarse-grained plutonic igneous rocks, in which the three minerals can be identified and their percentages determined. However, problems arise with volcanic and related fine-grained igneous rocks in which many (possibly all) of the minerals are too small for identification. In this case, the name must be based upon the minerals that can be identified, i.e., the phenocrysts. A secondary criterion is rock color: lighter colors are typically associated with felsic compositions, darker with mafic. Criteria for this IUGS "field name" are shown in Table 4.3.

Alternatively, where chemical analyses are available, names may be based on certain chemical characteristics. The most common chemical classification, called TAS, is based on a plot of total alkalis ($Na_2O + K_2O$) versus silica (SiO_2) (Figure 4.2). It is important to note that the TAS system combines the alkalis (Na and K) and thus removes the possibility of distinctions based upon type of feldspar, which is the basis for the IUGS QAP system. Furthermore, in the case of the Carolina Terrane, where metamorphism has affected all rocks and chemical alteration has affected at least some, the oxide values upon which TAS is based may not represent the original rock (and magma) composition.

Another classification option when a chemical analysis is available is to determine normative minerals, which are hypothetical mineral percentages calculated from the analysis. Then the normative Q, A, and P values may be plotted on the IUGS triangular diagram.

Pyroclastic rocks are named according to the grain size of the tephra, as described above. But the root name may be modified by a term describing the nature of the fragmental material (vitric for glassy, lithic for rock fragments, and crystal for phenocrysts). Another modifying term may be based on the rock composition, so, for example, one might have a dacitic crystal-lithic lapilli tuff.

In this study, the rocks have been metamorphosed. If the metamorphic changes in the rock obscure the properties of the parent rock, then the rock should be given a metamorphic rock

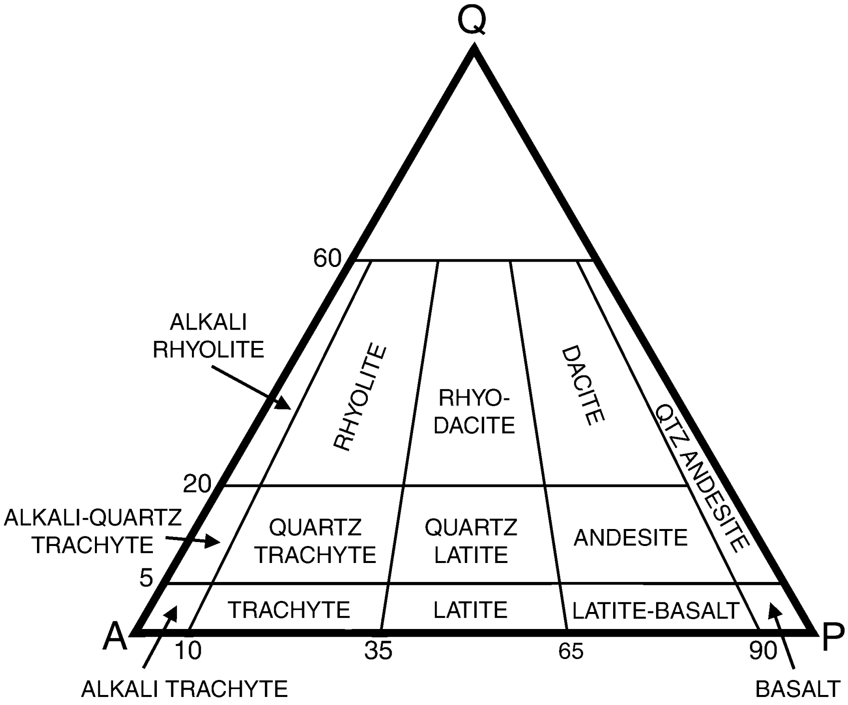

Figure 4.1. IUGS classification for volcanic igneous rocks (from Winter 2001).

name, such as slate or phyllite. However, where the relict primary features of a metamorphic rock dominate over those created during metamorphism, the common practice is to apply a name reflecting the parent rock, preceded by the prefix "meta." This is the case for nearly all rocks in the Carolina Terrane. Thus we have metarhyolite, metamudstone, and metatuff, or even dacitic crystal-lithic lapilli metatuff!

A final caveat in classifying the rocks in this study is that they may have been chemically altered, either shortly following eruption or deposition, or at the time of metamorphism. In this case, the rock name based on phenocrysts would be the most reliable indicator of the original rock type, while those based upon chemistry, either using TAS or norms, reflect the chemical alteration. Rock names determined for the specimens in this study, using these techniques, are given in Table 4.1.

Table 4.3. Practical Field Guide to Volcanic Rock Classification.[a]

Phenocryst Minerals	Typical Color	Possible Rock Types
Quartz only	brown, pink, red	rhyolite
Quartz and alkali feldspar	brown, pink, red	rhyolite, quartz trachyte
Alkali feldspar only	brown, black	trachyte
Quartz and plagioclase feldspar	gray	dacite
Plagioclase feldspar and alkali feldspar	brown	latite
Quartz, plagioclase feldspar, and alkali feldspar	red, brown, pink	rhyodacite or rhyolite
Plagioclase feldspar only	gray, purple, black	andesite or basalt

[a] From Cepeda (1994).

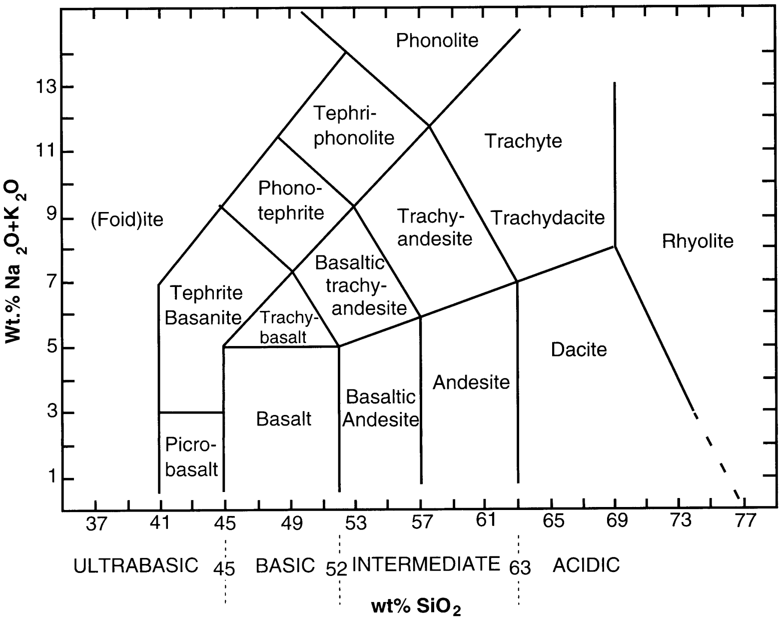

Figure 4.2. Total alkalis versus silica (TAS) classification of volcanic rocks (LeMaitre 1989).

Results

Of the twelve different quarry zones that were studied, ten are sufficiently distinctive that they hold some promise for sourcing. These ten quarry zones include five in the Uwharries region: Uwharries Eastern, Uwharries Western, Uwharries Southern, Uwharries Asheboro, and Uwharries Southeastern. Two quarries are located in Chatham County (Chatham Pittsboro and Chatham Silk Hope), and the remaining are from Person, Durham, and Orange Counties. Samples from Chatham Siler City and Cumberland County are extremely heterogeneous and these zones are therefore unlikely to be of much use in sourcing lithic artifacts. Four of the five Uwharries quarry zones were previously identified by Daniel and Butler (1996). A synopsis of the quarry zones and their distinguishing characteristics follows; descriptions of individual samples may be seen in Appendix C. Colors given refer to fresh rock material; all rocks examined weather to lighter colors, typically tan or light gray.

Table 4.4 summarizes the results. The samples from seven of the ten distinctive quarries are inferred to be primarily of volcanic origin, while those from the remaining three (Chatham Pittsboro, Person County, and Durham County) are thought to be primarily metasedimentary. Each of the seven metavolcanic quarry zones is texturally and mineralogically distinctive. Relict volcanic features include porphyritic texture, flow banding, amygdules, inferred glass shards, spherulites, and pyroclastic material. Metamorphic features include phyllosilicate cleavage. Relict minerals are quartz, plagioclase, and K-feldspar phenocrysts; metamorphic minerals include chlorite, biotite, epidote, calcite, actinolite, titanite, pyrite, garnet, stilpnomelane, and piedmontite. The three metasedimentary quarries preserve relict sedimentary features including laminations, ripples, and graded bedding. Possible cross-bedding and trace fossils are present. Individual samples from each of these metasedimentary sites may not be distinguishable, although the Chatham Pittsboro quarry is overall finer grained and the other two contain more obvious volcaniclastic material.

Table 4.4. Petrographic Features of Quarry Zones.

Quarry Zone	Map Unit (Formation)	Assemblage Type	Rock Types	Textures	Phenocrysts	Metamorphic Minerals
Uwharries Eastern	Tillery	metavolcanic rocks	dacite flows; crystal-lithic tuffs	quartz-epidote-chlorite clusters	plagioclase + quartz	green biotite; stilpnomelane
Uwharries Western	Cid	metavolcanic rocks	dacite; rhyodacite	spherulites; no flow banding	plagioclase; K-feldspar	green biotite; no stilpnomelane
Uwharries Southern	Tillery	metavolcanic rocks	dacite; felsite	spherulites; banding; cleavage	none	stilpnomelane
Uwharries Asheboro	Uwharrie and Tillery	metavolcanic rocks	dacite tuffs and flows	epidote-calcite-pyrite clusters; pumice lapilli	plagioclase; quartz	garnet; brown biotite; stilpnomelane
Uwharries Southeastern	Uwharrie	metavolcanic rocks	dacite flows and porphyries	spherulites; quartz amygdules; banding	quartz + plagioclase	actinolite; epidote; sphene
Chatham Silk Hope		metavolcanic rocks	dacitic lapilli; crystal-lithic tuff; breccia	volcanic rock fragments; glass shards; flow banding	plagioclase; K-feldspar	piedmontite
Orange County		metavolcanic rocks	dacite porphyry; crystal-lithic tuff	no banding; saussuritization	(coarse) quartz + plagioclase	calcite; low-T feldspar clots
Chatham Pittsboro		metasedimentary rocks	mudstone; siltstone; sandstone	bedding; laminae; graded beds; ripples; cross-beds		
Durham County		metasedimentary rocks	dacite tuff; tuffaceous sandstone	rock fragments; epidote veins; layering		
Person County		metasedimentary rocks	mudstone; siltstone; sandstone; tuff	bedding; graded beds; trace fossils(?); pumice(?); microfaults		
Chatham Siler City		heterogeneous	metasedimentary rocks; crystal-lithic tuff			
Cumberland County		heterogeneous	aplite; greenstone; (meta)gabbro; basalt; andesite/diorite; lapilli tuff			

Uwharries Eastern

Rocks of this zone, from Shingle Trap, Hattaway, and Sugarloaf Mountains, are mainly light to dark gray metadacite porphyry or metadacitic crystal-lithic tuff. All seven samples contain plagioclase and quartz phenocrysts (Figure 4.3). Samples from Shingle Trap and Hattaway Mountains are phenocryst-poor, having 2% or less. Samples from Sugarloaf Mountain are more crystal-rich, containing up to 7%. The maximum phenocryst dimension in all Uwharries Eastern samples is between 1.0 and 1.6 mm. This zone includes rocks interpreted as lava flows (e.g., FBL004) and others inferred to be of pyroclastic origin (e.g., FBL005, FBL006). A common textural feature in these rocks is small mineral clusters composed of quartz ± epidote ± chlorite. These may be amygdules, or filled-in vesicles, perhaps modified during metamorphism. Pumice lapilli, flow banding (Figure 4.4), and possible glass shards are locally present. These rocks are interpreted as dacitic crystal-lithic tuffs and dacitic flows within the Tillery Formation. Because they are light-colored rocks with plagioclase and quartz phenocrysts, in the field these rocks would be called dacite. Using normative minerals they are dacite and rhyodacite, and using the TAS chemical classification they are rhyolite. Metamorphic minerals in this group include common green biotite and stilpnomelane (Figure 4.5), and locally calcite. This group corresponds to the plagioclase-quartz phyric rocks of Daniel and Butler (1996).

Uwharries Western

Six samples are from the Wolf Den and Falls Dam area and one sample is from near Eldorado. These gray to black felsic volcanic rocks contain plagioclase phenocrysts and have no obvious flow banding (Figure 4.6). Because of the lack of quartz phenocrysts and their relatively dark color, in the field these rocks might be classified as meta-andesite and metalatite. However, based upon normative mineralogy they are dacite and based upon the TAS chemical classification they are rhyolite. Plagioclase phenocrysts have rounded corners and are locally grouped together as glomerocrysts (FBL008). There are sparse possible K-feldspar phenocrysts in at least one sample. Green biotite and pale green amphibole (actinolite) are present locally (FBL009). Spherulites are present in some samples. They are inferred to be pyroclastic in origin, and are likely ash-fall or ash-flow tuffs within the Cid Formation. These are the plagioclase-phyric rocks of Daniel and Butler (1996).

Uwharries Southern

The five samples in this category were collected from Morrow and Tater Top Mountains. These dark gray metavolcanic rocks are extremely fine grained and contain no obvious phenocrysts. Because of the lack of phenocrysts, the most appropriate field designation is felsite. However, names based on normative mineralogy and the TAS classification are dacite and rhyolite, respectively. Some samples have spherulites (Figure 4.7), and some are banded. In hand specimen, the felsic composition of these rocks may be inferred based upon their high hardness and good conchoidal fracture. These rocks may have originated as ash-flow tuffs, glassy flows, or possibly felsic domes within the Tillery Formation, although it should be noted that there continues to be uncertainty about the stratigraphic sequence within the Albemarle group and specifically the Morrow Mountain felsite (e.g., Hibbard et al. 2002). Most samples contain brown metamorphic biotite and exhibit a local biotite cleavage oblique to banding (FBL019). Metamorphic stilpnomelane, epidote, titanite, chlorite, and actinolite are also present in some samples. These are the aphyric rocks of Daniel and Butler (1996).

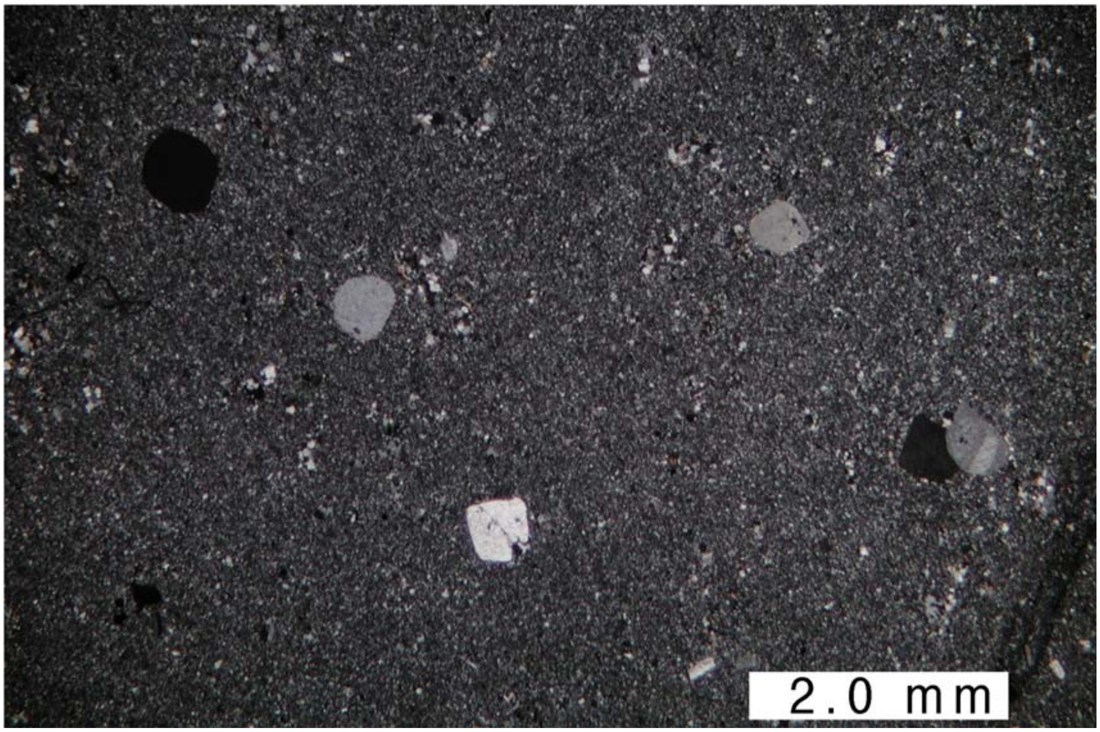

Figure 4.3. Typical Uwharries Eastern sample with quartz and plagioclase phenocrysts (FBL004; crossed polars).

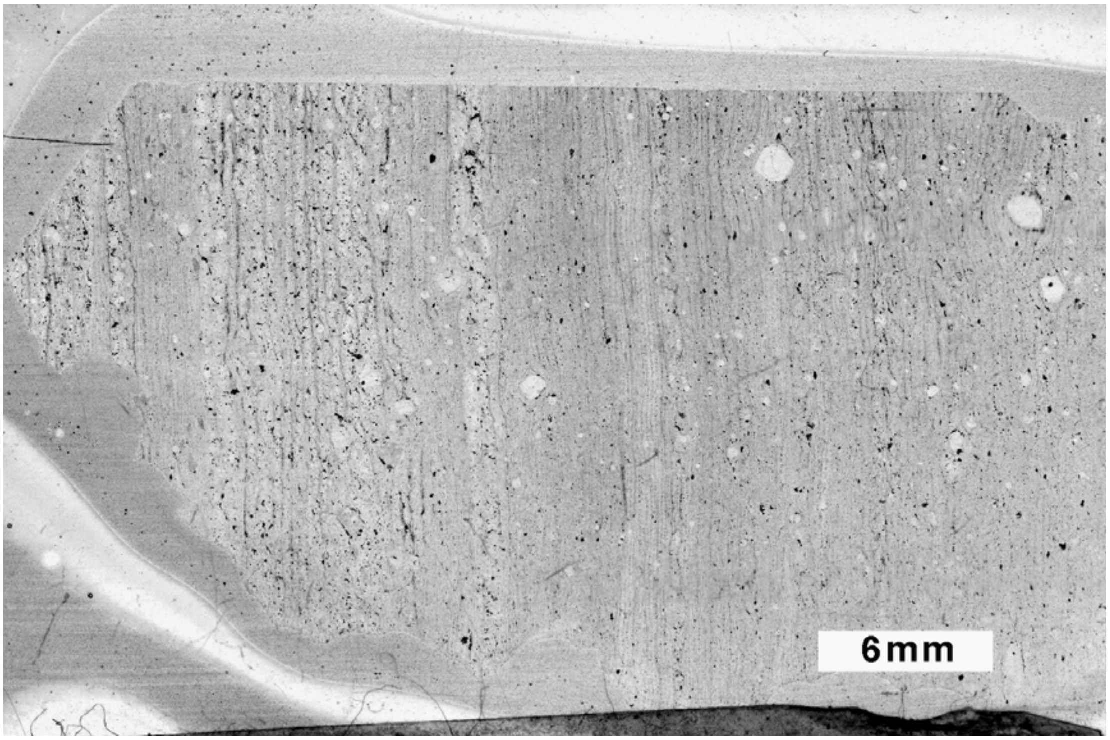

Figure 4.4. Strongly flow-banded dacite with quartz and plagioclase phenocrysts (FBL006; scanned thin section, plane-polarized light).

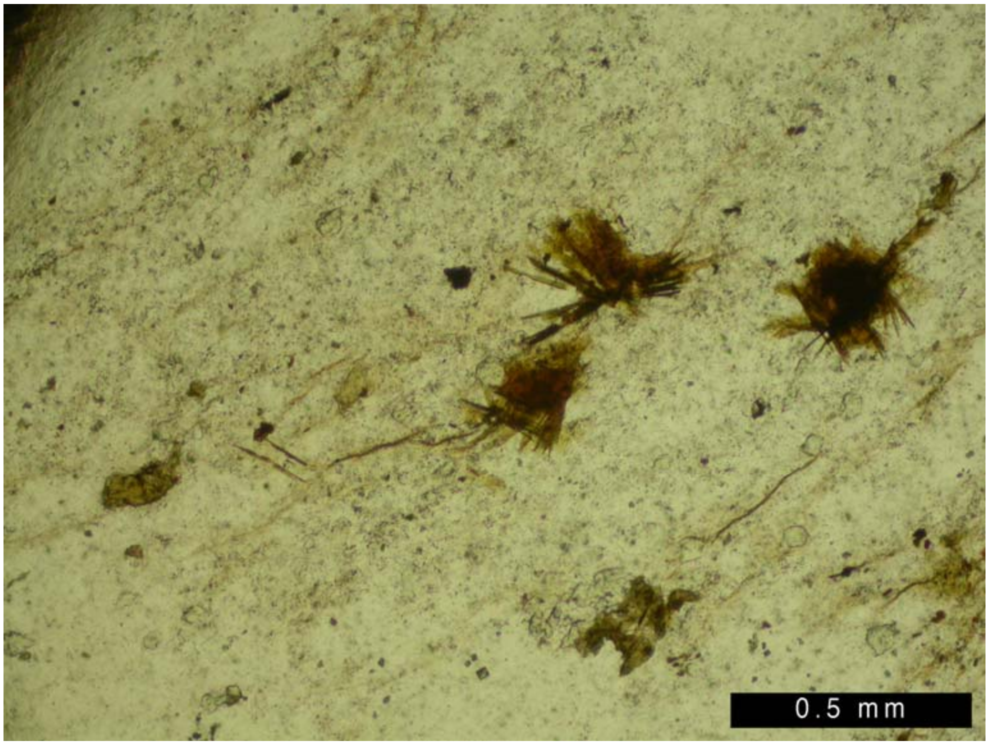

Figure 4.5. Metamorphic stilpnomelane (needle-like aggregates) in Uwharries Eastern sample (FBL005; plane-polarized light).

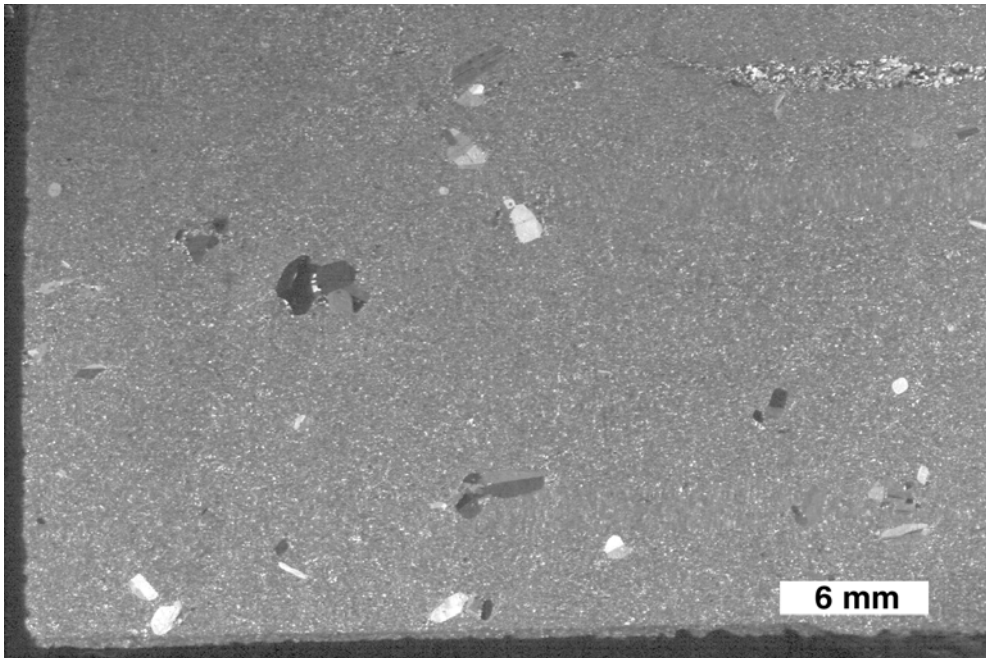

Figure 4.6. Uwharries Western sample with sparse plagioclase phenocrysts and fine groundmass (FBL010; scanned thin section, crossed polars).

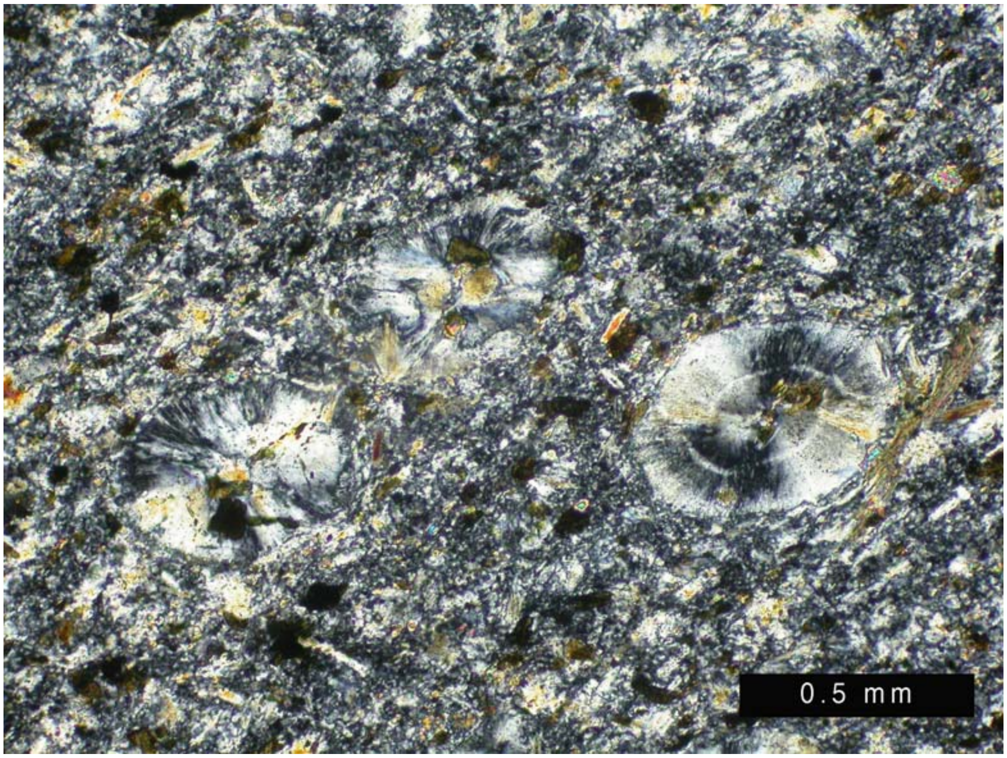

Figure 4.7. Uwharries Southern sample with spherulites (FBL017; crossed polars).

Uwharries Asheboro

This zone consists of five samples collected by Daniel and Butler from Dave's Mountain, Caraway Mountain, and other sites in the northern Uwharries near Asheboro, plus one sample collected for this study in Asheboro (FBL055). The zone is dominated by relatively coarse-grained, dark- to medium-gray pyroclastic rocks. They are mostly classified as metadacite tuffs. There are some fine-grained ash-lapilli tuffs but most are coarse-grained crystal-lithic tuff. Sample FBL023 is extremely crystal-rich (estimated 15% phenocrysts) with crystals ranging to at least 2.5 mm, the largest phenocrysts of any of the Uwharries zones examined. There is at least one possible flow rock (FBL022). Four of the six specimens contain phenocrysts of plagioclase and quartz, while the other two are aphyric. Clusters of epidote with calcite and pyrite occur and may be metamorphosed amygdules (Figure 4.8). Euhedral to subhedral garnet porphyroblasts are common in this zone (Figure 4.9), as is brown biotite. Calcite and stilpnomelane occur locally. These correspond to Daniel and Butler's (1996) northern Uwharries sites and are from the Uwharrie and Tillery Formations. Using normative minerals, these rocks are dacite; using the TAS classification they are rhyolite.

Uwharries Southeastern

This zone of newly collected samples includes two from Horse Trough Mountain and four from Lick Mountain, all from the Uwharrie Formation. Samples contain 1-3% phenocrysts of plagioclase and quartz ranging in size up to 1.6 mm, though the Lick Mountain specimens are

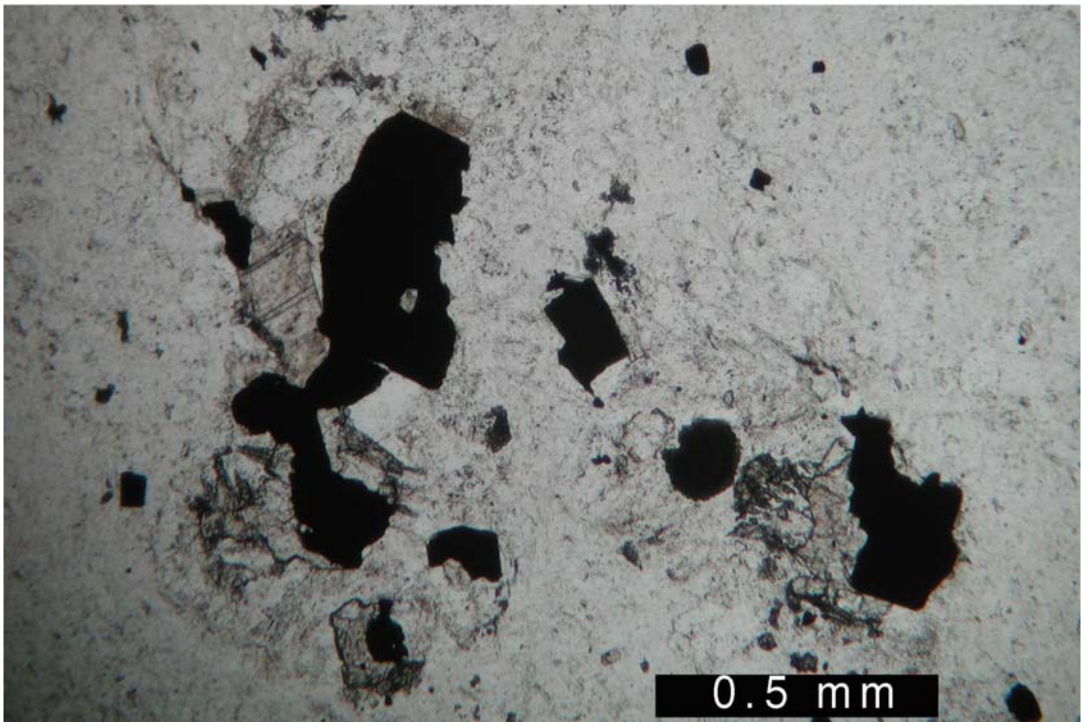

Figure 4.8. Uwharries Asheboro sample with mineral clusters of pyrite + calcite + epidote (FBL021; plane-polarized light).

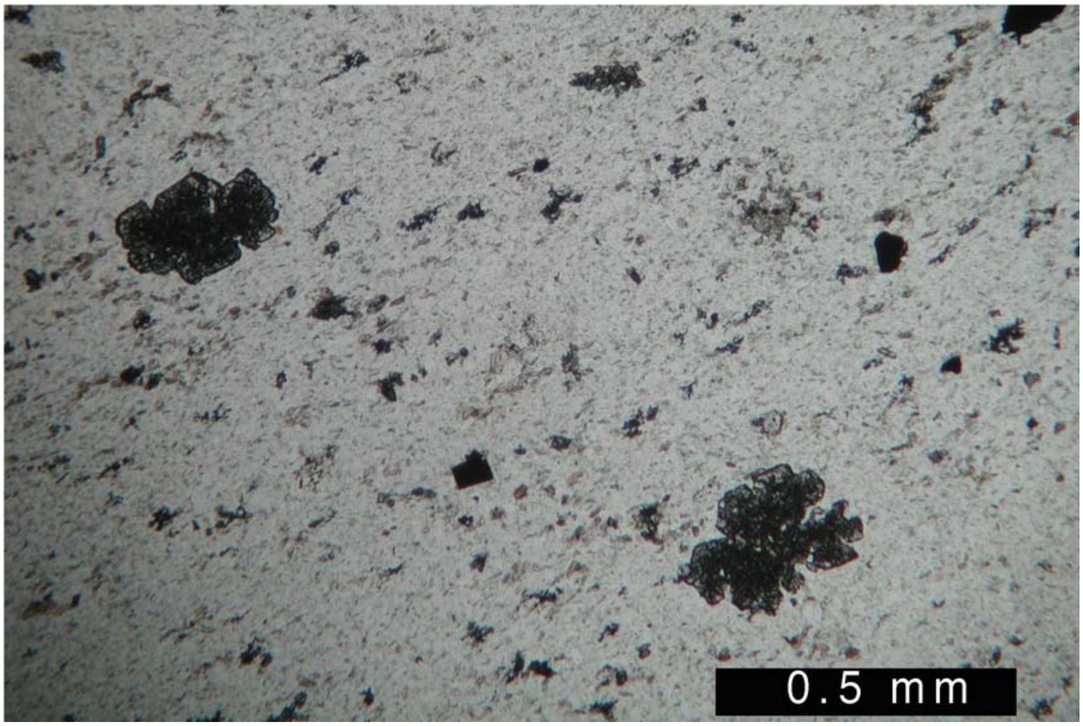

Figure 4.9. Garnet porphyroblasts in Uwharries Asheboro sample (FBL022; plane-polarized light).

more crystal-rich and slightly coarser than the Horse Trough specimens. In the Lick Mountain samples especially, the quartz phenocrysts show good β-quartz morphology, though some grains are partially resorbed (Figure 4.10). The presence of amygdules in the Horse Trough samples is indicated by ovoid polycrystalline aggregates of quartz ranging to at least 3 mm; these constitute 5-10% of the rock (Figure 4.11). Spherulites are also present in the Horse Trough samples. The specimens in this zone contain a number of metamorphic minerals, including pyrite, muscovite, epidote, titanite, chlorite, biotite, and notably actinolite. The field name is metadacite or metadacite porphyry. The normative QAP name is rhyodacite or dacite, although one sample has more than 60% normative quartz and is outside the range of igneous rocks. The TAS name is rhyolite for three of the samples; the other three have too much silica for an igneous rock and must therefore be silicified. This extra silica is at least in part present in the quartz amygdules.

Chatham Pittsboro

These six specimens are exclusively greenish-gray metasedimentary rocks, with metamudstone, metasiltstone, and less commonly very fine metasandstone. Samples contain abundant relict sedimentary features, including bedding, laminations, grading, and ripples (Figures 4.12-4.13). Grain size is generally too small to identify many of the minerals except in FBL030, a metasandstone. In this sample, clasts of quartz and plagioclase are present and are likely phenocrysts eroded from a felsic volcanic source material. The chemical analyses give some clues about the mineralogy. Metavolcanic rocks in this study, and generally metavolcanic rocks throughout the Carolina Terrane, contain less K_2O than Na_2O. In contrast, most of the Chatham Pittsboro samples, especially the finer-grained ones, have high K_2O, with more K_2O than Na_2O (Table 4.1). In fact, two of the samples have normative mineralogy that plots in the alkali feldspar rhyolite field in terms of QAP. The siltstone and mudstone represent sediment that had undergone weathering and transport for greater time and distance from the volcanic source, likely producing clay minerals such as kaolinite and illite. During metamorphism, clays would have been converted to K-mica (muscovite). It is worth noting that the coarser metasandstone contains less K_2O than Na_2O, and chemically is similar to many of the felsic volcanic rocks. The sodic plagioclase grains in this rock apparently did not have the opportunity to weather and thus were not converted to clay.

Chatham Silk Hope

These six samples include purple, dark gray, or black heterolithic volcanic breccia, tuff breccia, lapilli tuff, and crystal-lithic tuff. These unusual and especially distinctive rocks contain abundant intermediate to mafic pyroclastic fragments (Figure 4.14) as well as more abundant felsic ones. Though most identifiable lithic tephra in these samples are lapilli size, some are blocks (> 64 mm). Phenocrysts are plagioclase plus local K-feldspar. Amygdules of quartz + epidote are present as well. These samples preserve features that are generally not seen in metavolcanic rocks of the Carolina Terrane, owing to the length of geological time during which devitrification and alteration may have affected them. Some rock fragments are vitric (glassy) and contain glass shards (Figure 4.15) and flow bands. In addition to epidote, chlorite, titanite, and unidentified opaque minerals, metamorphic piedmontite is common in these samples and adds to the distinctiveness of this zone (Figure 4.16). Normative QAP rock names are rhyodacite and dacite; TAS names are rhyolite.

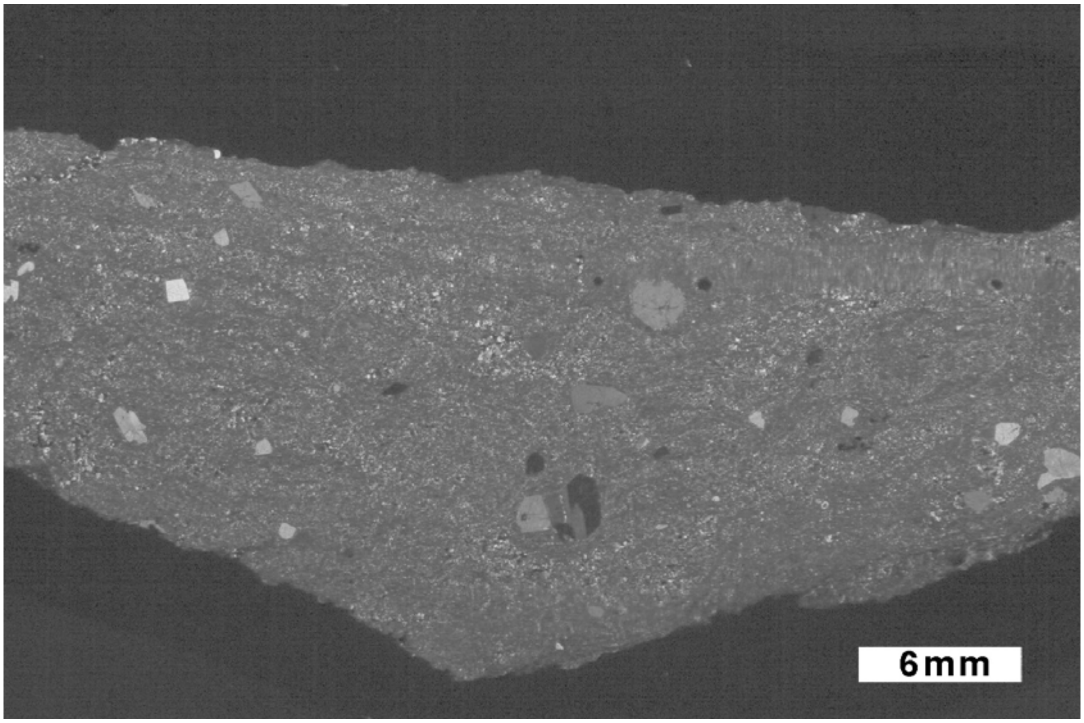

Figure 4.10. Uwharries Southeastern sample with quartz and plagioclase phenocrysts and weak banding (FBL052; scanned thin section, crossed polars).

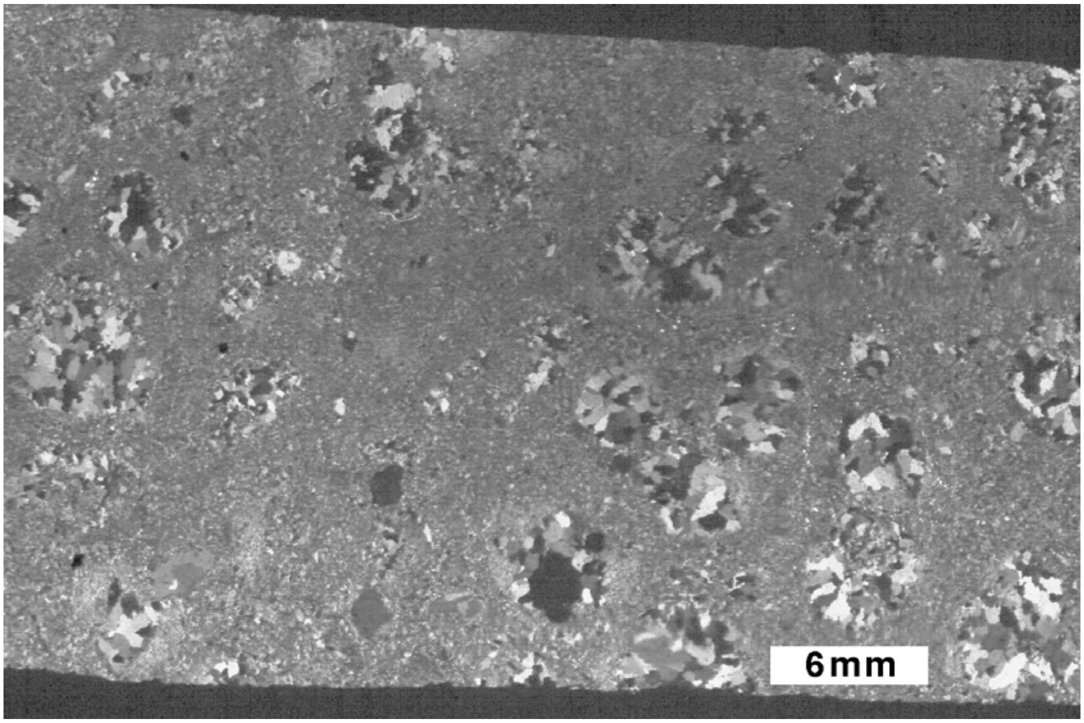

Figure 4.11. Uwharries Southeastern sample with circular quartz amygdules and sparse phenocrysts (FBL025; scanned thin section, crossed polars).

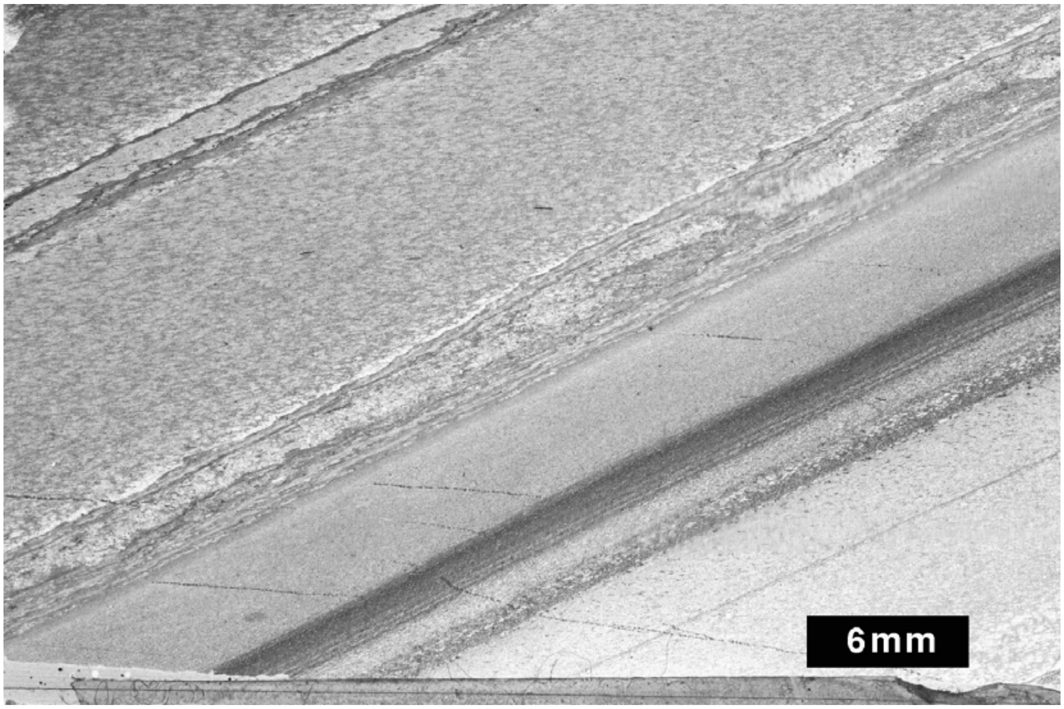

Figure 4.12. Chatham Pittsboro sample with fine laminae, grading, possible current ripples, and incipient cleavage (FBL028; scanned thin section, plane-polarized light).

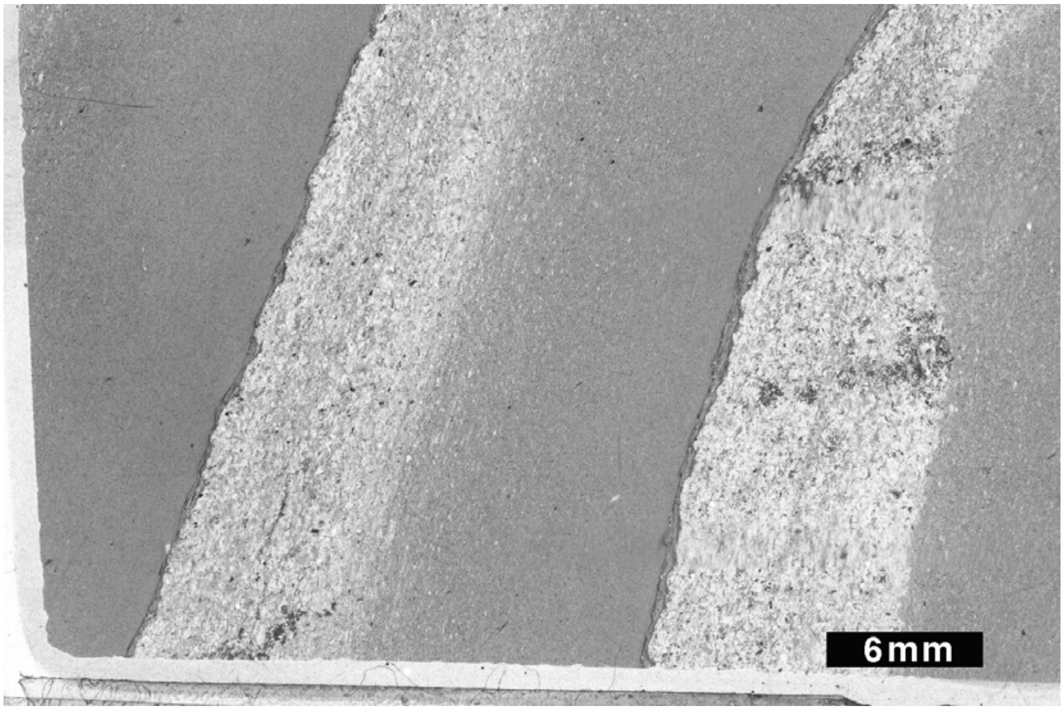

Figure 4.13. Chatham Pittsboro sample with graded bedding couplets (FBL029; scanned thin section, plane-polarized light). Stratigraphic younging direction is to the right.

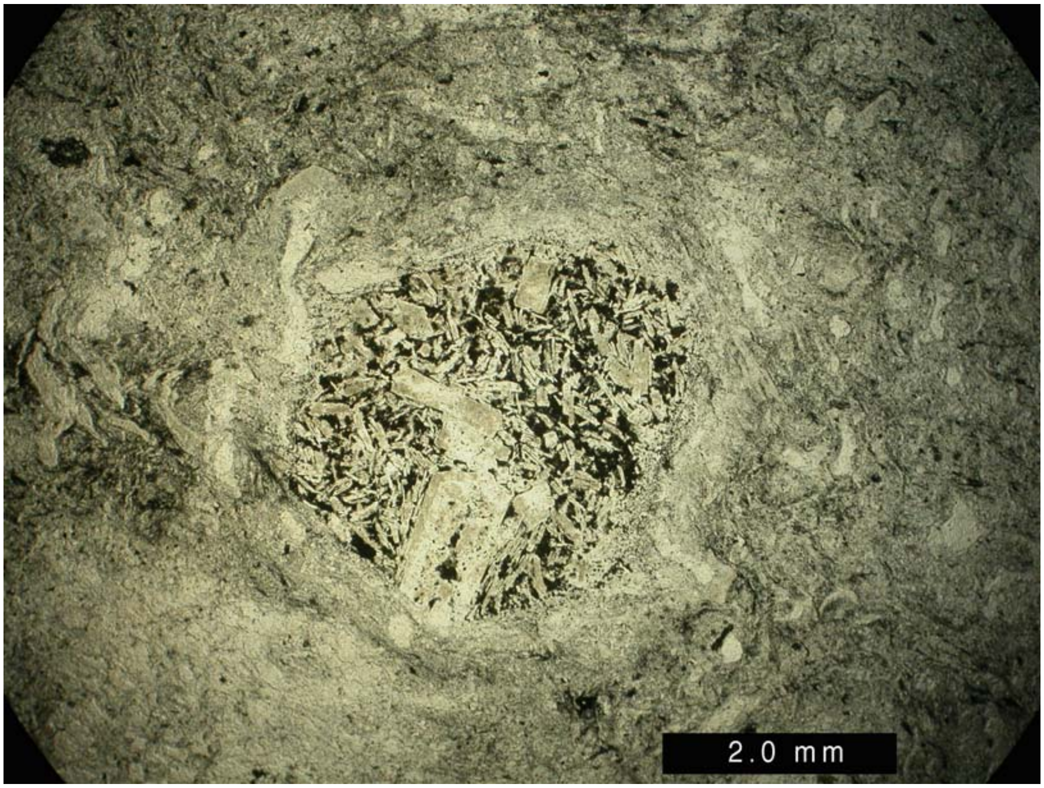

Figure 4.14. Basaltic fragment in Chatham Silk Hope sample (FBL034; plane-polarized light).

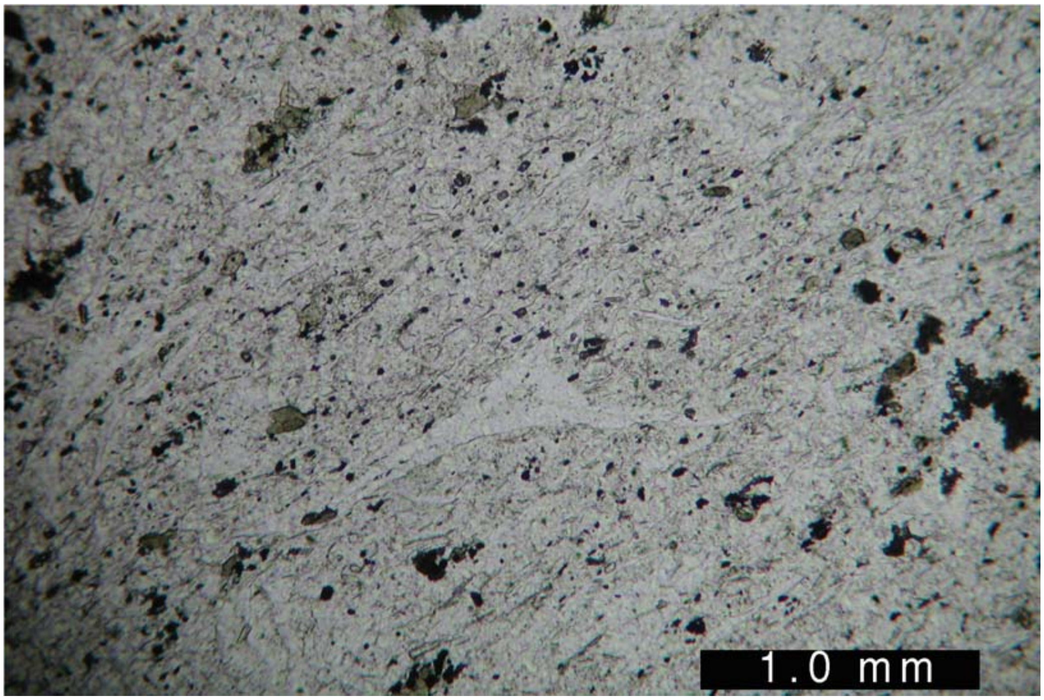

Figure 4.15. Y-shaped glass shard in Chatham Silk Hope sample (FBL031; plane-polarized light).

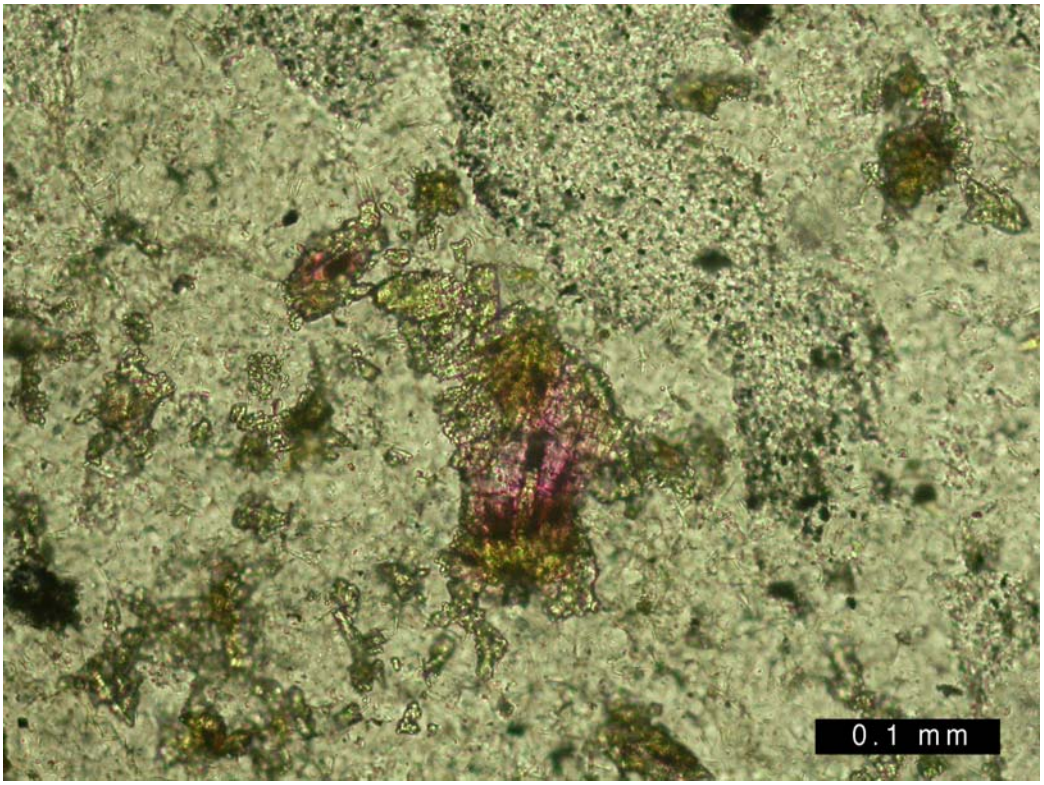

Figure 4.16. Piedmontite in groundmass of Chatham Silk Hope sample (FBL031; plane-polarized light). In color, this relatively rare mineral is bright pink and yellow pleochroic.

Orange County

This is a zone of relatively coarse-grained and crystal-rich rocks, with phenocrysts up to at least 3 mm constituting 15-20% of the volume. The six samples from this zone are distinctive and homogeneous. Phenocrysts are plagioclase, which is commonly partially saussuritized (replaced by epidote or clinozoisite), and quartz, which occurs in well-formed squat dipyramids of β morphology. Quartz phenocrysts are commonly partially resorbed, indicating late reaction with the magma during crystallization (Figure 4.17). The groundmasses of these rocks are exceedingly fine grained. Elongate and locally ovoid clots of feldspar and quartz are common in these rocks and are interpreted as devitrification features similar to spherulites. No flow banding was observed. In addition to epidote, metamorphic minerals include chlorite and calcite. The normative QAP name is dacite except for one sample, which falls just in the rhyodacite field; the TAS name for all is rhyolite. The field name is dacite porphyry or crystal-rich dacitic crystal tuff. These rocks may have originated as a shallow intrusive or an ash-flow tuff.

Durham County

Of the six samples examined, some samples possess sedimentary characteristics, including obvious clastic textures. The coarsest one is a metasandstone with subangular grains of plagioclase approximately 0.25 mm in size (Figure 4.18). However, they are poorly bedded and do not show sedimentary structures such as grading or ripples. Other samples appear to be

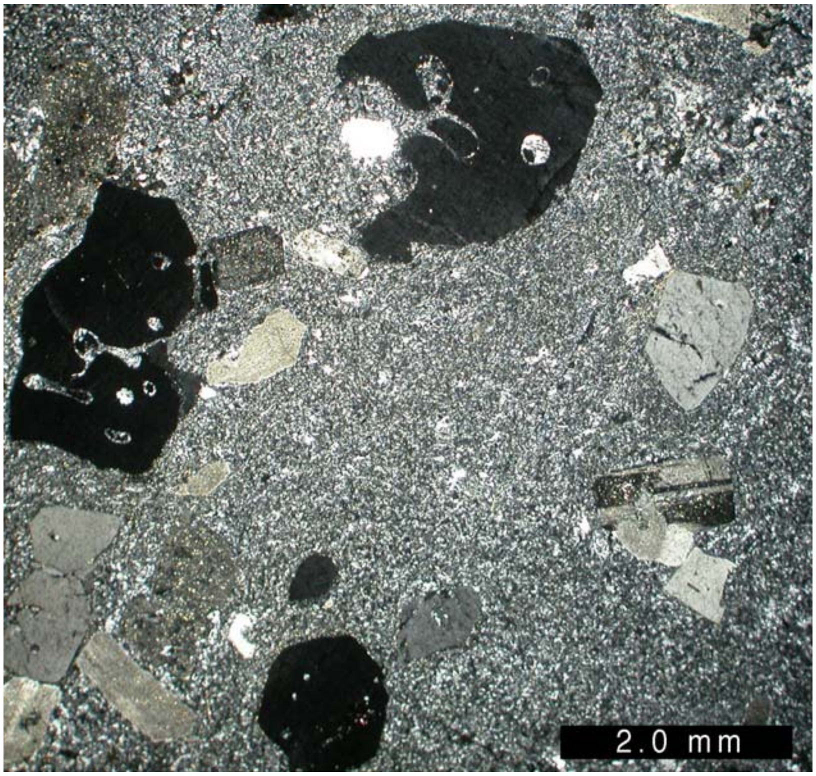

Figure 4.17. Euhedral and resorbed quartz phenocrysts, with plagioclase, in Orange County sample (FBL061; crossed polars).

crystal-lithic tuffs, with sparse plagioclase phenocrysts and volcanic lapilli. All samples contain metamorphic epidote, either replacing plagioclase, as veins, or as large clots that may be amygdules or pseudomorphs after amphibole or clinopyroxene. In addition to the epidote, these rocks contain metamorphic titanite, chlorite, and pyrite. Where sedimentary features dominate, these rocks are tuffaceous sandstones, while others are dacitic crystal-lithic lapilli tuffs. In terms of major element chemistry, this zone stands out due to extremely low K_2O, relatively high CaO and very high Na_2O, while having SiO_2 that is not particularly high. As a result the normative mineralogy, in terms of QAP, is dominated by plagioclase, placing most of this zone within the andesite/basalt field in the IUGS triangle. In terms of the TAS classification, four are rhyolites, one is a trachyte, and one is a trachydacite.

Person County

Yet another quarry of metasedimentary origin, the Person County quarry has samples that are mostly very fine-grained metamudstone and metasiltstone, although two of the specimens are sufficiently coarse grained to be very fine metasandstone. Four of the specimens contain bedding, but in two of them it is very weakly developed. Two of these specimens display graded bedding (Figure 4.19). One extremely distinctive feature occurs in FBL045. In this fine-grained sample, consistently shaped ovoid blobs about 2 mm in length are distributed throughout the section (Figure 4.20). The blobs are outlined by a thin dark band, but the grain texture and mineralogy is the same within and outside of the blobs. Although their origin is unclear, one

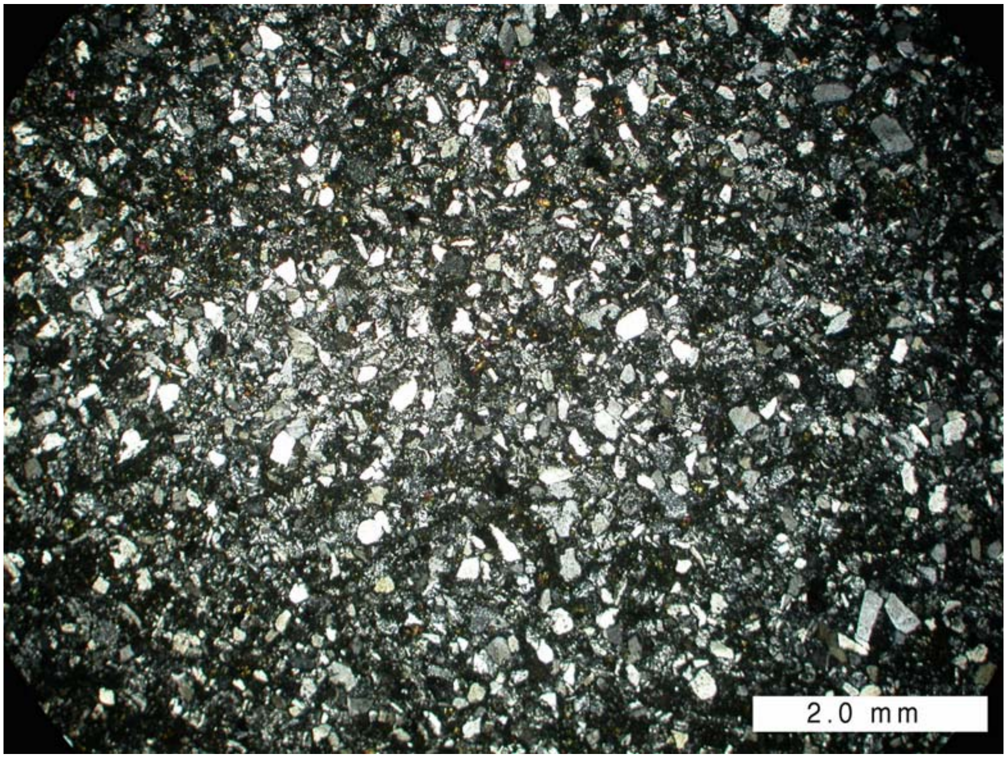

Figure 4.18. Durham County volcanic sandstone with clastic texture (FBL067; crossed polars).

possibility is that they may be trace fossils, possibly fecal pellets. In addition, tiny microfaults and veinlets of metamorphic minerals (chlorite or epidote) indicate some brittle deformation during or before metamorphism. Metamorphic calcite, pyrite, titanite, and needles of biotite or stilpnomelane also occur. In FBL046, detrital opaque grains are present and help to show grading. One sample contains possible pumice lapilli and sparse tiny plagioclase crystals and may be a tuff (FBL044), but the others are inferred to be metasedimentary. Like the Durham County samples, these rocks are chemically potassium-poor, and several plot in the andesite/basalt field using normative QAP, while the remainder are dacitic. Using TAS, one sample is a trachyte and the remaining samples are rhyolites.

Chatham Siler City

The four samples collected here include a laminated metamudstone/metasiltstone, a nonlaminated metamudstone, a volcanic crystal-lithic tuff, and a metasandstone. Samples from this diverse assemblage bear similarities to several of the other quarries, but they do not appear to have sufficient shared distinctive characteristics to make the quarry useful in sourcing. Nevertheless, only four samples have been examined; it is possible that further study might yield useful information. Sample FBL036, collected from outcrop in the Rocky River, is a dacitic or andesitic crystal-lithic tuff, with plagioclase phenocrysts up to 3 mm and relatively abundant lapilli and blocks of andesite and basalt. This specimen also contains glass shards and abundant small clusters of epidote, titanite, and opaque minerals. Many of these features are reminiscent of the Chatham Silk Hope samples, and it is likely that they may be correlative. The remaining

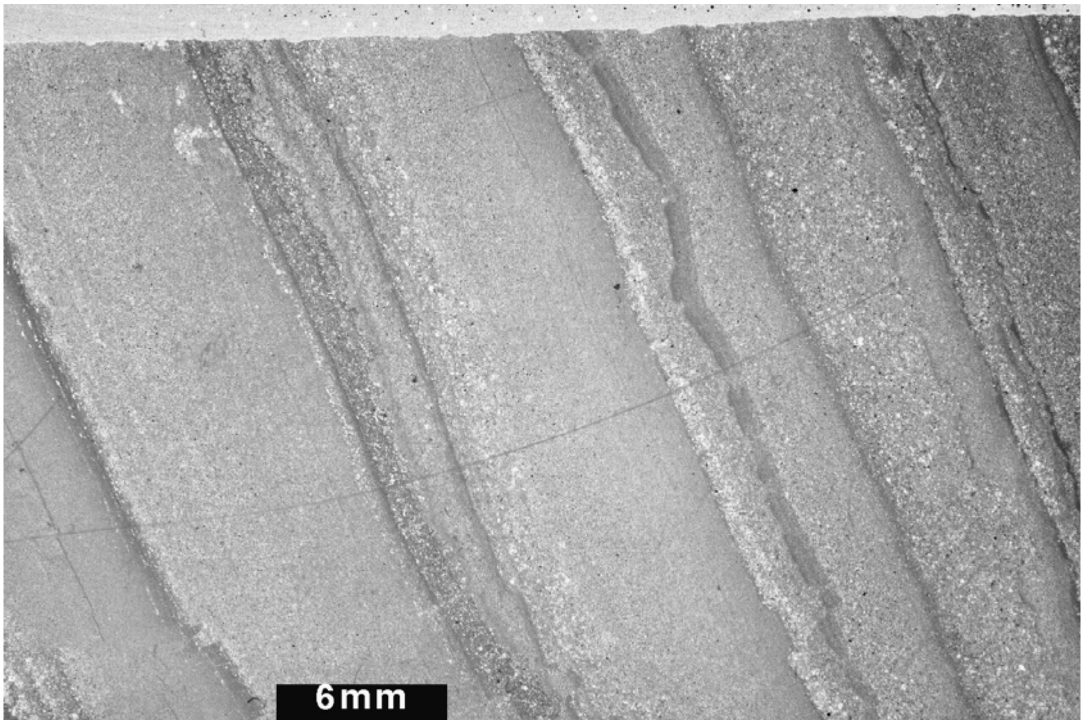

Figure 4.19. Person County sample with sedimentary laminae, grading (top to the right), and micro-faults (FBL046; scanned thin section, plane-polarized light).

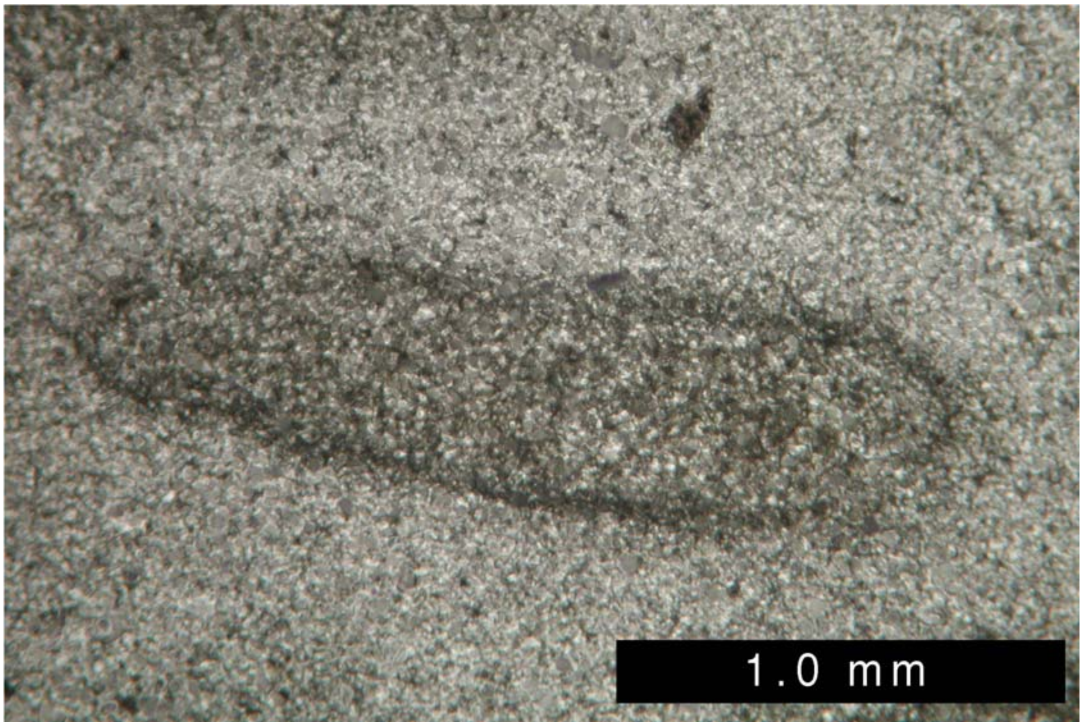

Figure 4.20. Elliptical feature (perhaps a trace fossil?) in metasiltsone from Person County (FBL045; plane-polarized light).

samples, however, resemble the Chatham Pittsboro and Person County quarries, with sedimentary laminations (FBL035), graded bedding (FBL038), and possible cross-laminations (FBL035). At least three of the four specimens contain porphyroblasts of greenish metamorphic biotite, and a weak muscovite foliation is visible throughout the groundmass. Using normative QAP percents, the volcanic rock falls just inside the andesite/basalt field; it is a rhyolite using TAS. The metasedimentary rocks are dacite, rhyodacite, and andesite/basalt using QAP, and dacite and trachyandesite using TAS.

Cumberland County

This zone of highly variable samples includes one that is probably not from the Carolina Terrane at all: sample FBL039 is a plutonic rock of granitic composition, a medium-grained muscovite aplite. It shows no evidence of metamorphism and is probably from a late Paleozoic granitic pluton. The other six samples are all consistent with having been derived from the Carolina Terrane, because they show greenschist facies metamorphic effects. Nevertheless, they are compositionally and texturally inhomogeneous. Two of the samples are metamorphosed intrusive rocks, one a metadiorite with a trachytic texture of aligned plagioclase laths, now strongly sericitized (FBL041). The other inferred metaplutonic rock is FBL071, which is thought to be highly altered metagabbro, with possible pseudomorphs after euhedral pyroxene. FBL040 is a metabasalt with a well-preserved igneous texture but having chlorite, quartz, albite, epidote, titanite and actinolite instead of the original calcic clinopyroxene and calcic plagioclase. FBL070 is an altered greenstone and FBL042 is a highly altered very fine-grained metatuff with ghosts of possible pumice lapilli. Chemical analyses of rocks from this zone, as would be expected, are inhomogeneous. The young granitic rock shows its felsic composition and plots with rhyodacite or rhyolite. The others plot as andesite/basalt using QAP and as basalt, basaltic trachyandesite, or trachybasalt using TAS. It is noteworthy that four of the five nongranite specimens have normative anorthite percentage (An%) greater than 32, by far the highest among all of the metaigneous rocks analyzed. Therefore, excluding the granite, one thing the remaining rocks at this site have in common is that they are intermediate or mafic in composition, not felsic. As mentioned earlier, the heterogeneity of this site is a consequence of the fact that it consists of large clasts removed from their bedrock sources, transported downstream, and redeposited, likely by the ancestral Cape Fear River.

Petrographic Descriptions of Artifacts

As discussed in Chapter 1, nine lithic artifacts collected on the Fort Bragg Military Reservation were analyzed petrographically for comparison to the quarry samples. Brief descriptions and discussion of these specimens follow. The most important petrographic characteristics of these nine artifacts are summarized in Table 4.5. Possible quarry sources indicated in the table are those suggested by comparison of these characteristics to those of the quarry zones described above.

FBL072

This is a fine-grained metadacite with plagioclase phenocrysts less than 1 mm in size constituting about 2% of the rock (Figures 4.21-4.22). Untwinned groundmass plagioclase

Table 4.5. Petrographic Features of Fort Bragg Artifacts.

Sample	Site	Rock Type	Textures	Phenocrysts	Metamorphic Minerals	Possible Source
FBL072	31Hk100	dacite	aligned plagioclase laths; flow banding	plagioclase (zircon inclusions)	garnet; brown biotite; stilpnomelane?	Uwharries Asheboro
FBL073	31Hk148	dacite porphyry	coarse; crystal-rich; mafic pseudomorphs	plagioclase; quartz (resorbed)	epidote; possible piedmontite	Orange County
FBL074	31Hk173	dacitic tuff	saussuritization; amygdules?; weak alignment	quartz; plagioclase (sparse)	epidote; biotite; actinolite; chlorite	Uwharries Eastern?
FBL075	31Hk182	andesite	fine-grained; saussuritization	plagioclase	epidote	
FBL076	31Hk224	dacitic tuff or siltstone	almost aphyric or featureless	plagioclase (tiny); clasts?	actinolite; epidote; brown biotite	
FBL077	31Hk737	siltstone	very fine-grained	fine clasts	green biotite	
FBL078	31Hk999	dacite crystal-lithic tuff or porphyry	flow banding; zoned, saussuritized plagioclase; mafic pseudomorphs; quartz-epidote amygdules	plagioclase; quartz	epidote; actinolite; opaque minerals	Uwharries Asheboro? Uwharries Southeastern?
FBL079	31Hk1408	dacitic tuff	crystal-poor; quartz-epidote amygdule	sparse plagioclase	brown biotite; epidote; actinolite; muscovite	Uwharries Asheboro? Uwharries Southeastern?
FBL080	Flat Creek	dacite	plagiclase lath fabric; banding	plagioclase (sparse, euhedral)	brown biotite; garnet; epidote; muscovite	Uwharries Asheboro? Uwharries Southeastern?

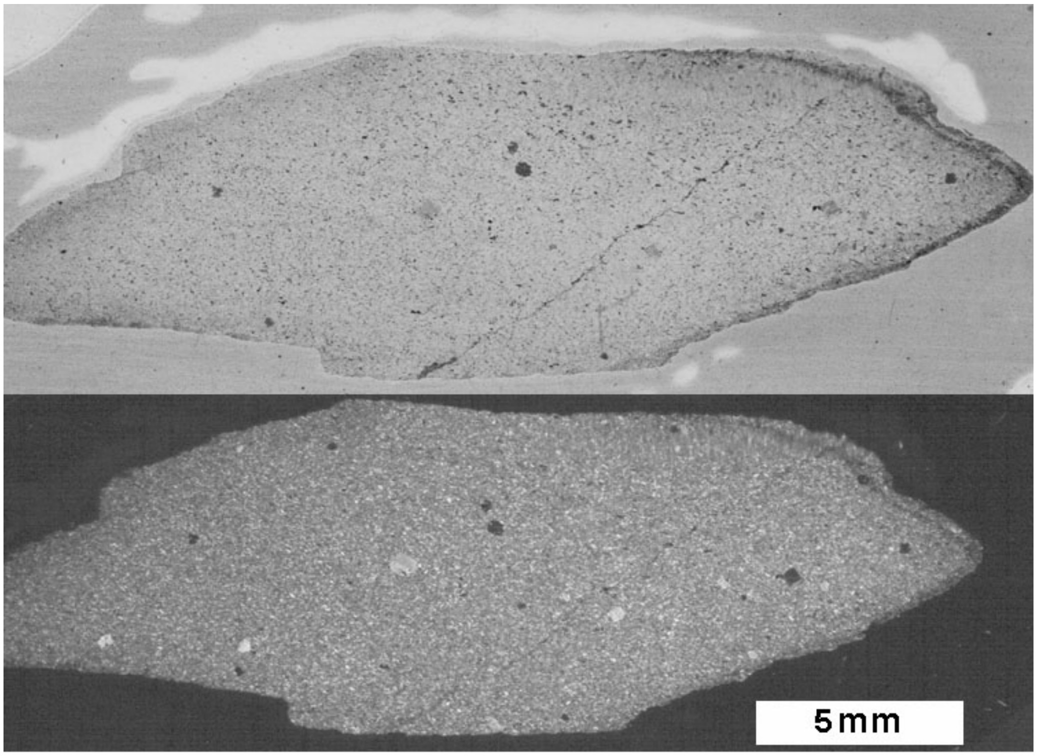

Figure 4.21. Artifact FBL072 (scanned thin section, plane-polarized light [top] and crossed polars [bottom]).

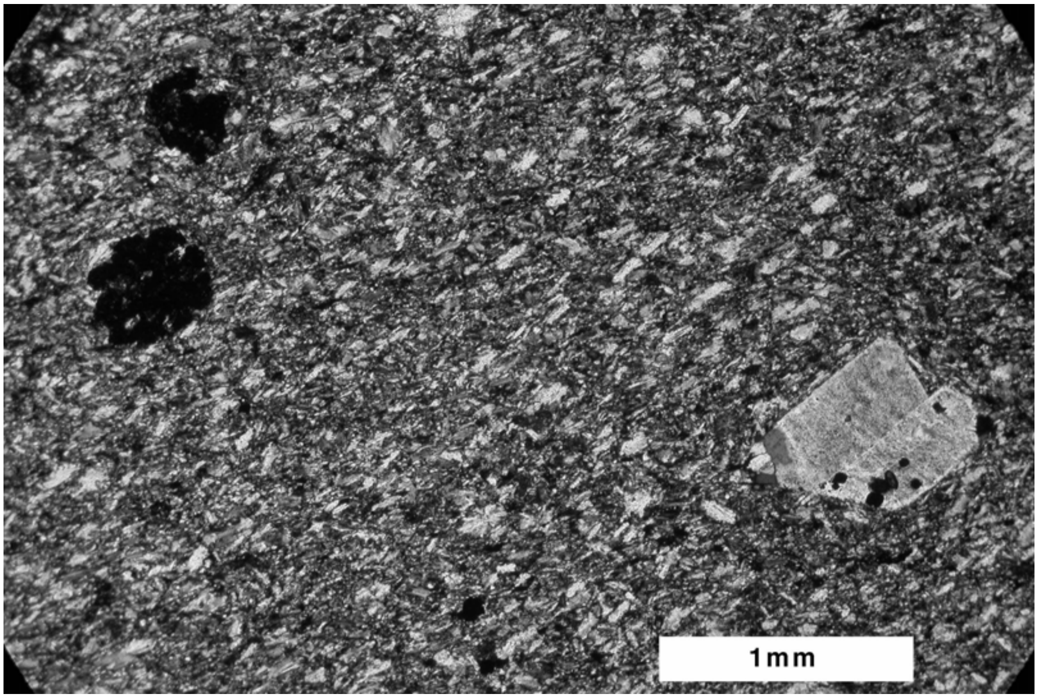

Figure 4.22. Groundmass lath alignment, plagioclase phenocryst, and garnet porphyroblasts in artifact FBL072 (crossed polars).

carries a pronounced alignment suggesting flow during emplacement. There are no quartz phenocrysts. One of the plagioclase phenocrysts has inclusions of zircon. The rock carries metamorphic brown biotite and garnet, with possible stilpnomelane, in addition to epidote and titanite. Using the normative minerals it is a dacite, and using the TAS system it is a rhyolite. Mineralogically this sample resembles the Uwharries Asheboro specimens, especially FBL055, although it is somewhat coarser grained and the garnet is more poikiloblastic. It lacks the mineral clusters that some of the Asheboro samples have, but the metamorphic mineral assemblage is identical. The major element chemistry is similar to that of FBL055 as well.

FBL073

This is a strongly porphyritic plagioclase + quartz dacite (Figure 4.23). Phenocrysts up to and in excess of 2 mm constitute about 20% of the sample. These crystals are euhedral and, in the case of the quartz, they are β-forms with common embayments. Plagioclase is clouded with minute opaque or dark minerals but is not strongly saussuritized. Epidote is common, however, locally with probable piedmontite, and is inferred to be pseudmorphous after amphibole or pyroxene. This sample bears strong resemblance to the Orange County quarry in terms of primary texture, phenocryst assemblage, and phenocryst morphology. It differs in its lack of some of the low-temperature and/or metamorphic features exhibited by the Orange County rocks, notably the saussuritization and the inferred devitrification features described above. Still, the similarities are striking, and the artifact could have been derived from a nearby outcrop. There are no metamorphic differences between FBL073 and the Orange County samples that would preclude them from coming from the same zone. The difference could be as simple as being erupted from different levels of the same magma chamber.

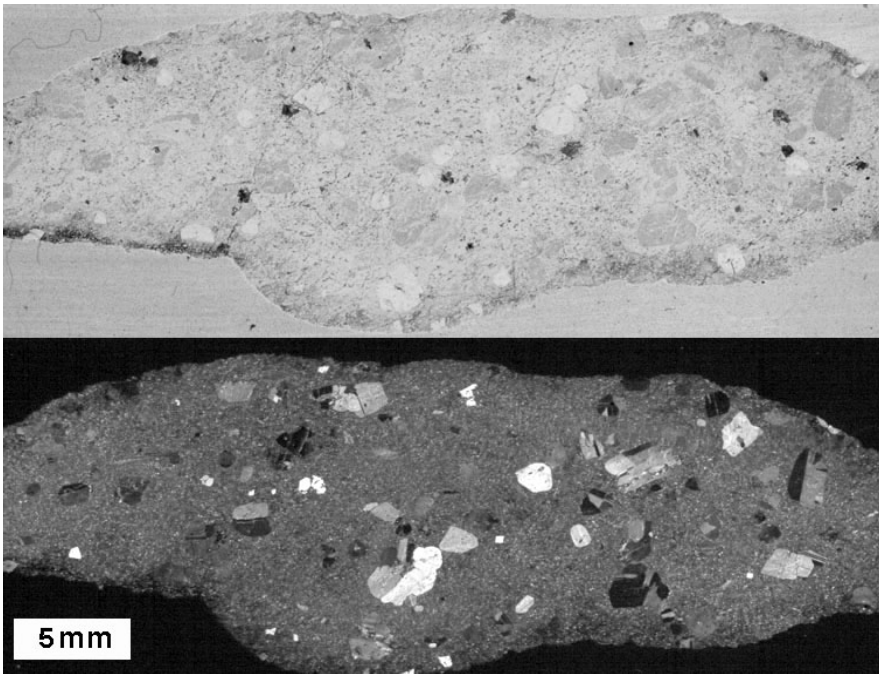

Figure 4.23. Artifact FBL073 (scanned thin section, plane-polarized light [top] and crossed polars [bottom]). Note euhedral and resorbed quartz phenocrysts and crystal-rich texture.

FBL074

This is a sparsely porphyritic, quartz + plagioclase-phyric metadacitic tuff (Figure 4.24). The plagioclase phenocrysts are strongly saussuritized, and there are elongate epidote + quartz clots that may represent amygdules. There is alignment of the sparse phenocrysts and the epidote aggregates, but the groundmass consists of more equidimensional grains, most of which appear to be quartz. Quartz phenocrysts are relatively euhedral β-forms and do not appear to be resorbed. Phenocrysts range to 0.5 mm, with plagioclase more abundant than quartz. The metamorphic minerals include epidote, titanite, actinolitic amphibole, sparse brown biotite or stilpnomelane, and possible chlorite. Chemically it is dacite (QAP) or rhyolite (TAS). This specimen bears strongest association with the Uwharries Eastern zone but is finer grained.

FBL075

This specimen, petrographically and chemically, is of andesitic composition (Figure 4.25). It is extremely fine grained and contains sparse tiny (< 0.5 mm) plagioclase phenocrysts. The rock contains abundant epidote, and the plagioclase is saussuritized. Though the rock would appear to be altered, its chemical composition shows major oxide values (SiO_2, Al_2O_3, TiO_2, MgO, CaO, Na_2O, and K_2O) consistent with an intermediate igneous rock composition (see Appendix C). Its normative QAP plots in the andesite/basalt field, and its normative plagioclase composition is 23% An. In terms of TAS it is a dacite. The material is unlike any of the quarry specimens.

FBL076

This sample is exceedingly fine grained and lacks any petrographic characteristics of clear volcanic origin, such as flow banding or spherulites, or of sedimentary origin, such as laminations or a clearly clastic texture (Figure 4.26). The largest grains are plagioclase crystals 0.05 mm in diameter. The metamorphic minerals include abundant tiny actinolite and epidote and sparse brown biotite. The rock is either a dacitic (ash) tuff, or a tuffaceous metasiltstone/metamudstone. Chemically and petrographically this sample is similar to FBL077, and the two artifacts may well be from the same source, but FBL076 cannot be associated with one of the quarries in this study based on petrographic criteria.

FBL077

This is a fine-grained metasedimentary rock with maximum clast size about 0.05 mm (Figure 4.27). Although a clastic texture is apparent in the sample, it appears to be devoid of any distinguishing features such as laminations or grading, and the minerals are too small to be identified with any confidence. There is in abundance a green, strongly pleochroic metamorphic mineral that is probably biotite. Chemically it falls in with the dacite/rhyolite specimens. This is the only artifact that is of clear metasedimentary origin, and it lacks any features to tie it to any of the quarries. It is, however, similar to another artifact, FBL076.

FBL078

This point is from a flow-banded quartz + plagioclase phyric metavolcanic rock (Figures 4.28-4.29). The phenocrysts are relatively abundant and range larger than 1 mm. Some of the

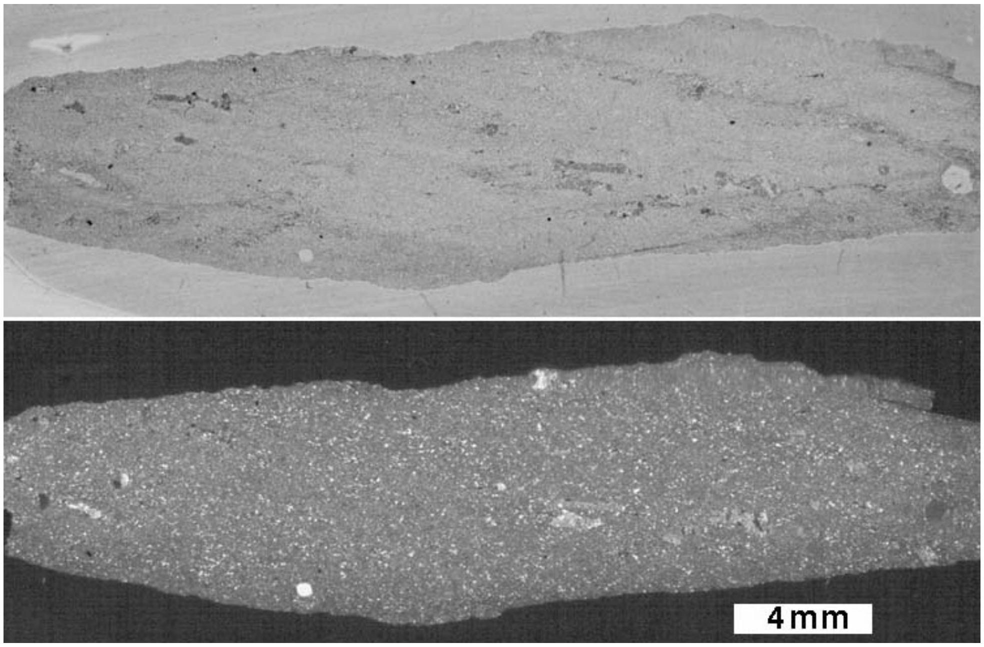

Figure 4.24. Artifact FBL074 (scanned thin section, plane-polarized light [top] and crossed polars [bottom]).

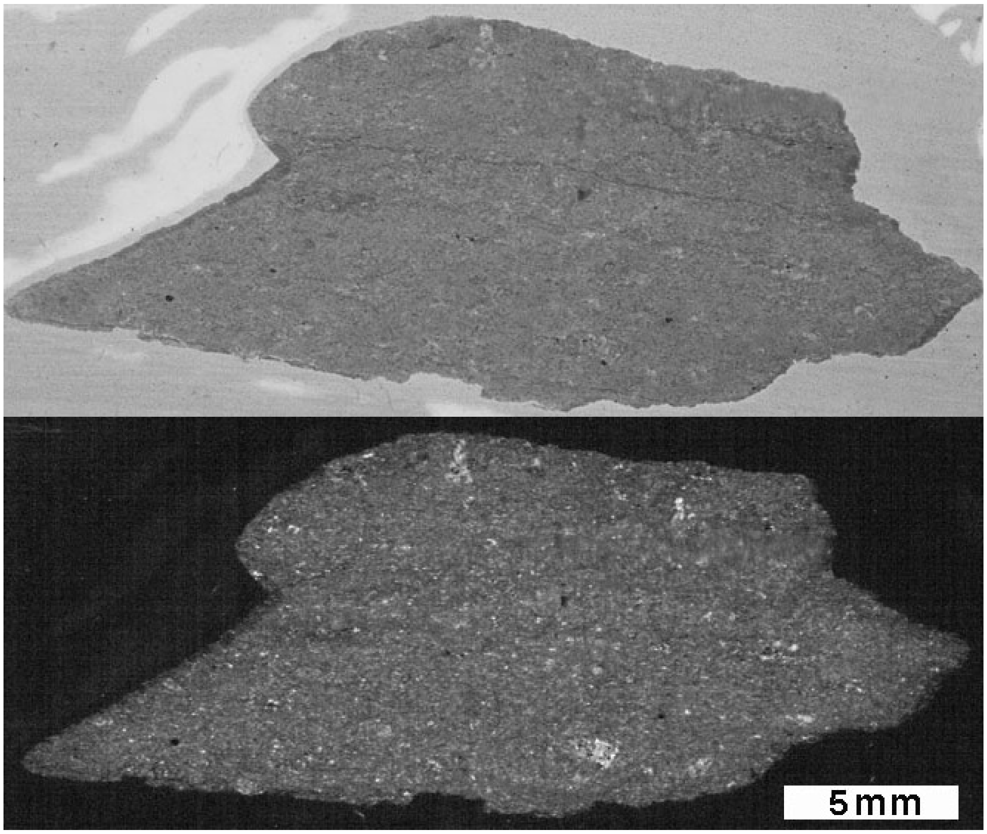

Figure 4.25. Artifact FBL075 (scanned thin section, plane-polarized light [top] and crossed polars [bottom]).

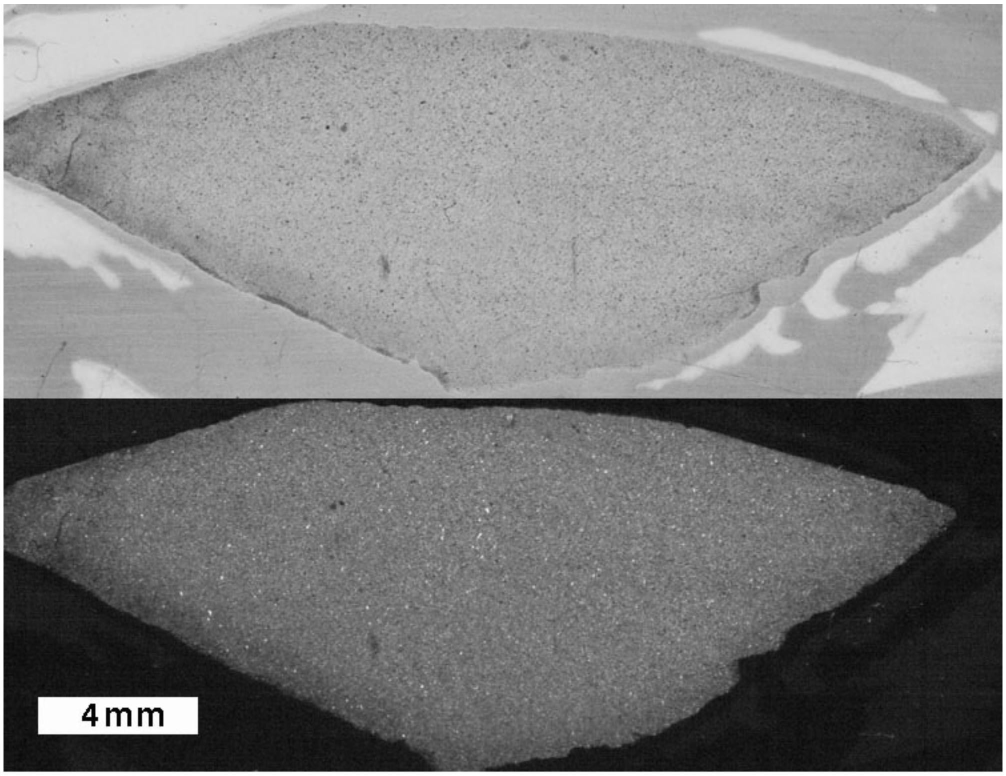

Figure 4.26. Artifact FBL076 (scanned thin section, plane-polarized light [top] and crossed polars [bottom]).

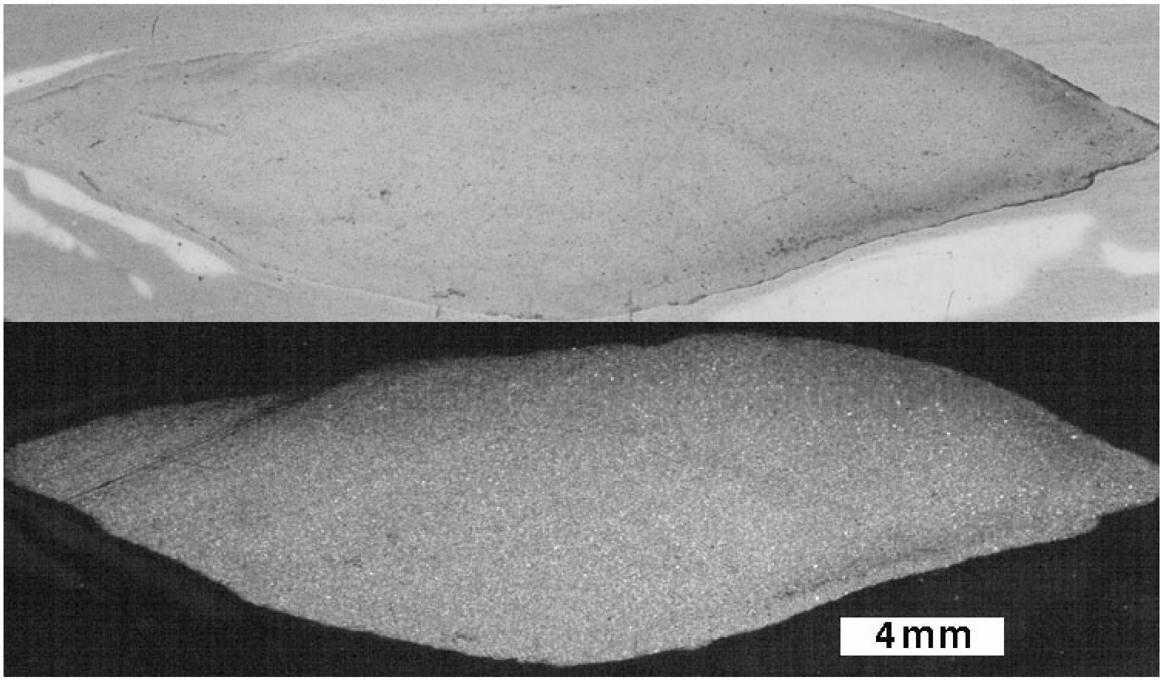

Figure 4.27. Artifact FBL077 (scanned thin section, plane-polarized light [top] and crossed polars [bottom]). Parallel lines are saw marks.

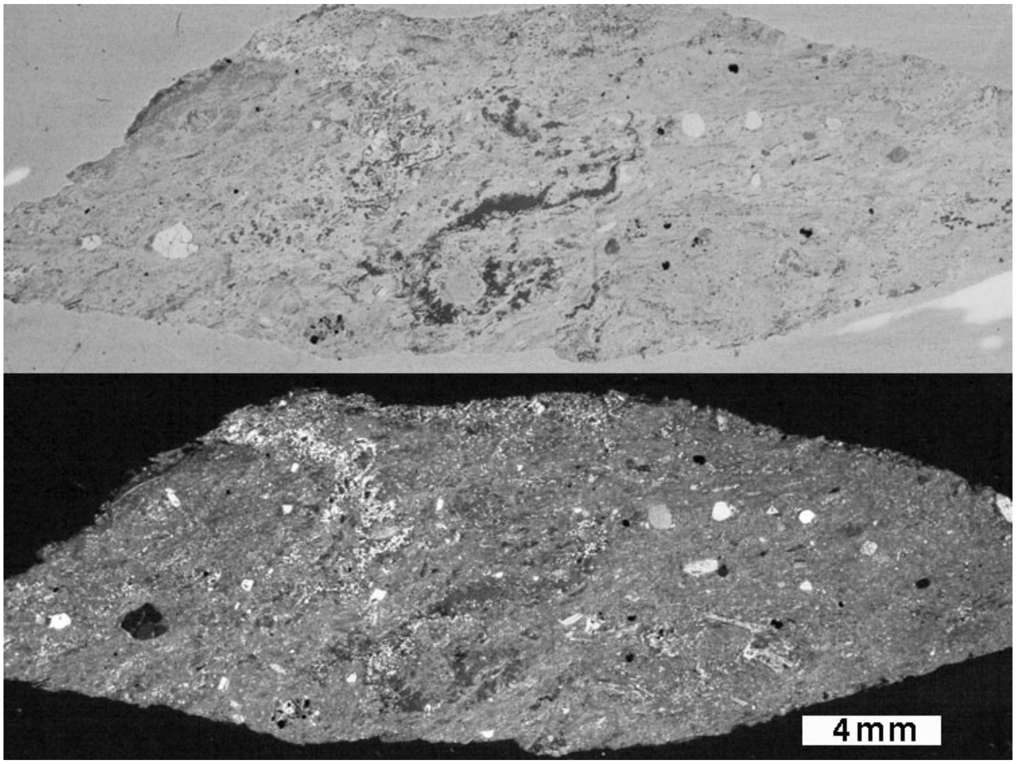

Figure 4.28. Artifact FBL078 (scanned thin section, plane-polarized light [top] and crossed polars [bottom]).

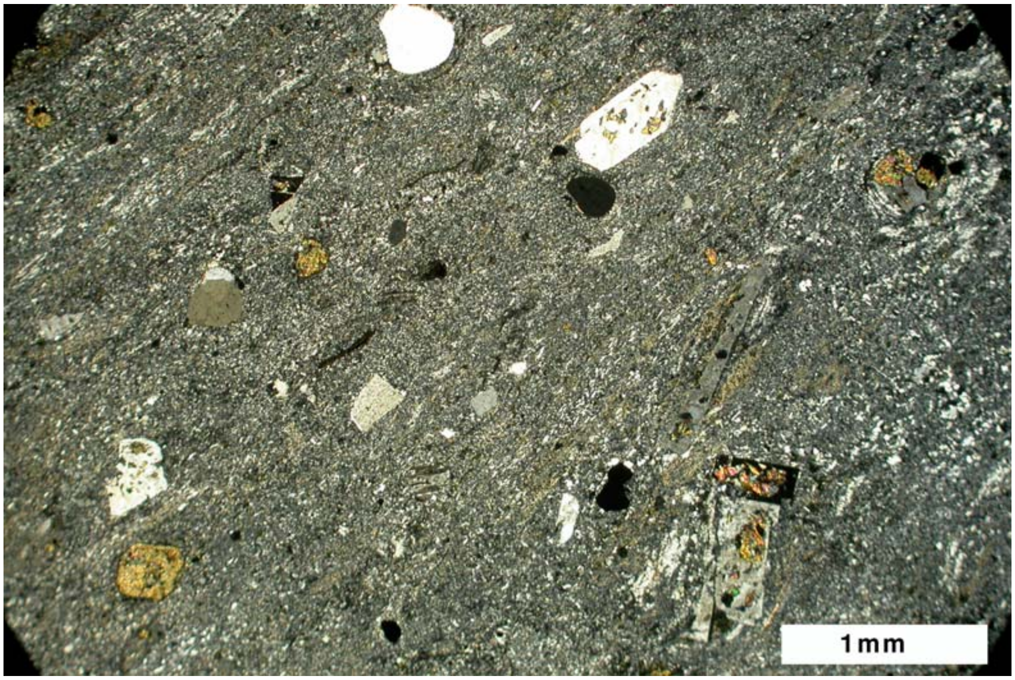

Figure 4.29. Weak alignment, phenocrysts, and pseudomorphs after amphibole or pyroxene (lower left and lower right) in artifact FBL078 (crossed polars).

plagioclase phenocrysts exhibit relict compositional zoning, manifested by the more calcic cores having been preferentially replaced by epidote-group minerals. The specimen contains at least one very nice pseudomorph of epidote after hornblende or augite. Quartz + epidote amygdules are also present, as are lapilli. In addition to abundant epidote, the rock carries considerable titanite and also chlorite. The rock is a dacitic crystal-lithic metatuff. Chemically it is similar to many of the metavolcanic rocks from the Uwharries quarries, especially the Asheboro zone, and plots as dacite using norms and rhyolite using TAS. However, the metamorphic assemblage does not match the Uwharries Asheboro zone. The presence of amygdules suggests the possibility of a source in the Uwharries Southeastern zone, although chemically the most similar rocks there appear to have been silicified.

FBL079

This is a sparsely porphyritic, fine-grained dacitic tuff containing plagioclase phenocrysts up to 0.5 mm (Figure 4.30). The groundmass contains abundant epidote, titanite, brown biotite, actinolite, and relatively coarse muscovite. At the edge of the specimen, there is one ovoid epidote + quartz cluster that may be an amygdule. It has some similarities to several of the Uwharries quarries, but no convincing petrographic connection to any.

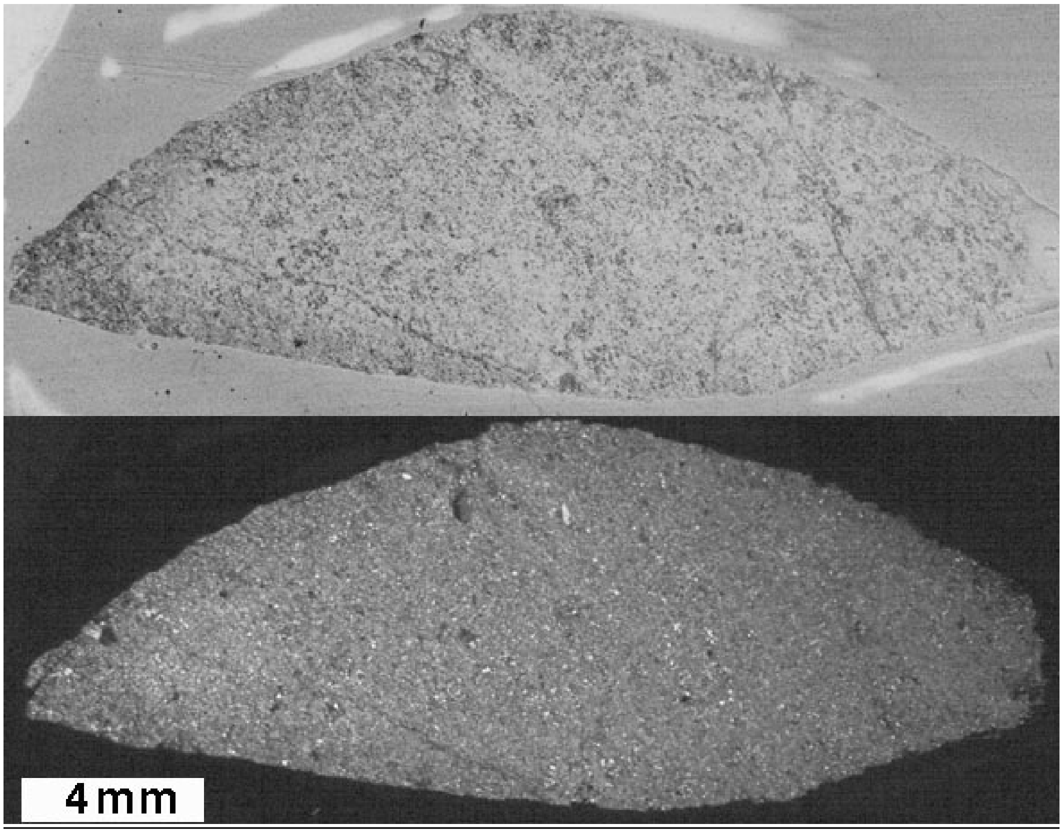

Figure 4.30. Artifact FBL079 (scanned thin section, plane-polarized light [top] and crossed polars [bottom]).

FBL080

This specimen is extremely similar to the preceding one, having euhedral plagioclase phenocrysts, epidote, brown biotite, titanite, and muscovite (Figure 4.31). The major differences are that it has a well-developed alignment of its phenocrysts and groundmass plagioclase laths, and it contains sparse garnet porphyroblasts. The combination of brown biotite, actinolite, and garnet suggests that the strongest connections of this specimen (and possibly FBL079) may be to the Asheboro or Southeastern Uwharries zones.

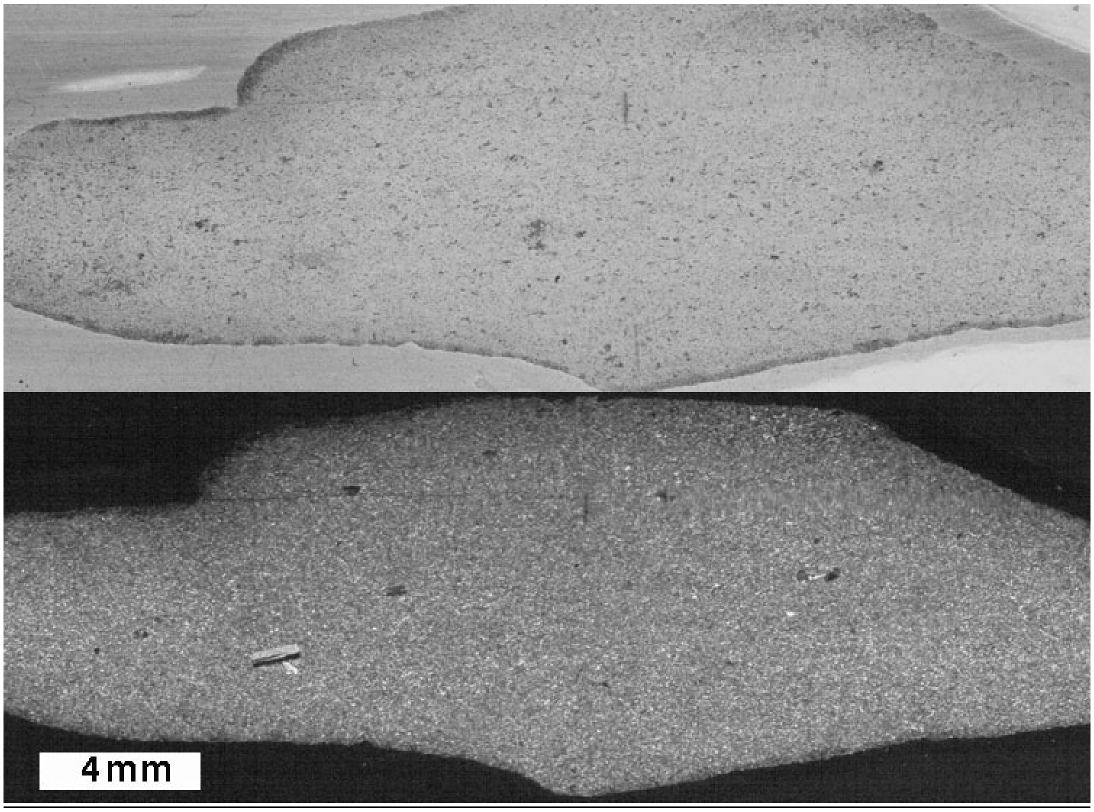

Figure 4.31. Artifact FBL080 (scanned thin section, plane-polarized light [top] and crossed polars [bottom]).

Summary

A number of archaeological quarry sites in the central North Carolina Piedmont were studied in order to characterize them petrographically for the purposes of comparison with lithic artifacts. In this study, nine artifact specimens from Fort Bragg, North Carolina were also examined. Several of them have petrographic similarities with one or more of the studied quarry sites, and some tentative correlations are offered. Perhaps with the use of trace-element and isotopic data, these suggestions may be corroborated or refuted.

Acknowledgments

I thank the staff of the Cultural Resources Office at Fort Bragg, especially Chris Moore and Jeff Irwin, for providing samples and assistance. Vin Steponaitis provided advice and specimens previously collected by Daniel and Butler (1996). Brent Miller accompanied us on numerous field excursions and offered valuable advice. Holly Woodward, Allison Gresham, and Stephen Fuemmeler assisted in the field, lab, and office. This study was supported by TRC Garrow Associates, under contract with ERDC-CERL, USACE. I also thank Paul Webb for managing this project and for timely communications.

Chapter 5

Geochemistry: Elements

Michael D. Glascock and Robert J. Speakman

As part of the study of metavolcanic and metasedimentary rocks found in the Carolina Slate Belt, 80 samples were submitted to the Archaeometry Laboratory at the University of Missouri Research Reactor Center (MURR) for chemical analysis. The goal was to determine the range of variability in the elemental composition of these rocks.

The samples included 71 rock specimens obtained from the 12 quarry zones surrounding Fort Bragg and nine Savannah River projectile points found at Fort Bragg itself (see Appendix A). Three different methods were used to measure the concentrations of elements within these samples: instrumental neutron activation analysis (NAA), x-ray fluorescence spectrometry (XRF), and inductively coupled plasma mass spectrometry (ICP-MS).

In this chapter, we briefly review the analytical methods used for determining composition, describe the quantitative methods used to examine the elemental data set, and statistically identify a number of compositional groups that correspond to the quarry zones described in previous chapters.

Analytical Methods

The rock samples and artifacts were ground into powders at the University of North Carolina at Chapel Hill using an aluminum-oxide shatter box. The samples were then shipped to MURR in powdered form. The original sample material was subdivided into aliquots of 350 mg for NAA, 150 mg for ICP-MS, and the remainder (typically 2.5 g) for XRF. The details of our analytical procedures are presented in Appendixes D-F, along with complete tabulations of the data. Here we provide only a brief overview of each method.

NAA is perhaps the most widely used method in archaeological provenance studies. It involves bombarding the samples with neutrons in a nuclear reactor and then measuring the gamma radiation emitted by these samples. The gamma counts can be used to derive very precise estimates of the concentrations of various elements present. A protocol involving two irradiations and three counts yielded data on a total of 33 elements: Al (aluminum), Ba (barium), Ca (calcium), Dy (dysprosium), K (potassium), Mn (manganese), Na (sodium), Ti (titanium), V (vanadium), As (arsenic), La (lanthanum), Lu (lutetium), Nd (neodymium), Sm (samarium), U (uranium), Yb (ytterbium), Ce (cerium), Co (cobalt), Cr (chromium), Cs (cesium), Eu (europium), Fe (iron), Hf (hafnium), Ni (nickel), Rb (rubidium), Sb (antimony), Sc (scandium), Sr (strontium), Ta (tantalum), Tb (terbium), Th (thorium), Zn (zinc), and Zr (zirconium). These data were tabulated in parts per million (Appendix D).

XRF has also been widely used to determine the chemical composition of rocks. The sample is bombarded with x-rays, and the secondary x-rays emitted by the sample are measured to estimate the elements that are present. These measurements resulted in data for 21 elements, namely Na, Mg (magnesium), Al, Si (silicon), K, Ca, Ti, Mn, Fe, Cu (copper), Zn, Ga (gallium), Rb, Sr, Y (yttrium), Zr, Nb (niobium), Ba, Pb (lead), Th, and U. In accordance with geological convention, the major elements were converted to percent oxides and the trace elements are listed in parts per million (Appendix E).

ICP-MS is a very sensitive method capable of measuring many elements, including some that cannot be detected by NAA. The method works by injecting the sample, often in dissolved form, into a chamber containing an extremely hot gas (plasma). In this ultra-hot environment, the molecules in the sample are broken down into charged atoms that can be identified and counted with a mass spectrometer. Data were obtained for the 14 rare earths: La, Ce, Pr (praseodymium), Nd, Sm, Eu, Gd (gadolinium), Tb, Dy, Ho (holmium), Er (erbium), Tm (thulium), Yb, and Lu. Also measured were Hf, Ta, and Th. All values were reported in parts per million (Appendix F).

Comparison of the NAA, XRF, and ICP-MS data finds excellent agreement throughout. The NAA data cover a wider range of elements than either XRF or ICP-MS. XRF permitted measurement of several elements not possible by NAA, including Mg, Si, Cu, Ga, Y, Nb, and Pb. Although ICP-MS is more laborious, five rare-earth elements (Pr, Gd, Ho, Er, and Tm) not possible by NAA or XRF were also measured. The suites of elements obtained with XRF and ICP-MS are especially useful for geological interpretations and are used accordingly in other chapters of this report. For the purpose of archaeological interpretation, specifically for sourcing artifacts, NAA provides the largest and most precise suite of elements. Thus, we will focus only on the NAA data in the remainder of this chapter.

Quantitative Analysis of the Chemical Data

The NAA analyses at MURR determined concentrations for 33 elements. However, a few elements, especially As, Cr, Ni, and V, were below detection in half or more of the samples. U and Sr were also missing for samples from specific quarries. Treatment of missing values for small groups can be difficult, and as a consequence these six elements were deleted from consideration during statistical analysis. Missing values for the remaining elements were replaced by substituting numbers according to a "best fit" criterion that minimized the Mahalanobis distance of each specimen to the centroid of its quarry zone. Analysis was subsequently carried out on base-10 logarithms of concentrations for the 27 elements that remained. Use of log concentrations instead of raw data compensates for differences in magnitude between major elements such as Fe on one hand and trace elements such as the rare-earth or lanthanide elements on the other. Transformation to base-10 logarithms also yields a more nearly normal distribution for many trace elements.

The primary goal of quantitative analysis of the chemical data is to recognize compositionally homogeneous groups within the analytical database. Based on the "provenance postulate" (Weigand et al. 1977), such groups are assumed to represent geographically restricted sources or source zones. The location of sources or source zones may be inferred by comparing the unknown groups to knowns (source raw materials) or by indirect means. Such indirect means include the "criterion of abundance" (Bishop et al. 1982) or arguments based on geological and sedimentological characteristics (e.g., Steponaitis et al. 1996).

Principal components analysis (PCA) is one of the techniques that can be used to identify patterns (i.e., subgroups) in compositional data. PCA provides new reference axes that are arranged in decreasing order of variance subsumed. The data can be displayed on combinations of these new axes, just as they can be displayed relative to the original elemental concentration axes. PCA can be used in a pure pattern-recognition mode, i.e., to search for subgroups in an undifferentiated data set, or in a more evaluative mode, i.e., to assess the coherence of hypothetical groups suggested by other archaeological criteria. Generally, compositional differences between specimens can be expected to be larger for specimens in different groups than for specimens in the same group, and this implies that groups should be detectable as distinct areas of high point density on plots of the first few components.

One strength of PCA, discussed by Baxter (1992) and Neff (1994), is that it can be applied as a simultaneous R- and Q-mode technique, with both variables (elements) and objects (individual analyzed samples) displayed on the same set of principal component reference axes. The two-dimensional plot of element coordinates on the first two principal components is generally the best possible two-dimensional representation of the correlation or variance-covariance structure in the data: small angles between vectors from the origin to variable coordinates indicate strong positive correlation; angles close to 90° indicate no correlation; and angles close to 180° indicate negative correlation. Likewise, the plot of object coordinates is the best two-dimensional representation of Euclidean relations among the objects in log-concentration space (if the PCA was based on the variance-covariance matrix) or standardized log-concentration space (if the PCA was based on the correlation matrix). Displaying objects and variables on the same plots makes it possible to observe the contributions of specific elements to group separation and to the distinctive shapes of the various groups. Such diagrams are often called “biplots” in reference to the simultaneous plotting of objects and variables. The variable interrelationships inferred from a biplot can be verified directly by inspection of bivariate elemental concentration plots (note that a bivariate plot of elemental concentrations is not a biplot).

Whether a group is discriminated easily from other groups can be evaluated visually in two dimensions or statistically in multiple dimensions. A metric known as Mahalanobis distance (or generalized distance) makes it possible to describe the separation between groups or between individual points and groups on multiple dimensions. The Mahalanobis distance of a specimen from a group centroid (Bieber et al. 1976; Bishop and Neff 1989; Neff 2001; Harbottle 1976; Sayre 1975) is:

$$D^2_{y,X} = [y - \overline{X}]^t I_x [y - \overline{X}] \tag{1}$$

where y is $1 \times m$ array of logged elemental concentrations for the individual point of interest, X is the $n \times m$ data matrix of logged concentrations for the group to which the point is being compared with $\overline{X}$ being its $1 \times m$ centroid, and I_x is the inverse of the $m \times m$ variance-covariance matrix of group X. Because Mahalanobis distance takes into account variances and covariances in the multivariate group, it is analogous to expressing distance from a univariate mean in standard deviation units. Like standard deviation units, Mahalanobis distances can be converted into probabilities of group membership for each specimen (e.g., Bieber et al. 1976; Bishop and Neff 1989; Harbottle 1976). For relatively small sample sizes, it is appropriate to base probabilities on Hotelling’s T^2, the multivariate extension of the univariate Student’s t test.

With small groups, Mahalanobis-distance-based probabilities of group membership may fluctuate dramatically depending on whether or not each specimen is assumed to be a member of the group to which it is being compared. Harbottle (1976) calls this phenomenon "stretchability" in reference to the tendency of an included specimen to stretch the group in the direction of its own location in the elemental concentration space. This problem can be circumvented by cross-validation (or "jackknifing"), that is, by removing each specimen from its presumed group before calculating its own probability of membership (Baxter 1994; Leese and Main 1994). This is a conservative approach to group evaluation that may sometimes exclude true group members. All probabilities discussed below are cross-validated.

In this study, several of the group sizes are smaller than the total number of variates, and this places a further constraint on use of Mahalanobis distance: with more variates than objects, the group variance-covariance matrix is singular, thus rendering calculation of I_x (and D^2 itself) impossible. Dimensionality of the groups therefore must be reduced somehow. One approach to dimensionality reduction would be to eliminate elements considered irrelevant or redundant. The problem with this approach is that the investigator's preconceptions about which elements should best discriminate sources may not be valid; it also squanders one of the major strengths of NAA, namely its capability to determine a large number of elements simultaneously. An alternative approach to dimensionality reduction, used here, is to calculate Mahalanobis distances not with log concentrations but with scores on principal components extracted from the variance-covariance or correlation matrix of the complete data set. This approach entails only the assumption, entirely reasonable in light of the above discussion of PCA, that most group-separating differences should be visible on the largest several components. Unless a data set is highly complex, with numerous distinct groups, using enough components to subsume 90% of total variance in the data may be expected to yield Mahalanobis distances that approximate Mahalanobis distances in the full elemental concentration space.

Results and Conclusions

After eliminating the six elements mentioned earlier (i.e., As, Cr, Ni, Sr, U, and V), the NAA data were converted to logarithms. An RQ-mode PCA transformation of the 80-specimen dataset was performed using the variance-covariance matrix of the logged data (Table 5.1). Based on the calculated eigenvalues, the first seven components subsume at least 90% of the variance in the dataset, and the first 15 components subsume more than 99% of the variance. From the biplots in Figures 5.1 and 5.2 showing the samples and element vectors for the first three principal components, it is noted that the first principal component is dominated by enrichment of the transition metals Co, Fe, Mn, and Ca and dilution of Ta and Th and the alkali elements K and Rb. The second principal component is dominated by enrichment of Ba and dilution of Sb and the rare-earth elements. The third principal component shows enrichment of Na and dilution of K, Rb, Ba, and Cs.

Based on the elemental data and spatial proximity among quarries, the 71 source samples from the Fort Bragg area were subdivided into the eight chemical groups shown in Figures 5.1 and 5.2. The chemical groups are Uwharrie 1, Uwharrie 2, Chatham 1, Chatham 2, Cumberland, Durham, Orange, and Person. Sample FBL039 was removed from the Cumberland group because it was found to be an extreme outlier relative to the five remaining samples. Figures 5.3 through 5.7 illustrate the basic data structure for the analyzed source samples and group

Table 5.1. Principal Components Analysis.[a]

	Principal Components									
	1	2	3	4	5	6	7	8	9	10
La	-0.129	-0.122	-0.017	-0.021	-0.043	-0.012	-0.028	0.001	0.004	0.031
Lu	-0.167	-0.063	0.022	-0.054	0.008	-0.024	0.030	-0.004	0.025	-0.038
Nd	-0.094	-0.149	-0.003	-0.017	-0.009	-0.012	-0.025	0.027	-0.007	0.022
Sm	-0.097	-0.112	-0.006	-0.049	-0.003	-0.026	0.013	0.006	0.007	-0.008
Yb	-0.170	-0.067	0.018	-0.058	0.009	-0.025	0.029	0.003	0.027	-0.035
Ce	-0.126	-0.124	-0.015	-0.012	-0.035	-0.009	-0.017	0.004	0.003	0.018
Co	0.568	-0.141	-0.136	0.097	-0.102	-0.065	-0.013	0.029	0.067	-0.019
Cs	0.005	0.019	-0.274	-0.023	-0.005	-0.003	0.092	0.033	-0.034	0.028
Eu	0.072	-0.006	-0.015	-0.119	-0.075	-0.003	0.034	-0.006	-0.037	0.002
Fe	0.247	-0.108	-0.030	-0.010	0.034	-0.054	0.005	-0.055	-0.001	-0.015
Hf	-0.147	-0.133	0.031	-0.004	-0.018	0.006	-0.025	-0.016	-0.023	-0.035
Rb	-0.233	0.011	-0.242	-0.011	0.109	-0.062	-0.008	0.006	0.008	-0.015
Sb	0.051	-0.177	-0.079	0.091	0.032	0.182	0.074	-0.038	0.000	0.017
Sc	0.224	0.063	-0.057	-0.091	-0.045	0.016	0.061	-0.027	-0.001	-0.036
Ta	-0.249	-0.113	-0.053	0.022	-0.044	0.003	-0.006	0.016	0.013	0.012
Tb	-0.130	-0.090	-0.001	-0.063	0.025	-0.026	0.041	0.000	0.013	-0.023
Th	-0.319	-0.086	-0.063	0.003	-0.112	0.019	-0.021	0.026	-0.021	0.017
Zn	0.126	-0.101	-0.042	0.016	0.017	-0.075	0.032	-0.059	-0.004	0.031
Zr	-0.148	-0.150	0.021	-0.003	-0.038	0.018	-0.036	-0.026	-0.034	-0.023
Al	0.054	-0.016	-0.006	-0.009	0.003	0.007	-0.015	-0.011	0.010	-0.008
Ba	-0.022	0.182	-0.207	-0.084	-0.107	0.055	-0.056	-0.038	0.010	-0.019
Ca	0.352	-0.120	-0.022	-0.153	0.084	0.104	-0.065	0.056	0.034	-0.003
Dy	-0.162	-0.093	-0.002	-0.058	0.019	-0.019	0.036	0.008	0.016	-0.026
K	-0.206	0.008	-0.202	0.054	0.062	0.013	-0.078	-0.059	0.017	-0.022
Mn	0.211	-0.064	-0.004	-0.102	0.026	-0.040	-0.038	-0.057	-0.030	0.082
Na	0.010	-0.025	0.110	-0.014	-0.045	0.024	0.011	-0.078	0.027	-0.030
Ti	0.285	-0.076	-0.034	0.039	0.019	-0.011	-0.030	0.021	-0.115	-0.068
Eigenvalue	1.123	0.282	0.269	0.102	0.091	0.074	0.050	0.037	0.029	0.023
Variance (%)	51.6	12.9	12.4	4.7	4.2	3.4	2.3	1.7	1.3	1.1
Cumulative (%)	51.6	64.6	76.9	81.6	85.8	89.2	91.5	93.2	94.5	95.6

[a] Based on variance-covariance matrix for all 80 samples (FBL001-FBL080).

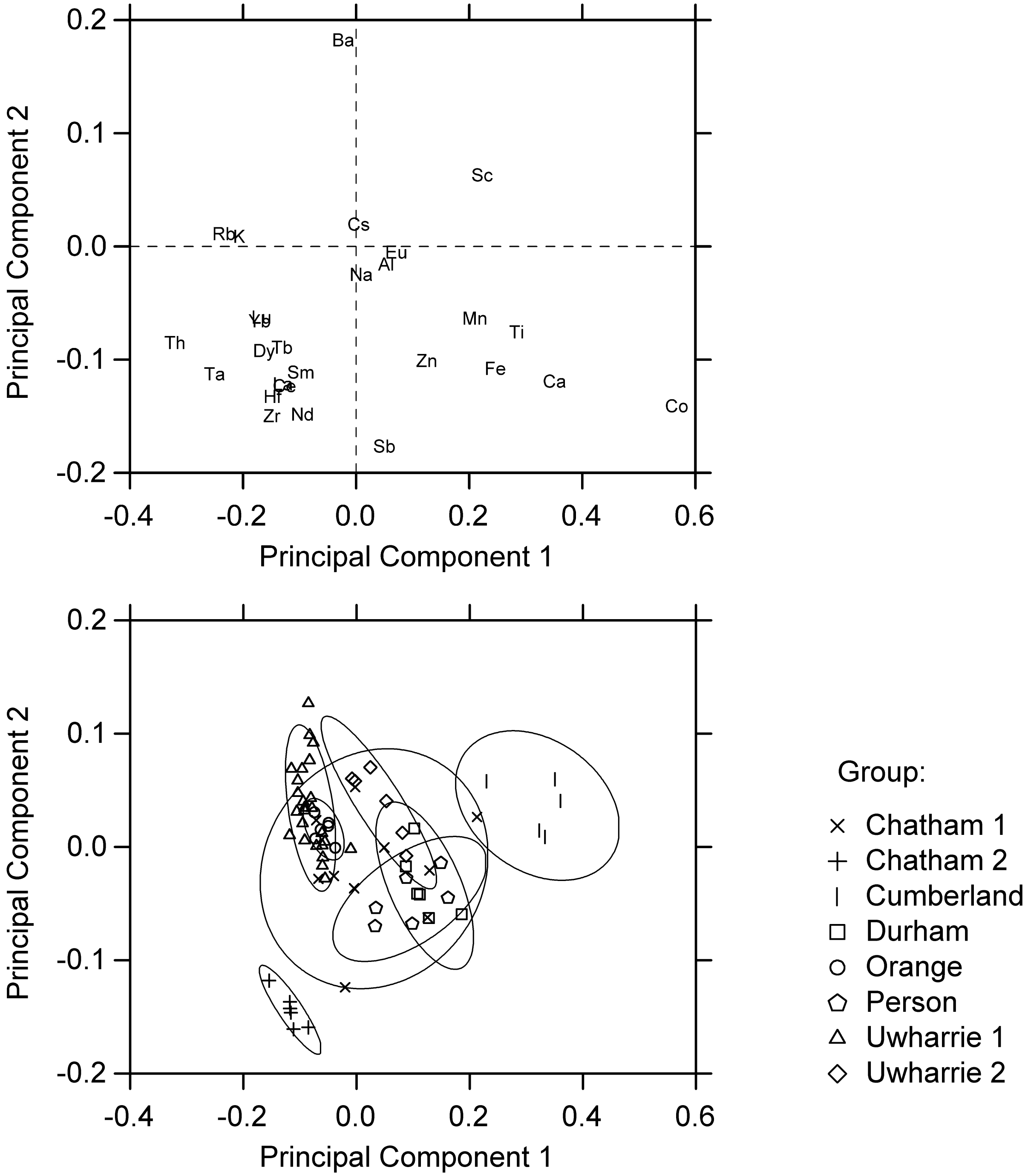

Figure 5.1. Biplot derived from PCA of the variance-covariance matrix of the NAA data showing principal component 1 versus principal component 2. Elements are shown in the top graph; analyzed specimens are shown in the bottom graph. Ellipses represent 90% confidence level for membership in the groups.

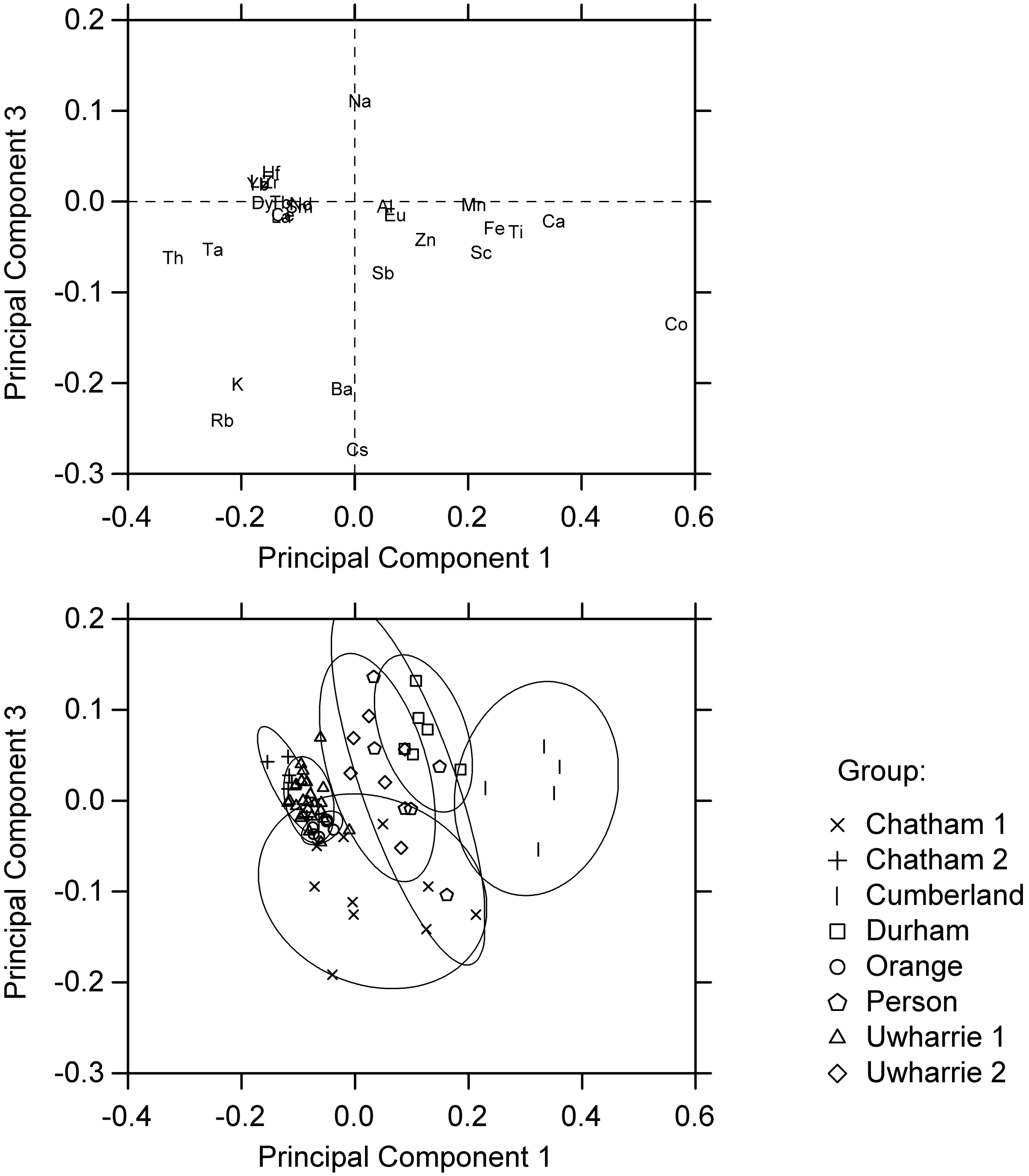

Figure 5.2. Biplot derived from PCA of the variance-covariance matrix of the NAA data showing principal component 3 versus principal component 1. Elements are shown in the top graph; analyzed specimens are shown in the bottom graph. Ellipses represent 90% confidence level for membership in the groups.

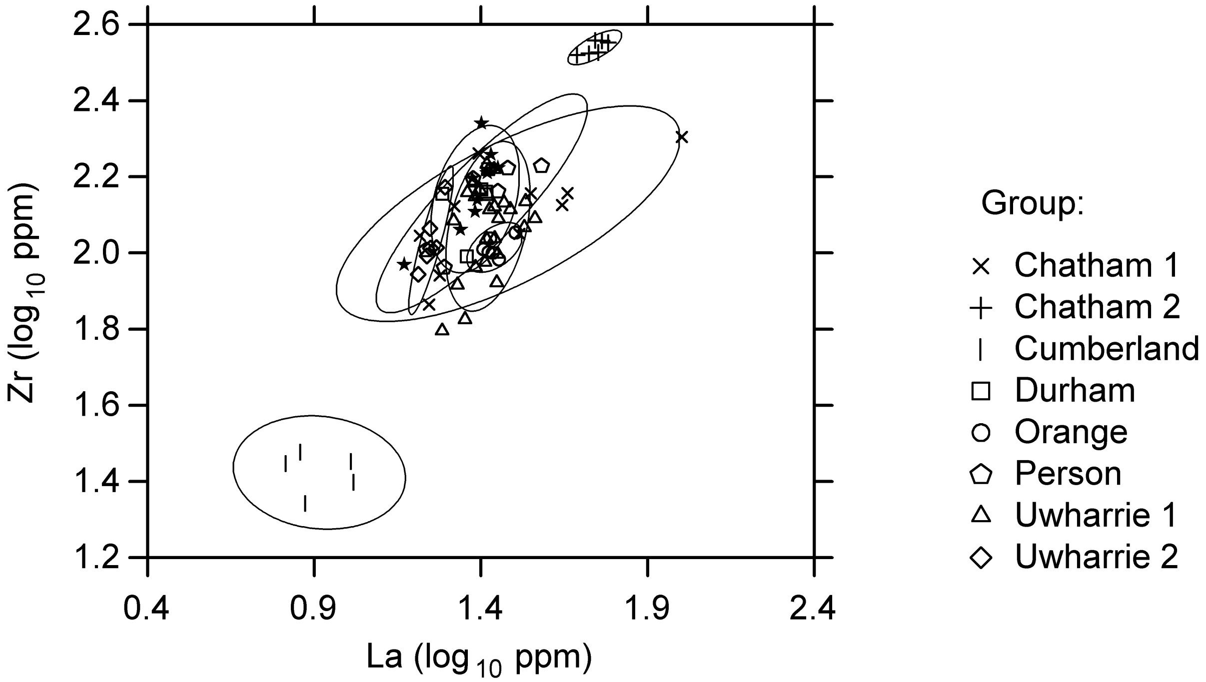

Figure 5.3. Bivariate plot of Zr versus La for the chemical groups. Ellipses represent 90% confidence level for membership in the groups. Artifacts are plotted as solid stars.

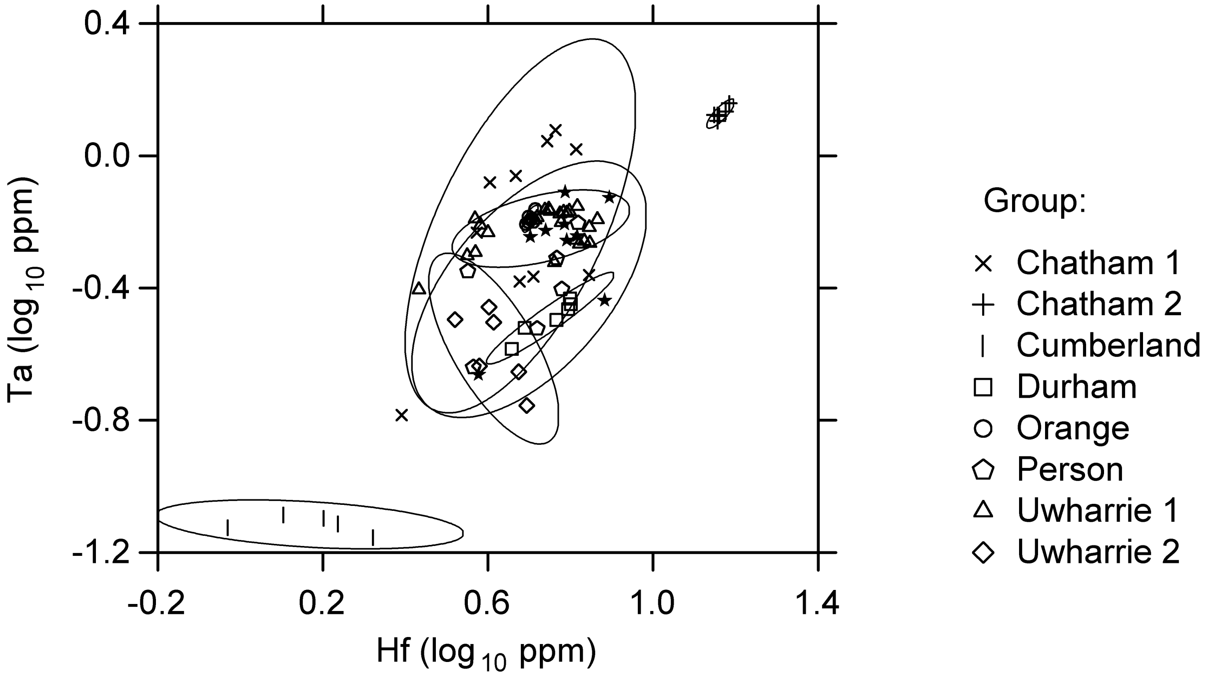

Figure 5.4. Bivariate plot of Ta versus Hf for the chemical groups. Ellipses represent 90% confidence level for membership in the groups. Artifacts are plotted as solid stars.

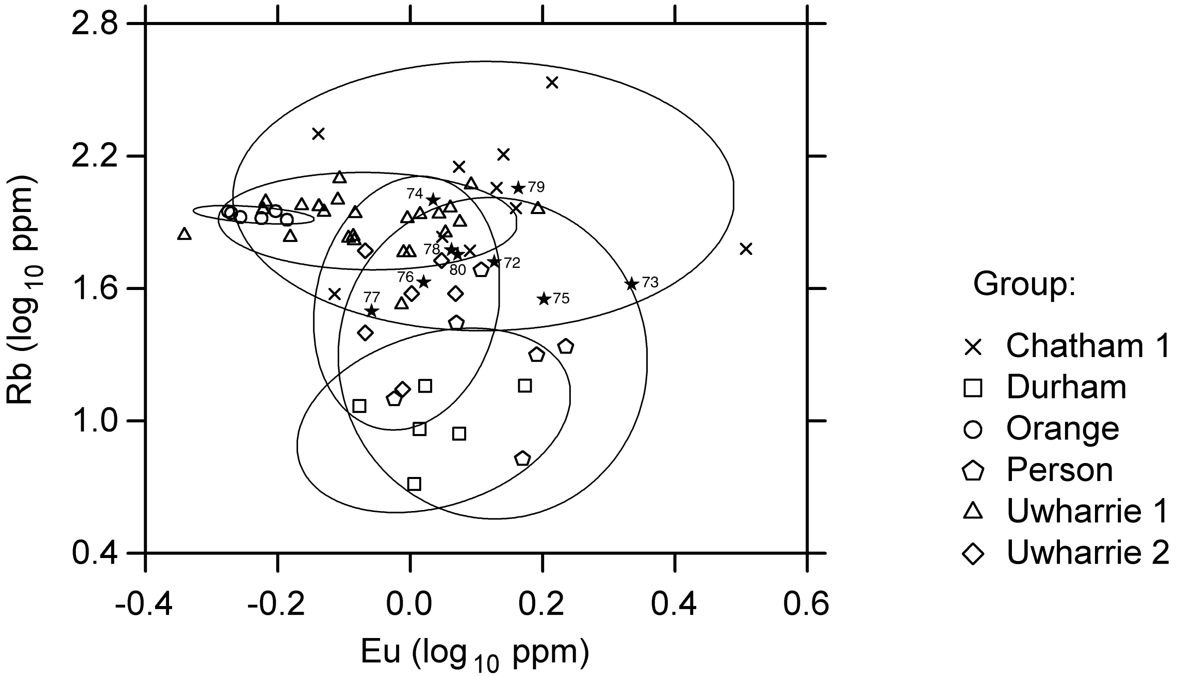

Figure 5.5. Bivariate plot of Rb versus Eu for six of the chemical groups. Ellipses represent 90% confidence level for membership in the groups. Artifacts are plotted as solid stars; individual artifacts are labeled with their FBL-number suffixes.

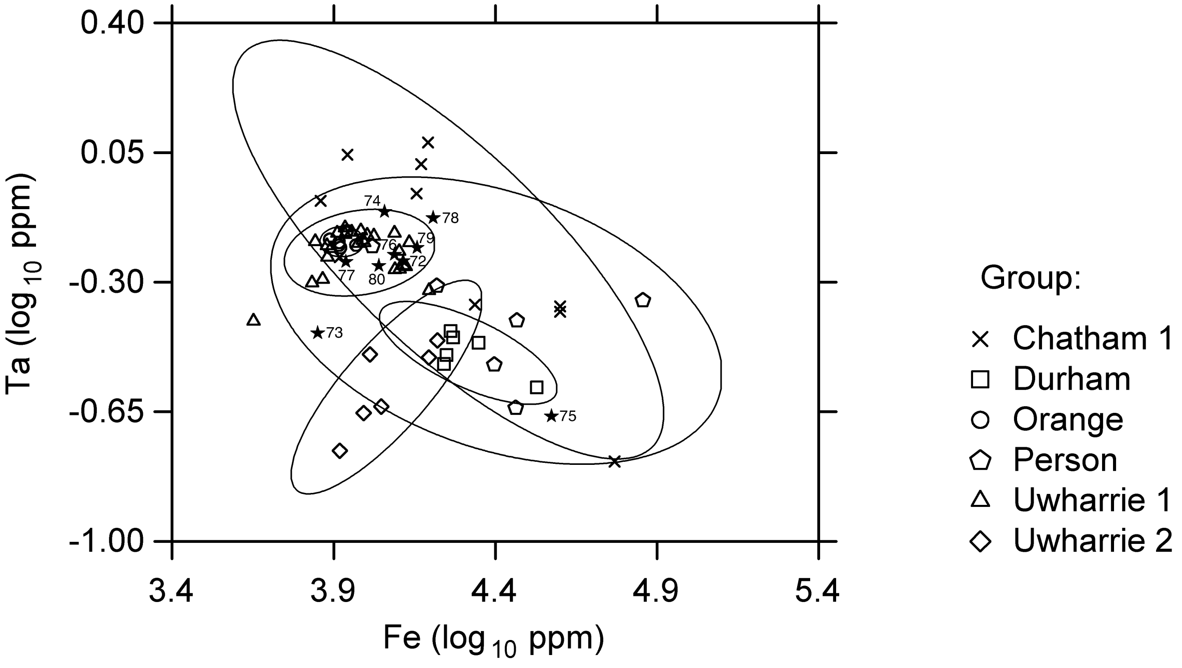

Figure 5.6. Bivariate plot of Ta versus Fe for six of the chemical groups. Ellipses represent 90% confidence level for membership in the groups. Artifacts are plotted as solid stars; individual artifacts are labeled with their FBL-number suffixes.

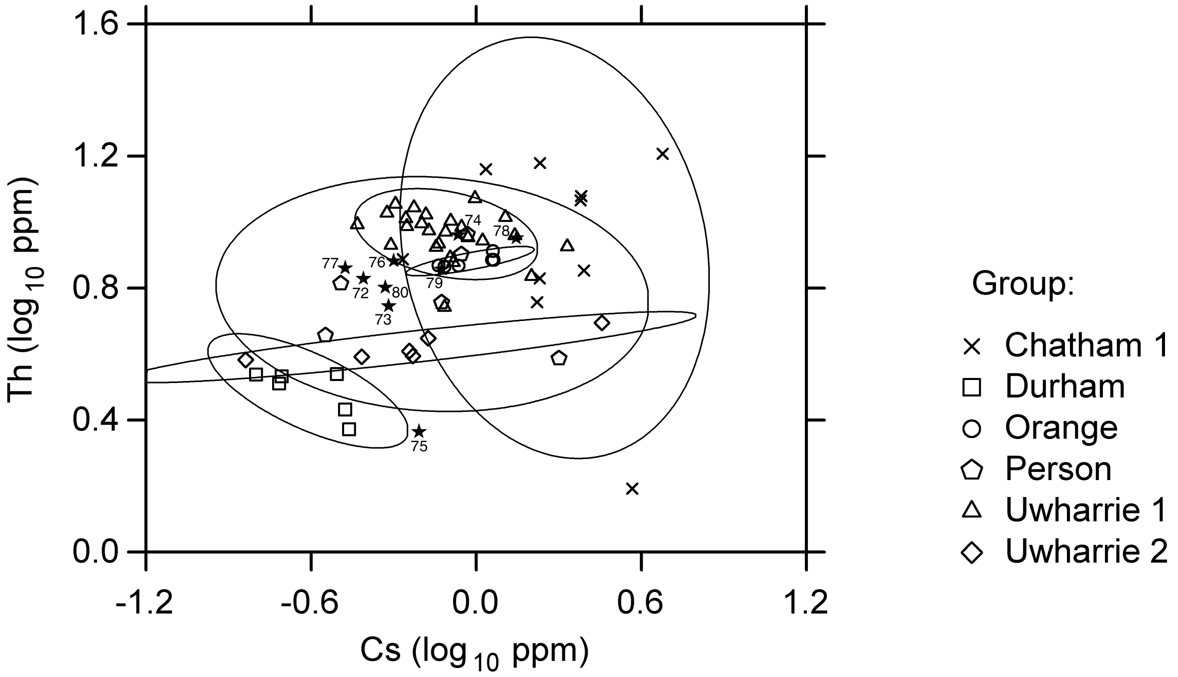

Figure 5.7. Bivariate plot of Th versus Cs for six of the chemical groups. Ellipses represent 90% confidence level for membership in the groups. Artifacts are plotted as solid stars; individual artifacts are labeled with their FBL-number suffixes.

assignments and also show the artifact data projected against the source groups. Table 5.2 lists the means and standard deviations for each of the compositional groups based on NAA data.

The Uwharrie 1 group is statistically the most valid of the groups, a consequence of the number of samples having membership in the group. Additional analyses of source specimens from this quarry would not be likely to affect the overall basic structure of this group. According to Mahalanobis distance calculations for samples in the Uwharrie 1 group, membership probabilities based on the first 15 principal components are greater than 1% for all members of this group (except FBL013 and FBL014). The results are shown in Table 5.3.

A comparison of specimens from the other compositional groups to Uwharrie 1 illustrates that with the exception of the Orange group all other chemical groups have low probabilities of overlap with Uwharrie 1 (Table 5.3). Due to the limited numbers of samples in the individual groups (ranging from 5 to 10 samples), we are unable to perform the same test to differentiate between the other quarries.

As shown in Figures 5.3 and 5.4, the rock specimens exhibit some significant patterns in geochemistry. Three distinct clusters are present, with the Chatham 2 and Cumberland groups well separated from the remaining compositional groups on the basis of Hf, Ta, and Zr. The Chatham 2 source samples are an intermediate metavolcanic rock, and the Cumberland specimens are largely greenstone. Both groups are small but compositionally very homogeneous. Although it is unlikely that additional samples from these quarries would have much effect on the basic structure of the database, the analysis of additional specimens would enable more rigorous testing.

Table 5.2. Element Means and Standard Deviations Within Chemical Groups.

Element	Uwharrie 1 (n = 25)	Uwharrie 2 (n = 6)	Chatham 1 (n = 10)	Chatham 2 (n = 6)	Cumberland (n = 5)	Durham (n = 6)	Orange (n = 6)	Person (n = 6)
La (ppm)	26.7 ± 4.2	17.8 ± 1.1	35.7 ± 25.2	55.4 ± 4.1	8.4 ± 1.8	24.3 ± 2.8	27.7 ± 2.2	26.2 ± 7.7
Lu (ppm)	0.858 ± 0.239	0.564 ± 0.137	0.566 ± 0.269	1.152 ± 0.059	0.249 ± 0.089	0.446 ± 0.038	0.661 ± 0.07	0.507 ± 0.158
Nd (ppm)	24.2 ± 4.2	19.0 ± 3.2	35.6 ± 22.1	73.3 ± 20.6	12.5 ± 3.8	27.6 ± 7.6	33.3 ± 4.6	30.2 ± 9.4
Sm (ppm)	6.64 ± 1.67	4.76 ± 0.59	7.46 ± 3.97	12.73 ± 0.71	3.48 ± 1.37	5.06 ± 0.56	6.42 ± 0.60	6.04 ± 1.54
Yb (ppm)	5.78 ± 1.63	3.72 ± 0.82	4.04 ± 1.97	7.99 ± 0.34	1.73 ± 0.62	2.95 ± 0.23	4.50 ± 0.45	3.18 ± 1.05
Ce (ppm)	56.5 ± 9.3	37.8 ± 3.1	70.6 ± 34.0	124.1 ± 6.6	19.6 ± 5.5	52.4 ± 6.2	61.2 ± 5.6	56.9 ± 12.6
Co (ppm)	0.43 ± 0.16	1.44 ± 1.15	6.36 ± 6.99	0.70 ± 0.49	24.84 ± 9.82	5.03 ± 2.95	0.67 ± 0.18	6.88 ± 7.69
Cs (ppm)	0.85 ± 0.40	0.87 ± 0.99	2.24 ± 1.23	0.45 ± 0.12	0.78 ± 0.40	0.27 ± 0.09	0.97 ± 0.20	0.86 ± 0.62
Eu (ppm)	0.895 ± 0.246	0.996 ± 0.13	1.406 ± 0.696	0.43 ± 0.052	1.163 ± 0.371	1.103 ± 0.22	0.582 ± 0.05	1.358 ± 0.28
Fe (ppm)	9909 ± 2676	11963 ± 3370	22910 ± 17360	19008 ± 968	72284 ± 11336	21339 ± 6321	8432 ± 540	30334 ± 21627
Hf (ppm)	5.51 ± 1.27	4.15 ± 0.60	4.96 ± 1.35	14.59 ± 0.46	1.53 ± 0.44	5.69 ± 0.78	5.05 ± 0.10	5.15 ± 1.27
Rb (ppm)	82.9 ± 19.6	37.9 ± 16.9	127.8 ± 91.2	115.9 ± 21.5	23.8 ± 11.8	11.0 ± 3.9	85.9 ± 3.3	22.9 ± 14.5
Sb (ppm)	0.172 ± 0.139	0.145 ± 0.087	0.312 ± 0.22	0.49 ± 0.163	0.397 ± 0.592	0.331 ± 0.135	0.307 ± 0.076	0.444 ± 0.123
Sc (ppm)	5.83 ± 1.73	7.70 ± 2.47	9.90 ± 4.52	1.70 ± 0.40	26.93 ± 10.35	8.17 ± 2.60	5.31 ± 0.42	12.87 ± 10.85
Ta (ppm)	0.608 ± 0.079	0.269 ± 0.068	0.709 ± 0.35	1.342 ± 0.056	0.077 ± 0.005	0.325 ± 0.04	0.645 ± 0.025	0.415 ± 0.141
Tb (ppm)	1.119 ± 0.293	0.751 ± 0.088	0.99 ± 0.565	1.911 ± 0.131	0.532 ± 0.264	0.614 ± 0.082	1.1 ± 0.101	0.789 ± 0.215
Th (ppm)	9.31 ± 1.43	4.20 ± 0.44	9.83 ± 4.75	12.78 ± 0.46	0.53 ± 0.37	3.11 ± 0.47	7.62 ± 0.32	6.32 ± 2.04
Zn (ppm)	39.7 ± 13.7	40.1 ± 15.2	58.9 ± 21.3	77.0 ± 27.6	100.8 ± 27.1	54.2 ± 13.2	33.4 ± 7.0	97.0 ± 84.3
Zr (ppm)	121.4 ± 29.8	109.6 ± 21.3	132.2 ± 39.4	346.8 ± 14.5	26.7 ± 3.2	140.2 ± 22.5	103.6 ± 6.3	138.8 ± 33.7
Al (ppm)	55640 ± 5324	57312 ± 5749	68527 ± 12938	61232 ± 2284	92072 ± 6069	75798 ± 7137	64847 ± 2936	66258 ± 11079
Ba (ppm)	511 ± 127	340 ± 88	1026 ± 515	67 ± 8	246 ± 49	314 ± 156	694 ± 74	367 ± 241
Ca (ppm)	2843 ± 1643	9534 ± 4486	9969 ± 9902	4186 ± 1483	50932 ± 24188	13940 ± 7499	4862 ± 558	8128 ± 4617
Dy (ppm)	6.53 ± 1.69	4.00 ± 0.29	5.84 ± 3.28	11.57 ± 0.31	2.40 ± 1.18	3.46 ± 0.38	6.38 ± 0.68	4.31 ± 1.61
K (ppm)	23411 ± 6230	13532 ± 3766	36108 ± 15997	35210 ± 6863	6864 ± 5154	7764 ± 2671	30612 ± 2411	10122 ± 8068
Mn (ppm)	324 ± 106	605 ± 87	679 ± 366	413 ± 88	1588 ± 331	750 ± 170	263 ± 69	555 ± 157
Na (ppm)	25864 ± 3909	27432 ± 5168	20559 ± 13100	26636 ± 4362	25145 ± 11777	42853 ± 4957	27469 ± 2554	36661 ± 5724
Ti (ppm)	616 ± 309	1068 ± 273	1862 ± 1198	976 ± 194	4933 ± 1790	2062 ± 890	757 ± 151	2046 ± 590

Table 5.3. Rock Samples Arranged by Chemical Group, With Mahalanobis Probabilities of Membership in the Uwharrie 1 Group.

Chemical Group: Sample	Quarry Zone	Field Name	Normative Name	TAS Name	Probability of Membership in Uwharrie 1
Cumberland:					
FBL040	Cumberland County	basalt	andesite/basalt	basaltic trachyandesite	0.000
FBL041	Cumberland County	diorite	andesite/basalt	basaltic trachyandesite	0.000
FBL042	Cumberland County	tuff?	andesite/basalt	trachybasalt	0.000
FBL070	Cumberland County	greenstone	andesite/basalt	basalt	0.000
FBL071	Cumberland County	metagabbro	andesite/basalt	basalt	0.000
Chatham 1:					
FBL027	Chatham Pittsboro	mudstone	rhyodacite	-	0.177
FBL028	Chatham Pittsboro	mudstone	alkali feldspar rhyolite	rhyolite	0.000
FBL029	Chatham Pittsboro	siltstone	rhyodacite	rhyolite	0.016
FBL030	Chatham Pittsboro	fine sandstone	dacite	rhyolite	0.001
FBL035	Chatham Siler City	mud/siltstone	dacite	dacite	0.035
FBL036	Chatham Siler City	dacite	andesite/basalt	rhyolite	0.039
FBL037	Chatham Siler City	mudstone	rhyodacite	dacite	0.005
FBL038	Chatham Siler City	sandstone	andesite/basalt	trachyandesite	0.001
FBL056	Chatham Pittsboro	mudstone	alkali feldspar rhyolite	-	0.009
FBL057	Chatham Pittsboro	mudstone	dacite	rhyolite	0.155
Chatham 2:					
FBL031	Chatham Silk Hope	dacite/rhyodacite	rhyodacite	rhyolite	0.000
FBL032	Chatham Silk Hope	lithic tuff	dacite	rhyolite	0.000
FBL033	Chatham Silk Hope	dacite	rhyodacite	rhyolite	0.000
FBL034	Chatham Silk Hope	lithic tuff	dacite/rhyodacite	rhyolite	0.000
FBL058	Chatham Silk Hope	lithic tuff	rhyodacite	rhyolite	0.000
FBL059	Chatham Silk Hope	lithic tuff	rhyodacite	rhyolite	0.000
Durham:					
FBL047	Durham County	dacite	dacite	rhyolite	0.017
FBL048	Durham County	sandstone	andesite/basalt	trachyte	0.026
FBL049	Durham County	sandstone	andesite/basalt	rhyolite	0.084
FBL050	Durham County	tuff	andesite/basalt	rhyolite	0.032
FBL066	Durham County	dacite	andesite/basalt	rhyolite	0.041
FBL067	Durham County	sandstone	andesite/basalt	trachydacite	0.016
Orange:					
FBL060	Orange County	dacite	dacite	rhyolite	45.135
FBL061	Orange County	dacite	dacite	rhyolite	42.825
FBL062	Orange County	dacite	dacite	rhyolite	51.821
FBL063	Orange County	dacite	dacite	rhyolite	63.075
FBL064	Orange County	dacite	rhyodacite	rhyolite	74.721
FBL065	Orange County	dacite	dacite	rhyolite	80.739
Person:					
FBL043	Person County	mudstone?	andesite/basalt	trachyte	0.009
FBL044	Person County	tuff	dacite	rhyolite	1.518
FBL045	Person County	mudstone	andesite/basalt	rhyolite	0.020
FBL046	Person County	sandstone	dacite	rhyolite	0.025
FBL068	Person County	siltstone	dacite	rhyolite	0.032
FBL069	Person County	siltstone	dacite	rhyolite	0.012

Table 5.3. Rock Samples Arranged by Chemical Group, With Mahalanobis Probabilities of Membership in the Uwharrie 1 Group (continued).

Chemical Group: Sample	Quarry Zone	Field Name	Normative Name	TAS Name	Probability of Membership in Uwharrie 1
Uwharrie 1:					
FBL001	Uwharries Eastern	dacite	dacite	rhyolite	16.259
FBL002	Uwharries Eastern	dacite	dacite	rhyolite	55.101
FBL003	Uwharries Eastern	dacite	dacite/rhyodacite	rhyolite	20.157
FBL004	Uwharries Eastern	dacite	dacite	rhyolite	4.879
FBL005	Uwharries Eastern	dacite	dacite	rhyolite	1.858
FBL006	Uwharries Eastern	dacite	dacite	rhyolite	90.923
FBL007	Uwharries Eastern	dacite	rhyodacite	rhyolite	34.740
FBL008	Uwharries Western	andesite	dacite	rhyolite	86.592
FBL009	Uwharries Western	andesite	dacite	rhyolite	45.329
FBL010	Uwharries Western	andesite	dacite	rhyolite	12.279
FBL011	Uwharries Western	andesite	dacite	rhyolite	94.411
FBL012	Uwharries Western	andesite/latite	dacite	rhyolite	94.736
FBL013	Uwharries Western	andesite	dacite	rhyolite	0.231
FBL014	Uwharries Western	andesite/latite	dacite	rhyolite	0.612
FBL015	Uwharries Southern	felsite	dacite	rhyolite	84.734
FBL016	Uwharries Southern	felsite	dacite	rhyolite	64.795
FBL017	Uwharries Southern	felsite	dacite	rhyolite	63.901
FBL018	Uwharries Southern	felsite	dacite	rhyolite	66.801
FBL019	Uwharries Southern	felsite	dacite	rhyolite	89.434
FBL025	Uwharries Southeastern	dacite	rhyodacite	rhyolite	87.153
FBL026	Uwharries Southeastern	dacite	dacite	rhyolite	37.897
FBL051	Uwharries Southeastern	dacite	rhyodacite	-	95.755
FBL052	Uwharries Southeastern	dacite	-	-	3.543
FBL053	Uwharries Southeastern	dacite	dacite	rhyolite	79.296
FBL054	Uwharries Southeastern	dacite	rhyodacite	-	56.695
Uwharrie 2:					
FBL020	Uwharries Asheboro	tuff	dacite	rhyolite	0.404
FBL021	Uwharries Asheboro	dacite/andesite	dacite	rhyolite	0.138
FBL022	Uwharries Asheboro	dacite/andesite	dacite	rhyolite	0.587
FBL023	Uwharries Asheboro	dacite	dacite	rhyolite	0.045
FBL024	Uwharries Asheboro	tuff	dacite	rhyolite	0.991
FBL055	Uwharries Asheboro	dacite	dacite	rhyolite	1.164
Ungrouped:					
FBL039	Cumberland County	aplite	rhyodacite	rhyolite	

From Figures 5.3 and 5.4, it is obvious that both Chatham 2 and Cumberland can be excluded as possible sources for the nine artifacts in this study. In Figures 5.5 through 5.7, the artifacts are projected against the remaining six chemical groups. Examination of the plots suggests that Uwharrie 1 is the most probable source for all of the artifacts except FBL073 and FBL075. The latter two artifacts have greater likelihood of belonging to the Chatham 1 or Person sources. We support this observation by calculating the Mahalanobis distance probabilities where the probabilities of the artifacts relative to the Uwharrie 1 source were determined using 99% of the variance in the database (Table 5.4). Probabilities are high for FBL074, FBL076, and FBL077 to belong to the Uwharrie 1 group. Samples FBL072, FBL078, FBL079, and FBL080 have modest probabilities of membership. The extremely low probabilities for FBL073 and FBL075 suggest they are from a different source.

Table 5.4. Fort Bragg Artifacts, With Mahalanobis Probabilities of Membership in the Uwharrie 1 Group.

Sample	Site	Field Name	Normative Name	TAS Name	Probability of Membership in Uwharrie 1
FBL072	31Hk100	dacite	dacite	rhyolite	3.287
FBL073	31Hk148	dacite	dacite	rhyolite	0.006
FBL074	31Hk173	dacite	dacite	rhyolite	27.184
FBL075	31Hk182	andesite	andesite/basalt	dacite	0.041
FBL076	31Hk224	tuff/siltstone	dacite	rhyolite	37.415
FBL077	31Hk737	siltstone	dacite	rhyolite	20.243
FBL078	31Hk999	dacite	dacite	rhyolite	1.536
FBL079	31Hk1408	dacite	dacite	rhyolite	5.457
FBL080	Flat Creek	dacite	dacite	rhyolite	1.163

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Chapter 6

Geochemistry: Neodymium Isotopes

Drew S. Coleman and Brent V. Miller

Seventy-one samples of metamorphosed volcanic rocks (dacite, andesite, and rhyolite) and metamorphosed volcaniclastic rocks (e.g., mudstones, siltstones, sandstones, and volcanic breccia) from archaeological quarry sites in North Carolina and nine samples of lithic artifacts from archaeological sites on Fort Bragg were analyzed for neodymium (Nd) isotope geochemistry. The isotopic ratios, corrected for radioactive decay of parent samarium (Sm), were used to develop a database for North Carolina quarry samples and to determine if artifacts could be sourced to individual geologic formations or quarries. This report summarizes the first attempt to source artifacts from Fort Bragg using Nd isotope geochemistry and is based on the method presented by Brady and Coleman (2000).

Background

Because interpretation of Nd isotope data in archaeological studies is somewhat unconventional, it is worthwhile to explain the theory behind the technique and differences between this analysis and more conventional approaches before presenting the results. Previous attempts to discriminate lithic artifact quarry sites have mainly focused on petrographic analysis and analysis of major-element compositions using a variety of techniques (Daniel and Butler 1991, 1996; Daniel 1994a). Both petrography and major-element concentrations are very useful for broad characterization of igneous rocks. However, these analyses can overlook important genetic differences between similar rock types. A volcanic rock of rhyolitic composition, for example, is defined mineralogically by the abundance of quartz, alkali feldspar, and plagioclase and is defined chemically by the proportions of major cations — silicon (Si), calcium (Ca), sodium (Na), aluminum (Al), iron (Fe), and magnesium (Mg). Magmas of rhyolitic composition, however, can be produced in different geological settings and by partial melting of different types of source rocks. Trace-element geochemical signatures and Nd-isotopic compositions are much more powerful tools by which modern geochemists are able to characterize and discriminate ancient volcanic rocks that formed in different geological settings and were derived from melting of different source rocks.

The isotope approach (Brady and Coleman 2000) is distinct from elemental approaches because geologic processes occurring in the earth's crust are incapable of fractionating *isotopes* of the "heavy elements" (e.g., Nd) from one another. Thus, if a magma with an isotopic ratio of ^{143}Nd/^{144}Nd = 0.5125 is cooling and crystallizing, all of the minerals crystallizing from that magma will have the same ratio of ^{143}Nd/^{144}Nd = 0.5125. Geologic processes do, however, segregate different *elements* (e.g., Sm from Nd). Thus, if the magma with ^{143}Nd/^{144}Nd = 0.5125 has a Sm/Nd ratio of 0.25, minerals crystallizing from the magma will all have the same ^{143}Nd/^{144}Nd but could theoretically inherit a range of Sm/Nd from 0 to ∞. These relations can be plotted on a bivariate diagram, with Sm/Nd expressed in terms of isotopes of the elements (i.e., ^{147}Sm/^{144}Nd) for reasons that will be apparent below (Figure 6.1). On this plot, the theoretical magma and its crystallizing minerals plot along a horizontal line ($m = 0$) with the same ^{143}Nd/^{144}Nd isotopic ratio but different Sm/Nd elemental ratios at the time of crystallization.

Herein lies the advantage of isotopic approaches over elemental approaches. If samples are taken from the crystallized magma the absolute Sm and Nd concentrations, and even the Sm/Nd ratio, can vary from sample to sample. The problem becomes less acute when large samples can be collected, but this is not always possible in archaeological studies. If isotopic ratios are compared, however, all samples, and even individual minerals within the samples, should have the same initial isotopic ratio.

The isotope approach can be applied as a sourcing tool only if the potential source rocks inherited different original Nd isotope ratios. The ^{143}Nd/^{144}Nd of rocks is variable because ^{147}Sm undergoes radioactive decay to ^{143}Nd with a half-life of 106 billion years ($\lambda = 6.54\text{E}^{-12}$). Thus, the ratio of ^{143}Nd/^{144}Nd in any magma source is dependent on ^{147}Sm/^{144}Nd and time and varies by geologic setting and age. This relation can be expressed as

$$^{143}\text{Nd}/^{144}\text{Nd}_{(\text{now})} = (^{143}\text{Nd}/^{144}\text{Nd}_{(\text{original})} + {}^{147}\text{Sm}/^{144}\text{Nd}_{(\text{now})})\ (\exp^{\lambda t} -1) \qquad (1).$$

This is the equation of a line in a bivariate plot of ^{143}Nd/^{144}Nd$_{(\text{now})}$ versus ^{147}Sm/^{144}Nd$_{(\text{now})}$ with the y-intercept equal to ^{143}Nd/^{144}Nd$_{(\text{original})}$ and the slope proportional to the age of the sample, t (hence the choice of axes in Figure 6.1).

Returning to the theoretical magma in Figure 6.1, as time passes, samples and minerals with high ^{147}Sm/^{144}Nd will show a relatively rapid increase in ^{143}Nd/^{144}Nd and samples and minerals with low ^{147}Sm/^{144}Nd will show a relatively slow increase in ^{143}Nd/^{144}Nd. At any time, however, the samples will all fall on a line with a slope

$$m = (\exp^{\lambda t} -1) \qquad (2)$$

and by rearranging

$$t = \ln(m + 1) / \lambda \qquad (3).$$

Therefore, assuming the ^{143}Nd/^{144}Nd and ^{147}Sm/^{144}Nd ratios can be measured and the *geologic* age of the sample (t) can be estimated, it is possible to calculate ^{143}Nd/^{144}Nd$_{(\text{original})}$, which should be the same for any geologic sample or artifact collected from the same volcanic rock.

A few final points regarding the utility of the Sm/Nd isotopic approach are important to summarize. First, the present-day isotopic ratios (^{143}Nd/^{144}Nd$_{(\text{now})}$ and ^{147}Sm/^{144}Nd$_{(\text{now})}$) are potentially (and likely) useless for comparison depending on the scale of variation of Sm/Nd and the geologic age of the sample. More useful is the *initial* ^{143}Nd/^{144}Nd (^{143}Nd/^{144}Nd$_{(\text{original})}$) at the time of magma or lava crystallization. Initial ratios are better geological discriminants because they are indicative of distinct geological processes and magma sources. Calculation of ^{143}Nd/^{144}Nd$_{(\text{original})}$ requires that the ^{143}Nd that has accumulated due to the decay of ^{147}Sm be stripped out of the measured, present-day ^{143}Nd/^{144}Nd ratio. This requires knowledge of the amount of time that has passed since crystallization.

Second, as a consequence of the foregoing process, the *geologic* age of the sample must be known. Accumulation of ^{143}Nd through the decay of ^{147}Sm occurs independently of collecting a sample and/or fashioning it into a tool. Because dating rocks is a costly and time-consuming

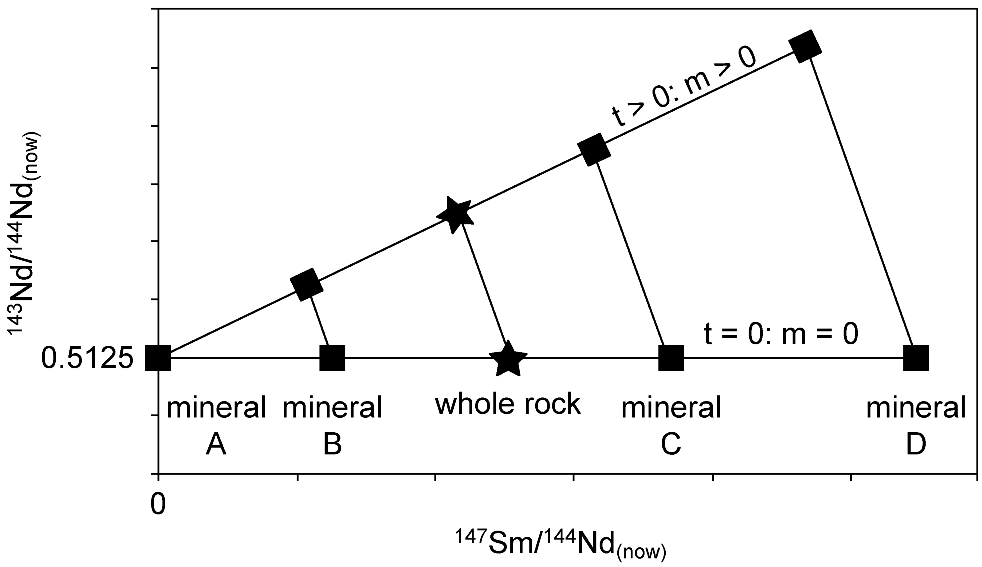

Figure 6.1. Conventional Sm/Nd isochron diagram. Samples from a single magma will have identical ^{143}Nd/^{144}Nd and variable ^{147}Sm/^{144}Nd at the time of crystallization. Through time, however, these ratios will change (^{143}Nd/^{144}Nd will increase and ^{147}Sm/^{144}Nd will decrease) as the result of decay of parent isotope ^{147}Sm to daughter ^{143}Nd. If the geologic age of a sample collected today is known, the effects of decay can be corrected for and initial isotope ratios can be compared. Samples of a single rock (a homogeneous quarry) should have identical ^{143}Nd/^{144}Nd$_{(initial)}$ despite having variable concentrations of Sm and Nd and variable Sm/Nd ratios that may be introduced through sampling bias caused by necessarily small samples of artifacts.

endeavor, the geologic age is commonly estimated with only a minor effect on the accuracy of ^{143}Nd/^{144}Nd$_{(original)}$. Since the geologic age of an artifact cannot be estimated through geological correlation and reasoning, its ^{143}Nd/^{144}Nd$_{(original)}$ must be calculated using the age of each quarry to which it is being compared.

Third, the technique depends on the assumption that ^{143}Nd/^{144}Nd$_{(original)}$ of an outcrop is homogeneous. The necessity of this assumption poses two potential problems relevant to this study. First, heterogeneous outcrops with variable rock types cannot be used unless all rock types are sampled and direct comparisons of artifacts to specific rock types are made. Second, sedimentary rocks must be approached with caution as they are aggregates of different rocks and minerals from different sources with (almost certainly) variable ^{143}Nd/^{144}Nd$_{(original)}$. An important corollary is that metamorphosed rocks (with igneous or sedimentary protoliths) can be used if ^{143}Nd/^{144}Nd is homogenized during metamorphism (although this would need to be independently verified).

Fourth, the Sm/Nd approach has a distinct advantage over other isotopic and elemental approaches in that Sm and Nd are both rare-earth elements and therefore behave very similarly during post-magmatic processes. Thus, the technique is relatively impervious to alteration of samples and artifacts. Secondary alteration likely impacts the absolute concentrations of most elements (including Sm and Nd), but it is unlikely to significantly impact Sm/Nd and will certainly not impact ^{143}Nd/^{144}Nd. Consequently, unlike other isotopic systems (e.g., rubidium/strontium [Rb/Sr]) and elemental data, the Sm/Nd system can “see through” all but the worst alteration.

Results

The quarry zones form distinct trends or clusters on the conventional Sm/Nd isochron diagram (Figure 6.2; Appendix G). Most samples from the Uwharries form a broadly linear array that spans much of the total range of $^{147}Sm/^{144}Nd_{(now)}$, although two Uwharries Asheboro samples fall off this trend at significantly higher $^{143}Nd/^{144}Nd_{(now)}$ (FBL021 and FBL022). Most Cumberland County samples lie along the same trend defined by the Uwharries samples, but at higher $^{147}Sm/^{144}Nd_{(now)}$, and one sample from Cumberland County (FBL070) plots with the two Uwharries Asheboro outliers. Chatham Pittsboro samples form a trend with distinctly low $^{143}Nd/^{144}Nd_{(now)}$, although there is one outlier at higher $^{143}Nd/^{144}Nd_{(now)}$ (FBL056). Chatham Silk Hope and Chatham Siler City samples cluster tightly together. Durham and Person County samples also overlap significantly, and together with the Chatham Silk Hope and Chatham Siler City samples they define a trend at nearly constant $^{143}Nd/^{144}Nd_{(now)}$ over a range of $^{147}Sm/^{144}Nd_{(now)}$. The Orange County samples define a tight cluster distinct from other quarries.

Within the Uwharrie Mountains, some clear Sm-Nd isotopic distinctions can be correlated with geological formation and quarry zone (Figure 6.2). Generally speaking, samples from the Uwharrie Formation (Uwharries Southeastern and Asheboro zones) anchor the low end of the linear trend, samples from the Cid Formation (Uwharries Western zone) comprise the high end, and samples from the Tillery Formation (Uwharries Asheboro, Southern, and Eastern zones) fall in the middle. With a few exceptions, samples from individual quarry zones tend to form distinct clusters on the graph. Whether the exceptions result from mapping errors or real variation within the formations is unclear. Of all the quarry zones within the Uwharries, Uwharries Asheboro seems to show the greatest variation.

Artifacts from Fort Bragg show significant variability in both $^{143}Nd/^{144}Nd_{(now)}$ and $^{147}Sm/^{144}Nd_{(now)}$ (Figure 6.2). Two artifacts yield results along the relatively flat data array defined by samples from Chatham, Cumberland, Durham, Orange and Person Counties. Two artifacts have isotopic ratios within the array defined by quarries within the Uwharries. Together, the artifacts lie along a poorly defined trend with a much steeper slope than arrays defined by quarry samples.

Age of the Quarries

The crystallization ages of the rocks from the quarries must be reasonably well known in order to compare initial isotopic ratios with the artifacts. The crystallization age of the rocks from the Uwharries is known to be between 540 and 580 million years ago (Ma) based on U-Pb zircon geochronology (Wright and Seiders 1980; Mueller et al. 1996; Ingle 1999). A single rhyolite sample collected by one of us (BVM) from bedrock at the top of Morrow Mountain (equivalent to FBL015) yielded a U-Pb zircon crystallization age of 569 ± 4 Ma. Samples from Chatham, Durham, Orange, and Person Counties are derived from rocks in the Virgilina sequence, which consistently yields ages of approximately 600 Ma (Wortman et al. 2000). Samples from Cumberland County were collected from river gravels; thus, it is impossible to assign a precise geologic age with confidence. Fortunately, because the samples have similar Sm/Nd, and because the half-life of ^{147}Sm is so long (106 billion years), correction of all the Nd isotopic data to initial ratios between 500 and 700 Ma yields similar results. Consequently, we compare initial ratios at 550 Ma.

Age information for the quarries may also be obtained from the Sm/Nd data by solving equation (3) if the samples are geologically related and shared a common initial $^{143}Nd/^{144}Nd$. For

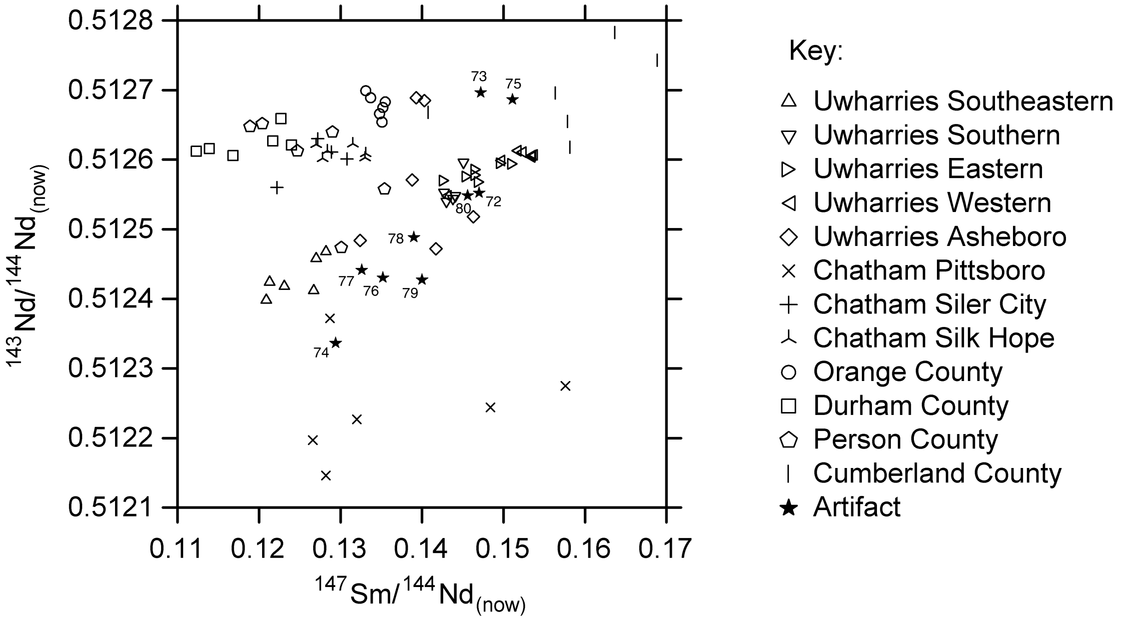

Figure 6.2. Conventional isochron diagram showing isotope ratio plots for quarry and artifact samples. Samples from the Uwharries form a fairly consistent sloping array. Although artifacts are anchored within the array at high ^{147}Sm/^{144}Nd, they deviate from the trend with decreasing ^{147}Sm/^{144}Nd. Individual artifacts are labeled with their FBL-number suffixes.

example, most samples from the Uwharries appear to fall along a linear sloping array in Figure 6.2. However, regression of a line through the Sm/Nd data yields a slope corresponding to a geologically unreasonable age of nearly 900 Ma. Closer inspection of data from a single quarry locality at Shingle Trap Mountain (FBL001-FBL004) yields a Sm/Nd age of 546 Ma, which is very close to the 538 ± 6 Ma crystallization age reported by Ingle (1999; her "Morrow Mountain rhyolite" was actually collected from Shingle Trap Mountain). These trends from the Uwharries imply that magmas were isotopically homogeneous locally, but overall reflect mixing of magma sources. This results in samples from the Uwharries having initial isotopic ratios from 0.51195 to 0.51207.

With the exceptions of one Chatham Pittsboro sample (FBL056), two Person County samples (FBL044, FBL068), and the Cumberland County samples, the remaining quarries define relatively small ranges in isotopic ratios at 550 Ma that are distinct from the initial ratios of the Uwharries.

Although it is tempting to attach significance to the fairly coherent linear trend defined by the artifacts, there is no a priori reason to believe that the samples have any geologic relation. Therefore, the apparent trend is likely meaningless. The artifacts correct back to initial ^{143}Nd/^{144}Nd between 0.51187 and 0.51218 at 550 Ma (Appendix G).

Matching Artifacts to Quarries

Comparison of isotopic ratios at 550 Ma reveals significant overlap between the artifacts and quarries within the Uwharries (Appendix G). One sample from Chatham Pittsboro (FBL056) has a ^{143}Nd/^{144}Nd$_{(550\ \mathrm{Ma})}$ ratio that comes close to samples from the Uwharries and is quite distinct from other Chatham Pittsboro samples. Whereas other Chatham Pittsboro samples were collected from outcrop, FBL056 was collected from float at the quarry and showed clear evidence for working. This raises the possibility that the sample was in fact transported from the Uwharries — perhaps it was abandoned at the quarry site thousands of years ago, or perhaps it is a piece of modern construction trash. Yet it is equally possible that this variation is characteristic of the metasedimentary rocks in the Virgilina sequence, of which the Chatham Pittsboro quarries are a part. Similarly, two samples from Person County (FBL044, FBL068) have Uwharrie-like isotope ratios, but again these are metasedimentary rocks, which seem to exhibit much more isotopic variation than the metavolcanics from any given locality.

To help identify potential matches between quarries and artifacts, $^{143}Nd/^{144}Nd_{(550\text{ Ma})}$ is plotted against ratios of immobile elements (i.e., elements not readily impacted by alteration, such as lanthanum/lutetium [La/Lu] and tantalum/ytterbium [Ta/Yb]; Figures 6.3-6.4). Note that the artifact samples have trace element ratios very similar to quarries that the Nd isotope ratios exclude as possible sources. For example, most artifacts have La/Lu (Figure 6.3) and Ta/Yb (Figure 6.4) ratios similar to quarry samples from Chatham, Durham, Orange and Person Counties, but with few exceptions the Nd isotopic data exclude these localities as sources.

Using a combination of isotopic and immobile element ratios, several fairly reliable matches between artifacts and quarries can be made. Two artifacts (FBL072, FBL080) consistently match Uwharries Southern samples collected from Morrow Mountain and Tater Top Mountain and Uwharries Eastern sample FBL006 collected from Sugarloaf Mountain. Two additional artifacts (FBL077 and FBL078) are consistent matches for the Uwharries Southeastern samples collected from Lick Mountain. The petrographic description of FBL078 also matches the Lick Mountain quarries quite well, but petrographic data tentatively identify FBL077 as being derived from a metasedimentary rock. Therefore, the isotopic correlation of FBL077 with Lick Mountain volcanic rocks is either fortuitous (emphasizing the importance of a multidisciplinary approach to this exercise), or the artifact was derived from a very closely related volcaniclastic rock. Artifact FBL076 is described as petrographically similar to FBL077, and there is significant overlap in the initial Nd isotopic ratio of these two artifacts and samples from Lick Mountain and the Uwharries Asheboro zone. The trace element ratios of FBL076, however, are significantly different from those of FBL077 and both quarry localities. This may indicate that the artifact was derived from an unidentified quarry in immature metasedimentary rock that is closely related to the Lick Mountain and Uwharries Asheboro volcanic rocks.

Two additional artifacts (FBL073, FBL075) are good geochemical matches for the Uwharries Asheboro quarries at Caraway (FBL021) and Tater Head (FBL022) Mountains. However, artifact FBL073 was positively identified as derived from Orange County on the basis of petrographic data. There is also a good isotopic match between Orange County quarries and FBL073, but the trace element ratios are a poor fit. One possible explanation for this poor fit is the difference in alteration between Orange County quarry samples and the artifact (as described in Chapter 4): despite remarkable similarity in petrography, the artifact was significantly less altered. As described above, alteration would impact trace element ratios without impacting isotopic compositions, possibly offering an explanation for the discrepancy. As a result of the excellent match in isotopic ratios and petrography, we tentatively correlate FBL073 with the Orange County quarries.

Two final artifacts (FBL074, FBL079) have isotopic ratios lower than those from the Uwharries samples. Chatham Pittsboro sample FBL056 provides the closest match for these artifacts, but it is a better match for FBL079 on the La/Lu plot and for FBL074 on the Ta/Yb plot, suggesting that the match is not particularly robust.

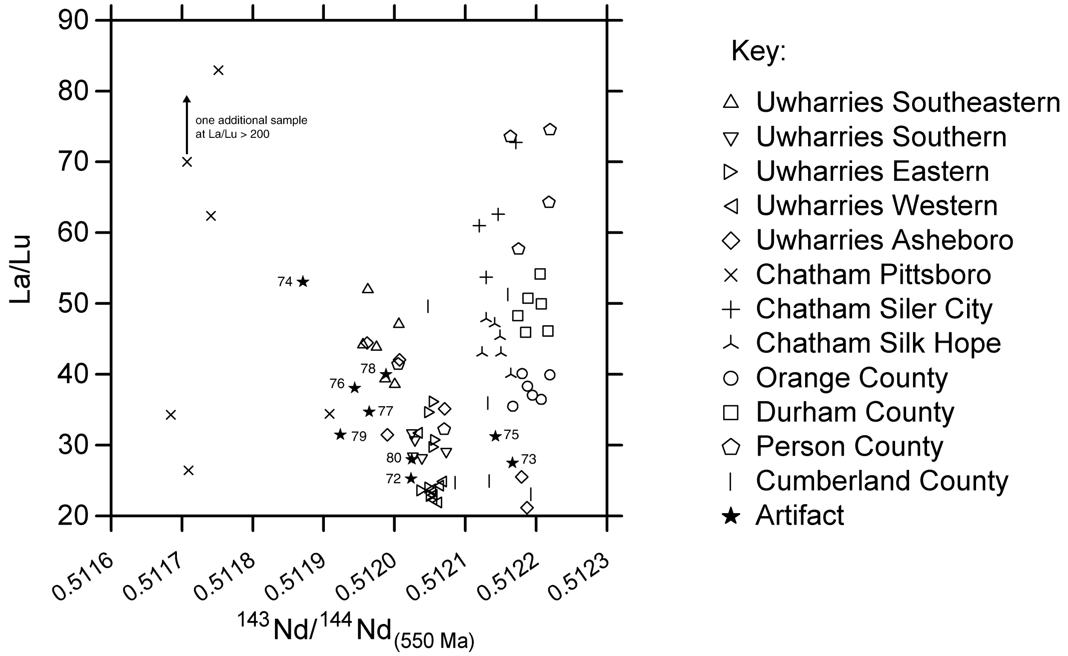

Figure 6.3. Isotope and trace element ratio plot for quarry and artifact samples showing Nd isotopes calculated at 550 Ma (the nominal age of rocks in the Uwharries) versus La/Lu. La/Lu provides an index of magmatic differentiation (more evolved magmas and sedimentary rocks have higher La/Lu) and is fairly insensitive to alteration. Individual artifacts are labeled with their FBL-number suffixes.

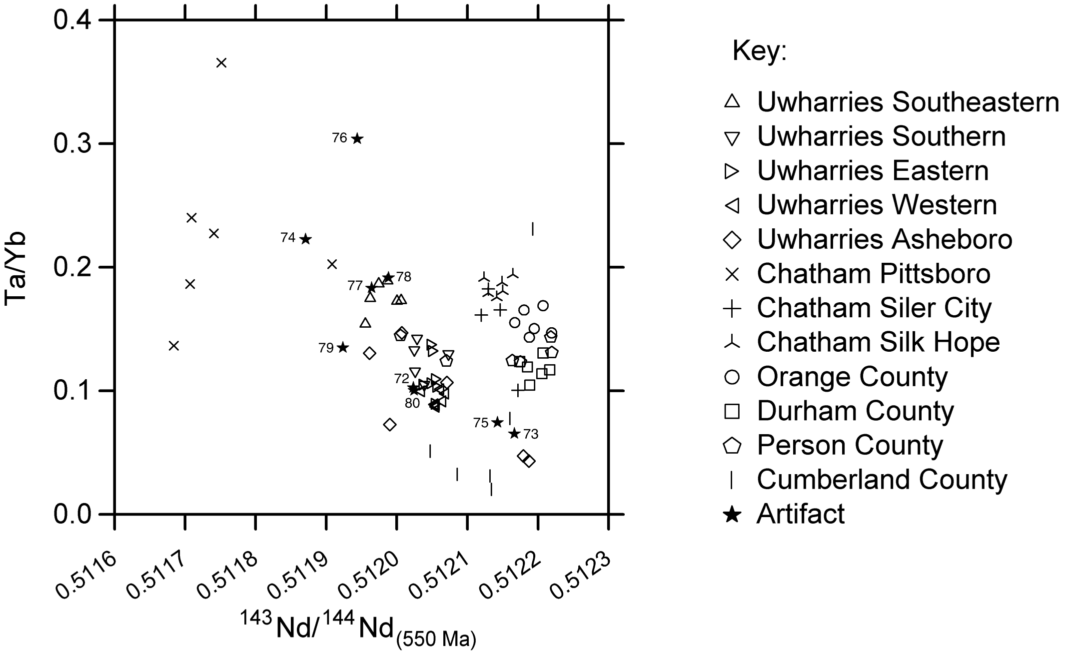

Figure 6.4. Isotope and trace element ratio plot for quarry and artifact samples showing Nd isotopes calculated at 550 Ma (the nominal age of rocks in the Uwharries) versus Ta/Yb. The Ta/Yb ratio was chosen because both elements are considered “immobile,” and their ratio should be fairly resistant to metamorphism and alteration. Individual artifacts are labeled with their FBL-number suffixes.

Summary and Conclusions

Several of the artifacts from Fort Bragg can be sourced with some confidence to locations within the Uwharrie Mountains, and a single artifact is likely derived from Orange County. The remainder of the artifacts variably share petrographic and trace element affinities with samples from the Uwharries and most other quarries, but in initial Nd isotopic composition overlap only with samples from the Uwharries and one sample each from the Chatham Pittsboro and Person County zones. The close match of at least one, and possibly two, artifacts fashioned from metasedimentary rocks with elemental and isotopic data for volcanic rocks in the Uwharrie Mountains suggests a search for quarries within immature sedimentary rocks in the region may yield sources for these artifacts. There is also a suggestion in the quarry isotopic data that suitable sources may be located in the Chatham Pittsboro and Person County zones. Specifically, a closer investigation for variable rock types within the quarries from which FBL056 and FBL068 were collected seems warranted.

The multidisciplinary approach presented here demonstrates that no single data type (petrographic, elemental, or isotopic) can be relied upon to provide unique results. The isotopic approach described in this chapter has the distinct advantages, however, of (*a*) being independent of sample bias introduced by extremely limited sample sizes common in archaeological analysis, and (*b*) being able to distinguish common volcanic rocks that often share closely similar petrographic and geochemical signatures.

Acknowledgments

John Rogers has been extremely helpful with all aspects of data analysis and report preparation. Jim Hibbard provided discussion and expertise in Carolina geology. Greg Weiss was indispensable during organization and preparation of samples. Dan Pignatello and Kate Renken did most of the elemental separation with a little help from Adam Tripp. Staci Loewy assisted with data collection.

Chapter 7

Conclusions

Vincas P. Steponaitis, Jeffrey D. Irwin, and John J. W. Rogers

In the preceding chapters, we have laid out our research design, outlined the geology of our study area, described the quarries and artifacts on which our study is based, and presented three different approaches to characterizing the composition of our samples. It now remains to pull the various lines of evidence together in assigning the artifacts to geological sources and to discuss the methodological and archaeological conclusions that have emerged.

We begin by reviewing the results presented in each of the analytical chapters in turn. Then we synthesize these results and consider their implications.

Petrography

Stoddard's petrographic study in Chapter 4 presents considerable information on the composition and character of the rocks in our sample. Through microscopic examination of thin sections, he identifies the larger mineral grains and also makes observations on textures and qualitative features that allow him to infer the processes by which the rocks were formed. He classifies the rocks based not only on mineralogy, but also on the major-element chemistry as determined by x-ray fluorescence.

Of the 12 quarry zones that were sampled, ten yielded relatively homogeneous rock assemblages, while the remaining two zones (Cumberland County and Chatham Siler City) produced assemblages that Stoddard describes as petrographically "heterogeneous." Each of the zones, particularly the homogeneous ones, is marked by certain distinctive features that set it apart from the others (Table 7.1; also see Table 4.4). These features are well summarized in Chapter 4 and need not be repeated here. For present purposes, it is most useful to focus on certain general trends in the distribution of rock types and minerals across the study area, at least as represented in the zones that we studied.

Particularly striking are the petrographic distinctions between the southern and northern portions of the study area (Figure 7.1), roughly corresponding to the Uwharrie and Virgilina rock sequences described in Chapter 2. In the southern zones, from Asheboro southward, all our quarry samples were metavolcanic rocks. In the northern zones, from Chatham County northward, our quarries yielded a mixture of metavolcanic and metasedimentary rocks. To some extent, this distinction is a product of our sampling strategy, but not entirely so. The Uwharrie Mountains are peppered with well-known metavolcanic quarries that were heavily used by ancient peoples, and it was these quarries on which we focused in selecting samples. Metasedimentary rocks also outcrop in the Uwharries, but these are generally not associated with

Table 7.1. Selected Petrographic Features of Quarry Zones.[a]

Quarry Zone[b]	Generalized Rock Types	Rock Types	Phenocrysts	Distinctive Metamorphic Minerals
Person County	metasedimentary, metavolcanic	mudstone, siltstone, sandstone, tuff		pyrite, calcite
Durham County	metasedimentary, metavolcanic	dacite tuff, tuffaceous sandstone	plagioclase	pyrite
Orange County	metavolcanic	dacite porphyry, crystal-lithic tuff	(coarse) quartz + plagioclase	calcite, low-T feldspar clots
Chatham Pittsboro	metasedimentary	mudstone, siltstone, sandstone		
Chatham Silk Hope	metavolcanic	dacitic lapilli, crystal-lithic tuff, breccia	plagioclase, K-feldspar	piedmontite, calcite, opaque minerals
Chatham Siler City	metasedimentary, metavolcanic	metasedimentary rocks, crystal-lithic tuff	plagioclase	green biotite
Cumberland County	metavolcanic	aplite, greenstone, (meta)gabbro, basalt, andesite/diorite, lapilli tuff, heterolithic tuff breccia		
Uwharries Asheboro (Tillery Formation)	metavolcanic	dacite tuffs and flows	plagioclase	garnet, pyrite, calcite, stilpnomelane[?]
Uwharries Asheboro (Uwharrie Formation)	metavolcanic	dacite tuffs and flows	plagioclase, quartz	garnet, brown biotite, stilpnomelane[?]
Uwharries Western	metavolcanic	dacite, rhyodacite	plagioclase, K-feldspar	green biotite, opaque minerals
Uwharries Eastern	metavolcanic	dacite flows, crystal-lithic tuffs	plagioclase + quartz	green biotite, stilpnomelane, pyrite, calcite, garnet, piedmontite
Uwharries Southern	metavolcanic	dacite, felsite		stilpnomelane
Uwharries Southeastern	metavolcanic	dacite flows and porphyries	quartz + plagioclase	actinolite, stilpnomelane[?], pyrite, epidote, sphene[?]

[a] Compiled from Tables 4.4 and C.1.

[b] Quarry zones are arranged in order from north to south (Figure 7.1).

known quarries and are not as desirable for making stone tools (Daniel 1998; North Carolina Geological Survey 1985). North of the Uwharrie Mountains, good metavolcanic sources seem to be scarcer, so metasedimentary quarries were probably more frequently used and thus more represented in our sampling.

Equally important is the observation made by Stoddard that rocks in the southern part of our study area show higher degrees of metamorphism than those in the north. This trend is clearly evident in the petrography of our quarry samples. Metamorphic minerals that form at higher temperatures and pressures, such as garnet and biotite, only occur in the more southerly zones: garnet is confined only to the Uwharries zones, and biotite occurs no farther north than Chatham

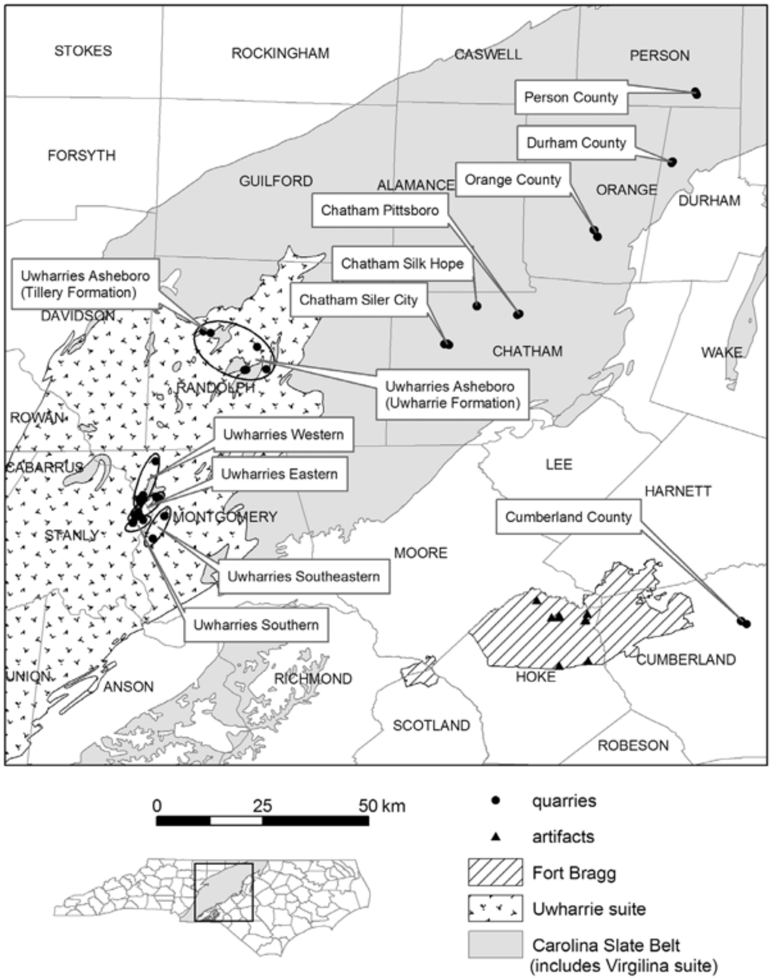

Figure 7.1. Geographical distribution of quarry zones. Note that the Uwharries Asheboro zone includes quarries from two different formations.

Siler City (Table 7.1). Thus, any rock that exhibits these distinctive minerals is much more likely to have originated in the southern portion of the Carolina Slate Belt.

Stoddard also examines the artifacts from Fort Bragg and attempts to match them with geological sources (Table 7.2). Interestingly, only two artifacts can be confidently matched with rocks from particular quarry zones: one with Uwharries Asheboro and another with Orange County. Four more are *tentatively* assigned to sources in the Uwharries: three to either Uwharries Asheboro or Uwharries Southeastern, and one to Uwharries Eastern. The remaining three samples are left unassigned.

Geochemistry: Elements

In Chapter 5, Glascock and Speakman look at the elemental composition of the quarry samples and artifacts as determined by neutron activation. Of the 33 elements detected, 27 are subjected to a principal components analysis and other calculations designed to help search for clustering among the samples, based on overall similarities in bulk composition.

Table 7.2. Selected Petrographic Features and Assignments of Fort Bragg Artifacts.[a]

Artifact	Generalized Rock Type	Rock Type	Phenocrysts	Distinctive Metamorphic Minerals	Quarry Zone Assignment (Chapter 4)
FBL072	metavolcanic	dacite	plagioclase	garnet, brown biotite	Uwharries Asheboro
FBL073	metavolcanic	dacite porphyry	plagioclase, quartz	-	Orange County
FBL074	metavolcanic	dacitic tuff	quartz, plagioclase	biotite, actinolite	Uwharries Eastern?
FBL075	metavolcanic	andesite	plagioclase	-	-
FBL076	metasedimentary?	dacitic tuff or siltstone	plagioclase	actinolite, brown biotite	-
FBL077	metasedimentary	siltstone	-	green biotite	-
FBL078	metavolcanic	dacite crystal-lithic tuff or porphyry	plagioclase, quartz	actinolite	Uwharries Asheboro?, Uwharries Southeastern?
FBL079	metavolcanic	dacitic tuff	plagioclase	brown biotite, actinolite	Uwharries Asheboro?, Uwharries Southeastern?
FBL080	metavolcanic	dacite	plagioclase	brown biotite, garnet	Uwharries Asheboro?, Uwharries Southeastern?

[a] Compiled from Tables 4.5 and C.1.

For the quarry samples, Glascock and Speakman define eight chemical groups, each of which corresponds to a geographical cluster of one or more quarry zones (Table 7.3). The patterns of chemical similarity are as follows:

- All of the quarry zones from the southern Uwharrie Mountains cluster to form the Uwharrie 1 group. The Uwharries Asheboro zone is sufficiently different to form another group, called Uwharrie 2.
- Chatham Pittsboro and Chatham Siler City – both mainly consisting of metasedimentary rocks – cluster to form the Chatham 1 group. The Chatham Silk Hope zone comprises the Chatham 2 group.
- Each of the remaining quarry zones forms a separate group, named Cumberland, Orange, Durham, and Person, respectively.

In other words, rock samples from the quarry zones south of Asheboro are similar enough chemically to constitute a single group, while the samples from other zones (except Chatham Pittsboro and Chatham Siler City) are distinctive enough to be placed in separate groups. The north-south distinction seen in the petrographic data is evident in the elemental data, although the geographic configuration of the compositional groups *within* the northern and southern parts of the study area is a bit different.

Glascock and Speakman then explore the relationships between these chemical groups and the artifacts from Fort Bragg using both graphs and Mahalanobis distance. The latter is a multivariate statistic that expresses the "probability of membership" of each artifact to any predefined group, based on proximity to the group's centroid and the dispersion (or variance) of the group's members. In this sense, it is analogous to a multivariate *z*-score. In order for this statistic to be valid, each reference group must have more members than the number of variables used in the calculation. In order to insure the most accurate possible results, Glascock and Speakman use 15 principal components, which together comprise more than 99% of the total variance, in making these calculations. This means that they can only determine the Mahalanobis probabilities of membership in Uwharrie 1, as that is the only group with more than 15 members.

Based on graphs of rare-earth element concentrations, Glascock and Speakman convincingly eliminate the Cumberland and Chatham 2 groups as possible sources for any of the artifacts. They then assign artifacts to the remaining sources by means of graphical comparisons and the Mahalanobis probabilities of membership in Uwharrie 1 (Table 7.4). Three of the artifacts have probabilities between 20% and 40%, four have probabilities between 1% and 6%, and the remaining two have probabilities of less than 1%. The first set is definitely assigned to Uwharrie 1, the second set is tentatively assigned to Uwharrie 1, and the last set is assumed to belong elsewhere – most likely to either the Chatham 1 or the Person group.

Glascock and Speakman's conclusions seem perfectly reasonable when the neutron activation data are considered in isolation. But if one looks at their assignments in light of the petrographic data discussed previously, some anomalies appear. Two of the three artifacts that Glascock and Speakman definitely assign to Uwharrie 1 are made of metasedimentary rocks, yet all of the quarry samples that comprise this group are metavolcanic. Moreover, both of the artifacts assigned to the Chatham 1 or Person groups are metavolcanic, while the quarries in these areas are mostly metasedimentary. Clearly, a closer look is warranted.

Table 7.3. Assignment of Quarry Zones to Chemical Groups, Based on Neutron Activation Analysis.[a]

Quarry Zone[b]	Generalized Rock Types	Chemical Group Assignment (Chapter 5)
Person County	metasedimentary, metavolcanic	Person
Durham County	metasedimentary, metavolcanic	Durham
Orange County	metavolcanic	Orange
Chatham Pittsboro	metasedimentary	Chatham 1
Chatham Silk Hope	metavolcanic	Chatham 2
Chatham Siler City	metasedimentary, metavolcanic	Chatham 1
Cumberland County	metavolcanic	Cumberland
Uwharries Asheboro (Tillery Formation)	metavolcanic	Uwharrie 2
Uwharries Asheboro (Uwharrie Formation)	metavolcanic	Uwharrie 2
Uwharries Western	metavolcanic	Uwharrie 1
Uwharries Eastern	metavolcanic	Uwharrie 1
Uwharries Southern	metavolcanic	Uwharrie 1
Uwharries Southeastern	metavolcanic	Uwharrie 1

[a] Compiled from Table 5.3.

[b] Quarry zones are arranged in order from north to south (Figure 7.1).

Table 7.4. Assignments of Fort Bragg Artifacts to Chemical Groups, Based on Neutron Activation Analysis.[a]

Artifact	Generalized Rock Type	Mahalanobis Probability of Membership in Uwharrie 1 Group	Chemical Group Assignment (Chapter 5)
FBL072	metavolcanic	3.29	Uwharrie 1?
FBL073	metavolcanic	0.01	Chatham 1?, Person?
FBL074	metavolcanic	27.18	Uwharrie 1
FBL075	metavolcanic	0.04	Chatham 1?, Person?
FBL076	metasedimentary?	37.42	Uwharrie 1
FBL077	metasedimentary	20.24	Uwharrie 1
FBL078	metavolcanic	1.54	Uwharrie 1?
FBL079	metavolcanic	5.46	Uwharrie 1?
FBL080	metavolcanic	1.16	Uwharrie 1?

[a] Based on Table 5.4 and discussion in Chapter 5.

One way that Glascock and Speakman's statistical analysis can be extended is by calculating Mahalanobis probabilities with reference to more than one group. Note that these probabilities are determined for each group independently, and so they need not sum to 100%. Thus, for example, a high probability of membership in Uwharrie 1 does not preclude an even higher probability of membership in another group. In this case, bringing additional groups into the calculation requires that we reduce the number of variables so that it is less than the number of members in the smallest group. The best solution is to use only the first four principal components, which together account for more than 80% of the total variance. While these four components contain less variance than the 15 used by Glascock and Speakman, they still capture most of the variation in the data and should produce interpretable results. The relatively small proportion of variance lost is more than offset by the advantage of being able to make comparisons with more than one reference group simultaneously.

Table 7.5 shows the Mahalanobis probabilities calculated in this way for each artifact, with reference to the six compositional groups that remain as plausible sources. One can see a more complex array of possibilities for group membership than was evident previously. If we were to make assignments based on the highest probability for each artifact, only one artifact would be assigned to Uwharrie 1, four would be assigned to Uwharrie 2, two would be placed in Chatham 1, and two would be assigned to the Durham group. Of course, such a decision rule may be too simplistic in this case, as some artifacts show comparably high probabilities of membership in more than one group. Also, because Mahalanobis probabilities behave like *z*-scores, reference groups with high internal variance tend to more easily "capture" additional members by means of the highest-probability criterion than do groups with smaller internal variance. This tendency must be taken into account when interpreting the numbers. It may, for example, explain why the probabilities of membership in the Uwharrie 2 and Person groups, with high internal variance, are generally greater than the probabilities for membership in the Orange group, which forms a very "tight" cluster (see Figure 5.5, noting the relative sizes of the confidence ellipses for each chemical group).

We will defer a further discussion of these relationships until later in this chapter, when we consider multiple lines of evidence in assigning provenance. For now, suffice it to say that the elemental data convincingly eliminate certain quarry zones (Cumberland County and Chatham Silk Hope) as sources for the Fort Bragg artifacts. The data further suggest that these artifacts show relationships to at least four different chemical groups corresponding to quarry zones located in both the southern and the northern portions of the study area.

Geochemistry: Isotopes

Coleman and Miller's analysis of neodymium (Nd) isotopes, presented in Chapter 6, provides additional useful information on patterns of compositional variability in the Carolina Slate Belt. Using a mass spectrometer, they measure the present-day ^{143}Nd/^{144}Nd ratio. Then, based on the known age of the rock and the abundance of ^{147}Sm (which radioactively decays to produce ^{143}Nd), they mathematically correct this ratio to estimate its original value at the time the rock was formed. This age-corrected Nd ratio is known to be constant for any given magma source. Thus, all the metavolcanic rocks that were formed from the same magma source would exhibit the same ratio. Moreover, the ratio is immune to accidental variation from

Table 7.5. Mahalanobis Probabilities of Group Membership, Based on Four Principal Components.[a]

	Chemical Group					
Artifact	Uwharrie 1	Uwharrie 2	Chatham1	Orange	Durham	Person
FBL072	12.82	**13.95**	1.28	0.80	9.76	11.76
FBL073	1.10	**14.90**	0.44	0.37	6.51	9.76
FBL074	**71.46**	13.54	23.99	3.16	9.28	16.87
FBL075	0.00	16.71	12.02	0.21	**38.41**	25.35
FBL076	9.69	16.33	**26.84**	10.64	20.30	20.98
FBL077	11.57	11.84	5.14	3.73	**23.60**	10.22
FBL078	2.83	13.74	**89.06**	5.29	10.41	45.61
FBL079	9.54	**21.82**	8.13	0.73	9.84	16.53
FBL080	1.29	**17.83**	0.54	0.37	7.14	10.22

[a] The highest probability in each row is shown in bold type.

inhomogeneities in the rock itself. This characteristic makes the numbers very reliable, even when dealing with limited powder samples taken from small artifacts.

Coleman and Miller demonstrate that each quarry zone tends to exhibit a restricted range of age-corrected Nd ratios, with some zones being more variable than others (Figure 7.2). For present purposes it is convenient to divide the Nd ratios into three categories, which we simply call low, medium, and high. Low ratios (below 0.51193) occur only in the Chatham Pittsboro zone. Medium ratios (0.51193-0.51210) are characteristic of almost all the samples from the Uwharrie Mountains, except for a few from the Uwharries Asheboro zone. High ratios (above 0.51210) are found in all the samples from the Chatham Siler City, Chatham Silk Hope, Orange County, and Durham County zones. The remaining three quarry zones – Uwharries Asheboro, Cumberland County, and Person County – have assemblages that include both medium and high ratios. Interestingly, the different Nd ratios found within the Uwharries Asheboro zone correlate perfectly with geological units: the rocks with medium values are from the Uwharrie Formation, while those with high values come from the Tillery Formation.

In addition to looking at the Nd isotopes, Coleman and Miller also compute ratios of selected rare-earth elements, specifically La/Lu and Ta/Yb, as supplemental evidence in making comparisons. When the Nd ratios are plotted against these rare-earth ratios, samples from individual zones tend to form clusters – a useful result for sourcing artifacts.

Based on these graphs, Coleman and Miller match artifacts with probable sources (Table 7.6). Three artifacts with medium Nd ratios are confidently assigned to sources in the Uwharrie Mountains south of Asheboro, with affinities to the Uwharries Southern, Eastern, or Southeastern samples. Two more artifacts with medium ratios do not match any of the known sources, but seem to come from metasedimentary sources closely related to rocks in the Uwharries Southeastern or Asheboro zones. Two artifacts with high Nd ratios are assigned to Orange County and Uwharries Asheboro, respectively. And, finally, two artifacts with low Nd ratios are left unassigned; their isotopic similarity to the Chatham Pittsboro samples is noted, but the relationship is discounted – and for good reason, since the artifacts are metavolcanic and the Chatham Pittsboro sources are metasedimentary.

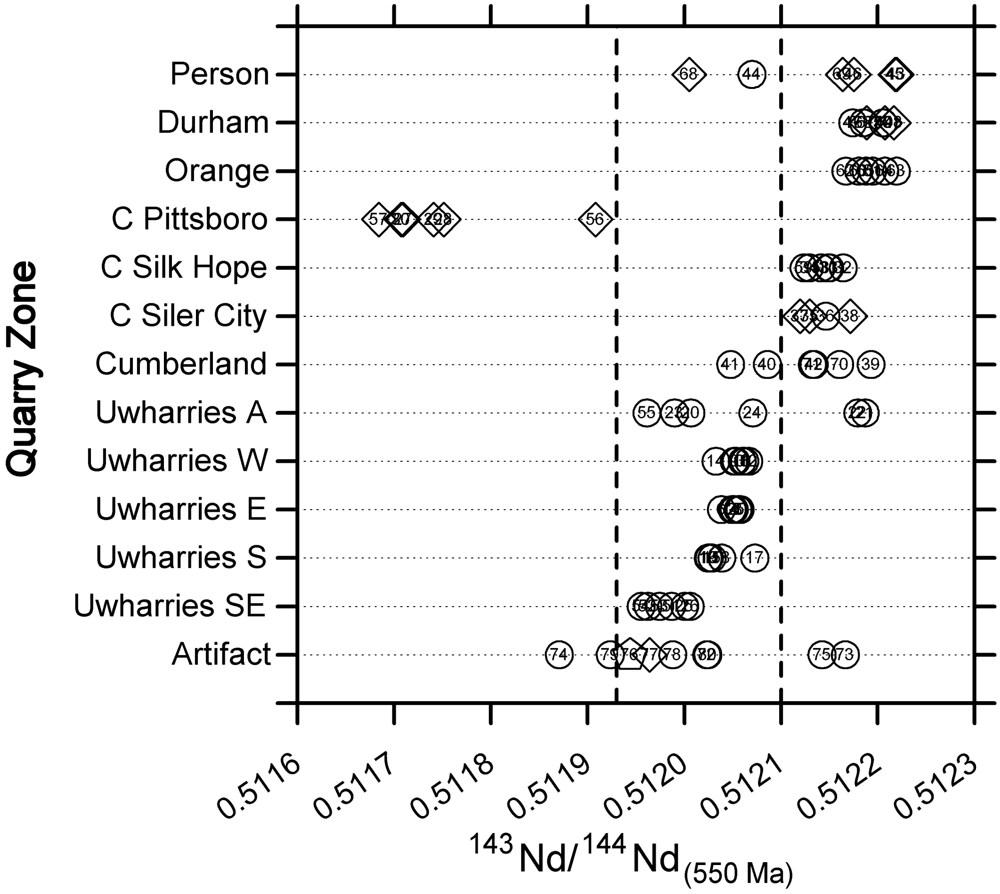

Figure 7.2. Dot plot showing Nd-isotope ratios for quarry zones and artifacts. The vertical dotted lines divide the ratios into three categories: low, medium, and high. Note that the quarry zones are arranged in order from north to south along the Carolina Slate Belt's strike. The Cumberland County zone is placed in the order according to where the Cape Fear River, the zone's major drainage feature, crosses the Slate Belt. Circles indicate metavolcanic rocks, diamonds indicate metasedimentary rocks, and a pentagon indicates the one rock of indeterminate type.

Moving beyond the specific assignments made in Chapter 6, two general patterns are evident in the Nd-isotope data, both of which can be seen clearly in Figure 7.2.

First, the Nd ratios in quarry zones dominated by metasedimentary rocks show much more internal variation than the ratios in zones dominated by metavolcanic rocks. Only two of the metavolcanic zones have comparably high variation, and both are clearly mixed assemblages: Uwharries Asheboro includes rocks from two different formations, and Cumberland County rocks were transported by water from within a large basin. Setting aside these exceptions, the metavolcanic rocks from each quarry zone show a very tight clustering of values, which is exactly what one would expect given the geological mechanism that determines these ratios.

Second, the Nd ratios in the Carolina Slate Belt exhibit a strong geographical trend, increasing from south to north along strike. This pattern plays out most consistently in the metavolcanic rocks. Not surprisingly, the only two zones that violate this trend – Chatham Pittsboro and, to a lesser extent, Person County – are predominantly metasedimentary units. Yet even with these exceptions, our data show that metavolcanic or metasedimentary rocks with high

Table 7.6. Assignments of Fort Bragg Artifacts to Quarry Zones, Based on Nd-Isotope Ratios.[a]

Artifact	Generalized Rock Type	$^{143}Nd/^{144}Nd_{(550\ Ma)}$	Nd-Isotope Category	Quarry Zone Assignment (Chapter 6)
FBL072	metavolcanic	0.512023	medium	Uwharries Southern, Uwharries Eastern
FBL073	metavolcanic	0.512167	high	Orange
FBL074	metavolcanic	0.511871	low	-
FBL075	metavolcanic	0.512143	high	Uwharries Asheboro (Tillery Formation)
FBL076	metasedimentary?	0.511944	medium	-
FBL077	metasedimentary	0.511964	medium	-
FBL078	metavolcanic	0.511988	medium	Uwharries Southeastern
FBL079	metavolcanic	0.511924	low	-
FBL080	metavolcanic	0.512024	medium	Uwharries Southern, Uwharries Eastern

[a] Compiled from Table G.1.

Nd ratios occur only from Asheboro northward, and metavolcanic rocks with medium ratios occur almost exclusively from Asheboro southward (i.e., within the Uwharrie Mountains). If the trend holds, by extension one might expect metavolcanics with low ratios to originate from somewhere south of the Uwharries, but this assumption has yet to be tested.

All in all, these general patterns provide useful benchmarks for sourcing artifacts, particularly if the rock comes from a quarry that has not yet been sampled and characterized.

Discussion and Synthesis

Based on our review of the individual studies, one thing is abundantly clear: in the matter of assigning artifacts to geological sources, there are significant discrepancies among the assignments made by different researchers working with different lines of evidence (Table 7.7). Indeed, there is not a single artifact in our pilot study for which all the assignments agree perfectly. At best, the three assignments show partial overlap; at worst, they are completely different. This illustrates the need for a synthetic approach, which considers and weighs all the lines of evidence together.

It is also worth noting that even when looking at the individual studies, very few of our artifacts match up exactly with *any* of the quarries we sampled. This should not be too surprising. For one thing, as discussed in Chapters 2 and 4, the rocks in the Carolina Slate Belt show a tremendous amount of variability. Moreover, as shown in Chapter 3, the number of quarries we sampled is only a small proportion of those that are known to exist, and many more remain to be discovered.

Yet even in the absence of an exact match, one may still draw inferences about geological provenance. It is reasonable to assume that a general similarity to a specific, known source

Table 7.7. Summary of Source Assignments for Fort Bragg Artifacts.

			Source Assignments			
Sample	Generalized Rock Type	Rock Type	Quarry Zone (Chapter 4)	Chemical Group (Chapter 5)	Quarry Zone (Chapter 6)	Source Area (Chapter 7)
FBL072	metavolcanic	dacite	Uwharries Asheboro	Uwharrie 1?	Uwharries Southern, Uwharries Eastern	Uwharries Asheboro (Uwharrie Formation)
FBL073	metavolcanic	dacite porphyry	Orange County	Chatham 1?, Person?	Orange County	Orange County
FBL074	metavolcanic	dacitic tuff	Uwharries Eastern?	Uwharrie 1	-	Uwharrie Mountains or farther south
FBL075	metavolcanic	andesite	-	Chatham 1?, Person?	Uwharries Asheboro (Tillery Formation)?	northern portion of study area
FBL076	metasedimentary?	dacitic tuff or siltstone	-	Uwharrie 1	-	-
FBL077	metasedimentary	siltstone	-	Uwharrie 1	-	-
FBL078	metavolcanic	dacite crystal-lithic tuff or porphyry	Uwharries Asheboro?, Uwharries Southeastern?	Uwharrie 1?	Uwharries Southeastern	Uwharrie Mountains
FBL079	metavolcanic	dacitic tuff	Uwharries Asheboro?, Uwharries Southeastern?	Uwharrie 1?	-	Uwharrie Mountains or farther south
FBL080	metavolcanic	dacite	Uwharries Asheboro?, Uwharries Southeastern?	Uwharrie 1?	Uwharries Southern, Uwharries Eastern	Uwharrie Mountains

provides at least a clue as to approximate source. In other words, usually there is enough regional consistency in the nature of rocks that one can make inferences about the general area from which an artifact may have come, even if one has not pinpointed the exact source. Identifying overall patterns and trends is critically important in making such assignments.

In the present case, all our lines of evidence point to major compositional differences between the rocks in the northern and southern portions of our study area. These differences correspond roughly to the distinction within the Carolina Slate Belt between the Uwharrie and Virgilina suites – the former making up the Uwharrie Mountains, and the latter constituting areas to the north. The boundary between these two compositional provinces occurs roughly at Asheboro, although the precise nature and location of the boundary varies depending on the analytical technique being used. The mineralogical and chemical differences between these provinces have already been mentioned in the preceding sections but are worth repeating here:

- Mineralogically, the southern province tends to show higher degrees of metamorphism than the northern province. This means that minerals such as garnet and biotite are more likely to appear in the south. Based on our quarry samples, these minerals do not occur in metavolcanics north of Asheboro or in metasedimentary rocks north of Chatham Siler City.

- In terms of elemental composition, the quarry samples in the southern province show considerable homogeneity in comparison to the northern province. The statistical analysis in Chapter 5 illustrates this pattern nicely. All the Uwharries zones fall into only two chemical groups, while the more northerly zones are much more variable and fall into five groups.

- The age-corrected Nd-isotope ratios show a consistent trend of increase from south to north, especially in the metavolcanic rocks. All the metavolcanics south of Asheboro exhibit medium values, and virtually all the metavolcanics north of Asheboro yield high values. In the Uwharries Asheboro zone itself, the results are mixed. Rocks in this zone from the Tillery Formation have high values (like the northern zones), while those from the Uwharrie Formation have medium values (like the southern zones).

With these patterns in mind, let us now weigh all the lines of evidence in assessing the likely geological sources for each of the nine artifacts in turn.

FBL072

This artifact is made of a fine-grained metadacite with sparse and small plagioclase phenocrysts. According to Stoddard, this material resembles the Uwharries Asheboro samples, particularly FBL055, in terms of both mineralogy and major-element chemistry. The neutron activation data confirm this assessment, as this artifact has the highest probability of membership in the Uwharrie 2 group, which contains all the Uwharries Asheboro samples. In terms of Nd-isotopes, the specimen has a medium value that falls within the range of values for the Uwharries Asheboro samples from the Uwharrie Formation, including FBL055. The La/Lu and Ta/Yb ratios fall within the range of those from the Uwharries Asheboro samples, although they are at the low end of those from the Uwharrie Formation. The presence of garnet and biotite are also consistent with a source in the Uwharrie Mountains.

In sum, all lines of evidence point to a source in the Uwharries Asheboro zone, particularly the portion within the Uwharrie Formation. No other artifact in our sample can be as confidently assigned to a single source.

FBL073

The raw material is a strongly porphyritic dacite with plagioclase and quartz phenocrysts comprising about 20% of the rock's volume. Stoddard notes its strong similarity to the Orange County rock samples in terms of petrographic characteristics. However, the Mahalanobis probabilities based on the neutron activation data suggest a much closer affinity to the Uwharrie 2, Person, and Durham groups, which correspond to the Uwharries Asheboro, Person County, and Durham County zones, respectively. Isotopically, the artifact has a high Nd-isotope ratio, consistent with rocks from the northern half of the study area, including Orange County, Durham County, Person County, and the Tillery Formation portion of the Uwharries Asheboro zone. Visual examination of rare-earth-element scatter plots leads Glascock and Speakman to suggest that this artifact shows the closest affinities to the Person and Chatham 1 groups. Despite the chemical similarities, however, the Person, Durham, and Chatham 1 groups consist mainly of metasedimentary rocks, which bear very little resemblance to the artifact under consideration. In terms of La/Lu and Ta/Yb ratios, this artifact comes closest to the Uwharries Asheboro (Tillery Formation) samples. One rock sample from the Uwharries Asheboro zone (FBL023) does have a phenocryst density almost as high as this artifact's, but it comes from the Uwharrie Formation, whose Nd-isotope ratios are in the medium range and therefore inconsistent with this artifact; FBL023 also contains biotite, which this artifact lacks.

Generally speaking, we can safely say that this artifact comes from the northern portion of the study area. Petrographically it is most similar to the Orange County samples, but chemically it most resembles the Uwharries Asheboro (Tillery Formation) samples. In this case, we find the former similarities more compelling than the latter, and therefore believe Orange County to be the most likely source.

FBL074

This is a sparsely porphyritic metadacitic tuff with quartz and plagioclase phenocrysts too small to be seen with the naked eye. Petrographically this artifact resembles samples from the Uwharries Eastern zone. The neutron activation data point in the same direction, with high probabilities of membership in the Uwharrie 1 group; on plots of the first three principal components, this artifact falls closest to the Uwharries Eastern samples. The presence of biotite also suggests a southerly source. Yet despite the petrographic and chemical similarities to rocks in the Uwharrie Mountains, the Nd-isotope ratio falls considerably *below* the known range of the Uwharries samples, and the La/Lu and Ta/Yb ratios fall slightly above the Uwharries range. These data lead Coleman and Miller to suggest a non-Uwharries origin for this piece. Given how specific and consistent the Nd ratios are for a particular magma source, and given how many samples we have from the Uwharries, the low Nd ratio presents a real anomaly that cannot be ignored. If this artifact is not from the Uwharries, then the north-south trend in Nd-isotope values would suggest that it comes from somewhere *south* of the Uwharries – an area we did not sample for this study.

Thus, our evidence suggests that this artifact comes either from the southern Uwharrie Mountains, or, even more likely, from an unknown source even farther south.

FBL075

Stoddard describes this specimen as an extremely fine-grained andesitic rock with sparse and very small plagioclase phenocrysts. He also says that petrographically it is "unlike any of the quarry specimens examined." Mahalanobis probabilities based on the neutron activation data show moderate probabilities of membership in the Durham, Person, and Uwharrie 2 groups, in that order, and an extremely low probability of membership in Uwharrie 1. The Nd-isotope ratio is high, which suggests an origin in the northern part of the study area. The La/Lu and Ta/Yb ratios fall closest to the Uwharries Asheboro (Tillery Formation) samples. Biotite and garnet are absent.

We can reasonably conclude that this artifact comes from a source located in the northern half of the study area, but one that we did not sample.

FBL076

The material in this artifact is difficult to characterize, and even more difficult to match reliably with any of our sources. Stoddard calls it an "exceedingly fine grained ... dacitic (ash) tuff, or a tuffaceous metasiltstone/metamudstone." In other words, he is unsure whether the rock is volcanic or sedimentary in origin. He also refrains from suggesting a possible source. Neutron activation data indicate a high probability (based on 15 principal components) of membership in the Uwharrie 1 group, but an even higher probability (based on only 4 components) of membership in the Chatham 1, Person, Durham, Uwharrie 2, and Orange groups. The Nd-isotope ratio has a middling value well below those found in the Chatham Siler City zone and slightly above those usually found in the Chatham Pittsboro zone, which makes a Chatham 1 assignment problematic, although not impossible. The isotope ratio is also well below those that typify the Orange and Durham County sources. By process of elimination, this leaves Person County and Uwharries Asheboro (Uwharrie Formation) as possibilities. But if the rock is sedimentary, then the latter falls away also. All in all, this sample seems chemically and isotopically most similar to FBL056, an outlier among the Chatham Pittsboro samples, but the match is not close enough to inspire confidence.

In sum, the Chatham Pittsboro and Person County zones are possibilities, but weak ones at best. The source might also be a metasedimentary rock from the Uwharrie Mountains, a type of rock we did not sample. Despite our best efforts, the only safe conclusion is that the source of this rock remains unknown.

FBL077

Stoddard describes this specimen as a fine-grained metasedimentary rock with mineral grains that are too small to be confidently identified in thin section. Even so, he observes an abundant metamorphic mineral that is probably green biotite. The neutron activation analysis suggests this artifact has a moderately high probability of membership in the Durham, Uwharrie 2, Uwharrie 1, Person, and Chatham 1 groups, in that order. Its middling Nd-isotope ratio would seem to eliminate the Durham County zone, and the likely presence of biotite would eliminate Person County. Its La/Lu and Ta/Yb ratios fall closest to individual specimens from the Uwharries Asheboro and Chatham 1 zones. The Nd ratio overlaps with samples from the Uwharries

Southeastern and Uwharries Asheboro (Uwharrie Formation) zones and is not far from one Chatham Pittsboro sample (FBL056).

If discretion is indeed the better part of valor, then we should be loath to make an assignment here. Be that as it may, the best guess would be either Chatham Pittsboro or an unknown metasedimentary source derived from the Uwharrie Mountains – but neither of these possibilities is strong enough to trust. For now, this artifact is best left unassigned.

FBL078

This rock is a dacitic crystal-lithic metatuff with flow banding and phenocrysts of quartz and plagioclase. Petrographically this artifact has many characteristics seen in the Uwharries, particularly in the Asheboro and Southeastern zones, but it does not exactly match any of the quarries we sampled. Mahalanobis probabilities based on neutron activation data suggest chemical affinities to the Chatham 1, Person, Uwharrie 2, and Durham groups, in that order; the probability of membership in the Uwharrie 1 group is very low. In contrast, the Nd-isotopes and rare-earth ratios are very similar to those from the Uwharries Southeastern and Uwharries Asheboro (Uwharrie Formation) zones and certainly rule out a Chatham 1 or Durham source. The metavolcanic nature of the rock would also tend to rule out these two sources, as well as the Person County zone.

The evidence is inconclusive and somewhat contradictory, but most indicators point to the Uwharries Asheboro (Uwharrie Formation) or Uwharries Southeastern zones as the likely sources.

FBL079

This artifact is made of a sparsely porphyritic, fine-grained, dacitic tuff with plagioclase phenocrysts. According to Stoddard, "it has some similarities to several of the Uwharries quarries, but no convincing petrographic connection to any." Mahalanobis probabilities based on neutron activation link this artifact to the Uwharrie 2, Person, Durham, and Uwharrie 1 groups, in that order. The presence of biotite eliminates the Person and Durham groups, leaving only the Uwharrie groups as possibilities. However, the Nd-isotope ratio is a bit lower than that of any of the Uwharries samples, which, following the argument made for FBL074, may mean that this artifact comes from a source even *farther* south. The Ta/Yb ratio falls close to some Uwharries Southeastern and Uwharries Asheboro samples; the La/Lu ratio is not close at all.

The lack of strong links to any of our quarry zones, coupled with the low Nd ratio, suggests that this rock does not come from any of the sources that we sampled. It may come from the Uwharrie Mountains or, quite possibly, from the Carolina Slate Belt south of the Uwharries.

FBL080

This artifact is very similar to FBL079; it is a sparsely porphyritic dacite with plagioclase phenocrysts. Petrographically, its closest analogs are samples from the Uwharries Asheboro and Uwharries Southeastern zones. Based on neutron activation data, the Mahalanobis probability of membership in the Uwharrie 2 group is high; that of membership in Uwharrie 1 is low. The Nd-isotope and rare-earth ratios are comfortably close to those of many Uwharries rock samples, including some from the Southern, Eastern, and Western zones – all of which, of course, belong to the Uwharrie 1 group. The presence of both garnet and biotite is consistent with a source in the Uwharries and inconsistent with a metavolcanic source farther north. The porphyritic nature of the rock eliminates the Uwharries Southern zone as a possibility; the middling Nd ratio eliminates the Tillery Formation portion of the Uwharries Asheboro zone. Beyond that, little more can be said.

All in all, this sample probably comes from somewhere in the Uwharrie Mountains, but exactly where is hard to say. The source is one that we did not sample.

Summary

When all lines of evidence are considered, most of the Fort Bragg artifacts can reasonably be assigned to geological sources, albeit with varying degrees of confidence and precision (Figure 7.3). Two artifacts probably come from the northern portion of the study area, one from the Orange County zone (FBL073) and the other from an unknown source (FBL075). Three probably come from the Uwharrie Mountains, one definitely from the Uwharries Asheboro zone (FBL072) and two from ambiguous or undefined sources (FBL078, FBL080). Two more may come from either the Uwharrie Mountains or areas farther south (FBL074, FBL079). The remaining two are simply left unassigned (FBL076, FBL077).

Clearly, a number of different quarries scattered over a wide area were used by the Late Archaic inhabitants of Fort Bragg. The archaeological implications of this pattern will be discussed presently, but first let us turn to an evaluation of our sourcing methods and their relative utility.

Evaluation of Methods

This investigation has used five methods to characterize and compare nine artifacts from Fort Bragg with 71 quarry samples from the Carolina Slate Belt. These methods differ in effectiveness, cost, and the amount of destruction that samples undergo during the analytical process. Each has advantages and disadvantages which must be evaluated relative to the circumstances of any given study. A brief assessment of each method follows, with particular reference to the provenance questions addressed in the present research.

- Petrographic examination of thin sections provides the most complete information about the nature of a rock, based on its mineralogy and texture. Thin sections may represent the only way to identify fine-grained rocks without phenocrysts. The method is quite destructive, particularly when used on artifacts, as it requires that a block of the specimen be cut away, glued to a glass slide, then ground to a thin section. However, there is no substitute for the kind of qualitative information this method provides.

- The ^{143}Nd/^{144}Nd ratio adjusted to the age of the rock is very diagnostic. Because the ratio is the same in all minerals that crystallized from the same magma, it can be obtained by drilling only a few tenths of a gram from anywhere in a sample, thus preserving the shapes of artifacts. A further advantage to measuring Nd ratios is that they are not affected by weathering, other surface processes, or inhomogeneities in the rock (such as phenocrysts), thus assuring that the ratio in any part of the artifact is the same as in the

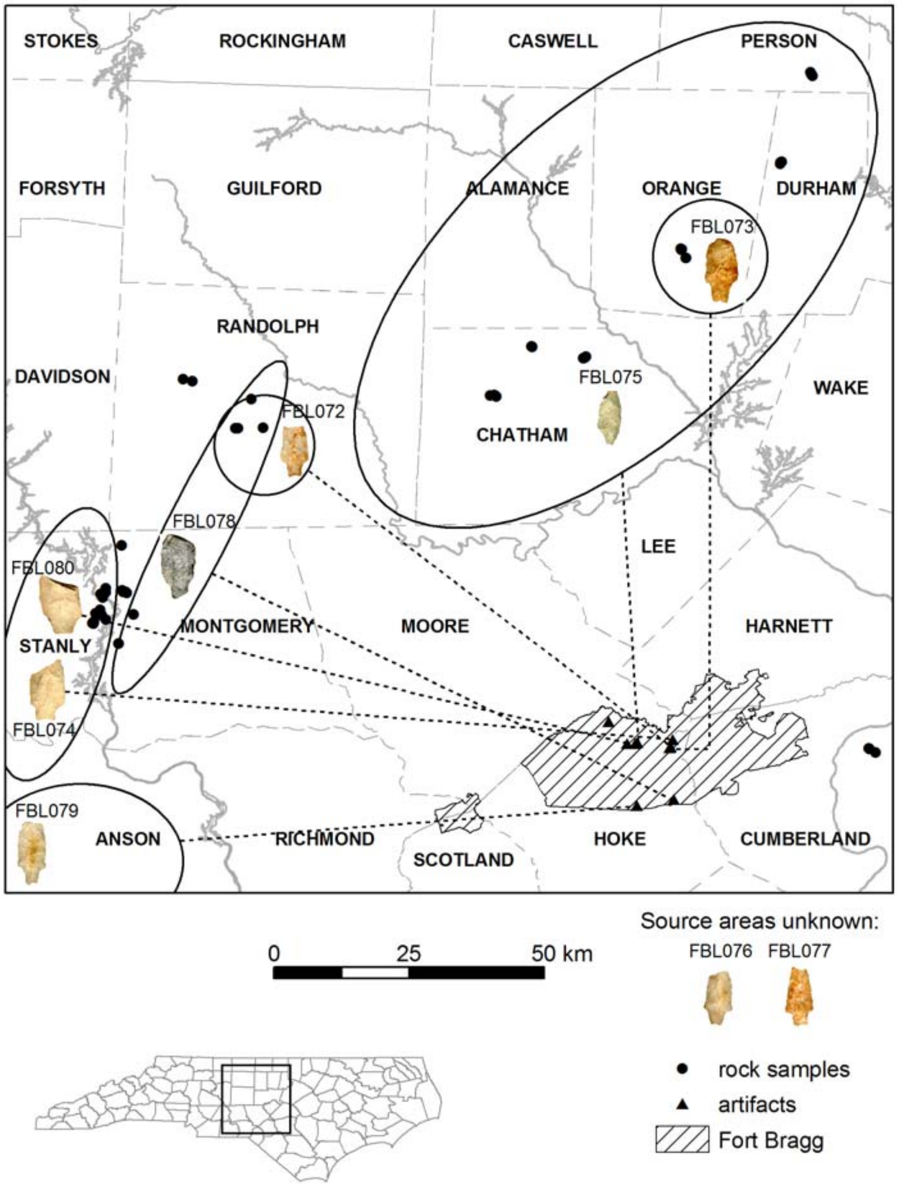

Figure 7.3. Map showing the likely source areas for Late Archaic artifacts from Fort Bragg.

quarry sample from which it was obtained. Although the cost of measuring Nd ratios is relatively high ($200 per sample), this method is very useful because it is relatively nondestructive and yields a value that is potentially very diagnostic of an artifact's source.

- Neutron activation analysis (NAA) provides absolute abundances of 33 elements, including most of the rare earths, with very high precision. The advantages of NAA are its accuracy, the broad range of elements that can be obtained with a single technique, and its widespread use in other archaeological studies, which facilitates comparisons. The main disadvantage is that it is incapable of detecting certain elements that are particularly important for geological interpretation, such as silicon (Si) and four of the rare earths (Gd, Ho, Er, Tm). NAA is also relatively destructive when used with porphyritic rocks like those in the present study. The analysis itself only requires a few milligrams of powder, but a much larger portion of the sample must be ground up and homogenized to insure that these few milligrams adequately represent the bulk composition of the sample as a whole.

- X-ray fluorescence analysis (XRF) provides abundances of 21 elements, many of which are so affected by weathering and other surface processes that they cannot be used for comparison of artifacts and quarry samples. The most useful elements are probably Si, Ti, Ga, and Zr. XRF data have been used here mainly for the purpose of classifying rocks according to standard geological typologies (see Chapter 4). Like NAA, traditional methods of XRF require destruction of samples by grinding and homogenizing the powder. Nondestructive XRF techniques are available, but these tend to be less precise and are only useful for sourcing of very homogeneous lithics in which the abundance of an element is not affected by the abundance of phenocrysts or sedimentary clasts on exposed surfaces. In other words, they are not likely to work very well with the kinds of rocks found in our study area.

- Inductively coupled plasma mass spectrometry (ICP-MS) is the only technique that yields abundances of all the rare-earth elements, which are important in making geological inferences and relatively immobile. Here the rare-earth concentrations obtained by ICP-MS were used in conjunction with the Nd-isotope ratios in defining compositional groups. Chondrite-normalized rare-earth concentrations can also be used to source artifacts, at least in some situations. In the present case, a preliminary investigation showed that chondrite-normalized rare-earth patterns were similar for all quarry and artifact samples except for rocks from the Chatham Siler City zone (Miller 2002), and so this approach was not pursued further. Like NAA and XRF, this measurement requires powdering a significant piece of each sample.

Based on our observations in this project, the two most useful methods for sourcing the artifacts from Fort Bragg proved to be petrography and the Nd-isotope ratios, although the elemental data were also very helpful in certain instances.

Even though the information gleaned from petrography is invaluable for sourcing, the utility of the technique is constrained by its destructiveness. Cutting a thin section necessitates destroying a large portion of the artifact being studied. To the extent that research questions can be answered by thin-sectioning quarry samples or debitage, this destructiveness is not a major concern. But if one is dealing with points or other formal tools, then it becomes a problem. We recommend that thin-section studies be continued, but that they be done selectively, balancing the information gained against that potentially lost when a portion of the sample is cut away.

As mentioned previously, the measurement of Nd-isotope ratios is the least destructive of all our approaches to sourcing. Moreover, the Nd ratios seem to show a geographical pattern of increase from south to north along the Carolina Slate Belt. If this trend holds up with further studies, then it may be possible to estimate the general location of a source from a Nd ratio, even if the quarry itself has not yet been sampled. For these reasons, Nd-isotope analysis is particularly attractive as a way of sourcing artifacts from our study area.

With regard to the techniques used to measure elements, NAA provides data on roughly the same suite of elements as XRF and ICP-MS combined. For purposes of archaeological sourcing alone, the former is cheaper and provides adequate data. For purposes of geological interpretation, however, the combination of XRF and ICP-MS provide certain critical elements (such as Si and several rare earths) that NAA cannot detect. Which of these techniques one uses in the future should therefore depend on the research questions being asked.

We recommend further studies of both quarries from the Carolina Slate Belt and artifacts from Fort Bragg. Additional quarries should be sampled in order to refine our understanding of their geographical variability and to answer some of the questions raised by this pilot study. It is especially important, for example, to sample areas south of the Uwharrie Mountains in order to see if the north-south trend in Nd ratios continues in this direction. We also need to learn more about the composition and distribution of metasedimentary rocks in the Uwharries – a category that was overlooked in our initial sample of quarries but which may be present among the artifacts from Fort Bragg. The sample of artifacts should also be expanded to include a wider variety of materials and periods other than the Late Archaic.

Archaeological Implications and Future Directions

While some ambiguity exists, the artifact assignments just described suggest that Late Archaic inhabitants of Fort Bragg utilized a number of quarries scattered over a wide area. As these assignments are based on only nine artifacts, it is safe to assume that the actual variation of raw material utilized throughout the Late Archaic period was considerably greater. Moreover, the fact that two of the artifacts fail to resemble any of the geological samples suggests the real possibility that some quarries or zones may never be identified. Nonetheless, the assignments made and the methods developed in this study are encouraging initial steps towards addressing archaeological sites and lithic assemblages in a broader cultural context. Using the Late Archaic period as our example, we outline below several key research problems that may be addressed as the methods and results presented here are expanded upon in the future.

The most obvious and perhaps most commonly addressed problem in lithic sourcing studies is the mobility scale of prehistoric hunter-gatherers. The artifacts studied were all discarded at the end of their use lives, following fracture of the blade. When we consider the distances at which these discarded points were found from their geological sources, we may appreciate the potential range of movement reflected. Before being discarded these hafted bifaces had likely been carried over routes covering minimally the linear distance of Fort Bragg to the Slate Belt quarries, i.e. some 70 to 80 km. Given the non-linear movement of hunter-gatherers (Close 2000), it is likely that these Fort Bragg finds were discarded after circuitous routes around or along major rivers, perhaps along overland paths, to and from certain natural resource draws or social meetings. The total distances covered in a seasonal round that included Slate Belt procurement would minimally double the linear path and more likely involve a lengthier meandering route. We might expect then a distance in some cases of well over 200 km, consistent with the mobility scale of ethnographically studied hunting and gathering groups (Kelly 1995: Table 4.1).

For the Late Archaic, this scale of mobility may be related to broader social and economic trends, or the lack thereof. In North Carolina the hallmarks of increasing social and economic complexity seen elsewhere during the Late Archaic are notably absent (Anderson 1996; Benson

2000; Phelps 1983; Ward 1983; Ward and Davis 1999). There may be a slight trend towards riverine settlement in the Coastal Plain (Phelps 1983) and sedentism overall (Ward 1983), and certainly sites such as Doerschuk and Lowder's Ferry suggest intensive occupations or frequent re-occupations (Coe 1964; Drye 1998). However, if there is a notable increase in sedentism as seen in other parts of the Southeast and Midwest, a pattern towards more localized use of raw materials and a more limited mobility scale may be expected.

The connection of sites like those found on Fort Bragg to riverine corridors is an important question for any prehistoric period. Three major river basins are represented in the distribution of quarry zones in the Slate Belt. The kind of sourcing methods developed can be used to evaluate riverine settlement. If groups at Fort Bragg were oriented along the Cape Fear or one of its major tributaries, e.g., the Deep or Haw Rivers, we may expect a high proportion of material from quarry zones along those drainages, e.g., Uwharries Asheboro or Chatham County. The glimpse provided here suggests the possibility of cross-drainage movement that may reflect use of the Sandhills by different social groups entering the area from different river basins or a settlement pattern that is not riverine-based.

Beyond simple distances and directions of movement, the potential to correlate variation in artifact form and raw material procurement is important as well. Benson (2000) suggests, based in part on Savannah River points morphologically divergent from those found in the Uwharrie Mountains, the possibility of regionalization of populations in the North Carolina Piedmont and inner Coastal Plain during the Late Archaic. Sassaman and Anderson (1995) suggest distinct Piedmont/Fall Zone and Coastal Plain populations in South Carolina during the Late Archaic Mill Branch phase, evidenced by local raw-material procurement. There is potentially significant variation in Savannah River Stemmed points, including size disparities (Oliver 1985) and manufacturing differences such as narrow stemmed, weak-shouldered variants like FBL075 (see Trinkley et al. 1996b:149-150). Variation in design that may reflect temporally or socially distinct groups could be correlated with differing procurement and mobility patterns.

The question of raw material selection in relation to technological organization may also be directly linked to sourcing. Again, with a small sample and some ambiguous results, it is difficult to conclude anything about Late Archaic technology, but research questions heretofore impractical may now be more easily addressed. While these tools may not have been curated, the size of the Savannah River points necessitated a certain core requirement that may have been more easily met by metavolcanic stone acquired directly from outcrops, as opposed to quartz that occurs in small packages. In these nine points there is little suggestion of a pattern of raw-material procurement, except for a possible emphasis on stone from the Uwharrie Mountains. There is quite obviously a significant range of variability in the material used. Each of the nine bifaces analyzed is unique and the types of stone include andesite, fine-grained metasedimentary material, and coarse-grained porphyritic tuff. Factors affecting such variable selection will be difficult to model, but the potential to recognize patterns of raw material selection and address these critical elements of archaeological cultures is evident.

Related to the question of technological organization is raw-material quality, an issue that should be addressed through experimental studies of rocks from the different quarry zones. Along with more systematic study of quarries to understand the density of debris, intensity and temporal range of activity, and the range of materials exploited, some knowledge of the quality of stone for making tools would benefit our understanding of these sites. The quality of stone may affect the types of tools manufactured (e.g., expedient or formal) and the distance carried. It may also affect the likelihood of a material being used or widely distributed. In some cases there may be preferences for a higher-quality material (e.g., Cable and Mueller 1980), or only selected material types from a particular quarry may have been widely dispersed (e.g., Abbott 1987). Replication experiments would help to clarify these issues.

We recommend further studies of both quarries from the Carolina Slate Belt and artifacts from Fort Bragg. Additional quarries in the Piedmont should be sampled in order to refine our understanding of their geographical variability and to answer some of the questions raised by this pilot study. It is especially important, for example, to sample areas south of the Uwharrie Mountains in order to see if the north-south trend in Nd ratios continues in this direction. We also need to learn more about the composition and distribution of metasedimentary rocks in the Uwharries – a category that was overlooked in our initial sample of quarries but which may be present among the artifacts from Fort Bragg. We may eventually add other areas such as a western Slate Belt with quarries like Three Hat Mountain (Mountjoy and Abbott 1982; Abbott 1987). The sample of artifacts should also be expanded to include a wider variety of materials and periods other than the Late Archaic.

Additional studies should also be done of stone sources in the Coastal Plain. Our sample from the Cumberland County zone consists of metavolcanic material washed out of the Piedmont and deposited in the Coastal Plain. With one exception, this heterogeneous sample of rocks appears similar to material utilized locally around the Cape Fear River in the vicinity of Fayetteville. The ability to distinguish between redeposited material in the Coastal Plain and outcrops in the Piedmont is critical, as these represent two major physiographic provinces. Identification of Cape Fear material on Fort Bragg would tie settlement into a major river drainage as well as indicate a direction of movement away from the Slate Belt. Despite the heterogeneity of the sample, the geochemical results are encouraging. The Cumberland County sample is an important initial measure of Coastal Plain material. The redeposited Slate Belt material must be better characterized in order to see if chemical signatures of Coastal Plain provenance can be found.

It should be noted that modeling prehistoric mobility does not require that we be able to discriminate individual quarries or quarry zones. Rather, discriminating among larger provinces may be sufficient for many purposes. For example, the division of the Carolina Slate Belt into northern and southern provinces based on the results of the present study will surely be helpful in assessing mobility. While there is no a priori reason to suspect prehistoric groups organized themselves in a manner consistent with such a broad division, sourcing artifacts to these general areas will facilitate modeling range and directionality of movement at a scale not unlike Daniel's (1998) macroband.

Distinguishing between the southern and northern Uwharrie Mountains is also important for testing archaeological interpretations. The southern Uwharries, by virtue of including Morrow Mountain, rest at the core of Daniel's (1998) settlement model. In another settlement model proposed by Moore and Irwin (2002) for Fort Bragg, a specific overland route between the Cape Fear and southern Uwharries was posited. Furthermore, there are implications for modeling riverine-based settlement. The southern and northern Uwharrie Mountains are located in two separate river drainages, the Yadkin–Pee Dee and Cape Fear Rivers, respectively. For Fort Bragg and other areas, the level of specificity in regional settlement models will be somewhat contingent on our ability to assign artifacts to sources in these drainages.

Whether approached from a pure research perspective or used in cultural resource management, the methods developed here have great utility. In the archaeological study of prehistoric hunters and gatherers, analysis of individual occupations offers important but limited information. The duration of ephemeral camps in upland environments may involve days or weeks out of a seasonal round that lasts a year. An ephemeral campsite may be one stop in a mobility range that covers hundreds of kilometers. It is crucial to relate sites, artifacts, and behavior into a broader regional context.

Appendix A

Sample Descriptions

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Tables A.1 and A.2 describe the provenience and geology, respectively, of the 71 rock samples. Table A.3 contains similar descriptions of the nine artifacts, and Table A.4 lists their metric attributes.

Photographs of the rock samples and artifacts are presented in Figures A.1-A.9. For each specimen, three photographs are displayed at a 1:1 scale. A dry view of the cut surface reveals the true color of the fresh specimen, but some textural characteristics may be obscured by saw marks. A wet view of the same surface illuminates textural details but darkens the coloring. A dry view of cortex and/or an uncut surface shows the approximate appearance of a typical weathered, uncut specimen.

Table A.1. Descriptive Information for Rock Samples: Provenience.

Sample Number	Alternate Number	Quarry Zone	Site Name	State Site Number	UTM[a] Northing	UTM[a] Easting	Sample Type
FBL001	HD-18A	Uwharries Eastern	Shingle Trap Mountain	31Mg554	3917872	587452	outcrop/float
FBL002	HD-18A*	Uwharries Eastern	Shingle Trap Mountain	31Mg554	3918056	587342	float
FBL003	HD-18B	Uwharries Eastern	Shingle Trap Mountain	31Mg554	3918363	586781	outcrop/float
FBL004	HD-18B*	Uwharries Eastern	Shingle Trap Mountain	31Mg554	3918121	586929	float
FBL005	HD-19	Uwharries Eastern	Sugarloaf West	31St169[b]	3914124	582758	outcrop/float
FBL006	HD-21	Uwharries Eastern	Sugarloaf Mountain	31St107[b]	3913852	583741	outcrop/float
FBL007	HD-22	Uwharries Eastern	Hattaway Mountain	31St168[b]	3914765	583453	outcrop/float
FBL008	HD-4A	Uwharries Western	Falls Dam		3916984	583805	outcrop/float
FBL009	HD-8	Uwharries Western	Wolf Den 639	31Mg639	3918067	584251	outcrop/float
FBL010	HD-9*	Uwharries Western	Wolf Den 639	31Mg639	3917939	584300	outcrop/float
FBL011	HD-10	Uwharries Western	Wolf Den 117	31Mg117	3918742	584316	quarry debris (flaked cobble)
FBL012	HD-10*	Uwharries Western	Wolf Den 117	31Mg117	3918742	584316	outcrop/float
FBL013	HD-13	Uwharries Western	Wolf Den 640	31Mg640	3917723	583542	quarry debris (flake)
FBL014	HD-31	Uwharries Western		31Mg728[b]	3926732	586632	outcrop/float
FBL015	HD-20	Uwharries Southern	Morrow Mountain	31St18	3912209	582492	quarry debris (biface)
FBL016	HD-24	Uwharries Southern	Tater Top Mountain	31St166[b]	3912917	584354	outcrop/float
FBL017	HD-54	Uwharries Southern	Morrow Mountain	31St18	3912252	582362	outcrop/float
FBL018	HD-55	Uwharries Southern	Morrow Mountain	31St18	3912421	582459	outcrop/float
FBL019	HD-56	Uwharries Southern	Morrow Mountain	31St18	3912560	582554	outcrop/float
FBL020	HD-25B3	Uwharries Asheboro		31Rd37	3948533	603523	outcrop/float
FBL021	HD-33	Uwharries Asheboro	Carraway Mountain	31Rd1201[b]	3957237	596949	outcrop/float
FBL022	HD-34	Uwharries Asheboro	Tater Head Mountain	31Rd1202[b]	3957598	595573	outcrop/float
FBL023	HD-38	Uwharries Asheboro	Dave's Mountain		3954020	605891	outcrop/float
FBL024	HD-66	Uwharries Asheboro		31Rd37	3948601	603912	quarry debris (flake)
FBL025	HT-A	Uwharries Southeastern	Horse Trough Mountain	31Mg378/379	3908577	586311	outcrop/float
FBL026	HT-B	Uwharries Southeastern	Horse Trough Mountain	31Mg378/379	3908577	586311	float/quarry debris
FBL027	Ch729-A	Chatham Pittsboro	Joe Moylan Quarry	31Ch729	3962336	655804	float

Table A.1. Descriptive Information for Rock Samples: Provenience (continued).

Sample Number	Alternate Number	Quarry Zone	Site Name	State Site Number	UTM[a]		Sample Type
					Northing	Easting	
FBL028	Ch729-B	Chatham Pittsboro	Joe Moylan Quarry	31Ch729	3962336	655804	float
FBL029	Ch729-C	Chatham Pittsboro	Joe Moylan Quarry	31CH729	3962336	655804	float
FBL030	Ch729-D	Chatham Pittsboro	Joe Moylan Quarry	31Ch729	3962336	655804	float
FBL031	Ch741-A	Chatham Silk Hope	Chestnut Hill Quarry	31Ch741	3964340	647964	float
FBL032	Ch741-B	Chatham Silk Hope	Chestnut Hill Quarry	31Ch741	3964340	647964	float
FBL033	Ch741-C	Chatham Silk Hope	Chestnut Hill Quarry	31Ch741	3964340	647964	float
FBL034	Ch741-E	Chatham Silk Hope	Chestnut Hill Quarry	31Ch741	3964340	647964	float
FBL035	ChRR-F	Chatham Siler City	Rocky River 1		3955002	642790	float
FBL036	ChRR-R	Chatham Siler City	Rocky River 2		3955158	642626	outcrop/float
FBL037	ChRR-T	Chatham Siler City	Rocky River 3		3955297	642445	float
FBL038	Ch427	Chatham Siler City		31Ch427	3955164	641835	float
FBL039	400-1	Cumberland County		31Cd400	3890907	700336	float
FBL040	400-2	Cumberland County		31Cd400	3890907	700336	float
FBL041	400-3	Cumberland County		31Cd400	3890907	700336	float
FBL042	424-1	Cumberland County		31Cd424	3890818	700408	float
FBL043	PCQ-A	Person County	Powerline Quarry	31Pr115	4015567	688965	float
FBL044	PCQ-B	Person County	Powerline Quarry	31Pr115	4015567	688965	float/quarry debris
FBL045	PCQ-C	Person County	Powerline Quarry	31Pr115	4015567	688965	float
FBL046	PCQ-D	Person County	Powerline Quarry	31Pr115	4015567	688965	float
FBL047	DUR-A	Durham County	Cains Chapel Quarry	31Dh703	3999181	684723	float
FBL048	DUR-B	Durham County	Cains Chapel Quarry	31Dh703	3999181	684723	float
FBL049	QNWD-C	Durham County	Cains Chapel Quarry	31Dh703	3999181	684723	float
FBL050	QNWD-D	Durham County	Cains Chapel Quarry	31Dh703	3999181	684723	quarry debris (flaked cobble)
FBL051	Mg222	Uwharries Southeastern	USS Ranger Quarry	31Mg222	3913923	588488	float
FBL052	Mg222b	Uwharries Southeastern	USS Ranger Quarry	31Mg222	3913923	588488	quarry debris (flake)
FBL053	HFLK-1	Uwharries Southeastern	USS Ranger Quarry	31Mg222	3913923	588488	outcrop/float
FBL054	HFLK-2	Uwharries Southeastern	USS Ranger Quarry	31Mg222	3913923	588488	float

Table A.1. Descriptive Information for Rock Samples: Provenience (continued).

Sample	Alternate				UTM[a]		
Number	Number	Quarry Zone	Site Name	State Site Number	Northing	Easting	Sample Type
FBL055	Rd852	Uwharries Asheboro	Northhampton Road Quarry	31Rd1350[b]	3948745	607738	outcrop
FBL056	Ch729-5	Chatham Pittsboro	Joe Moylan Quarry	31Ch729	3962589	656168	quarry debris (flake)
FBL057	Ch729-6	Chatham Pittsboro	Joe Moylan Quarry	31Ch729	3962454	655975	float
FBL058	Ch741-5	Chatham Silk Hope	Chestnut Hill Quarry	31Ch741	3964275	648050	float
FBL059	Ch741-6	Chatham Silk Hope	Chestnut Hill Quarry	31Ch741	3964353	647937	float
FBL060	ORNG-1	Orange County	Bald Mountain Quarry	31Or564	3982716	670171	outcrop
FBL061	ORNG-2	Orange County	Bald Mountain Quarry	31Or564	3982672	670133	outcrop
FBL062	ORNG-3	Orange County	Bald Mountain Quarry	31Or564	3982816	670076	outcrop
FBL063	ORNG-4	Orange County		31Or549	3981131	670883	outcrop
FBL064	ORNG-5	Orange County		31Or549	3981195	670815	outcrop
FBL065	ORNG-6	Orange County		31Or549	3981171	670810	outcrop
FBL066	DUR-5	Durham County	Cains Chapel Quarry	31Dh703	3998905	684667	quarry debris (flake)
FBL067	DUR-6	Durham County	Cains Chapel Quarry	31Dh703	3999235	684872	float
FBL068	PCQ-5	Person County	Powerline Quarry	31Pr115	4015213	689130	outcrop/float
FBL069	PCQ-6	Person County	Powerline Quarry	31Pr115	4015889	688827	float
FBL070	402	Cumberland County		31Cd402	3890184	701416	float
FBL071	424-4	Cumberland County		31Cd424	3890818	700408	float

[a] NAD 1927 datum.

[b] The RLA site number differs from the state site number; see Appendix B.

Table A.2. **Descriptive Information for Rock Samples: Geology.**

Sample		Field	State Geologic Map[a]		Other Geologic Map[b]		
Number	Quarry Zone	Description	Unit	Description	Unit	Description	Formation
FBL001	Uwharries Eastern	dacite	CZfv	felsic metavolcanic rock	Ctr	rhyolitic rocks	Tillery
FBL002	Uwharries Eastern	dacite	CZfv	felsic metavolcanic rock	Ctr	rhyolitic rocks	Tillery
FBL003	Uwharries Eastern	dacite	CZfv	felsic metavolcanic rock	Ctr	rhyolitic rocks	Tillery
FBL004	Uwharries Eastern	dacite	CZfv	felsic metavolcanic rock	Ctr	rhyolitic rocks	Tillery
FBL005	Uwharries Eastern	dacite	CZfv	felsic metavolcanic rock	Ctr	rhyolitic rocks	Tillery
FBL006	Uwharries Eastern	dacite	CZfv	felsic metavolcanic rock	Ctr	rhyolitic rocks	Tillery
FBL007	Uwharries Eastern	dacite	CZfv	felsic metavolcanic rock	Ctr	rhyolitic rocks	Tillery
FBL008	Uwharries Western	andesite	CZfv	felsic metavolcanic rock	Ccmb	basaltic rocks	Cid
FBL009	Uwharries Western	andesite	CZfv	felsic metavolcanic rock	Ccmr	rhyolitic rocks	Cid
FBL010	Uwharries Western	andesite	CZfv	felsic metavolcanic rock	Ccmr	rhyolitic rocks	Cid
FBL011	Uwharries Western	andesite	CZfv	felsic metavolcanic rock	Ccmr	rhyolitic rocks	Cid
FBL012	Uwharries Western	andesite/latite	CZfv	felsic metavolcanic rock	Ccmr	rhyolitic rocks	Cid
FBL013	Uwharries Western	andesite	CZfv[c]	felsic metavolcanic rock	Ccmr	rhyolitic rocks	Cid
FBL014	Uwharries Western	andesite/latite	CZmv$_1$	mafic metavolcanic rock	Ccmr	rhyolitic rocks	Cid
FBL015	Uwharries Southern	felsite	CZfv	felsic metavolcanic rock	Ctr	rhyolitic rocks	Tillery
FBL016	Uwharries Southern	felsite	CZmd$_1$	metamudstone and meta-argillite	Ctr	rhyolitic rocks	Tillery
FBL017	Uwharries Southern	felsite	CZfv	felsic metavolcanic rock	Ctr	rhyolitic rocks	Tillery
FBL018	Uwharries Southern	felsite	CZfv	felsic metavolcanic rock	Ctr	rhyolitic rocks	Tillery
FBL019	Uwharries Southern	felsite	CZfv	felsic metavolcanic rock	Ctr	rhyolitic rocks	Tillery
FBL020	Uwharries Asheboro	tuff	CZmv	mafic metavolcanic rock	Czufc	felsic volcaniclastic rocks	Uwharrie
FBL021	Uwharries Asheboro	dacite/andesite	CZmd$_1$	metamudstone and meta-argillite	Ctf[d]	felsite	Tillery
FBL022	Uwharries Asheboro	dacite/andesite	CZfv	felsic metavolcanic rock	Ctf	felsite	Tillery
FBL023	Uwharries Asheboro	dacite	CZfv$_1$	felsic metavolcanic rock	CZuf	felsite	Uwharrie
FBL024	Uwharries Asheboro	tuff	CZmv	mafic metavolcanic rock	CZufc	felsic volcaniclastic rocks	Uwharrie
FBL025	Uwharries Southeastern	dacite	CZfv$_1$	felsic metavolcanic rock	CpCur/CpCut[e]	rhyolitic rocks/tuffs[e]	Uwharrie
FBL026	Uwharries Southeastern	dacite	CZfv$_1$	felsic metavolcanic rock	CpCur/CpCut[e]	rhyolitic rocks/tuffs[e]	Uwharrie
FBL027	Chatham Pittsboro	mudstone	CZmd	metamudstone and meta-argillite			

Table A.2. Descriptive Information for Rock Samples: Geology (continued).

Sample		Field	State Geologic Map[a]		Other Geologic Map[b]		
Number	Quarry Zone	Description	Unit	Description	Unit	Description	Formation
FBL028	Chatham Pittsboro	mudstone	CZmd	metamudstone and meta-argillite			
FBL029	Chatham Pittsboro	siltstone	CZmd	metamudstone and meta-argillite			
FBL030	Chatham Pittsboro	fine sandstone	CZmd	metamudstone and meta-argillite			
FBL031	Chatham Silk Hope	dacite/rhyodacite	CZiv^{f}	intermediate metavolcanic rock			
FBL032	Chatham Silk Hope	lithic tuff	CZiv^{f}	intermediate metavolcanic rock			
FBL033	Chatham Silk Hope	dacite	CZiv^{f}	intermediate metavolcanic rock			
FBL034	Chatham Silk Hope	lithic tuff	CZiv^{f}	intermediate metavolcanic rock			
FBL035	Chatham Siler City	mud/siltstone	CZmd	metamudstone and meta-argillite			
FBL036	Chatham Siler City	dacite	CZmd	metamudstone and meta-argillite			
FBL037	Chatham Siler City	mudstone	CZmd	metamudstone and meta-argillite			
FBL038	Chatham Siler City	sandstone	CZmd	metamudstone and meta-argillite			
FBL039	Cumberland County	aplite					
FBL040	Cumberland County	basalt					
FBL041	Cumberland County	diorite					
FBL042	Cumberland County	tuff?					
FBL043	Person County	mudstone?	CZfv	felsic metavolcanic rock			
FBL044	Person County	tuff	CZfv	felsic metavolcanic rock			
FBL045	Person County	mudstone	CZfv	felsic metavolcanic rock			
FBL046	Person County	sandstone	CZfv	felsic metavolcanic rock			
FBL047	Durham County	dacite	CZfv	felsic metavolcanic rock			
FBL048	Durham County	sandstone	CZfv	felsic metavolcanic rock			
FBL049	Durham County	sandstone	CZfv	felsic metavolcanic rock			
FBL050	Durham County	tuff	CZfv	felsic metavolcanic rock			
FBL051	Uwharries Southeastern	dacite	CZfv$_{1}$	felsic metavolcanic rock	CpCur	rhyolitic rocks	Uwharrie
FBL052	Uwharries Southeastern	dacite	CZfv$_{1}$	felsic metavolcanic rock	CpCur	rhyolitic rocks	Uwharrie
FBL053	Uwharries Southeastern	dacite	CZfv$_{1}$	felsic metavolcanic rock	CpCur	rhyolitic rocks	Uwharrie
FBL054	Uwharries Southeastern	dacite	CZfv$_{1}$	felsic metavolcanic rock	CpCur	rhyolitic rocks	Uwharrie

Table A.2. Descriptive Information for Rock Samples: Geology (continued).

Sample		Field	State Geologic Map[a]		Other Geologic Map[b]		
Number	Quarry Zone	Description	Unit	Description	Unit	Description	Formation
FBL055	Uwharries Asheboro	dacite	$CZfv_1$	felsic metavolcanic rock	CZufc	felsic volcaniclastic rocks	Uwharrie
FBL056	Chatham Pittsboro	mudstone	CZmd	metamudstone and meta-argillite			
FBL057	Chatham Pittsboro	mudstone	CZmd	metamudstone and meta-argillite			
FBL058	Chatham Silk Hope	lithic tuff	CZiv	intermediate metavolcanic rock			
FBL059	Chatham Silk Hope	lithic tuff	CZiv[f]	intermediate metavolcanic rock			
FBL060	Orange County	dacite	CZfv	felsic metavolcanic rock			
FBL061	Orange County	dacite	CZfv	felsic metavolcanic rock			
FBL062	Orange County	dacite	CZfv	felsic metavolcanic rock			
FBL063	Orange County	dacite	PzZg[f]	metamorphosed gabbro and diorite			
FBL064	Orange County	dacite	PzZg[f]	metamorphosed gabbro and diorite			
FBL065	Orange County	dacite	PzZg[f]	metamorphosed gabbro and diorite			
FBL066	Durham County	dacite	CZfv	felsic metavolcanic rock			
FBL067	Durham County	sandstone	CZfv	felsic metavolcanic rock			
FBL068	Person County	siltstone	CZfv	felsic metavolcanic rock			
FBL069	Person County	siltstone	CZfv	felsic metavolcanic rock			
FBL070	Cumberland County	greenstone					
FBL071	Cumberland County	metagabbro					

[a] North Carolina Geological Survey (1985).

[b] Entries for samples FBL001-FBL019, FBL025-FBL026, and FBL051-FBL054 are based on Stromquist and Henderson (1985). Entries for samples FBL020-FBL024 and FBL055 are based on Seiders (1981).

[c] Near contact with CZmv1 (mafic metavolcanic rock).

[d] Near contact with Ctm (laminated to thin-bedded graded mudstone).

[e] On contact between CpCur (rhyolitic rocks) and CpCut (rhyolitic tuffs).

[f] Near contact with CZfv (felsic metavolcanic rock).

Table A.3. Descriptive Information for Artifact Samples: Provenience, Geology, and Type.

Sample Number	Accession Number	Site Name	Site Number	UTM[a] Northing	UTM[a] Easting	Field Description	Projectile Point Type
FBL072	19A978.1		31Hk100	3890370	670080	dacite	Savannah River Stemmed
FBL073	19A775.1		31Hk148	3890600	670270	dacite	Savannah River Stemmed
FBL074	19A1159.1		31Hk173	3891970	670560	dacite	Savannah River Stemmed
FBL075	19A12.1		31Hk182	3891290	665200	andesite	Savannah River Stemmed
FBL076	19A100.1		31Hk224	3895060	660730	tuff/siltstone	Savannah River Stemmed
FBL077	990957A135		31Hk737	3891053	664850	siltstone	Savannah River Stemmed
FBL078	990743A1		31Hk999	3880860	670910	dacite	Savannah River Stemmed
FBL079	200755A1		31Hk1408	3879599	665320	dacite	Savannah River Stemmed
FBL080	2435A62.1	Flat Creek		3891062	663638	dacite	Savannah River Stemmed

[a] NAD 1927 datum.

Table A.4. Descriptive Information for Artifact Samples: Measurements.

Sample Number	Maximum Length (mm)	Blade Length (mm)	Blade Width (mm)	Stem Width (mm)	Base Width (mm)	Maximum Thickness (mm)	Stem Height (mm)	Weight (g)
FBL072	62.3	40.9	34.5	20.4	16.4	11.6	20.8	25.8
FBL073	79.9	47.9	41.2	23.3	20.2	13.4	25.0	40.9
FBL074	75.8	53.9	43.5	24.9	23.2	10.8	19.5	34.7
FBL075	66.2	49.2	29.6	16.0	10.8	12.4	17.8	23.3
FBL076	67.2	49.4	35.2	21.4	13.5	13.4	19.8	27.7
FBL077	72.4	56.0	34.7	20.3	18.1	10.7	12.3	24.9
FBL078	76.4	58.1	41.5	22.0	20.8	12.6	20.1	41.7
FBL079	65.5	48.0	29.8	16.0	13.7	10.7	17.2	20.4
FBL080	74.7	48.6	50.6	32.2	25.6	14.9	17.1	51.1

FBL001

FBL002

FBL003

FBL004

FBL005

FBL006

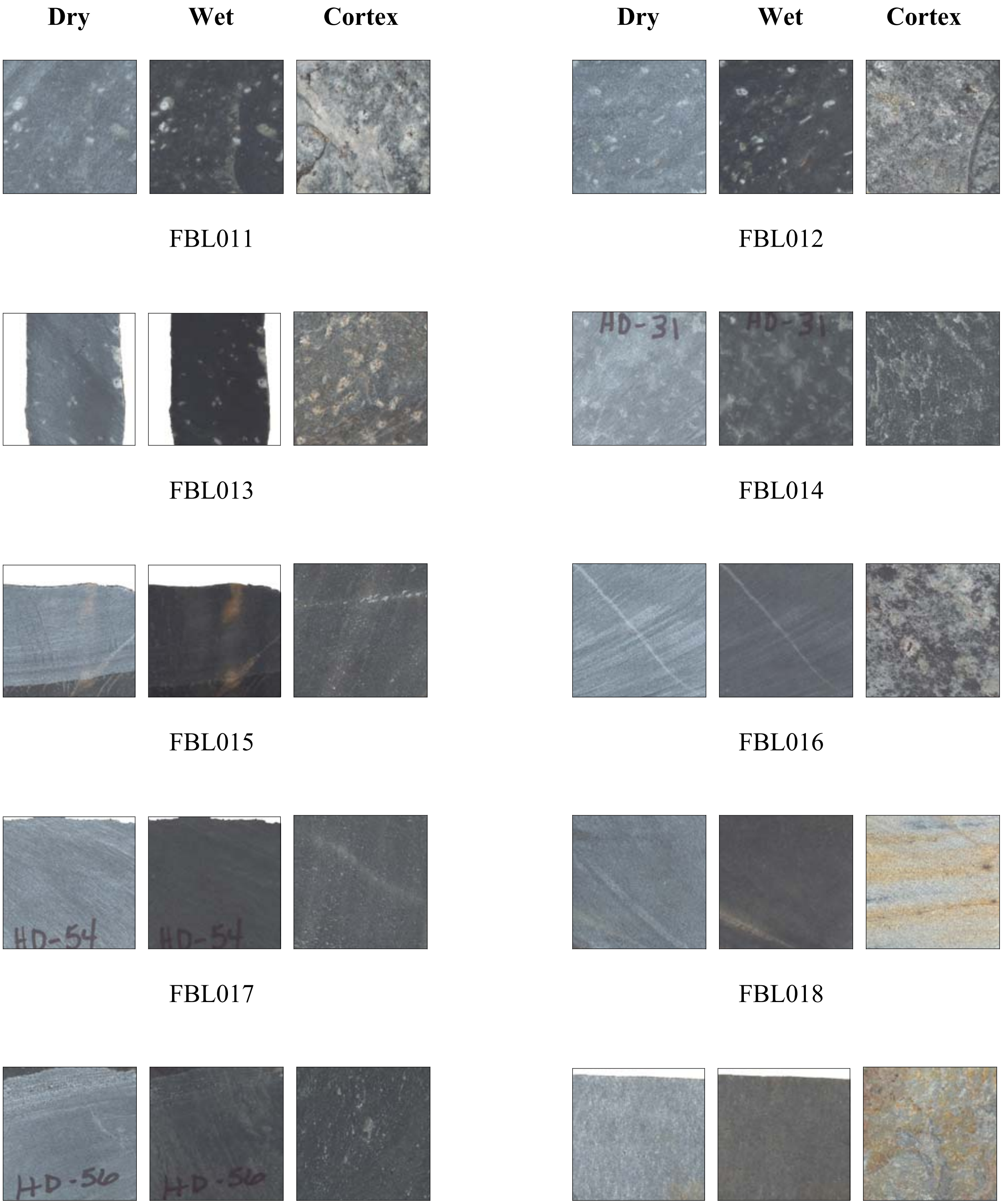
FBL007

FBL008

FBL009

FBL010

Figure A.1. Samples FBL001-FBL010.



FBL011 FBL012

FBL013 FBL014

FBL015 FBL016

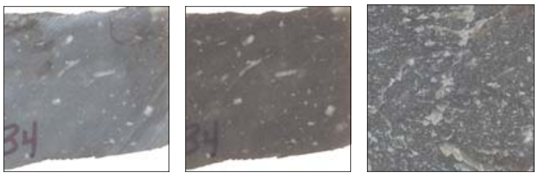
FBL017 FBL018

FBL019 FBL020

Figure A.2. Samples FBL011-FBL020.

Dry **Wet** **Cortex** **Dry** **Wet** **Cortex**

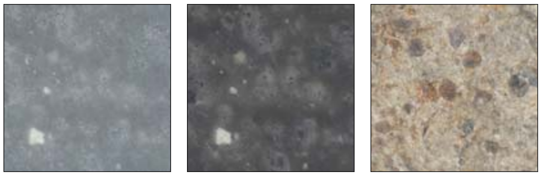
FBL021



FBL022

FBL023

FBL024



FBL025

FBL026

FBL027

FBL028

FBL029

FBL030

Figure A.3. Samples FBL021-FBL030.

FBL031 FBL032

FBL033 FBL034

FBL035 FBL036

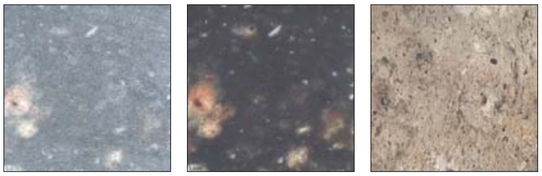
FBL037 FBL038

FBL039 FBL040

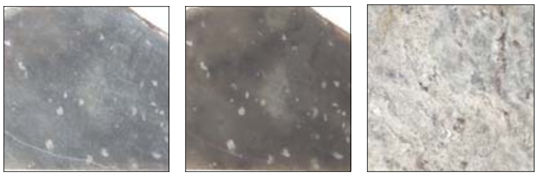
Figure A.4. Samples FBL031-FBL040.

Figure A.5. Samples FBL041-FBL050.

Dry **Wet** **Cortex** **Dry** **Wet** **Cortex**

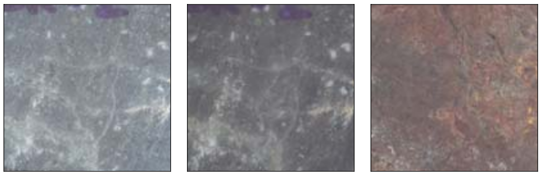


FBL051



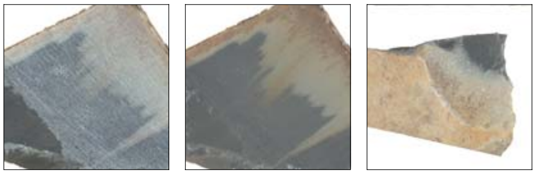
FBL052

FBL053



FBL054

FBL055

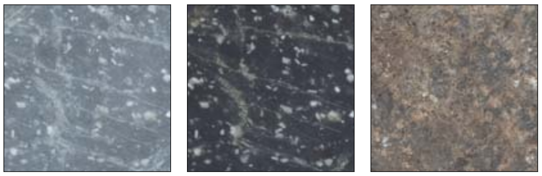


FBL056

FBL057

FBL058

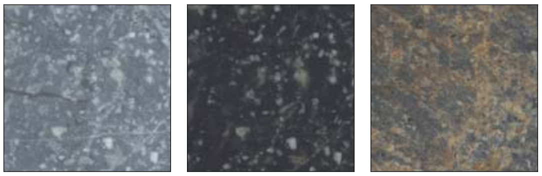
FBL059



FBL060

Figure A.6. Samples FBL051-FBL060.

Dry **Wet** **Cortex** **Dry** **Wet** **Cortex**



FBL061

FBL062

FBL063

FBL064

FBL065

FBL066

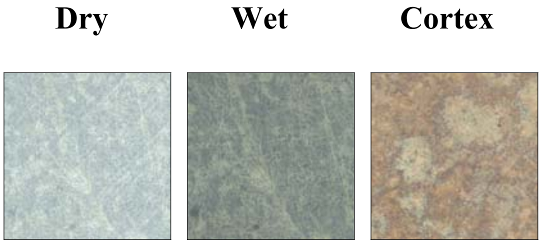
FBL067

FBL068

FBL069

FBL070

Figure A.7. Samples FBL061-FBL070.



FBL071

Figure A.8. Sample FBL071.

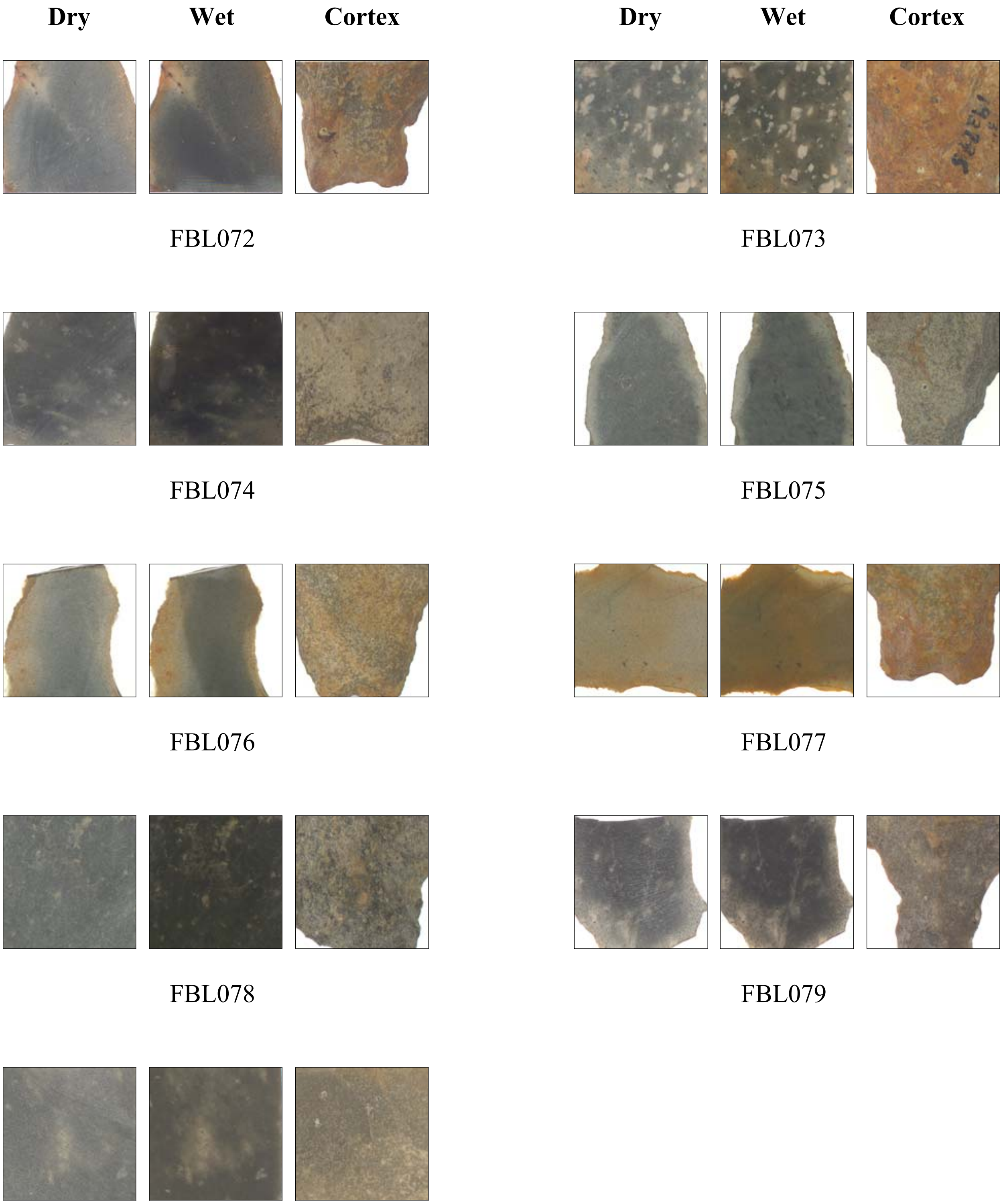


Figure A.9. Artifacts FBL072-FBL080.

Appendix B

Quarry Database

Christopher R. Moore

Two sources of information were used in compiling this database of quarry sites in the North Carolina Piedmont. First, the site files at the North Carolina Office of State Archaeology (OSA) were reviewed for sites coded as quarries, quarry workshops, or possible quarries; with the help of state archeologists Dolores Hall and John Mintz, numerous possible quarry sites were identified. Second, additional quarries were discovered during the field investigations undertaken as part of this study; many such sites in regions outside the Uwharrie Mountains were identified and brought to our attention by local amateur archaeologists.

Table B.1 lists all of the currently known prehistoric quarries, but many more remain to be found through additional surveys and in the archaeological gray literature, which no doubt contains numerous references to such sites. It is also likely that a small percentage of the quarry sites listed in the database will, upon field examination, turn out to be misidentified. Older reports sometimes refer to sites as "quarry workshops," "quarry-related workshops," or "quarries" based on the presence of small amounts of primary flaking debris in areas thought to be source locations. Such errors will only be corrected by revisiting these sites. Even so, the current compilation, which includes over 100 quarries and limited-use extraction sites, serves as a useful baseline for further refinement and additions.

Two kinds of site numbers appear in Table B.1: (*a*) the state site numbers assigned by OSA, and (*b*) the site numbers historically used by the Research Laboratories of Archaeology (RLA) at the University of North Carolina at Chapel Hill. Many quarry sites surveyed and described by Daniel and Butler are listed with RLA site numbers. We use state site numbers as our primary identifiers, but also note the RLA numbers when they differ from the OSA numbers or have already been used in print (e.g., Daniel and Butler 1996). Universal Transverse Mercator (UTM) grid system coordinates (NAD 27 datum) are included for each quarry. In general, the bibliographic references listed are the most recent surveys. Such references are presented either in standard bibliographic form or as OSA report numbers.

Also included in this appendix are detailed topographic maps showing the locations of all the samples examined in this study (Figures B.1-B.13).

Table B.1. Quarry Database.

State Site Number	RLA Site Number	Site Name	County	UTM^a Northing	UTM^a Easting	Rock Samples Collected	References
31Am391		Bass Mountain Quarry	Alamance	3975096	640000	no	
31An40			Anson	3855359	599440	no	Ward 1977
31Ch427			Chatham	3955167	641837	yes	Baker 1980; Cable and Mueller 1980
31Ch430			Chatham	3957552	639802	no	Baker 1980
31Ch578			Chatham	3954912	643242	vicinity	
31Ch729		Joe Moylan Quarry	Chatham	3962321	655811	yes	
31Ch741		Chestnut Hill Quarry	Chatham	3964338	647968	yes	
31Dh312			Durham	4006134	684712	no	
31Dh314			Durham	4006414	684532	no	
31Dh617			Durham	4002170	684504	no	
31Dh644			Durham	4002124	697562	no	Sara 1999
31Dh703		Cains Chapel Quarry	Durham	3999243	684745	yes	
31Dv31			Davidson	3960642	576221	no	Sellon 1980
31Dv36			Davidson	3942383	572042	no	Cusick and Smith 1997
31Dv51		Three-Hat Mountain	Davidson	3957728	577978	no	Mountjoy and Abbott 1982
31Dv224			Davidson	3960922	576731	no	Sellon 1980
31Dv621			Davidson	3942681	572641	no	Cusick and Smith 1997
31Mg744	Mg117	Wolf Den Quarry	Montgomery	3918992	584397	yes	Daniel and Butler 1996
31Mg119	Mg119		Montgomery	3917823	585474	no	Daniel and Butler 1996; Benson 1999
31Mg127			Montgomery	3910896	601673	no	Cooper 1976
31Mg140		Lost Trowel Site	Montgomery	3919001	586551	no	Cooper and Hanchette 1977
31Mg141		Halozone Quarry Site	Montgomery	3918816	585825	no	Cooper and Hanchette 1977
31Mg142		Jones Quarry Site	Montgomery	3918931	586271	no	Cooper and Hanchette 1977
31Mg155		"Poryphyritic rhyolite" quarry	Montgomery	3919162	585340	no	Cooper and Hanchette 1977
31Mg160	Mg644	Acorn Quarry Site	Montgomery	3919381	585101	no	Cooper and Hanchette 1977
31Mg163		Old Glory Quarry Site	Montgomery	3919656	585449	no	Cooper and Hanchette 1977
31Mg164	Mg646		Montgomery	3919915	585552	no	Daniel and Butler 1996
31Mg169			Montgomery	3920044	585838	no	Cooper and Hanchette 1977
31Mg171		McNeil Quarry Site	Montgomery	3919871	585201	no	Cooper and Hanchette 1977

Table B.1. Quarry Database (continued).

State Site Number	RLA Site Number	Site Name	County	UTM^a Northing	UTM^a Easting	Rock Samples Collected	References
31Mg173		Skyline Quarry Site	Montgomery	3920599	586054	no	Cooper and Hanchette 1977
31Mg175		Longworth Quarry Site	Montgomery	3920304	585725	no	Cooper and Hanchette 1977
31Mg176		Suede Glove Quarry Site	Montgomery	3920441	585391	no	Cooper and Hanchette 1977
31Mg184		Apostrophe Quarry Site	Montgomery	3920591	585351	no	Cooper and Hanchette 1977
31Mg185		Basalt Breccia Quarry	Montgomery	3920451	585101	no	Cooper and Hanchette 1977
31Mg192			Montgomery	3918841	584574	vicinity	Benson 1999
31Mg200		Wither's Quarry Site	Montgomery	3913701	591331	no	Cooper and Hanchette 1977
31Mg204		Hee Haw Site	Montgomery	3912901	591151	no	Cooper and Hanchette 1977
31Mg210		Robbin Quarry Site	Montgomery	3912321	590901	no	Cooper and Hanchette 1977
31Mg217		Corsair Quarry Site	Montgomery	3913973	588857	no	Cooper and Hanchette 1977
31Mg222		U.S.S. Ranger Quarry	Montgomery	3913878	588461	yes	Cooper and Hanchette 1977
31Mg238		Stuka Quarry Site	Montgomery	3912101	589971	no	Cooper and Hanchette 1977
31Mg246		Caesar Quarry Site	Montgomery	3912379	588644	no	Cooper and Hanchette 1977
31Mg268			Montgomery	3922205	594947	no	Cooper and Norville 1978; Benson 1999
31Mg270		Thicket Quarry Site	Montgomery	3922833	594724	no	Cooper and Norville 1978
31Mg325			Montgomery	3921561	584581	no	Harmon and Snedeker 1993b
31Mg328			Montgomery	3921701	584721	no	Harmon and Snedeker 1993b
31Mg532			Montgomery	3919501	586901	no	
31Mg544	Mg642		Montgomery	3917335	586512	yes	Daniel and Butler 1996
31Mg554	Mg554	Shingle Trap Mountain	Montgomery	3917945	587113	yes	Daniel and Butler 1996
31Mg559	Mg559		Montgomery	3919058	586896	no	Daniel and Butler 1996
31Mg568	Mg568	Shingle Trap Mountain	Montgomery	3918301	586521	vicinity	NC OSA bib# 1805
31Mg593			Montgomery	3908948	587047	no	
31Mg639	Mg639		Montgomery	3917941	584301	yes	Daniel and Butler 1996
31Mg640	Mg640		Montgomery	3917722	583543	yes	Daniel and Butler 1996
31Mg645	Mg645		Montgomery	3920762	585441	no	Daniel and Butler 1996
31Mg661		Burnt Hill Site	Montgomery	3910660	602479	no	Cooper 1976
31Mg728	Mg641		Montgomery	3926661	586821	yes	Daniel and Butler 1996; NC OSA bib# 2318
31Mg874			Montgomery	3924781	584671	no	Harmon and Snedeker 1991

Table B.1. Quarry Database (continued).

State Site Number	RLA Site Number	Site Name	County	UTM^a		Rock Samples Collected	References
				Northing	Easting		
31Mg875			Montgomery	3925611	583871	no	Harmon and Snedeker 1991
31Mg889			Montgomery	3916491	589291	no	Hall and Baker 1991
31Mg906			Montgomery	3905905	600660	no	Walling et al. 1992
31Mg910	Mg643		Montgomery	3918729	585242	no	Daniel and Butler 1996
31Mg968			Montgomery	3907981	605741	no	Harmon and Snedeker 1993a
31Mg1031			Montgomery	3918329	584152	vicinity	Benson 1999
31Mg1035			Montgomery	3921841	588301	no	Harmon and Snedeker 1993c
31Mg1051			Montgomery	3918201	584641	vicinity	NC OSA bib# 3402, 4282
31Mg1198			Montgomery	3929811	599431	no	Benson 1999
31Mg1200			Montgomery	3929271	598561	no	Benson 1999
31Mg1211			Montgomery	3929801	598581	no	Benson 1999
31Mg1212			Montgomery	3929501	598951	no	Benson 1999
31Mg1219			Montgomery	3929661	599781	no	Benson 1999
31Mg1226			Montgomery	3925341	591271	no	Benson 1999
31Mg1357			Montgomery	3919353	584074	no	Benson 1999
31Mg1358			Montgomery	3919395	583890	no	Benson 1999
31Mg1400			Montgomery	3919741	583701	no	Benson 1999
31Mg1424			Montgomery	3918743	584318	yes	Benson 1999
31Mg1436			Montgomery	3918092	584436	vicinity	Benson 1999
31Mg1437			Montgomery	3918163	584462	vicinity	Benson 1999
31Mg1438			Montgomery	3918330	584695	vicinity	Benson 1999
31Mg1444			Montgomery	3918243	584780	vicinity	Benson 1999
31Mg1457			Montgomery	3917836	583019	vicinity	Benson 1999
31Mg1459			Montgomery	3917685	583007	vicinity	Benson 1999
31Mg1460			Montgomery	3919203	584268	vicinity	Benson 1999
31Mg1465			Montgomery	3917505	584558	no	Benson 1999
31Mg1469			Montgomery	3918280	583475	vicinity	Benson 1999
31Mg1471			Montgomery	3918222	583403	vicinity	Benson 1999
31Mg1473			Montgomery	3918104	583856	vicinity	Benson 1999

Table B.1. Quarry Database (continued).

State Site Number	RLA Site Number	Site Name	County	UTM^a Northing	UTM^a Easting	Rock Samples Collected	References
31Mg1474			Montgomery	3917615	584103	vicinity	Benson 1999
31Mg1480			Montgomery	3917793	583703	vicinity	Benson 1999
31Mg1483			Montgomery	3918629	583771	vicinity	Benson 1999
31Mg1495			Montgomery	3917532	583177	vicinity	Benson 1999
31Mg1505			Montgomery	3917331	585171	no	Benson 1999
31Mg1508			Montgomery	3917684	585785	no	Benson 1999
31Mg1517			Montgomery	3918041	585888	no	Benson 1999
31Mg1539			Montgomery	3920941	593691	no	Harmon et al. 1998
31Or549			Orange	3981230	670818	yes	
31Or564		Bald Mountain Quarry	Orange	3982644	670149	yes	
31Pr110			Person	4020909	686892	no	Jorgenson et al. 2002
31Pr115		Powerline Quarry	Person	4015893	688833	yes	
31Rd37	Rd37		Randolph	3948594	603702	yes	Daniel and Butler 1996
31Rd333		Prinz Eugen Site	Randolph	3942881	599942	no	Cooper and Hanchette 1977
31Rd336		Tirpitz Site	Randolph	3941751	599152	no	Cooper and Hanchette 1977
31Rd339		Scharnhorst Quarry Site	Randolph	3942981	599502	no	Cooper and Hanchette 1977
31Rd341		Gneisnau 2 Quarry Site	Randolph	3942661	599402	no	Cooper and Hanchette 1977
31Rd346	Rd346	Days End Quarry Site	Randolph	3941331	599632	no	Cooper and Hanchette 1977
31Rd349	Rd349	Peter Pan Quarry Site	Randolph	3940501	599382	no	Cooper and Hanchette 1977
31Rd366			Randolph	3942611	599002	no	Cooper and Hanchette 1977
31Rd374		Count Quarry Site	Randolph	3940861	598082	no	Cooper and Hanchette 1977
31Rd1028			Randolph	3952782	609432	no	Robinson 1990
31Rd1039		Howell 1	Randolph	3956112	601932	no	
31Rd1040		N Henry 2	Randolph	3947721	603822	vicinity	
31Rd1050	Rd853	Arsenault Quarry Site	Randolph	3959202	596952	no	Daniel and Butler 1996
31Rd1128			Randolph	3966562	605782	no	Lautzenheiser et al. 1997
31Rd1199	Rd850		Randolph	3947761	604072	vicinity	Daniel and Butler 1996
31Rd1200	Rd851	Hillcrest Stable Quarry	Randolph	3948601	607882	vicinity	Daniel and Butler 1996
31Rd1201	Rd854	Caraway Mountain	Randolph	3957459	597060	yes	Daniel and Butler 1996

Table B.1. Quarry Database (continued).

State Site Number	RLA Site Number	Site Name	County	UTM[a] Northing	UTM[a] Easting	Rock Samples Collected	References
31Rd1202	Rd855	Tater Head Mountain	Randolph	3957812	595812	yes	Daniel and Butler 1996
31Rd1211			Randolph	3930182	598178	no	Benson 1999
31Rd1212			Randolph	3930128	598541	no	Benson 1999
31Rd1219			Randolph	3930211	599071	no	Benson 1999
31Rd1223			Randolph	3932441	595401	no	NC OSA bib# 4280
31Rd1350	Rd852		Randolph	3948601	607882	yes	Daniel and Butler 1996
31Rh270			Richmond	3861952	605072	no	Errante and Drucker 1993
31St6	St6		Stanly	3916723	584052	vicinity	Hargrove 1989
31St18	St18	Morrow Mountain	Stanly	3912278	582415	yes	Daniel and Butler 1996
31St101			Stanly	3913377	582788	no	Hargrove 1989
31St102		Sugarloaf Mountain	Stanly	3913714	583081	no	Hargrove 1989
31St107	St66	Sugarloaf Mountain	Stanly	3913854	583742	yes	Daniel and Butler 1996
31St108		Sugarloaf Mountain	Stanly	3913571	583417	no	Hargrove 1989
31St109			Stanly	3916081	584381	no	Hargrove 1989
31St112			Stanly	3915057	585121	no	Hargrove 1989
31St115			Stanly	3914519	585768	no	Hargrove 1989
31St166	St64	Tater Top Mountain	Stanly	3912961	584361	yes	Daniel and Butler 1996
31St167	St65	Mill Mountain	Stanly	3913851	585526	yes	Daniel and Butler 1996
31St168	St67	Hattaway Mountain	Stanly	3914821	583501	yes	Daniel and Butler 1996
31St169	St68	Sugarloaf West	Stanly	3914181	582735	yes	Daniel and Butler 1996
31Un16			Union	3893041	562930	no	

[a] NAD 1927 datum.

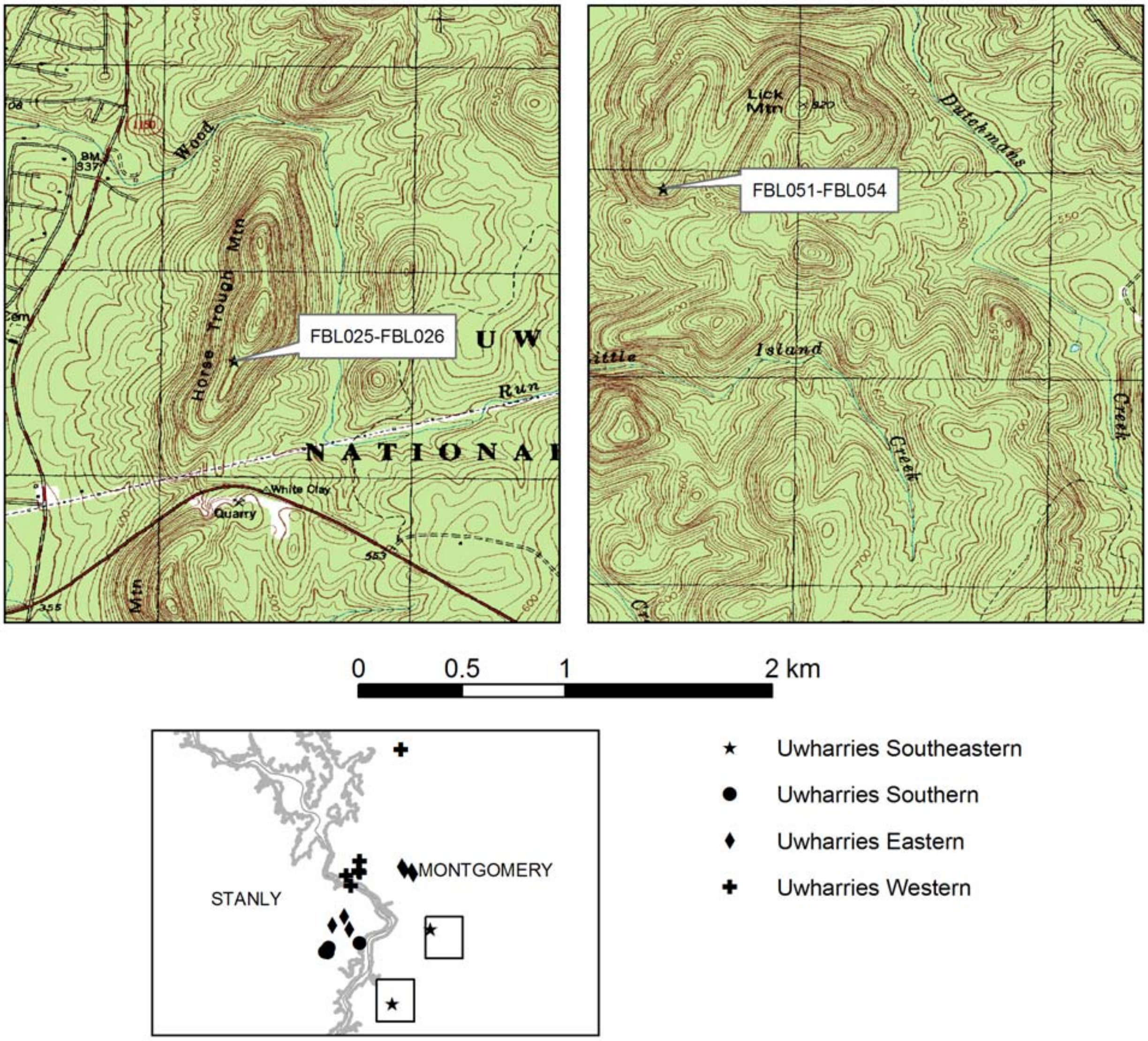


Figure B.1. Sample locations in the Uwharries Southeastern zone.

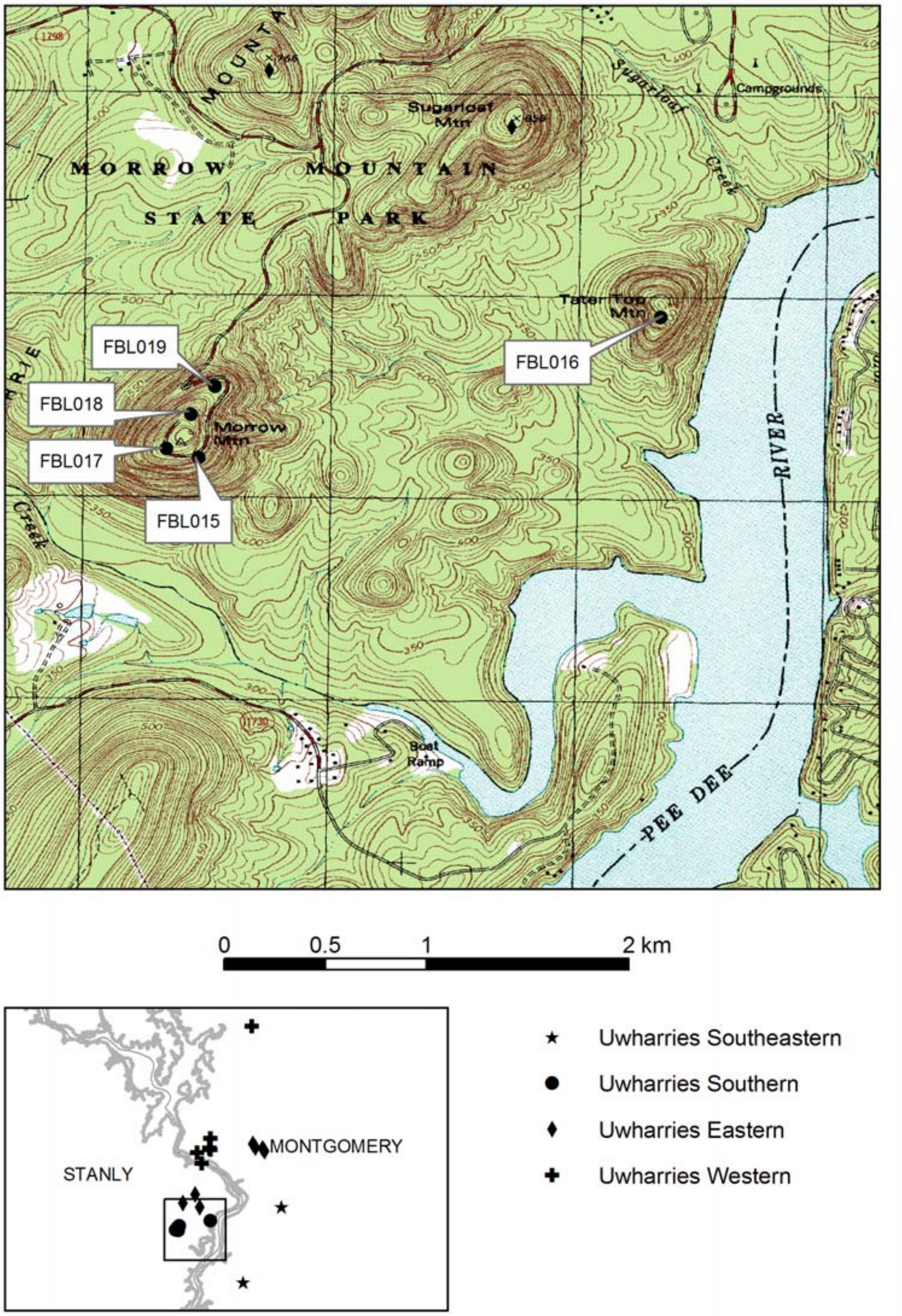


Figure B.2. Sample locations in the Uwharries Southern zone.

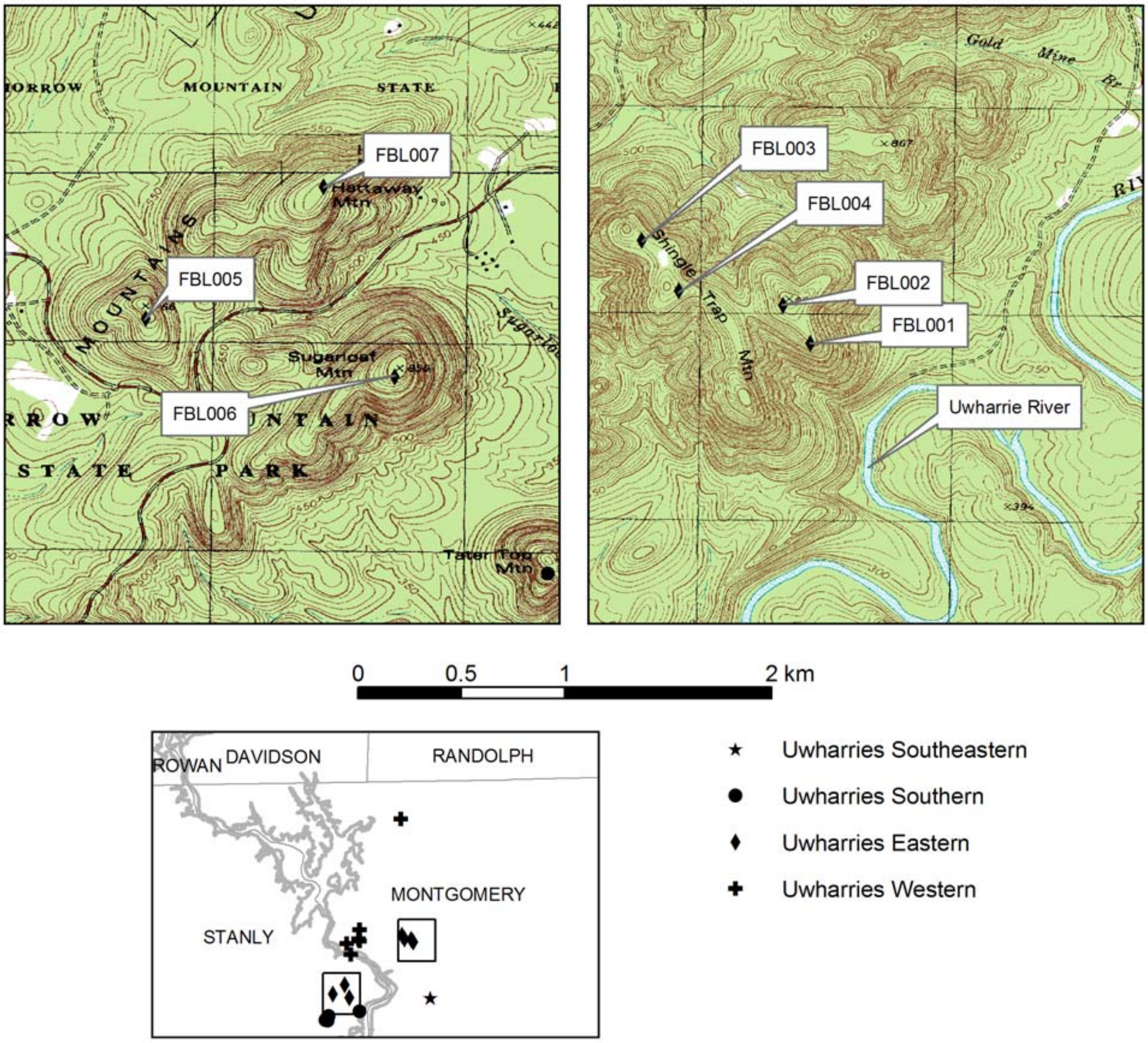


Figure B.3. Sample locations in the Uwharries Eastern zone.

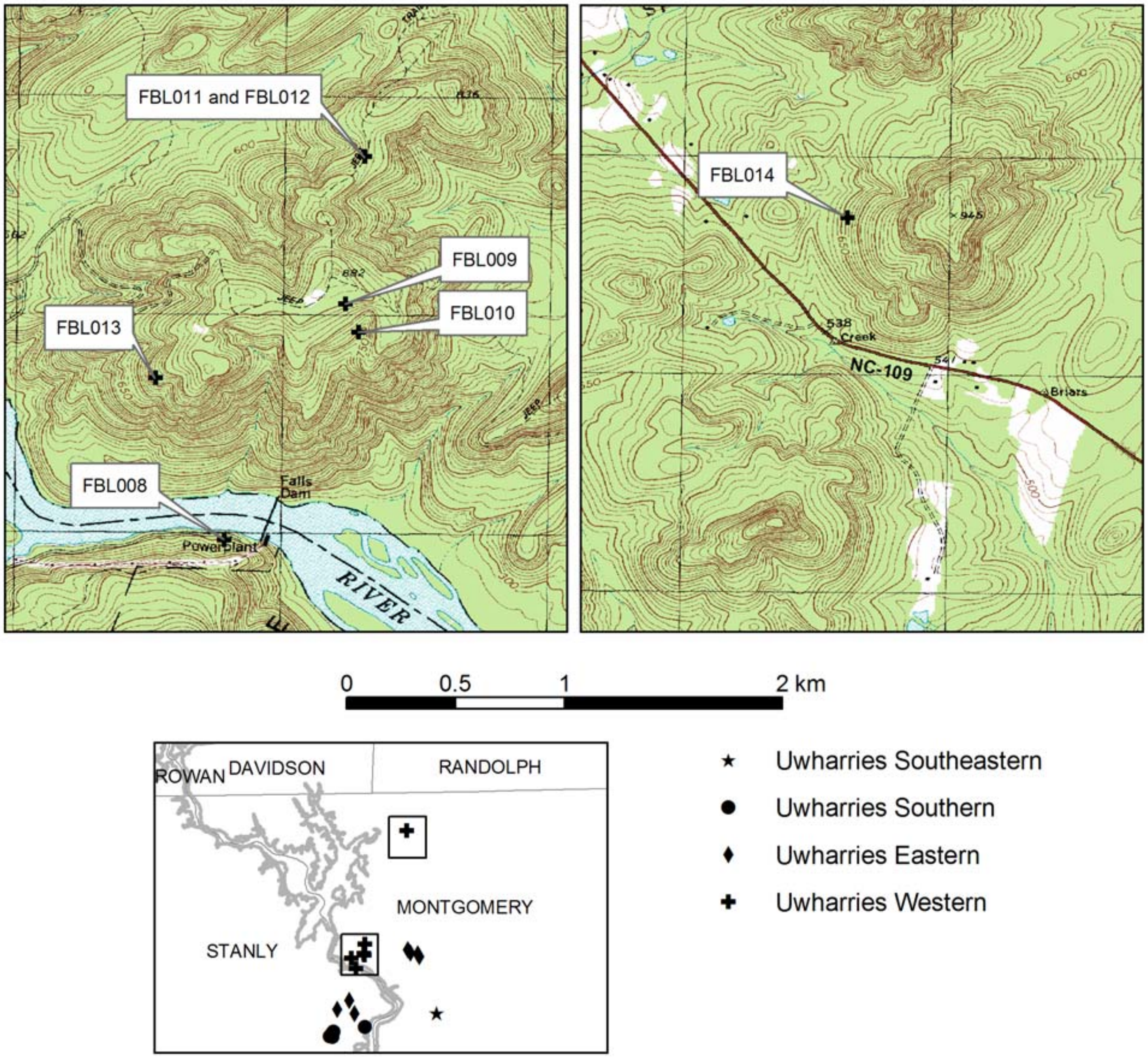


Figure B.4. Sample locations in the Uwharries Western zone.

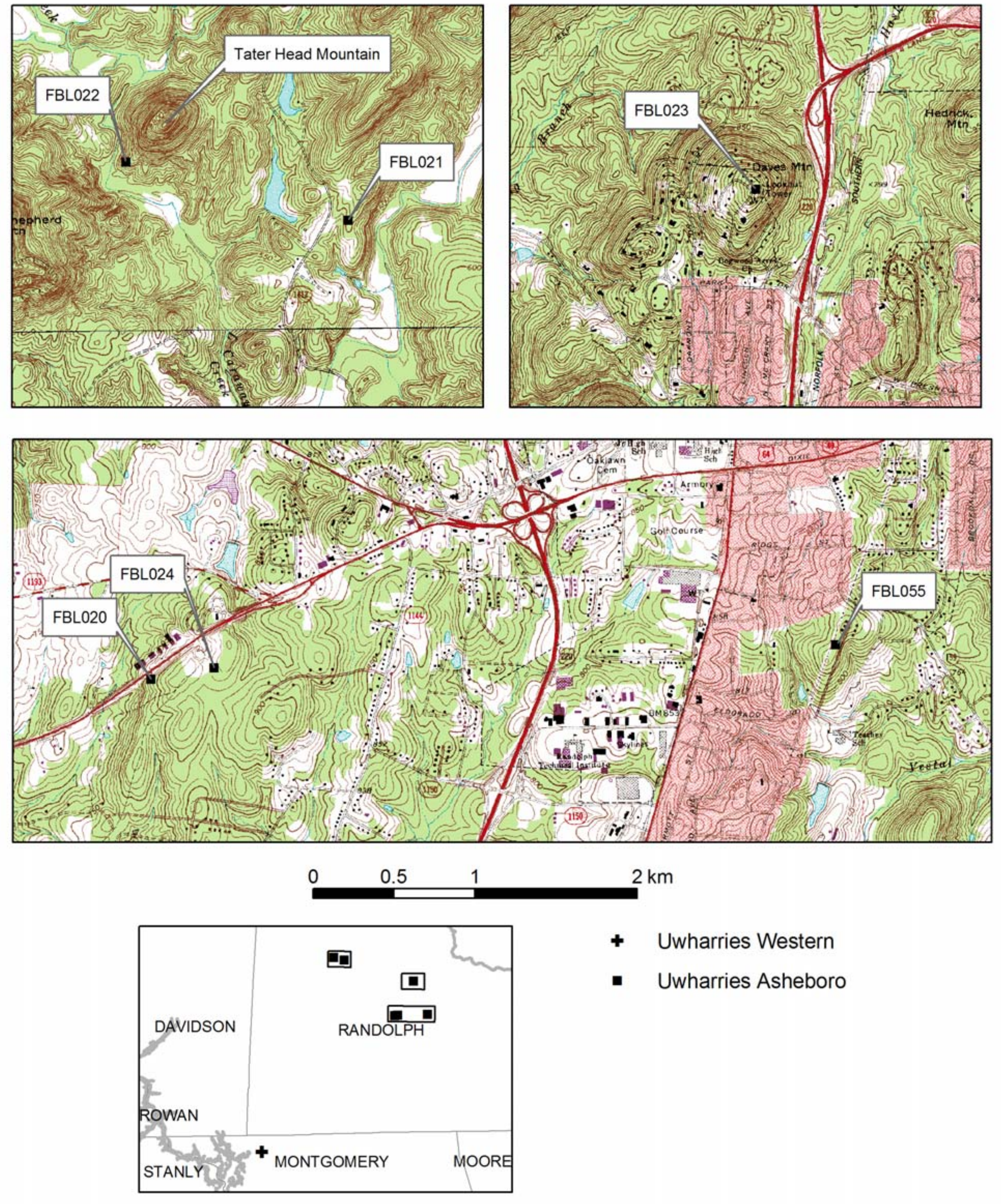


Figure B.5. Sample locations in the Uwharries Asheboro zone.

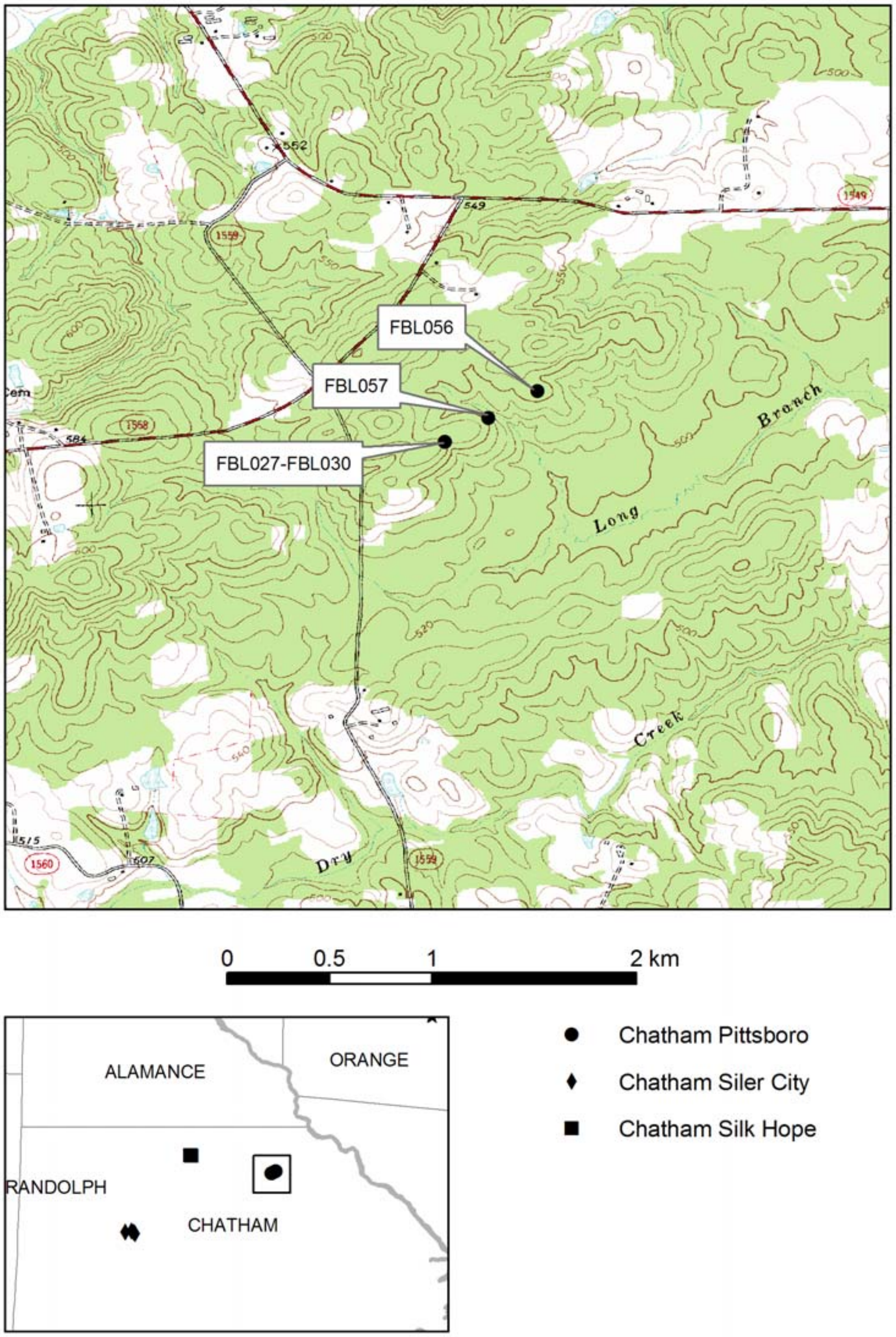


Figure B.6. Sample locations in the Chatham Pittsboro zone.

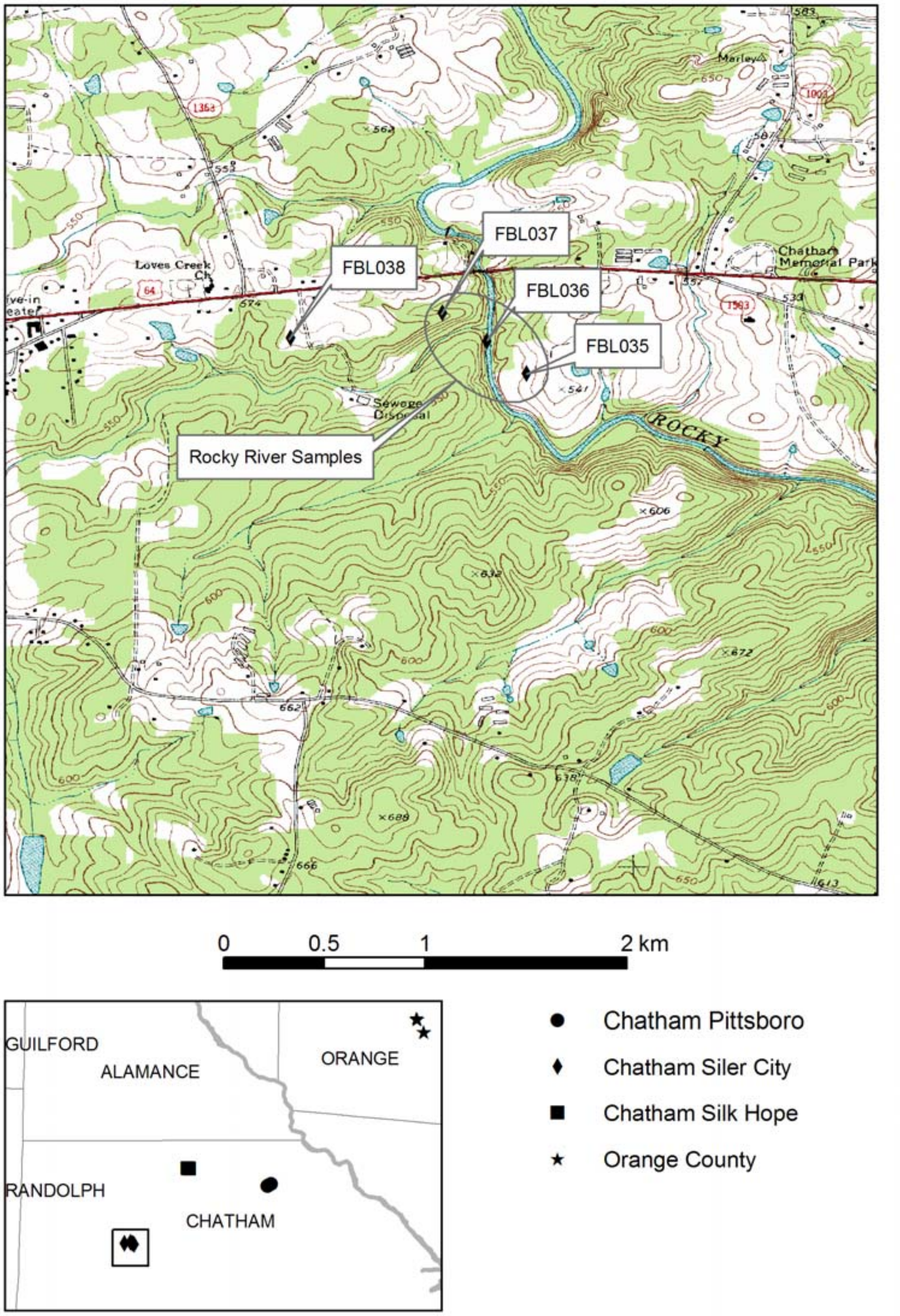


Figure B.7. Sample locations in the Chatham Siler City zone.

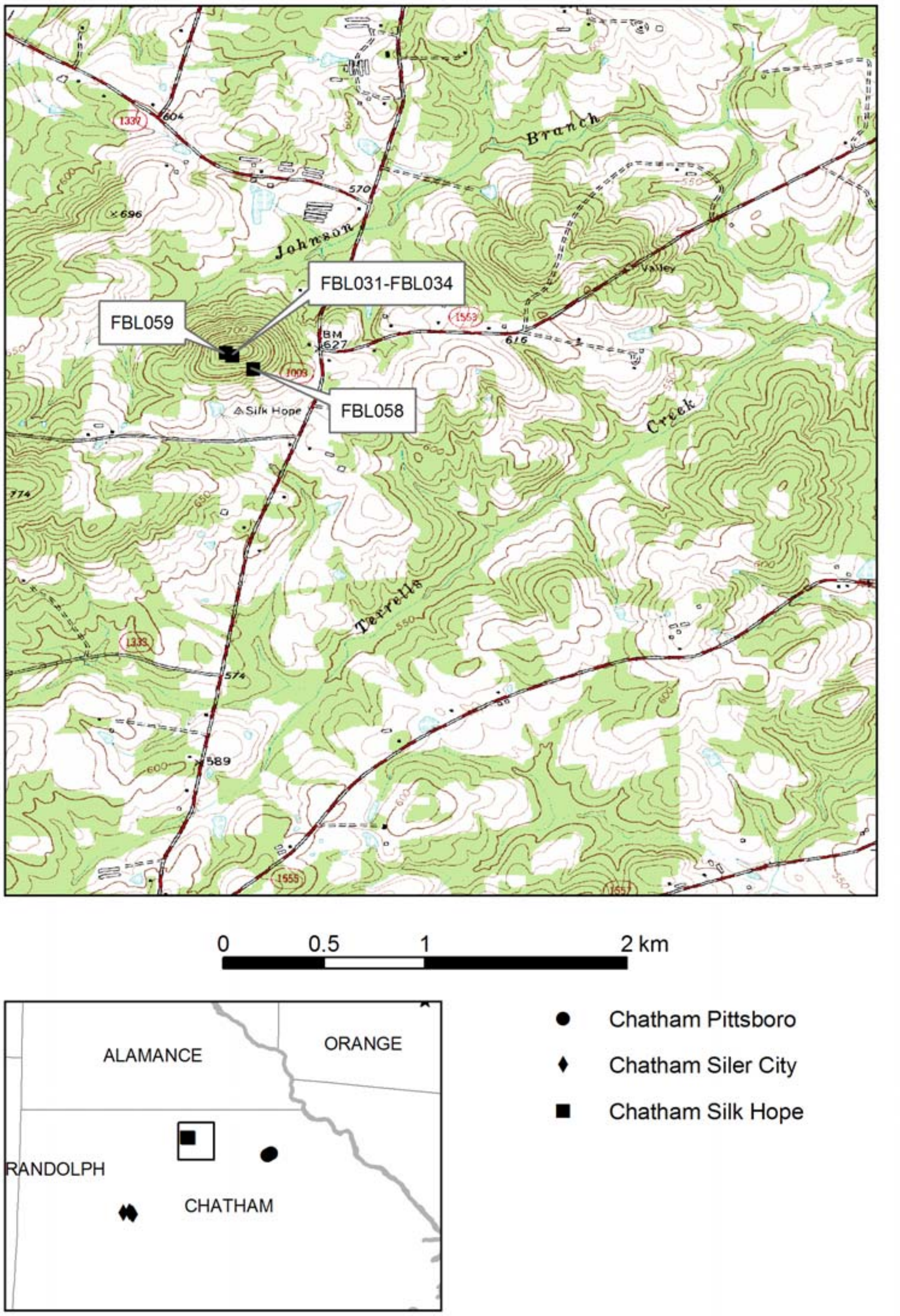


Figure B.8. Sample locations in the Chatham Silk Hope zone.

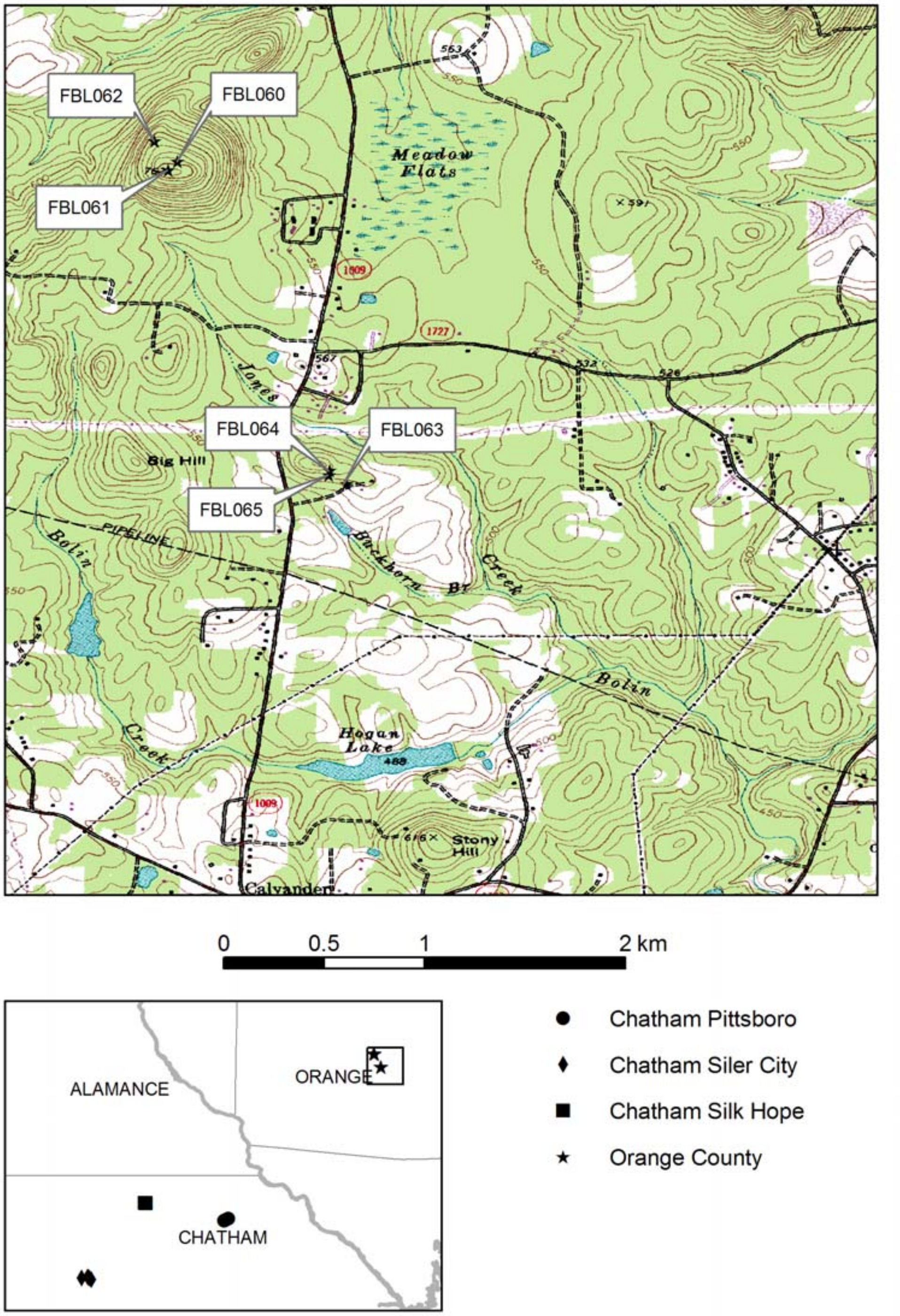


Figure B.9. Sample locations in the Orange County zone.

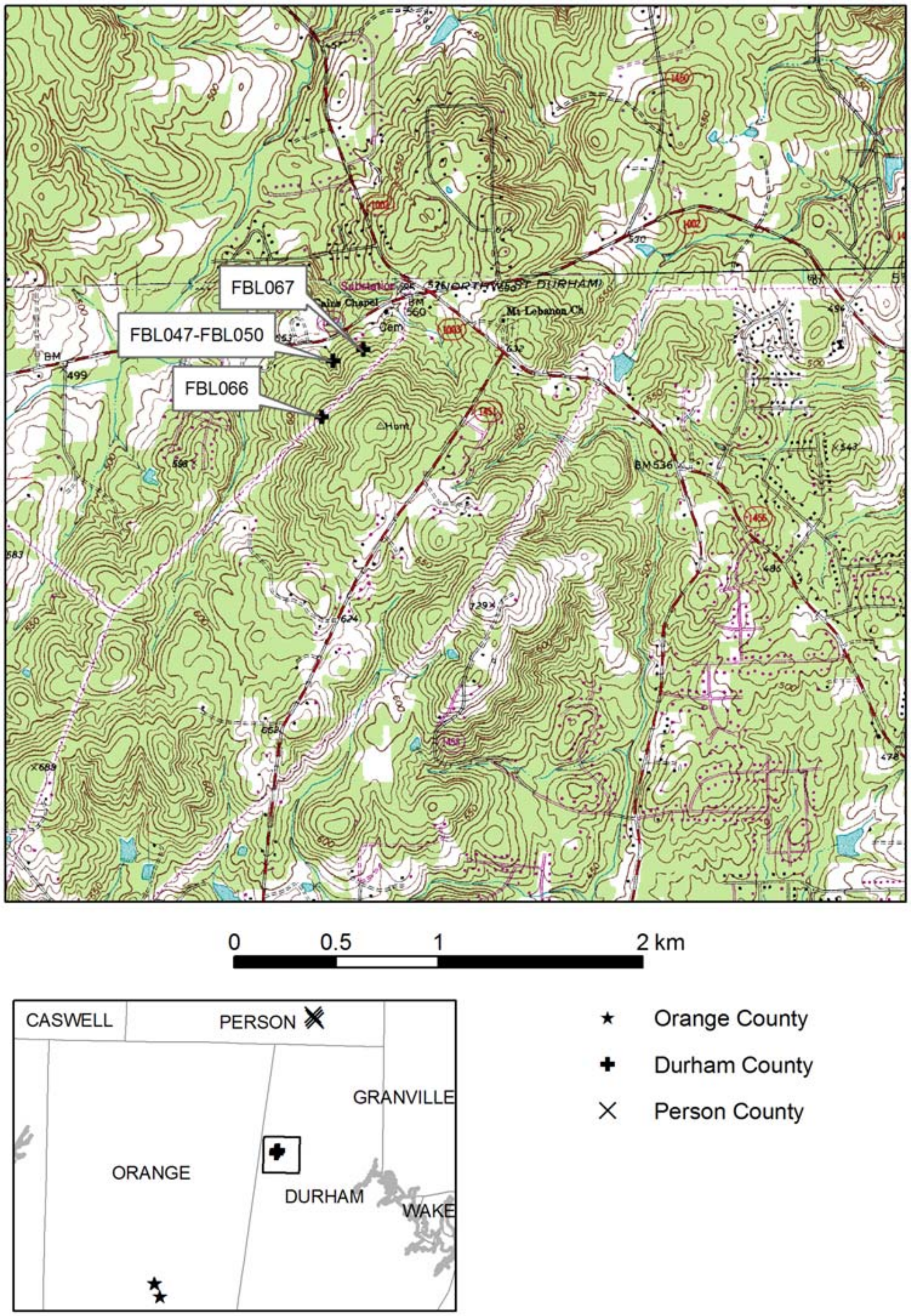


Figure B.10. Sample locations in the Durham County zone.

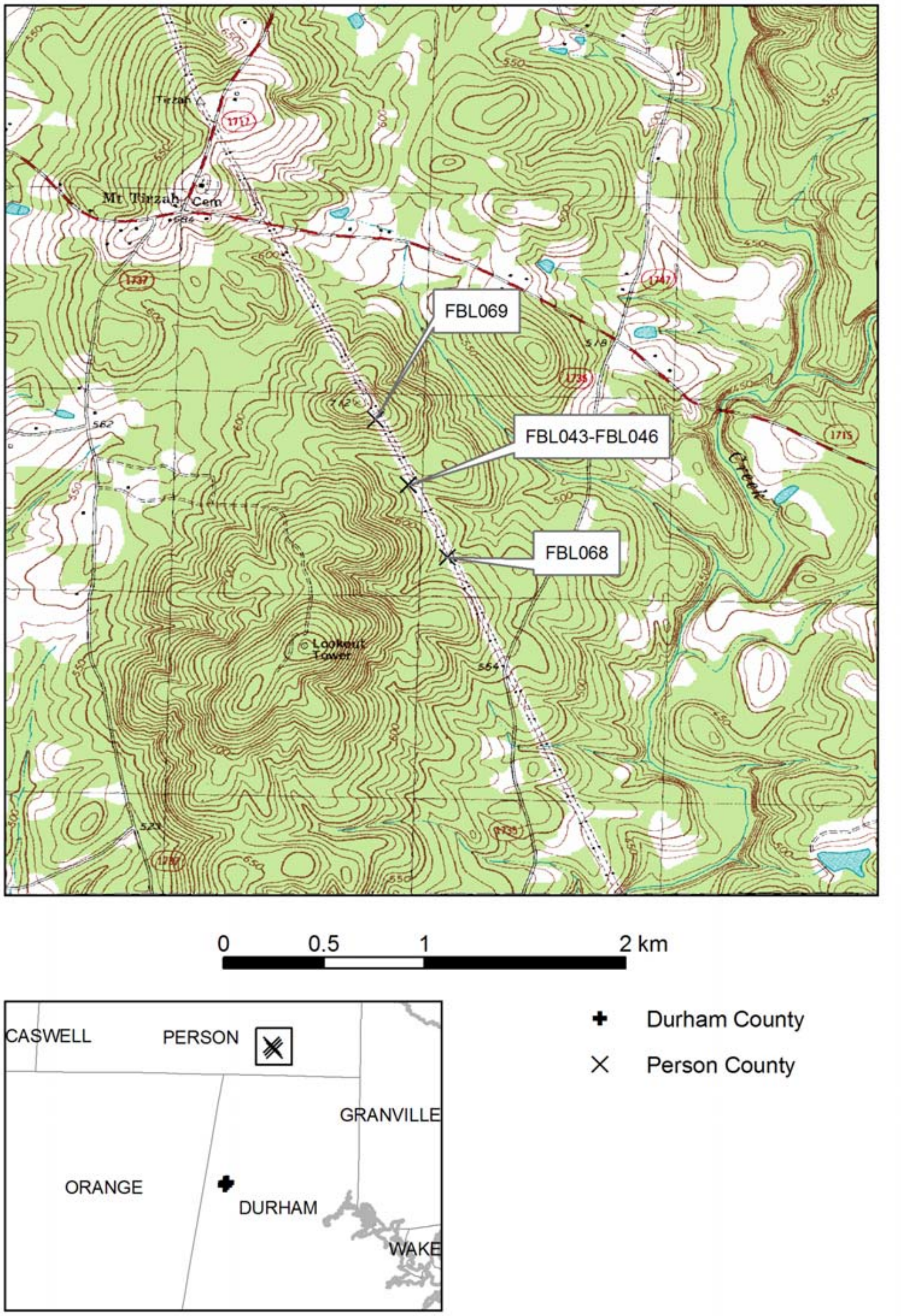


Figure B.11. Sample locations in the Person County zone.

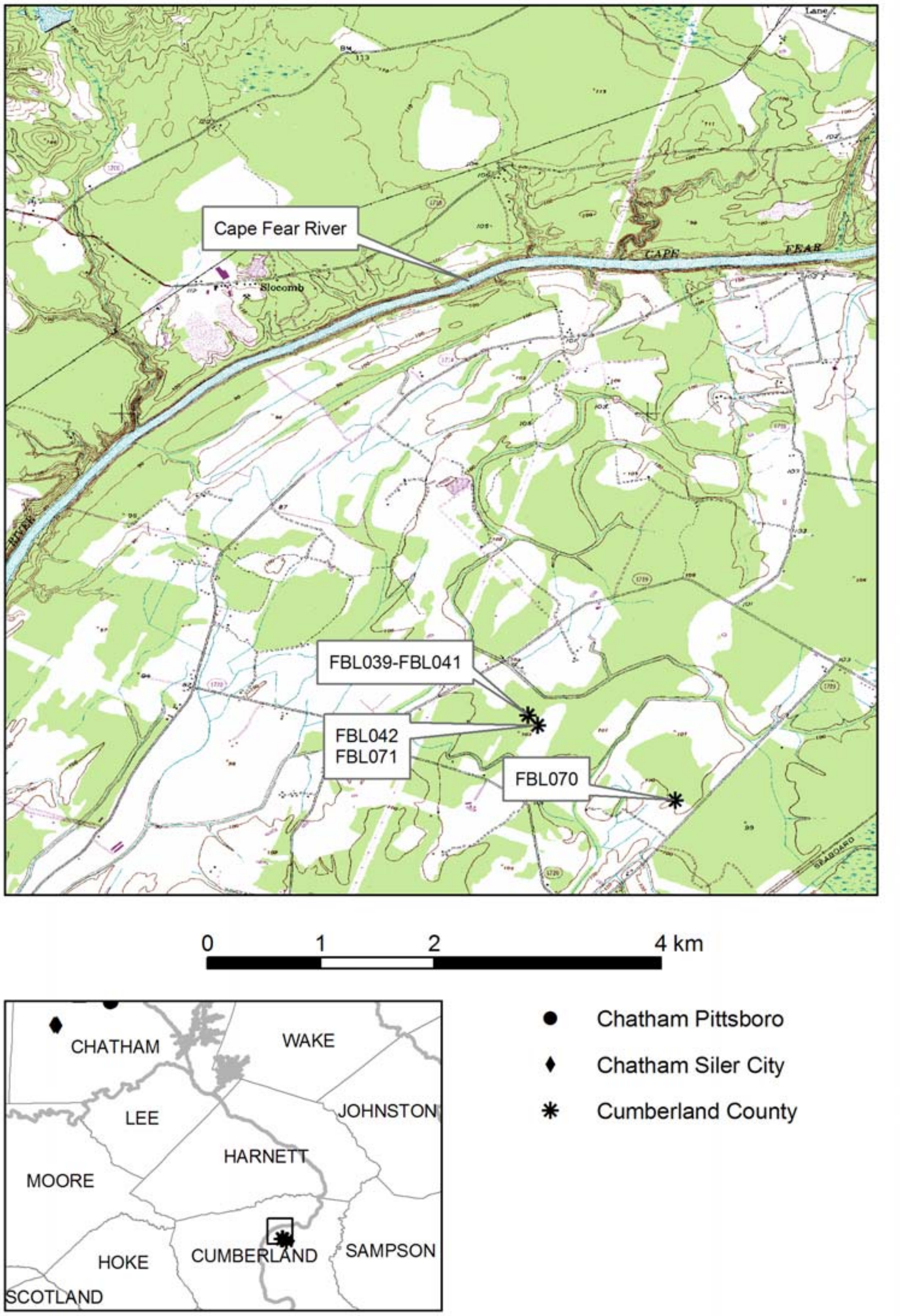


Figure B.12. Sample locations in the Cumberland County zone.

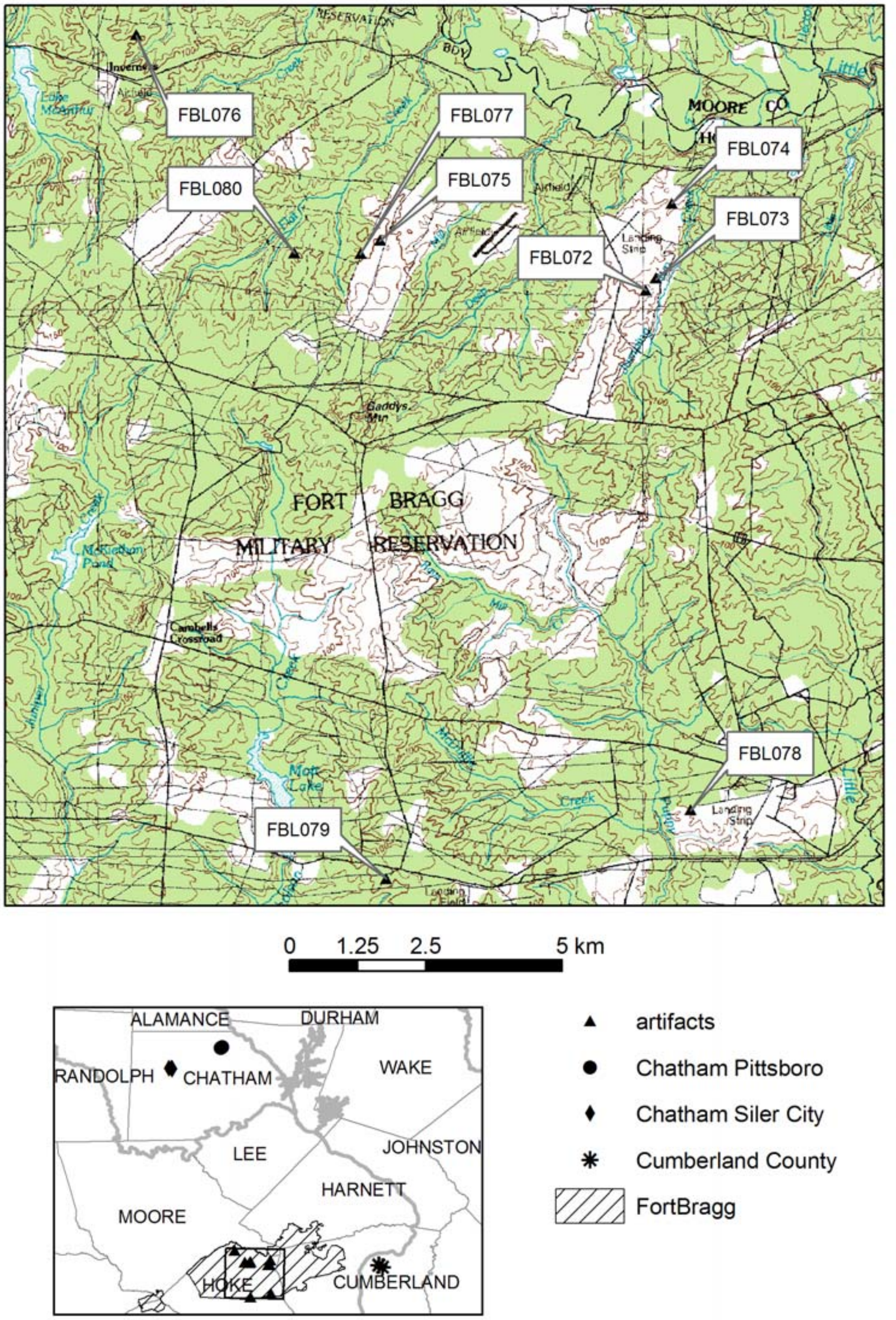


Figure B.13. Artifact sample locations, all on Fort Bragg.

Appendix C

Petrographic Data

Edward F. Stoddard

Standard size (27 × 46 mm) petrographic thin sections (30 µm) of all rock and artifact samples were examined with a binocular Zeiss polarizing microscope using standard techniques. Sections were studied under both plane-polarized light and crossed polars. Photomicrographs of thin sections were taken using a Nikon Coolpix 4500 digital camera integrated with a Nikon Optiphot-Pol microscope. Lower magnification images were captured by manually scanning the thin sections, with polarizing filters, using a 35 mm slide scanner. Length measurements of microscopic features were determined by reference to a calibrated ocular micrometer. Table C.1 summarizes the petrographic features. For metavolcanic rocks containing phenocrysts, the visually estimated percentage of phenocrysts is given. In addition, the typical maximum dimension of individual phenocrysts is tabulated, although it should be understood that phenocrysts commonly occur in clumps (glomerocrysts) and these would be larger. For metasedimentary rocks, typical maximum grain size for clastic grains is given where determinable.

Table C.1. Selected Petrographic Characteristics.

	Primary Igneous Features				Primary Sedimentary Features				
	Phenocrysts								
Sample	Type[a]	Volume (%)	Size (mm)	Other Features	Clast Size (mm)	Structures	Distinctive Metamorphic Minerals[b]	Secondary Features[c]	Other
FBL001	Pl; Qtz	1	1.2	glass shards?	-	-	gBt; Stp	Ep/Qtz clusters	-
FBL002	Pl; Qtz	1	1.4	-	-	-	-	Ep/Qtz clusters	-
FBL003	Pl; Qtz	1	1	-	-	-	-	Chl/Ep clusters	-
FBL004	Pl; Qtz	2	1.3	-	-	-	Py; Cal; Grt; Pd	Qtz clusters	-
FBL005	Pl; Qtz	4	1.6	flow banding; rock fragments; pumice	-	-	Stp	-	-
FBL006	Pl; Qtz	7	1.2	flow banding	-	-	-	-	-
FBL007	Pl; Qtz	2	1.2	flow banding; pumice	-	-	Stp	Qtz veins	-
FBL008	Pl	2	1.1	-	-	-	gBt	-	-
FBL009	Pl	1	1	-	-	-	-	Qtz/Ep clusters	-
FBL010	Pl	2	2.1	-	-	-	gBt	Qtz/Ep veins; Qtz/Chl veins	-
FBL011	Pl	1	1.8	spherulites	-	-	-	-	-
FBL012	Pl; Kfs	2	2	spherulites	-	-	Op	-	-
FBL013	Pl	3	2.1	-	-	-	-	-	-
FBL014	Pl; Kfs?	2	1.5	-	-	-	-	-	sericitized phenocrysts
FBL015	-	-	0.1	spherulites	-	-	Stp?	-	-
FBL016	-	-	-	-	-	-	Stp	-	-
FBL017	-	-	0.1	spherulites	-	-	-	cleavage	layers
FBL018	-	-	0.1	-	-	-	-	-	layers
FBL019	-	-	-	-	-	-	Stp	cleavage	layers
FBL020	-	-	-	pumice	-	-	bBt; Grt	-	-
FBL021	Pl	1	1	-	-	-	Py; Cal; Grt	-	-
FBL022	Pl	1	1.2	-	-	-	Py; Grt	-	sericitized phenocrysts
FBL023	Pl; Qtz	15	2.5	-	-	-	bBt	-	-
FBL024	-	-	-	-	-		Grt	-	-
FBL025	Pl; Qtz	1	1.5	spherulites	-	-	-	Qtz clusters[d]	-
FBL026	Pl; Qtz	1	1.5	spherulites	-	-	-	Qtz clusters[e]	-

Table C.1. Selected Petrographic Characteristics (continued).

	Primary Igneous Features				Primary Sedimentary Features				
	Phenocrysts								
Sample	Type[a]	Volume (%)	Size (mm)	Other Features	Clast Size (mm)	Structures	Distinctive Metamorphic Minerals[b]	Secondary Features[c]	Other
FBL027	-	-	-	spherulites	0.05	X	-	cleavage	layers
FBL028	-	-	-	-	0.08	X	-	cleavage	layers
FBL029	-	-	-	-	0.3	X	-	-	layers
FBL030	-	-	-	rock fragments	0.6	-	-	-	-
FBL031	Pl; Kfs	1	0.6	glass shards; rock fragments	-	-	Op; Pd	Ep/Qtz clusters	-
FBL032	-	-	-	glass shards; mafic rock fragments	-	-	Pd	-	-
FBL033	Pl	<1	1	rock fragments	-	-	-	-	-
FBL034	-	-	-	glass shards; mafic rock fragments	-	-	Pd	-	-
FBL035	-	-	-	-	0.03	graded bedding	-	-	layers
FBL036	Pl	5	1.3	glass shards; mafic rock fragments	-	-	-	-	-
FBL037	-	-	-	pumice	-	-	gBt	-	layers
FBL038	-	-	-	-	0.4	graded bedding	gBt	-	layers
FBL039	-	-	-	-	-	-	-	-	aplite
FBL040	-	-	-	-	-	-	-	-	metabasalt
FBL041	-	-	-	-	-	-	-	Qtz/Chl/Ep veins	-
FBL042	-	-	-	pumice	-	-	-	Czo clusters	-
FBL043	-	-	-	-	-	-	-	Qtz/Chl/Cal/Ep veins	-
FBL044	-	-	-	pumice	0.1	-	Cal	-	layers
FBL045	-	-	-	-	0.04	-	-	-	layers
FBL046	-	-	-	-	0.15	better graded bedding	-	-	layers
FBL047	Pl	3	0.7	rock fragments	-	-	-	-	-
FBL048	-	-	0.15	-	-	-	Py	Ep veins	layers
FBL049	-	-	0.15	-	-	-	Py	Ep veins	layers
FBL050	-	-	-	rock fragments	-	-	-	Ep veins	layers
FBL051	Pl; Qtz	3	1.3	-	-	-	Act	-	-

Table C.1. Selected Petrographic Characteristics (continued).

	Primary Igneous Features				Primary Sedimentary Features				
	Phenocrysts								
Sample	Type[a]	Volume (%)	Size (mm)	Other Features	Clast Size (mm)	Structures	Distinctive Metamorphic Minerals[b]	Secondary Features[c]	Other
FBL052	Pl; Qtz	2	1.6	-	-	-	Act	-	-
FBL053	Pl; Qtz	3	1.5	-	-	-	Stp	-	-
FBL054	Pl; Qtz	2	1.2	-	-	-	Py; Act	-	-
FBL055	Pl	1	0.7	flow banding	-	-	bBt; Grt	-	-
FBL056	-	-	-	-	0.01	-	-	-	layers
FBL057	-	-	-	-	-	-	-	Qtz veins	-
FBL058	Pl	<1	0.5	glass shards; mafic rock fragments	-	-	-	-	-
FBL059	Pl	<1	0.5	glass shards; mafic rock fragments; felsic rock fragments	-	-	Cal; Pd	-	-
FBL060	Pl; Qtz	15	2	-	-	-	-	-	-
FBL061	Pl; Qtz	15	2	-	-	-	-	-	-
FBL062	Pl; Qtz	20	2.1	-	-	-	-	-	-
FBL063	Pl; Qtz	15	1.8	-	-	-	-	-	-
FBL064	Pl; Qtz	20	2.5	-	-	-	-	-	-
FBL065	Pl; Qtz	20	1.9	-	-	-	-	-	-
FBL066	Pl	1	0.3	-	-	-	-	-	-
FBL067	-	-	-	-	0.25	cluster of minerals	-	-	-
FBL068	-	-	-	-	0.1	-	Py	-	-
FBL069	-	-	-	-	0.05	graded bedding	-	faults	layers
FBL070	-	-	-	-	-	-	-	-	greenstone
FBL071	-	-	-	-	-	-	-	-	metagabbro
FBL072	Pl	2	0.7	aligned plagioclase laths; flow banding	-	-	bBt; Grt; Stp?	-	-
FBL073	Pl; Qtz	20	2	-	-	-	Ep; Pd?	mafic pseudomorphs	-
FBL074	Pl; Qtz	1	0.5	weak alignment	-	-	Ep; Bt; Act; Chl	saussuritization; amygdules?	-
FBL075	Pl	<<1	0.3	-	-	-	Ep	saussuritization	-

Table C.1. Selected Petrographic Characteristics (continued).

	Primary Igneous Features				Primary Sedimentary Features				
	Phenocrysts								
Sample	Type[a]	Volume (%)	Size (mm)	Other Features	Clast Size (mm)	Structures	Distinctive Metamorphic Minerals[b]	Secondary Features[c]	Other
FBL076	Pl	<<1	0.05	-	0.05	-	Act; Ep; bBt	-	-
FBL077	-	-	-	-	0.05	bedding?	gBt	-	-
FBL078	Pl; Qtz	3	1.2	flow banding; zoned plagioclase	-	-	Ep; Act; Op	saussuritization; mafic pseudomorphs; quartz-epidote amygdules	pseudomorph of epidote after clinopyroxene?
FBL079	Pl	1	0.5	-	-	-	bBt; Ep; Act; Ms	quartz-epidote amygdule	-
FBL080	Pl	1	1.2	oriented plagioclase laths; banding	-	-	bBt; Grt; Ep; Ms	-	-

[a] Key: Kfs, K-feldspar; Pl, plagioclase; Qtz, quartz.

[b] Key: Act, actinolite; Bt, biotite; bBt, brown biotite; Cal, calcite; Chl, chlorite; Ep, epidote; gBt, green biotite; Grt, garnet; Ms, muscovite; Op, opaque minerals; Pd, piedmontite; Py, pyrite; Stp, stilpnomelane.

[c] Key: Cal, calcite; Chl, chlorite; Czo, clinozoisite; Ep, epidote; Qtz, quartz.

[d] Size ranges to at least 3 mm; abundance is 10%.

[e] Size ranges to at least 3 mm; abundance is 5%.

Appendix D

Neutron Activation Analysis Data

Michael D. Glascock and Robert J. Speakman

The rock samples and artifacts were ground into powders by Brent Miller at the University of North Carolina at Chapel Hill using an aluminum-oxide shatter box. The samples were then shipped to MURR in powdered form.

Once at MURR, approximately 350 mg aliquots of rock powder were placed in glass vials and oven-dried at 105°C for 24 hours before weighing. Portions weighing 150 mg each were weighed into clean 0.4-dram polyvials used for short irradiations at MURR. At the same time, a sample weighing 200 mg was weighed into the clean high-purity quartz vials used for long irradiations at MURR. Along with the unknown samples, a number of reference standards made from SRM-1633a (coal fly ash) and SRM-688 (basalt rock) were similarly prepared, as were quality control samples (i.e., standards treated as unknowns) made from SRM-278 (obsidian rock) and Ohio Red Clay.

Neutron activation analysis of geological and archaeological samples at MURR, which consists of two irradiations and a total of three gamma counts, constitutes a superset of the procedures used at most other laboratories (Glascock 1992; Neff 1992, 2000). As discussed in detail by Glascock (1992), a short irradiation is carried out through the pneumatic tube irradiation system. Samples in the polyvials are sequentially irradiated, two at a time, for five seconds at a neutron flux of 8×10^{13} n/cm^2/s. The 720-second count generally yields gamma spectra containing peaks for nine short-lived elements: aluminum (Al), barium (Ba), calcium (Ca), dysprosium (Dy), potassium (K), manganese (Mn), sodium (Na), titanium (Ti), and vanadium (V). The samples encapsulated in quartz vials are subjected to a 24-hour irradiation at a neutron flux of 5×10^{13} n/cm^2/s. This long irradiation is analogous to the single irradiation utilized at most other laboratories. After the long irradiation, samples decay for seven days and then are counted for 1,800 seconds (the “middle count”) on a high-resolution germanium detector coupled to an automatic sample changer. The middle count generally yields data for seven medium half-life elements, namely arsenic (As), lanthanum (La), lutetium (Lu), neodymium (Nd), samarium (Sm), uranium (U), and ytterbium (Yb). After an additional three- or four-week decay, a final count of 9,000 seconds is carried out on each sample. The latter measurement usually reports data for 17 long half-life elements, including cerium (Ce), cobalt (Co), chromium (Cr), cesium (Cs), europium (Eu), iron (Fe), hafnium (Hf), nickel (Ni), rubidium (Rb), antimony (Sb), scandium (Sc), strontium (Sr), tantalum (Ta), terbium (Tb), thorium (Th), zinc (Zn), and zirconium (Zr). Ratios of the decay-corrected counts per second per unit weight of the unknowns to the standards are used to calculate concentrations.

The NAA data from the two irradiations and three counts (a total of 33 elements) were tabulated with EXCEL and stored in a dBase file along with the descriptive information available for each sample. Tables D.1-D.2 present the NAA data in parts per million of the element with missing values (i.e., not detected) indicated by the presence of zeroes (i.e., 0.0).

Table D.1. Element Concentrations as Measured by Neutron Activation Analysis (As-Sb).

Sample	As (ppm)	La (ppm)	Lu (ppm)	Nd (ppm)	Sm (ppm)	U (ppm)	Yb (ppm)	Ce (ppm)	Co (ppm)	Cr (ppm)	Cs (ppm)	Eu (ppm)	Fe (ppm)	Hf (ppm)	Ni (ppm)	Rb (ppm)	Sb (ppm)
FBL001	0.00	34.2	0.915	29.9	8.00	2.74	6.15	68.6	0.482	0.00	0.673	1.105	10566	5.95	0.00	86.8	0.132
FBL002	0.00	29.5	1.077	28.1	7.66	2.94	7.10	63.3	0.283	0.00	0.559	1.034	8614	6.07	0.00	86.4	0.065
FBL003	0.00	36.5	1.216	29.9	9.44	1.91	8.38	75.9	0.570	0.00	0.633	1.236	12241	6.27	0.00	117.9	0.071
FBL004	1.44	20.8	0.887	20.7	6.23	2.57	6.03	46.4	0.307	0.00	1.275	0.820	8607	6.56	0.00	68.8	0.080
FBL005	18.47	33.9	1.149	35.8	9.54	1.94	7.93	74.9	0.334	0.77	0.989	0.659	8146	5.63	0.00	68.2	0.187
FBL006	0.00	30.8	1.161	27.3	8.17	2.97	7.56	65.7	0.348	0.00	0.369	0.977	10076	6.19	0.00	58.0	0.076
FBL007	0.00	27.5	0.800	21.2	6.37	1.69	5.25	47.9	0.377	0.00	0.773	0.777	7567	5.98	0.00	100.5	0.058
FBL008	1.56	26.4	1.038	29.7	8.04	2.59	7.19	59.5	0.544	0.00	1.054	1.188	12697	7.03	0.00	79.7	0.528
FBL009	0.00	24.9	0.970	23.8	7.58	2.22	6.61	55.7	0.571	0.00	2.139	1.149	13058	6.51	0.00	92.6	0.657
FBL010	0.77	23.9	1.071	19.6	7.42	2.54	6.97	54.0	0.626	0.00	0.730	0.997	12273	6.63	0.00	58.0	0.156
FBL011	0.00	26.1	1.029	22.8	7.73	2.39	7.01	57.8	0.811	0.00	0.883	0.989	12664	7.01	0.00	82.8	0.136
FBL012	1.94	27.5	1.069	26.3	8.24	2.36	7.16	61.0	0.733	0.00	0.807	1.130	13598	7.33	0.00	71.4	0.192
FBL013	0.00	22.8	0.965	24.4	6.43	1.67	6.14	51.3	0.644	0.00	0.489	0.970	13255	6.81	22.76	33.7	0.119
FBL014	0.00	24.1	0.779	24.5	6.86	1.84	5.29	52.2	0.575	0.00	1.587	1.559	15659	5.76	0.00	91.2	0.186
FBL015	0.00	28.3	0.804	21.9	6.39	3.32	5.60	60.6	0.299	0.00	0.508	0.823	9632	5.59	0.00	65.8	0.135
FBL016	0.00	26.1	0.928	23.3	6.58	3.87	6.22	56.0	0.314	0.00	0.656	0.782	9873	5.18	0.00	125.6	0.095
FBL017	0.00	27.6	0.861	23.2	6.67	3.08	6.22	59.8	0.377	0.00	0.594	0.825	9023	5.47	0.00	87.3	0.166
FBL018	0.00	25.8	0.894	25.9	6.01	2.86	5.89	54.6	0.345	0.00	0.555	0.727	9459	5.04	0.00	93.8	0.127
FBL019	0.00	26.6	0.833	23.7	6.71	2.26	5.62	57.4	0.256	0.00	0.474	0.807	9760	5.24	0.00	67.5	0.120
FBL020	0.00	18.5	0.473	15.7	4.32	1.04	3.16	37.9	3.372	5.48	2.859	0.855	16609	4.00	0.00	59.2	0.212
FBL021	6.54	17.6	0.711	16.7	5.05	0.83	4.61	37.7	0.426	0.00	0.589	1.115	8288	4.94	0.00	53.4	0.143
FBL022	2.36	19.6	0.733	21.9	5.63	0.83	4.79	42.5	0.571	0.00	0.384	1.170	9823	4.73	0.00	37.9	0.030
FBL023	0.00	16.3	0.557	17.2	4.21	1.06	3.63	33.0	0.574	0.00	0.145	0.855	11136	3.80	0.00	25.1	0.090
FBL024	0.00	17.7	0.530	18.6	5.10	1.39	3.47	39.0	1.826	0.00	0.669	0.974	15647	4.11	0.00	14.0	0.272
FBL025	0.00	28.2	0.636	19.0	5.58	2.27	4.27	59.0	0.362	0.65	0.933	0.685	6959	3.70	0.00	94.8	0.159
FBL026	0.00	28.0	0.613	25.1	5.47	1.30	4.29	58.0	0.413	0.00	1.381	0.728	7783	3.82	0.00	93.8	0.311
FBL027	15.27	16.5	0.586	22.5	6.55	2.78	4.22	55.6	0.780	2.56	2.394	1.185	7240	4.02	0.00	142.1	0.900
FBL028	0.00	44.0	0.528	46.3	9.00	3.98	4.06	92.9	2.105	3.90	4.750	1.637	15541	5.81	0.00	342.0	0.235
FBL029	0.00	35.4	0.557	38.7	7.32	2.46	4.31	76.6	2.933	11.46	2.404	1.383	14319	4.65	0.00	161.6	0.278

Table D.1. Element Concentrations as Measured by Neutron Activation Analysis (As-Sb) (continued).

Sample	As (ppm)	La (ppm)	Lu (ppm)	Nd (ppm)	Sm (ppm)	U (ppm)	Yb (ppm)	Ce (ppm)	Co (ppm)	Cr (ppm)	Cs (ppm)	Eu (ppm)	Fe (ppm)	Hf (ppm)	Ni (ppm)	Rb (ppm)	Sb (ppm)
FBL030	0.00	100.6	0.794	89.2	17.67	2.64	6.25	148.0	2.735	6.09	1.705	3.216	14813	6.51	0.00	60.4	0.260
FBL031	3.94	55.3	1.172	65.1	12.37	4.35	7.95	124.3	0.551	1.85	0.593	0.495	20571	14.47	0.00	125.5	0.549
FBL032	2.69	53.0	1.135	59.0	12.43	3.83	8.10	123.1	0.381	1.87	0.372	0.370	19301	14.35	0.00	86.5	0.546
FBL033	0.00	60.5	1.217	64.9	12.97	4.34	8.31	130.8	0.333	1.00	0.352	0.379	19342	15.00	0.00	115.6	0.221
FBL034	0.00	56.6	1.191	63.5	13.93	3.80	8.11	124.6	0.452	1.88	0.372	0.481	18815	14.34	0.00	111.2	0.634
FBL035	5.61	20.9	0.380	18.4	5.34	1.53	2.78	46.5	9.781	21.43	1.663	1.231	39870	4.75	0.00	59.2	0.211
FBL036	2.67	24.7	0.394	18.1	4.76	4.38	2.88	51.7	4.205	2.82	0.541	0.769	21699	7.00	0.00	37.7	0.311
FBL037	14.13	32.8	0.485	35.9	6.82	2.65	3.15	67.8	13.137	19.73	1.699	1.350	39828	5.13	0.00	114.0	0.407
FBL038	11.28	17.6	0.234	19.0	4.28	0.00	1.42	33.5	22.908	5.28	3.683	1.118	58740	2.46	0.00	68.3	0.192
FBL039	0.00	12.8	0.695	16.2	4.23	1.47	4.93	33.9	0.283	0.00	0.220	0.482	3876	6.80	0.00	88.8	0.159
FBL040	0.00	10.4	0.357	13.5	5.44	0.00	2.60	25.3	24.188	0.00	0.430	1.754	86274	2.10	0.00	0.0	0.085
FBL041	0.00	10.3	0.290	14.6	4.40	0.00	1.88	25.5	9.059	0.00	0.711	1.297	55005	1.73	0.00	34.3	0.136
FBL042	10.84	7.2	0.273	7.4	2.68	0.00	1.86	14.9	28.417	113.54	1.455	0.856	71010	1.60	0.00	33.2	1.455
FBL043	10.09	38.1	0.495	28.0	6.68	4.57	3.08	69.8	4.056	0.00	0.928	1.552	29253	6.01	0.00	20.0	0.460
FBL044	0.00	23.8	0.680	34.7	8.30	2.17	4.36	61.0	2.238	2.27	0.748	1.718	16551	5.85	0.00	21.8	0.319
FBL045	13.92	28.2	0.405	26.9	5.43	3.91	2.68	57.0	3.559	0.00	0.882	1.174	24916	5.24	0.00	27.9	0.448
FBL046	6.18	19.5	0.306	20.7	4.15	1.81	1.89	40.1	7.905	5.75	0.283	0.946	29026	3.67	0.00	12.6	0.452
FBL047	0.00	19.3	0.389	14.5	4.05	0.00	2.58	41.8	3.386	2.21	0.334	0.838	17432	4.89	21.22	11.7	0.266
FBL048	3.16	26.1	0.501	29.9	5.64	1.21	3.25	57.2	6.411	3.37	0.000	1.186	22284	6.23	0.00	0.0	0.528
FBL049	0.00	26.4	0.438	28.5	5.32	1.43	3.04	57.1	3.228	2.05	0.312	1.053	18595	6.33	0.00	14.4	0.173
FBL050	2.74	26.0	0.464	38.0	5.34	1.59	3.04	56.0	3.032	2.54	0.192	1.034	17739	5.83	0.00	9.2	0.395
FBL051	0.00	22.5	0.467	19.5	3.83	2.27	3.03	44.7	0.314	0.73	0.827	0.599	6808	3.55	0.00	90.9	0.109
FBL052	0.00	19.2	0.343	17.4	2.97	1.44	2.26	37.0	0.176	0.00	0.766	0.456	4486	2.71	0.00	69.5	0.173
FBL053	0.00	24.2	0.502	21.6	4.16	2.06	3.23	48.3	0.380	0.00	0.714	0.741	7596	3.98	0.00	88.7	0.155
FBL054	0.55	21.3	0.447	21.4	3.87	1.80	3.03	42.3	0.398	0.00	0.804	0.605	7339	3.71	0.00	98.5	0.108
FBL055	0.00	17.3	0.381	23.7	4.23	1.11	2.69	36.9	1.845	0.00	0.571	1.005	10273	3.31	0.00	37.9	0.121
FBL056	1.75	18.9	0.492	20.3	4.16	3.14	2.96	41.3	2.589	3.74	2.462	0.726	8292	3.74	0.00	200.4	0.206
FBL057	0.00	45.6	1.206	47.3	8.67	3.82	8.32	92.5	2.398	2.67	1.084	1.444	8760	5.54	0.00	92.3	0.125
FBL058	6.28	57.9	1.151	73.0	12.83	3.56	8.16	129.7	0.860	1.24	0.376	0.409	17963	15.30	0.00	105.4	0.622

Table D.1. Element Concentrations as Measured by Neutron Activation Analysis (As-Sb) (continued).

Sample	As (ppm)	La (ppm)	Lu (ppm)	Nd (ppm)	Sm (ppm)	U (ppm)	Yb (ppm)	Ce (ppm)	Co (ppm)	Cr (ppm)	Cs (ppm)	Eu (ppm)	Fe (ppm)	Hf (ppm)	Ni (ppm)	Rb (ppm)	Sb (ppm)
FBL059	1.97	48.8	1.046	114.4	11.85	4.81	7.34	112.4	1.630	2.66	0.604	0.446	18053	14.08	0.00	151.0	0.366
FBL060	2.53	25.5	0.596	28.5	5.97	2.49	4.02	58.4	0.683	4.38	0.766	0.554	8236	4.99	0.00	84.1	0.265
FBL061	3.66	26.8	0.657	31.7	6.12	2.88	4.31	58.4	0.917	1.74	0.862	0.626	9315	5.13	0.00	89.4	0.385
FBL062	3.58	26.5	0.601	33.8	6.10	2.71	4.26	56.1	0.836	6.43	0.729	0.596	8333	4.93	0.00	83.1	0.294
FBL063	3.56	28.4	0.668	33.6	6.44	2.55	4.68	63.0	0.523	35.42	1.142	0.536	7721	5.00	0.00	87.7	0.208
FBL064	1.79	27.3	0.654	30.6	6.28	3.07	4.44	59.7	0.456	2.82	1.156	0.531	8252	5.05	0.00	89.2	0.408
FBL065	1.84	31.9	0.790	41.7	7.58	2.64	5.31	71.7	0.602	10.40	1.149	0.651	8734	5.19	0.00	81.7	0.284
FBL066	0.00	25.2	0.461	27.1	4.81	1.58	2.99	54.3	3.642	3.07	0.159	1.014	18253	6.29	0.00	5.2	0.216
FBL067	9.17	22.8	0.424	27.8	5.17	1.15	2.80	48.2	10.474	12.86	0.345	1.491	33733	4.55	0.00	14.5	0.411
FBL068	3.66	30.2	0.707	47.0	6.89	2.11	4.52	69.6	1.598	2.64	0.322	1.478	10444	6.58	0.00	6.8	0.326
FBL069	13.86	17.2	0.448	23.9	4.76	4.37	2.53	44.1	21.915	204.81	1.997	1.280	71816	3.56	79.67	48.5	0.657
FBL070	0.00	7.5	0.123	17.1	2.53	0.00	0.96	18.0	35.801	42.69	0.526	0.983	76532	1.27	0.00	10.4	0.139
FBL071	2.49	6.5	0.203	10.1	2.37	0.00	1.34	14.2	26.717	64.96	0.757	0.927	72599	0.93	0.00	17.4	0.169
FBL072	0.00	26.2	0.891	31.4	6.98	1.53	6.25	56.5	0.169	0.91	0.389	1.339	13005	6.55	0.00	52.8	0.132
FBL073	0.00	26.9	0.905	40.8	9.30	1.92	6.07	55.1	0.064	3.32	0.480	2.160	7083	7.63	0.00	41.8	0.196
FBL074	0.00	28.2	0.569	30.6	5.77	2.93	3.80	59.4	0.364	3.58	0.858	1.083	11402	6.12	0.00	100.6	0.324
FBL075	0.00	14.8	0.448	31.1	5.15	0.00	2.89	34.8	4.703	2.32	0.619	1.592	37429	3.77	0.00	35.8	0.109
FBL076	0.00	24.1	0.613	20.9	5.12	1.76	4.24	51.1	0.948	2.56	0.501	1.048	12233	5.49	0.00	42.7	0.165
FBL077	0.00	21.8	0.535	21.8	4.70	2.16	3.65	45.4	0.487	1.27	0.334	0.874	8658	5.04	0.00	31.6	0.079
FBL078	1.94	25.2	0.585	26.9	5.48	2.63	4.10	54.4	1.454	2.13	1.396	1.154	16125	7.84	0.00	59.9	0.358
FBL079	0.00	23.6	0.724	27.3	5.93	2.10	4.63	51.2	0.454	5.08	0.749	1.456	14377	6.10	0.00	113.8	0.348
FBL080	0.00	24.5	0.842	30.9	6.69	1.39	5.74	53.6	0.087	0.00	0.467	1.179	10949	6.18	0.00	57.0	0.172

Table D.2. Element Concentrations as Measured by Neutron Activation Analysis (Sc-V).

Sample	Sc (ppm)	Sr (ppm)	Ta (ppm)	Tb (ppm)	Th (ppm)	Zn (ppm)	Zr (ppm)	Al (ppm)	Ba (ppm)	Ca (ppm)	Dy (ppm)	K (ppm)	Mn (ppm)	Na (ppm)	Ti (ppm)	V (ppm)
FBL001	5.06	65.7	0.668	1.246	9.43	33.6	136.6	59100	489	6549	7.15	24508	457	25157	512	0.0
FBL002	5.27	0.0	0.675	1.273	9.72	47.5	135.4	59308	525	2932	7.65	24150	261	28468	525	0.0
FBL003	5.71	44.7	0.680	1.655	9.91	68.5	123.2	55545	678	3104	9.53	27509	520	22641	0	0.0
FBL004	4.25	0.0	0.704	1.119	10.36	10.6	121.6	57835	423	1550	6.65	16164	231	31515	840	0.0
FBL005	5.22	0.0	0.681	1.531	11.81	47.8	116.7	56623	539	1759	9.32	21535	121	28626	697	0.0
FBL006	5.36	71.5	0.672	1.367	9.84	47.3	130.1	56734	494	2583	7.94	17156	391	29613	388	0.0
FBL007	3.99	38.0	0.629	0.945	9.35	32.4	132.2	57026	597	1611	5.21	30127	231	22069	250	0.0
FBL008	7.86	0.0	0.544	1.494	8.79	53.3	164.6	52836	407	4680	8.01	20215	267	24118	963	0.0
FBL009	7.44	75.3	0.557	1.312	8.43	53.0	146.5	53169	400	3246	7.91	24900	383	22277	611	0.0
FBL010	6.30	0.0	0.542	1.376	8.60	55.9	152.8	50935	401	2992	7.84	15226	375	25496	621	0.0
FBL011	7.42	67.0	0.607	1.307	9.66	29.8	171.1	53158	431	3952	7.77	23540	276	26848	742	0.0
FBL012	8.01	0.0	0.642	1.402	10.08	25.9	165.8	58339	445	4210	8.37	18128	257	29628	811	0.0
FBL013	7.29	0.0	0.552	1.253	8.52	28.3	144.3	49152	160	1155	7.04	10094	361	30491	543	0.0
FBL014	10.75	136.0	0.476	1.066	6.86	68.4	140.7	57970	434	6927	5.65	20241	598	25771	1628	0.0
FBL015	6.67	57.2	0.690	1.042	11.36	29.7	123.2	58537	539	2195	6.07	19271	366	27518	405	0.0
FBL016	6.14	36.5	0.641	1.103	10.53	44.9	109.0	54460	577	1490	6.64	26182	419	24297	488	0.0
FBL017	6.75	40.0	0.685	1.121	11.07	39.4	109.2	57168	618	3905	6.61	23203	342	26253	227	0.0
FBL018	6.05	53.6	0.638	1.043	10.26	32.2	94.6	56790	489	4165	6.15	22677	319	26344	604	0.0
FBL019	6.46	51.6	0.651	1.090	10.67	41.3	130.0	52519	410	2801	5.89	17043	391	27528	362	0.0
FBL020	9.66	213.7	0.349	0.732	4.96	44.7	103.3	60464	365	14304	3.53	14289	508	18753	1564	16.1
FBL021	5.83	176.8	0.176	0.837	3.94	38.7	116.0	52405	452	4946	4.11	17888	549	25923	1068	0.0
FBL022	4.25	167.4	0.222	0.849	3.92	29.1	148.9	50454	346	7386	4.12	13015	669	26230	821	0.0
FBL023	6.70	89.2	0.231	0.620	3.83	17.0	87.9	54050	363	8840	4.16	12607	657	28949	812	0.0
FBL024	10.45	196.7	0.314	0.781	4.46	56.8	102.9	62021	184	15773	4.30	7032	717	31059	1051	15.3
FBL025	4.18	25.4	0.645	0.804	8.99	22.1	99.3	62386	770	1806	5.23	33986	290	28354	465	0.0
FBL026	4.24	38.3	0.618	0.757	9.12	44.3	83.7	65645	671	3486	5.43	31839	322	29353	0	0.0
FBL027	5.26	72.8	0.832	0.946	11.65	27.5	111.1	51989	914	3689	6.52	37353	168	12784	585	7.8
FBL028	7.80	105.1	1.196	1.171	16.12	61.9	133.7	70548	2227	4989	7.15	71471	770	5014	1690	18.7
FBL029	8.47	346.2	0.870	0.965	12.00	62.3	143.5	56465	655	5369	6.05	38205	795	14478	1307	29.4

Table D.2. Element Concentrations as Measured by Neutron Activation Analysis (Sc-V) (continued).

Sample	Sc (ppm)	Sr (ppm)	Ta (ppm)	Tb (ppm)	Th (ppm)	Zn (ppm)	Zr (ppm)	Al (ppm)	Ba (ppm)	Ca (ppm)	Dy (ppm)	K (ppm)	Mn (ppm)	Na (ppm)	Ti (ppm)	V (ppm)
FBL030	8.01	405.1	1.046	2.374	15.12	57.6	201.7	66402	353	12323	13.31	11410	768	31596	699	21.7
FBL031	2.27	75.0	1.320	1.858	12.85	60.4	361.8	57578	0	3071	11.39	35505	412	24096	1131	0.0
FBL032	1.49	116.1	1.275	1.732	12.33	37.7	334.0	63252	60	5624	11.19	26501	399	31046	0	0.0
FBL033	1.23	71.2	1.360	1.874	13.16	89.4	356.9	59389	0	1845	11.65	32870	279	29276	874	0.0
FBL034	2.02	82.8	1.329	1.897	12.81	64.9	336.4	63136	0	4927	12.10	32981	544	29146	879	6.1
FBL035	14.02	188.2	0.417	0.660	5.73	92.8	132.7	83851	1131	13888	4.02	25179	1014	22975	3238	89.0
FBL036	7.51	56.3	0.436	0.542	7.73	42.0	182.7	75278	828	4024	2.80	28334	334	38000	1971	26.5
FBL037	14.66	495.0	0.431	0.750	6.76	71.2	112.3	74748	1279	35134	4.59	35925	873	8300	3582	101.2
FBL038	19.34	251.7	0.164	0.499	1.56	86.7	73.3	87090	1328	13871	2.38	31143	1341	35286	3463	179.2
FBL039	4.60	64.9	0.683	0.759	10.17	19.1	134.5	63978	320	0	6.10	37453	40	27030	727	0.0
FBL040	34.94	409.4	0.000	0.938	0.42	146.8	0.0	82900	256	48585	4.25	818	1776	25652	7918	243.7
FBL041	9.55	340.5	0.077	0.500	0.44	75.4	28.4	94277	273	10340	2.47	11139	1274	44556	3477	24.6
FBL042	34.18	365.1	0.000	0.597	0.38	91.0	0.0	89104	280	58865	2.36	12309	1922	23959	3661	259.6
FBL043	9.99	682.0	0.395	0.740	9.22	81.3	169.5	83047	515	16354	4.18	9596	749	43278	2716	27.4
FBL044	8.03	189.2	0.491	1.070	5.73	73.6	156.9	64209	110	2480	6.50	5211	566	38521	1367	20.6
FBL045	8.72	669.9	0.301	0.605	8.02	55.5	145.4	73416	592	8826	3.21	8887	651	39301	2141	0.0
FBL046	9.73	316.2	0.230	0.569	4.56	65.5	91.8	51954	305	8433	2.53	9222	599	26434	2498	65.3
FBL047	5.93	238.4	0.301	0.476	2.71	48.1	143.0	66960	520	8315	2.79	11351	730	36839	1225	21.4
FBL048	8.36	443.2	0.344	0.666	3.42	56.7	142.7	78294	0	13242	3.67	0	638	49802	2042	27.8
FBL049	7.00	296.1	0.356	0.583	3.47	48.6	166.1	75135	403	9211	3.78	9174	653	41342	1735	16.1
FBL050	6.95	448.8	0.319	0.602	3.25	35.9	144.9	72955	282	18885	3.45	5310	697	40445	2055	21.8
FBL051	3.85	41.2	0.499	0.672	7.56	31.9	66.9	53794	552	1172	3.91	28770	214	24816	653	0.0
FBL052	3.08	39.7	0.394	0.522	5.54	32.1	62.5	38510	427	936	3.13	22129	208	14578	563	0.0
FBL053	4.38	30.6	0.586	0.724	8.40	35.7	91.7	63095	645	0	4.29	32483	259	27398	0	0.0
FBL054	4.03	43.6	0.511	0.748	7.81	36.1	82.5	50377	651	886	3.85	34205	231	17440	1153	0.0
FBL055	9.30	74.1	0.320	0.689	4.07	54.4	98.2	64480	329	5957	3.79	16361	528	33681	1090	0.0
FBL056	7.23	55.7	0.586	0.598	7.14	54.6	87.3	48259	832	2631	3.28	50612	296	4461	1688	17.7
FBL057	6.67	83.9	1.108	1.392	14.48	32.4	143.7	70645	713	3767	8.31	31451	430	32691	395	0.0
FBL058	1.43	98.9	1.441	2.121	13.36	96.3	360.9	61579	0	4179	11.52	36008	461	27084	770	0.0

Table D.2. Element Concentrations as Measured by Neutron Activation Analysis (Sc-V) (continued).

Sample	Sc (ppm)	Sr (ppm)	Ta (ppm)	Tb (ppm)	Th (ppm)	Zn (ppm)	Zr (ppm)	Al (ppm)	Ba (ppm)	Ca (ppm)	Dy (ppm)	K (ppm)	Mn (ppm)	Na (ppm)	Ti (ppm)	V (ppm)
FBL059	1.79	119.0	1.329	1.983	12.18	113.5	330.8	62459	0	5471	11.60	47395	380	19168	1228	17.0
FBL060	4.81	74.5	0.631	1.024	7.34	38.8	102.4	65927	696	4689	5.65	26954	315	29242	0	0.0
FBL061	5.59	71.1	0.632	1.086	7.39	38.7	109.2	66979	575	5697	6.18	29384	308	28648	857	0.0
FBL062	5.08	77.7	0.622	0.999	7.40	30.4	100.6	66395	666	5187	5.63	29862	254	28313	545	0.0
FBL063	5.09	50.3	0.654	1.114	7.70	21.1	96.2	60983	703	4469	7.08	31500	155	27046	871	0.0
FBL064	5.32	27.9	0.642	1.087	7.69	38.4	100.1	61265	725	5009	6.54	33868	332	22503	753	0.0
FBL065	5.98	72.6	0.690	1.286	8.18	33.0	113.2	67536	800	4124	7.17	32105	213	29063	0	0.0
FBL066	7.55	199.7	0.370	0.646	3.46	61.4	146.8	73194	109	7413	3.29	5006	689	47941	1553	20.5
FBL067	13.23	304.1	0.260	0.712	2.36	74.3	97.9	88249	255	26574	3.76	7980	1090	40746	3762	85.9
FBL068	5.92	199.7	0.627	1.038	6.54	39.7	167.3	57826	68	6300	6.03	2287	294	37734	1292	21.7
FBL069	34.80	187.5	0.448	0.714	3.88	266.4	102.0	67095	611	6374	3.39	25529	473	34699	2261	25.3
FBL070	26.10	821.4	0.000	0.231	1.17	98.4	0.0	96748	0	66052	1.07	2287	1776	16410	5064	289.2
FBL071	29.88	519.4	0.000	0.395	0.20	92.5	0.0	97330	174	70819	1.83	7767	1192	15144	4543	284.8
FBL072	8.56	82.7	0.574	1.425	6.76	34.4	162.8	63172	418	2782	8.04	13349	616	35648	403	0.0
FBL073	8.60	189.8	0.366	1.702	5.59	26.2	181.9	67261	529	7818	9.70	21093	518	34937	1034	0.0
FBL074	8.42	102.6	0.779	0.911	9.18	43.8	167.8	65232	569	9864	5.34	27843	339	28020	699	0.0
FBL075	17.61	410.2	0.219	0.808	2.33	98.8	93.5	76656	275	29474	4.05	13916	1329	31086	5166	62.0
FBL076	7.77	108.9	0.597	0.887	7.65	53.6	128.9	58324	422	0	5.04	17291	685	33849	1138	0.0
FBL077	6.78	59.6	0.571	0.841	7.28	45.0	115.6	60946	381	850	4.69	16837	309	35927	516	0.0
FBL078	8.76	104.7	0.750	0.943	8.98	48.7	219.7	67281	385	9685	5.42	20888	488	32147	1492	0.0
FBL079	9.71	187.8	0.623	1.233	7.22	20.0	157.7	72850	682	11852	5.93	35191	825	26406	868	0.0
FBL080	8.04	141.2	0.557	1.379	6.36	49.1	138.3	66680	517	14391	7.95	18451	611	28134	0	0.0

Appendix E

X-Ray Fluorescence Spectrometry Data

Michael D. Glascock and Robert J. Speakman

The samples and artifacts were ground into powders by Brent Miller at the University of North Carolina at Chapel Hill using an aluminum-oxide shatter box and shipped to MURR in powdered form. Although about 3 grams of powder were requested for each sample to conduct the three analytical procedures at MURR, not all of the samples had this amount of material available. After aliquots totaling 500 mg were set aside for NAA and ICP-MS, the remainder (typically 2.5 grams) was used for x-ray fluorescence spectrometry (XRF). In a few samples, particularly among the artifacts, the amount left over for XRF was quite small, on the order of 1 gram.

The sample aliquots designated for XRF were used to make loss-on-ignition (LOI) measurements prior to preparation of the samples for XRF spectroscopy. The samples in glass vials were dried for 24 hours in an oven at 105°C before they were transferred into clean pre-weighed crucibles with weights recorded to the nearest 0.0001 gram. After cooling the samples for 30 minutes, the total weight of the sample and crucible were also recorded. The crucible and sample were placed in a furnace operating at 500°C for a period of four hours. The crucible and sample were removed and placed in a dessicator to fully cool. About two hours later, the crucible and ashed sample were reweighed. The percentage of LOI was then calculated.

The ashed samples were then mixed in equal parts with SpectroCertified X-Ray Mix Binding Powder Cat. No. 600 from Chemplex Industries. Mixing was performed on a Spex 8000 Mixer/Mill using a mixing time of 15 minutes. The blended mixtures of sample and binding powder were poured into 32 mm aluminum planchets with a stainless steel pellet die and placed under 25 tons of pressure. The Spectro X-Lab 2000 spectrometer produces chemical analyses of geological materials using the energy-dispersive XRF based on polarized or near monochromatic x-rays for optimal sample excitation. The X-Lab 2000 spectrometer used to perform these analyses incorporates an end-window x-ray tube that can be focused on various secondary targets to produce polarized x-rays. Using the combination of different targets, typical detection limits for the light elements (Si, Al, Mg, and Na) are in the range of 25-50 ppm. Limits of detection for the heavy elements are in the 1-5 ppm range. The Spectro X-lab 2000 spectrometer was factory calibrated using a number of international rock standards (Korotev 1996).

The recommended amount of rock sample to mix powder for proper measurement on the Spectro X-Lab 2000 is about 5.0 grams. However, several of the samples were limited to about only 0.5 grams of sample (i.e., total mass of 1.0 grams). The light mass samples made necessary development of a separate correction method after they were measured on the XRF. An experiment was conducted using a series of samples made by mixing USGS Rock Standard RGM-1 Rhyolite in equal parts with the binding powder (i.e., 0.5, 1.0, 1.5, 2.0, and 2.5 grams each of sample and binding powder). The USGS rock samples were measured under the same conditions as the unknowns in this study. A correction to normalize the data from the USGS rock samples to a total of 100% minus LOI was found to be successful for all elements except Ba. Ba concentrations were always high, and by calculating the ratio of the normalized USGS RGM-1 rock to the certified value for USGS RGM-1, an acceptable correction factor was determined for Ba.

The XRF measurements resulted in data for 21 elements, namely Na, Mg, Al, Si, K, Ca, Ti, Mn, Fe, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Ba, Pb, Th, and U. The data were tabulated with EXCEL and with the major elements converted to percent oxides and the trace elements listed in parts per million. The XRF results are presented in Tables E.1-E.2.

Table E.1. Major Element Concentrations as Measured by X-Ray Fluorescence.

Sample	LOI (%)	Na_2O (%)	MgO (%)	Al_2O_3 (%)	SiO_2 (%)	K_2O (%)	CaO (%)	TiO_2 (%)	MnO (%)	Fe_2O_3 (%)
FBL001	0.083	5.88	0.000	13.26	74.23	3.484	0.8667	0.1198	0.0693	1.5846
FBL002	0.124	6.38	0.000	12.96	75.36	3.321	0.2868	0.1145	0.0350	1.1844
FBL003	0.288	4.95	0.000	13.37	74.59	3.887	0.3954	0.1192	0.0747	1.7775
FBL004	0.034	7.22	0.000	13.29	75.55	2.427	0.2586	0.1098	0.0318	1.2161
FBL005	-0.074	6.57	0.000	12.51	76.20	2.862	0.2204	0.0888	0.0181	1.2047
FBL006	-0.244	7.05	0.000	12.70	75.68	2.234	0.2810	0.1126	0.0567	1.5487
FBL007	0.133	5.05	0.000	11.30	78.18	3.946	0.1672	0.1142	0.0305	1.0263
FBL008	0.209	5.52	0.183	11.47	77.70	2.664	0.5864	0.1564	0.0356	1.7471
FBL009	0.310	5.21	0.241	11.66	76.93	3.279	0.4434	0.1578	0.0517	1.8468
FBL010	0.291	5.88	0.392	11.37	77.44	2.190	0.3062	0.1526	0.0515	1.8007
FBL011	0.332	5.81	0.171	13.06	75.04	2.985	0.4302	0.1631	0.0367	1.8685
FBL012	0.484	6.96	0.277	13.06	73.68	2.604	0.4904	0.1780	0.0370	1.9382
FBL013	0.295	7.61	0.223	11.38	76.91	1.442	0.1865	0.1474	0.0526	1.8732
FBL014	0.341	5.74	0.383	15.14	71.42	3.191	1.0300	0.2335	0.0962	2.3953
FBL015	0.508	6.62	0.097	12.43	75.82	2.673	0.3572	0.1178	0.0497	1.2768
FBL016	-0.124	5.79	0.226	13.43	74.88	3.926	0.2351	0.1007	0.0625	1.4276
FBL017	0.295	5.89	0.000	12.90	75.89	3.169	0.3699	0.1089	0.0539	1.3827
FBL018	0.269	6.05	0.000	12.73	75.90	3.176	0.4632	0.1040	0.0442	1.4605
FBL019	0.221	6.11	0.000	12.35	76.57	2.421	0.3538	0.1038	0.0617	1.5878
FBL020	0.245	3.50	0.684	14.76	73.33	2.438	1.8233	0.2925	0.0773	2.7422
FBL021	0.303	5.62	0.424	12.73	75.42	2.801	0.8004	0.2317	0.0751	1.3753
FBL022	0.222	4.31	0.268	13.35	75.12	2.615	1.3203	0.2811	0.1240	2.0429
FBL023	0.166	4.92	0.091	11.64	78.60	1.359	1.1540	0.1856	0.0798	1.7190
FBL024	0.184	5.97	0.461	12.00	75.60	0.722	1.9274	0.2168	0.0788	2.3007
FBL025	0.322	4.55	0.000	12.30	76.21	4.387	0.2199	0.1266	0.0402	1.2554
FBL026	0.305	5.42	0.000	12.73	75.87	3.836	0.5397	0.1151	0.0454	1.1734
FBL027	0.494	2.49	0.322	10.39	79.67	4.618	0.5354	0.1696	0.0215	1.0791
FBL028	0.483	0.54	0.891	13.84	71.66	8.624	0.6038	0.2890	0.0988	2.2037
FBL029	0.641	2.59	0.804	11.22	76.51	4.617	0.7217	0.2926	0.0984	2.0260
FBL030	0.402	5.81	0.853	13.13	74.00	1.438	1.6343	0.3180	0.0980	2.1754
FBL031	0.204	5.41	0.099	12.02	74.47	4.122	0.3570	0.2009	0.0439	2.6870
FBL032	0.238	6.80	0.061	12.57	73.70	3.181	0.6985	0.1681	0.0439	2.4577
FBL033	0.232	6.06	0.091	12.41	73.81	3.946	0.3122	0.1639	0.0308	2.4347
FBL034	0.210	5.70	0.117	12.44	74.02	3.808	0.5301	0.1793	0.0646	2.5356
FBL035	1.176	3.75	3.021	16.76	63.85	3.224	1.8767	0.6200	0.1205	5.4675
FBL036	0.300	8.13	0.379	14.44	70.11	3.171	0.5505	0.3241	0.0372	2.7163
FBL037	0.834	1.43	2.499	14.73	65.32	4.531	4.6353	0.6367	0.1045	5.4385
FBL038	1.281	6.28	3.334	17.59	57.36	3.277	1.6458	0.7078	0.1660	8.0967
FBL039	0.229	4.58	0.000	13.95	75.85	4.707	0.0502	0.1526	0.0070	0.5355
FBL040	1.704	4.85	5.054	15.93	52.84	0.556	5.9895	1.3581	0.2080	11.8456
FBL041	1.840	5.69	5.588	20.27	54.50	1.208	1.5661	0.7413	0.1696	8.6345
FBL042	1.444	4.48	7.591	17.59	49.32	1.338	7.3508	0.6803	0.2285	9.4170
FBL043	0.787	9.07	1.949	16.11	64.53	1.005	2.0666	0.5892	0.0913	3.8764
FBL044	0.713	7.59	0.878	12.32	75.02	0.560	0.3180	0.2846	0.0657	2.2337
FBL045	0.856	7.79	1.278	14.81	68.78	1.097	1.2377	0.5258	0.0763	3.3633
FBL046	0.654	5.20	1.451	10.08	75.67	1.038	1.1717	0.4712	0.0715	3.8333
FBL047	0.642	7.18	1.253	12.37	73.45	1.144	0.8967	0.3162	0.0903	2.3509
FBL048	0.595	9.83	1.154	15.20	68.00	0.040	1.6969	0.3737	0.0757	2.9183
FBL049	0.593	8.39	1.080	13.88	70.87	1.194	1.1670	0.3534	0.0766	2.4593
FBL050	0.523	8.40	0.682	13.91	70.49	0.710	2.5056	0.3571	0.0803	2.3322
FBL051	0.312	4.35	0.000	11.19	79.21	3.480	0.1779	0.1117	0.0290	1.1887
FBL052	0.384	2.51	0.051	6.91	86.41	2.737	0.1528	0.0857	0.0296	0.7751
FBL053	0.273	4.57	0.000	12.25	77.40	3.516	0.1980	0.1070	0.0410	1.3318
FBL054	0.361	1.78	0.000	10.93	80.98	3.687	0.1344	0.0974	0.0350	1.5066
FBL055	0.425	6.84	0.409	12.41	75.79	1.813	0.7372	0.2402	0.0578	1.4947
FBL056	0.598	0.44	0.482	10.20	80.14	6.474	0.2812	0.2818	0.0375	1.2684
FBL057	0.494	6.21	0.555	13.31	73.60	3.557	0.4470	0.1990	0.0506	1.2894

Table E.1. Major Element Concentrations as Measured by X-Ray Fluorescence (continued).

Sample	LOI (%)	Na_2O (%)	MgO (%)	Al_2O_3 (%)	SiO_2 (%)	K_2O (%)	CaO (%)	TiO_2 (%)	MnO (%)	Fe_2O_3 (%)
FBL058	0.263	5.76	0.129	12.41	74.19	4.029	0.5296	0.1779	0.0563	2.4903
FBL059	0.276	4.07	0.413	13.46	72.70	5.634	0.6688	0.1945	0.0489	2.5977
FBL060	0.273	6.12	0.096	12.83	75.43	3.418	0.6291	0.1240	0.0360	1.1665
FBL061	0.430	6.32	0.178	13.16	74.37	3.424	0.7703	0.1340	0.0368	1.3119
FBL062	0.382	6.18	0.091	13.07	74.79	3.461	0.6557	0.1236	0.0283	1.1689
FBL063	0.282	5.77	0.153	12.51	76.29	3.591	0.4604	0.0981	0.0179	1.0737
FBL064	0.630	4.64	0.188	12.87	75.35	4.032	0.6781	0.1118	0.0413	1.1773
FBL065	0.289	6.15	0.250	13.46	74.00	3.642	0.5630	0.1077	0.0285	1.2442
FBL066	0.484	8.24	0.901	14.80	70.51	0.536	1.1654	0.4154	0.0869	3.0956
FBL067	1.135	6.67	2.497	15.89	63.09	1.226	3.4280	0.6767	0.1290	4.8699
FBL068	0.451	7.96	0.621	11.02	77.36	0.299	0.7528	0.2455	0.0352	1.5539
FBL069	0.480	6.89	0.536	13.33	72.13	2.699	0.7144	0.3803	0.0561	2.4524
FBL070	1.334	2.90	8.083	18.84	47.87	0.367	8.8655	0.9673	0.2086	10.6005
FBL071	1.872	2.71	6.089	18.12	49.69	1.032	8.7490	0.9117	0.1459	10.1513
FBL072	0.428	6.98	0.000	12.42	75.54	1.757	0.5730	0.1345	0.0665	2.0896
FBL073	0.486	7.17	0.216	13.04	73.98	2.309	0.8804	0.2152	0.0690	1.5076
FBL074	0.397	6.76	0.225	12.92	73.40	3.332	1.0884	0.1615	0.0409	1.7036
FBL075	1.089	5.38	2.645	15.59	63.06	1.540	3.8232	0.8575	0.1532	5.4919
FBL076	0.546	7.32	0.394	12.58	74.26	1.973	0.5412	0.2270	0.0858	1.9630
FBL077	0.412	7.29	0.106	12.05	77.01	1.736	0.0742	0.1447	0.0382	1.3417
FBL078	0.226	5.96	0.174	12.89	74.19	2.281	1.2817	0.2884	0.0580	2.5405
FBL079	0.374	5.29	0.451	14.33	71.10	4.125	1.5660	0.2600	0.0985	2.4181
FBL080	0.226	6.72	0.143	12.21	74.16	2.531	1.5529	0.1220	0.0691	1.6950

Table E.2. Trace Element Concentrations as Measured by X-Ray Fluorescence.

Sample	Cu (ppm)	Zn (ppm)	Ga (ppm)	Rb (ppm)	Sr (ppm)	Y (ppm)	Zr (ppm)	Nb (ppm)	Ba (ppm)	Pb (ppm)	Th (ppm)	U (ppm)
FBL001	2.8	41.6	16.2	90.2	53.7	59.1	187.6	9.1	568.8	20.4	8.6	3.2
FBL002	3.1	57.4	14.8	84.3	39.0	58.2	170.1	5.6	529.5	20.3	10.3	3.3
FBL003	4.8	69.7	17.3	120.0	59.9	79.5	187.1	7.4	746.0	17.6	10.9	4.2
FBL004	1.7	12.1	16.1	70.6	31.2	54.4	186.1	8.7	476.6	11.5	12.0	4.4
FBL005	5.0	50.6	17.6	67.8	39.8	69.3	146.6	7.3	486.3	21.3	12.9	3.9
FBL006	4.2	49.3	16.1	61.1	54.6	77.4	193.2	7.4	658.8	18.2	11.2	3.6
FBL007	2.1	40.8	9.9	97.0	45.6	41.3	149.1	6.0	616.0	7.7	10.2	3.7
FBL008	5.7	61.3	14.3	80.8	66.1	69.4	228.7	4.7	388.8	14.3	9.3	2.7
FBL009	5.2	57.1	14.0	86.2	69.8	63.3	200.7	5.5	406.6	11.3	8.2	4.0
FBL010	7.9	70.3	12.0	56.0	36.4	64.3	219.1	4.7	431.2	26.8	8.9	4.7
FBL011	6.0	27.7	15.7	91.0	61.4	71.3	249.1	2.6	529.1	12.1	10.6	2.3
FBL012	5.3	27.9	17.5	70.1	55.2	71.7	216.8	6.9	402.2	15.3	12.8	3.2
FBL013	0.0	31.5	14.3	36.6	18.3	60.8	234.3	3.3	246.6	16.2	11.7	5.8
FBL014	5.2	75.8	18.9	101.0	126.4	58.3	235.2	3.4	647.9	37.5	8.1	2.3
FBL015	4.5	29.2	12.3	60.3	54.5	45.0	140.9	5.6	505.3	10.2	12.0	2.3
FBL016	4.9	42.3	16.1	128.6	37.1	60.8	144.6	5.7	579.1	15.5	10.3	3.6
FBL017	4.2	44.4	13.2	92.8	68.9	61.2	172.8	5.4	729.7	25.7	12.8	4.9
FBL018	4.8	34.5	14.5	100.8	59.9	62.6	157.5	4.5	598.4	14.4	13.2	4.8
FBL019	10.9	45.6	16.0	79.0	64.5	64.8	178.3	5.8	662.3	14.8	14.1	4.2
FBL020	15.2	57.3	12.9	69.3	203.8	37.0	161.1	1.7	564.8	21.0	9.6	3.2
FBL021	3.0	48.2	10.3	57.2	194.3	47.7	213.5	4.5	570.0	10.4	4.5	0.0
FBL022	24.4	50.2	21.9	66.5	295.9	76.8	360.5	9.7	1083.4	19.6	8.0	4.7
FBL023	2.0	20.1	14.0	31.5	128.5	42.3	180.6	4.5	707.6	8.0	3.9	3.3
FBL024	2.5	46.8	14.8	13.8	214.8	34.9	160.7	3.1	268.8	14.9	4.3	1.7
FBL025	10.0	28.9	12.9	120.1	46.5	52.1	152.2	13.3	1163.2	16.2	14.9	7.3
FBL026	7.1	41.6	11.6	107.1	54.2	46.1	133.7	9.2	917.6	25.3	11.4	5.5
FBL027	4.0	33.4	9.1	141.0	64.5	47.5	124.7	10.6	990.3	10.7	14.6	5.1
FBL028	4.2	56.9	18.0	338.4	108.5	44.3	181.0	16.2	2303.1	26.8	17.1	5.7
FBL029	10.7	53.8	14.3	165.6	145.8	44.4	162.5	9.7	738.3	21.9	12.9	3.3
FBL030	9.0	37.7	16.6	71.8	389.5	124.9	300.1	16.3	548.9	26.7	21.3	6.9
FBL031	4.1	68.2	17.0	117.6	66.9	70.5	540.3	18.3	78.0	24.3	13.6	6.3
FBL032	2.5	40.2	19.0	77.5	90.7	68.5	507.5	17.2	45.3	18.1	13.4	5.5
FBL033	3.2	103.5	19.6	103.8	47.6	71.8	538.3	17.7	39.7	21.2	13.1	2.3
FBL034	2.0	79.4	16.2	107.8	85.3	77.2	566.1	16.6	70.9	23.7	13.0	3.9
FBL035	21.0	67.0	18.3	57.1	188.6	24.6	161.0	3.7	875.1	13.2	5.6	0.0
FBL036	14.2	47.5	12.4	35.3	71.1	22.5	222.5	3.7	584.1	13.6	7.2	4.0
FBL037	59.2	75.6	18.2	107.0	399.3	28.7	167.3	2.9	985.0	16.7	7.4	0.0
FBL038	120.3	91.4	17.8	70.8	254.0	15.8	75.4	0.0	1180.9	9.2	1.1	0.0
FBL039	4.2	20.4	17.6	87.8	44.7	44.8	168.2	7.4	301.3	23.9	11.8	2.3
FBL040	15.3	117.8	19.2	8.0	378.2	23.8	60.0	0.0	198.4	5.1	0.0	0.0
FBL041	9.7	99.4	14.3	34.7	371.0	20.2	54.6	0.0	418.9	4.6	0.0	0.0
FBL042	196.2	86.4	15.5	29.0	324.2	15.5	36.4	0.0	233.2	7.3	0.0	0.0
FBL043	5.3	72.2	15.9	17.2	583.7	31.6	208.7	4.1	438.2	10.5	8.6	5.2
FBL044	5.2	66.3	14.6	14.9	164.4	43.2	195.8	4.8	105.9	16.2	3.9	2.1
FBL045	4.3	63.6	10.6	22.3	565.8	25.9	180.2	3.0	500.1	7.0	6.3	2.3
FBL046	20.3	59.2	10.2	11.8	277.7	18.6	116.2	1.8	286.2	11.0	3.2	3.9
FBL047	16.1	51.1	12.3	9.8	235.7	21.1	159.5	1.2	435.9	13.9	2.4	0.0
FBL048	15.2	60.9	13.2	1.3	383.4	28.7	209.5	2.9	44.2	17.6	2.7	1.8
FBL049	3.3	53.3	10.3	13.1	278.9	27.4	213.6	1.9	374.2	8.7	2.9	2.9
FBL050	3.9	39.8	14.3	7.8	377.9	27.4	197.3	1.7	272.4	10.8	2.6	1.4
FBL051	4.7	38.1	7.7	106.5	71.1	34.2	121.9	5.6	730.4	13.7	10.4	0.0
FBL052	11.2	39.1	6.1	83.7	48.1	32.1	107.8	3.6	618.8	18.3	8.2	6.5
FBL053	3.5	36.3	9.1	111.0	56.3	41.5	159.6	6.7	785.9	13.8	10.7	3.4
FBL054	6.6	45.7	7.6	129.9	65.3	44.4	157.7	4.5	1160.3	23.9	12.5	5.8
FBL055	15.4	39.5	8.9	35.9	92.5	29.0	115.6	2.4	414.5	17.9	3.6	2.3
FBL056	50.8	52.7	11.9	201.1	42.4	25.9	105.8	6.4	676.5	22.2	6.1	4.8
FBL057	5.8	30.4	10.1	89.6	86.7	67.8	152.3	10.9	689.5	4.2	14.6	3.0

Table E.2. Trace Element Concentrations as Measured by X-Ray Fluorescence (continued).

Sample	Cu (ppm)	Zn (ppm)	Ga (ppm)	Rb (ppm)	Sr (ppm)	Y (ppm)	Zr (ppm)	Nb (ppm)	Ba (ppm)	Pb (ppm)	Th (ppm)	U (ppm)
FBL058	5.2	96.1	20.1	104.6	75.7	75.2	579.7	15.8	58.9	21.0	14.4	3.3
FBL059	10.9	114.9	16.2	155.0	99.3	68.3	559.8	15.4	111.3	22.8	13.3	3.5
FBL060	3.0	37.2	13.4	80.8	76.7	39.9	126.9	4.8	498.8	11.8	6.3	2.2
FBL061	5.3	36.3	14.5	88.1	82.9	42.1	138.6	8.0	512.7	11.5	7.5	2.2
FBL062	4.1	25.5	13.9	80.5	81.8	38.1	122.0	5.3	521.0	9.8	7.5	3.4
FBL063	2.8	18.4	11.9	86.7	47.5	43.9	118.0	5.3	547.8	10.3	7.4	2.9
FBL064	5.2	36.0	13.5	85.2	41.4	41.5	120.1	5.3	544.6	10.2	6.4	3.0
FBL065	4.7	29.7	17.2	80.4	74.6	51.7	143.5	5.9	605.0	9.4	7.3	2.5
FBL066	34.7	71.8	16.2	7.2	220.6	34.1	278.3	4.2	163.2	8.6	3.1	2.9
FBL067	17.2	72.3	16.7	15.4	304.6	27.3	164.8	3.4	382.6	8.9	2.1	0.0
FBL068	13.3	36.9	8.1	6.9	190.0	42.4	240.8	6.1	140.4	7.6	6.2	2.1
FBL069	9.0	38.2	10.8	39.3	88.1	22.4	167.3	0.0	558.3	18.8	6.4	1.6
FBL070	30.9	84.7	20.7	8.8	633.0	6.5	39.4	0.0	102.5	17.8	0.0	0.0
FBL071	27.1	74.2	16.9	14.1	505.7	10.1	22.8	0.0	155.4	6.1	0.0	0.0
FBL072	5.4	30.6	14.9	69.8	126.8	84.7	264.1	4.0	722.4	11.0	9.6	8.0
FBL073	9.8	28.0	23.0	80.0	311.8	117.4	382.2	0.0	1214.4	18.2	12.8	5.2
FBL074	4.2	43.9	9.5	112.4	113.6	46.3	226.0	7.4	706.0	17.4	10.3	2.0
FBL075	4.7	90.4	19.1	35.1	409.9	35.3	138.5	1.4	506.4	9.8	0.0	0.0
FBL076	5.7	60.8	11.9	54.1	158.6	54.7	239.2	8.0	696.9	19.0	10.5	4.6
FBL077	2.6	43.9	11.3	33.0	65.7	40.7	181.0	4.7	459.6	9.3	7.8	4.4
FBL078	0.0	48.1	14.1	72.4	121.0	49.6	383.1	9.1	578.0	22.2	15.7	3.5
FBL079	4.5	19.3	16.8	151.3	253.1	68.4	302.2	8.0	1048.7	21.6	12.4	0.0
FBL080	3.4	34.9	20.6	66.1	175.4	69.3	227.5	3.6	707.9	12.4	11.3	3.5

Appendix F

Inductively Coupled Plasma Mass Spectrometry Data

James M. Guthrie

The samples were ground into powders by Brent Miller at the University of North Carolina at Chapel Hill using an aluminum-oxide shatter box and sent to MURR in powdered form. Aliquots of 150 mg were set aside for inductively coupled plasma mass spectrometry (ICP-MS).

The rock samples from Fort Bragg were analyzed by ICP-MS to determine the rare-earth elements present in the rocks with high precision. The aliquot was weighed whole into a precleaned Teflon digestion vessel. Fisher brand Optima grade nitric acid (1 ml) and Fisher brand TraceMetal grade hydrofluouric acid (3 ml) were added. The vessels were sealed and samples were heated in a microwave digestion system. After digestion, the vessels were cooled to room temperature before opening. A second microwave cycle was then performed in which a solution of Aldrich brand 99.999% boric acid (4%, 30 ml) was added to the vessels. The vessels were resealed and heated again in the microwave. Vessel blanks containing only the digestion reagents were similarly prepared in order to check for analyte backgrounds. Quality control samples made from USGS RGM-1 rhyolite and NIST SRM-278 obsidian rock were also digested along with the unknown samples to provide accuracy checks.

The digested samples were transferred with rinsing (18.2 MΩ DI H_2O) to precleaned Nalgene bottles. These digestates were then diluted by a factor of 10 for ICP analysis, and an internal standard of Indium (In) was added to the diluted samples. Linearity standards made from diluted commercial High-Purity Standard stock solutions were prepared to calibrate the ICP-MS. The internal standard of In was also added to all linearity standards. Standards were re-analyzed repeatedly throughout the analytical run to ensure continuous correct instrument response.

Vessel backgrounds were found to be insignificant in comparison to the analyte levels in the samples. Table F.1 lists the results for the 14 rare-earth elements (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu) along with the data for Hf, Ta, and Th with all values reported in parts per million. Note that some elements are reported by measurement of more than one isotope (^{143}Nd and ^{146}Nd, ^{156}Gd and ^{157}Gd); in these cases, the values given in the table are for the element, not for the individual isotope. The agreement between element concentrations extrapolated from the measurement of different isotopes is excellent.

Table F.1. Element Concentrations as Measured by Inductively Coupled Plasma Mass Spectrometry.

Sample [a]	^{139}La (ppm)	^{140}Ce (ppm)	^{141}Pr (ppm)	^{143}Nd (ppm)	^{146}Nd (ppm)	^{147}Sm (ppm)	^{153}Eu (ppm)	^{156}Gd (ppm)	^{157}Gd (ppm)	^{159}Tb (ppm)	^{163}Dy (ppm)	^{165}Ho (ppm)	^{166}Er (ppm)	^{169}Tm (ppm)	^{172}Yb (ppm)	^{175}Lu (ppm)	^{178}Hf (ppm)	^{181}Ta (ppm)	^{232}Th (ppm)
FBL001	34.4	66.3	8.31	32.5	32.6	7.72	1.180	8.73	8.39	1.44	9.16	1.96	5.87	0.906	6.12	0.951	5.60	0.670	10.26
FBL002	33.0	67.7	8.62	33.5	34.0	8.22	1.241	9.99	9.19	1.69	10.90	2.42	7.45	1.239	8.35	1.373	7.26	0.886	12.99
FBL003	36.4	73.3	9.19	36.3	36.4	9.05	1.277	10.93	10.14	1.83	11.92	2.59	7.91	1.196	7.91	1.224	5.74	0.708	9.74
FBL004	24.2	52.5	6.62	26.7	26.3	6.96	0.970	8.29	8.07	1.46	9.49	2.06	6.20	0.998	6.57	1.063	7.21	0.869	12.59
FBL005	35.0	73.5	9.44	38.0	38.0	9.06	0.699	10.45	9.58	1.73	11.05	2.39	7.15	1.094	7.29	1.137	5.56	0.754	12.76
FBL006	34.4	71.7	9.16	36.1	36.5	9.09	1.164	10.54	9.86	1.84	11.96	2.71	8.31	1.348	8.86	1.457	7.46	0.931	13.75
FBL007	27.8	46.4	7.39	28.4	28.1	6.30	0.830	6.43	5.95	1.05	6.24	1.46	4.51	0.724	5.05	0.802	5.66	0.694	10.00
FBL008	27.9	60.5	7.81	32.8	32.2	8.14	1.321	9.74	9.22	1.63	10.83	2.39	7.21	1.138	7.31	1.148	6.97	0.669	10.15
FBL009	27.6	59.4	7.70	31.5	31.4	8.07	1.281	9.59	9.16	1.66	10.91	2.40	7.36	1.146	7.44	1.161	6.87	0.663	10.70
FBL010	24.2	53.1	6.90	28.7	28.2	7.25	1.043	8.32	7.91	1.42	9.16	2.09	6.53	1.018	6.80	1.086	6.25	0.593	8.87
FBL011	29.3	64.0	8.42	33.9	34.1	8.58	1.258	10.31	9.84	1.81	11.74	2.61	7.94	1.261	8.41	1.338	8.31	0.851	13.59
FBL012	28.8	62.1	8.03	33.0	32.6	8.25	1.182	9.86	9.26	1.68	10.99	2.43	7.36	1.130	7.41	1.158	7.07	0.724	11.11
FBL013	23.5	52.3	6.87	28.2	28.0	7.15	1.033	7.91	7.88	1.40	9.16	2.01	6.16	0.989	6.57	1.024	6.14	0.582	9.45
FBL014	25.4	53.4	6.87	28.5	28.3	6.73	1.623	7.60	7.04	1.23	7.46	1.71	5.18	0.798	5.17	0.801	5.89	0.515	7.73
FBL015	30.0	62.4	7.78	30.2	30.5	7.13	0.896	8.52	7.66	1.36	8.62	1.87	5.72	0.907	6.04	0.977	6.47	0.860	13.86
FBL016	27.0	55.7	6.81	26.7	26.7	6.40	0.859	7.65	7.06	1.27	8.46	1.90	5.83	0.914	5.99	0.949	5.37	0.695	11.43
FBL017	29.1	60.3	7.47	29.4	29.1	7.00	0.876	8.05	7.46	1.33	8.81	1.97	5.93	0.930	6.23	1.001	6.08	0.809	13.18
FBL018	26.9	55.4	6.83	26.8	26.4	6.23	0.790	7.25	7.09	1.24	8.33	1.87	5.73	0.904	6.09	0.952	5.19	0.638	11.41
FBL019	27.8	57.6	7.08	27.6	27.5	6.65	0.888	7.68	7.07	1.27	8.11	1.80	5.41	0.831	5.60	0.877	5.52	0.745	12.19
FBL020	19.5	39.6	4.91	19.3	19.3	4.32	0.914	4.74	4.32	0.73	4.62	0.99	2.97	0.453	2.91	0.464	3.11	0.428	5.42
FBL021	18.9	41.3	5.43	22.7	22.4	5.55	1.328	6.45	5.95	1.09	7.06	1.60	4.91	0.820	5.42	0.895	5.88	0.234	5.25
FBL022	19.9	42.8	5.57	23.1	23.2	5.28	1.238	6.01	5.59	0.99	5.95	1.41	4.45	0.698	4.80	0.778	5.05	0.227	4.50
FBL023	15.3	31.1	3.99	16.7	16.3	3.94	0.860	4.41	4.08	0.71	4.60	1.03	3.14	0.486	3.23	0.487	2.49	0.235	3.87
FBL024	18.9	40.8	5.35	22.3	22.1	5.07	1.094	5.53	5.10	0.88	5.47	1.21	3.55	0.548	3.59	0.537	3.56	0.383	5.43
FBL025	31.6	63.7	7.75	29.0	28.7	6.10	0.809	6.70	6.23	1.07	6.64	1.50	4.62	0.724	4.96	0.820	4.79	0.857	12.49
FBL026 (1)	28.1	55.8	6.64	25.0	24.5	5.41	0.748	5.79	5.26	0.88	5.61	1.22	3.74	0.575	3.82	0.598	3.65	0.661	9.06
FBL026 (2)	28.3	56.1	6.63	25.1	24.9	5.31	0.743	5.98	5.25	0.88	5.55	1.23	3.77	0.577	3.83	0.601	3.64	0.647	9.13
FBL027	18.2	60.8	7.06	29.0	28.3	7.24	1.387	7.96	7.34	1.23	7.79	1.71	5.10	0.755	4.63	0.688	4.45	1.110	15.17
FBL028	47.0	94.6	11.74	44.7	44.8	9.89	1.715	9.75	9.08	1.46	8.36	1.67	4.56	0.634	3.86	0.567	5.94	1.412	19.32
FBL029	35.2	74.2	9.27	35.2	35.3	7.27	1.428	6.85	6.68	1.11	6.70	1.37	4.05	0.604	3.81	0.565	3.95	0.865	12.74
FBL030	174.2	240.0	22.98	86.8	86.6	17.31	3.351	16.95	17.11	2.68	14.97	2.90	7.67	1.035	6.06	0.857	4.85	1.129	16.27
FBL031	57.3	209.7	16.10	62.8	62.5	13.65	0.529	12.64	12.72	2.14	12.94	2.71	8.08	1.248	8.18	1.262	15.46	1.536	14.75
FBL032	58.5	268.9	17.14	65.7	66.4	14.66	0.465	13.12	13.54	2.36	14.41	3.08	9.07	1.420	9.03	1.461	18.17	1.752	17.17
FBL033	63.4	266.0	17.60	68.1	67.6	14.40	0.422	13.38	13.95	2.35	14.35	3.06	9.22	1.452	9.26	1.473	17.72	1.673	16.39
FBL034	58.7	211.9	16.36	64.0	63.9	13.82	0.500	12.98	13.00	2.18	13.14	2.77	8.17	1.244	8.04	1.226	14.69	1.438	13.55

Table F.1. Element Concentrations as Measured by Inductively Coupled Plasma Mass Spectrometry (continued).

Sample [a]	^{139}La (ppm)	^{140}Ce (ppm)	^{141}Pr (ppm)	^{143}Nd (ppm)	^{146}Nd (ppm)	^{147}Sm (ppm)	^{153}Eu (ppm)	^{156}Gd (ppm)	^{157}Gd (ppm)	^{159}Tb (ppm)	^{163}Dy (ppm)	^{165}Ho (ppm)	^{166}Er (ppm)	^{169}Tm (ppm)	^{172}Yb (ppm)	^{175}Lu (ppm)	^{178}Hf (ppm)	^{181}Ta (ppm)	^{232}Th (ppm)
FBL035	22.1	48.4	6.21	24.9	25.0	5.44	1.334	5.56	5.21	0.81	4.43	0.99	2.89	0.430	2.74	0.412	4.16	0.500	6.54
FBL036	25.8	51.8	6.15	23.1	22.8	4.48	0.798	3.97	3.98	0.63	3.79	0.81	2.49	0.378	2.67	0.412	5.24	0.443	8.47
FBL037	35.4	73.4	9.18	36.5	36.3	7.34	1.463	7.49	6.86	1.02	5.96	1.26	3.63	0.540	3.61	0.580	5.50	0.581	8.90
FBL038	18.7	36.5	4.85	21.0	21.0	4.57	1.223	4.46	4.24	0.60	3.40	0.67	1.93	0.265	1.62	0.258	2.47	0.162	2.16
FBL039 (1)	12.9	33.8	4.17	15.9	15.7	3.98	0.494	3.99	3.79	0.71	4.65	1.03	3.30	0.522	3.58	0.557	6.45	0.828	11.82
FBL039 (2)	13.6	35.5	4.47	16.8	16.5	4.13	0.500	3.85	3.42	0.62	3.79	0.82	2.66	0.453	3.09	0.503	6.69	0.845	12.37
FBL040	11.9	31.7	4.92	23.6	23.3	6.23	2.081	6.63	6.38	1.02	6.26	1.29	3.55	0.513	3.27	0.483	1.92	0.106	0.35
FBL041	10.8	27.0	3.88	17.7	17.4	4.24	1.327	4.33	4.06	0.63	3.57	0.71	1.92	0.274	1.66	0.217	0.85	0.085	0.54
FBL042	7.9	18.9	2.64	12.1	11.8	3.07	1.004	3.60	3.53	0.59	3.69	0.79	2.31	0.330	2.22	0.319	1.27	0.045	0.45
FBL043	38.9	70.2	8.65	33.7	33.6	6.76	1.678	6.83	6.19	0.92	5.27	1.12	3.27	0.494	3.28	0.521	6.34	0.430	10.50
FBL044	26.0	65.1	9.18	37.8	37.5	8.76	1.943	8.96	8.12	1.31	7.57	1.59	4.66	0.737	4.94	0.807	7.19	0.614	7.38
FBL045	30.2	58.1	6.96	27.3	27.0	5.53	1.308	5.31	4.88	0.76	4.40	0.93	2.81	0.432	2.81	0.470	5.84	0.403	9.65
FBL046	21.3	43.0	5.38	21.2	21.2	4.61	1.091	4.26	3.98	0.64	3.76	0.78	2.30	0.344	2.41	0.369	4.31	0.298	6.17
FBL047	19.9	42.0	5.29	20.4	20.2	3.96	0.883	3.90	3.62	0.57	3.43	0.75	2.27	0.358	2.56	0.412	5.11	0.317	3.16
FBL048	27.6	59.0	7.67	29.5	29.3	5.88	1.320	5.90	5.23	0.84	5.11	1.09	3.34	0.528	3.58	0.599	7.12	0.419	4.43
FBL049 (1)	28.3	60.2	7.57	29.1	29.0	5.63	1.214	5.46	4.89	0.78	4.65	1.00	3.10	0.491	3.44	0.568	7.49	0.449	4.46
FBL049 (2)	28.1	60.7	7.58	29.2	29.3	5.74	1.212	5.35	4.81	0.76	4.73	1.01	3.13	0.493	3.44	0.565	7.29	0.428	4.36
FBL050	26.4	55.9	7.04	27.0	26.8	5.25	1.096	4.65	4.62	0.74	4.30	0.92	2.83	0.440	3.01	0.487	5.92	0.343	3.59
FBL051	21.8	43.5	5.13	19.2	18.9	4.16	0.632	4.63	4.18	0.73	4.65	1.02	3.15	0.505	3.45	0.554	3.80	0.653	9.89
FBL052	20.8	39.6	4.49	16.3	16.4	3.33	0.499	3.55	3.36	0.55	3.66	0.76	2.34	0.368	2.52	0.400	2.71	0.441	6.56
FBL053	24.6	48.4	5.60	20.6	20.9	4.48	0.786	4.82	4.34	0.73	4.32	1.04	3.26	0.522	3.41	0.562	3.75	0.637	9.46
FBL054	26.1	51.3	6.05	22.8	22.5	4.73	0.680	4.88	4.65	0.79	4.95	1.12	3.37	0.551	3.64	0.590	3.75	0.561	10.42
FBL055	17.4	36.9	4.71	19.2	19.2	4.33	1.036	4.84	4.46	0.71	4.35	0.94	2.78	0.410	2.60	0.392	2.57	0.340	4.55
FBL056	20.6	43.8	5.61	20.7	20.5	4.46	0.796	4.49	4.16	0.71	4.31	0.98	3.18	0.535	3.58	0.599	4.37	0.725	9.53
FBL057	46.8	93.3	11.54	43.6	43.6	9.32	1.559	9.69	8.56	1.51	10.17	2.41	8.36	1.445	8.93	1.365	5.00	1.219	16.84
FBL058	59.1	136.6	16.63	64.5	64.3	13.75	0.416	12.57	12.72	2.16	13.12	2.76	8.16	1.246	8.25	1.254	14.99	1.449	14.44
FBL059	51.3	191.6	15.03	58.9	58.8	13.00	0.472	11.99	12.15	2.08	12.36	2.61	7.61	1.174	7.69	1.192	14.98	1.471	14.19
FBL060	26.8	60.2	7.19	28.7	28.6	6.38	0.585	6.75	6.18	1.06	6.85	1.41	4.14	0.637	4.26	0.668	4.87	0.705	8.64
FBL061	25.7	55.7	6.86	27.5	27.3	6.21	0.644	6.77	6.30	1.07	6.78	1.44	4.34	0.671	4.39	0.694	4.56	0.660	7.95
FBL062	28.0	58.5	7.61	30.0	29.9	6.68	0.665	7.20	6.60	1.14	7.16	1.57	4.67	0.745	4.82	0.788	5.24	0.748	9.57
FBL063	28.8	61.2	7.68	30.2	30.0	6.60	0.546	7.04	6.40	1.11	6.99	1.47	4.50	0.702	4.65	0.722	4.58	0.682	8.12
FBL064	29.6	64.0	8.18	32.0	32.4	7.28	0.583	7.43	6.83	1.14	7.08	1.62	4.78	0.748	5.00	0.813	5.90	0.844	10.77
FBL065	33.7	73.3	9.22	36.8	37.0	8.27	0.702	9.02	8.25	1.39	8.62	1.85	5.43	0.839	5.58	0.880	5.42	0.800	9.93
FBL066	27.4	58.9	7.37	28.3	28.1	5.43	1.181	5.36	4.81	0.78	4.72	1.03	3.18	0.511	3.61	0.596	7.61	0.431	4.65
FBL067	23.9	50.9	6.60	26.9	27.3	5.57	1.633	5.74	5.22	0.81	4.90	1.04	3.05	0.458	2.95	0.471	4.41	0.308	2.97

Table F.1. **Element Concentrations as Measured by Inductively Coupled Plasma Mass Spectrometry (continued).**

Sample [a]	^{139}La (ppm)	^{140}Ce (ppm)	^{141}Pr (ppm)	^{143}Nd (ppm)	^{146}Nd (ppm)	^{147}Sm (ppm)	^{153}Eu (ppm)	^{156}Gd (ppm)	^{157}Gd (ppm)	^{159}Tb (ppm)	^{163}Dy (ppm)	^{165}Ho (ppm)	^{166}Er (ppm)	^{169}Tm (ppm)	^{172}Yb (ppm)	^{175}Lu (ppm)	^{178}Hf (ppm)	^{181}Ta (ppm)	^{232}Th (ppm)
FBL068 (1)	31.5	70.2	9.14	35.7	35.7	7.35	1.593	7.11	6.42	1.05	6.16	1.49	4.65	0.715	4.82	0.759	6.79	0.698	7.33
FBL068 (2)	31.0	69.3	9.03	35.6	35.4	7.33	1.559	7.09	6.46	1.06	6.23	1.47	4.62	0.717	4.85	0.758	6.82	0.716	7.37
FBL069	25.7	46.8	5.56	21.3	20.9	4.23	1.015	3.74	3.78	0.57	3.41	0.70	2.12	0.331	2.23	0.349	4.40	0.278	7.40
FBL070	8.0	19.1	2.66	11.9	12.1	2.80	1.038	2.55	2.44	0.36	2.02	0.39	1.12	0.154	0.97	0.155	0.75	0.075	1.42
FBL071	6.6	15.6	2.13	9.8	9.6	2.50	0.949	2.83	2.66	0.42	2.49	0.52	1.46	0.207	1.24	0.184	0.75	0.039	0.26
FBL072	27.8	59.8	7.92	32.3	32.4	8.17	1.549	9.68	8.95	1.65	10.71	2.35	7.13	1.102	7.06	1.097	6.09	0.726	9.19
FBL073	28.4	57.2	9.37	42.2	42.0	10.49	2.418	11.51	10.89	1.82	11.03	2.34	6.74	0.990	6.55	1.033	5.21	0.430	6.82
FBL074	28.7	59.3	7.26	27.8	27.3	5.85	1.136	6.37	5.72	0.96	5.81	1.23	3.72	0.572	3.60	0.541	4.29	0.803	9.99
FBL075	16.4	38.1	5.47	24.5	24.6	6.00	1.887	6.49	6.15	0.98	5.93	1.28	3.64	0.533	3.46	0.525	3.98	0.259	3.25
FBL076	33.1	66.2	8.10	30.1	29.9	6.55	0.867	7.16	6.58	1.17	7.48	1.65	5.01	0.819	5.47	0.869	10.24	1.663	16.37
FBL077	22.6	47.3	5.81	22.7	22.9	4.95	0.918	4.89	4.38	0.71	4.29	0.96	3.26	0.536	3.88	0.652	5.45	0.713	8.83
FBL078	25.7	54.1	6.55	25.2	25.2	5.69	1.214	6.25	5.82	0.98	6.06	1.34	4.01	0.625	4.11	0.642	7.22	0.789	9.82
FBL079	24.8	53.5	6.80	27.5	27.4	6.34	1.570	7.36	6.84	1.18	7.60	1.70	5.04	0.765	5.07	0.786	6.24	0.686	8.78
FBL080	25.5	54.2	6.94	29.0	28.9	6.97	1.242	8.28	7.82	1.37	8.73	1.93	5.82	0.899	5.83	0.908	5.41	0.587	6.93

[a] Samples FBL026, FBL039, FBL049, and FBL068 were each measured twice; the concentration values for each measurement are listed separately.

Appendix G

Neodymium Isotope Geochemistry

Brent V. Miller and Drew S. Coleman

To prepare the samples, any weathered surfaces or hydrothermal alteration zones along fractures were removed, and the remainder of the sample was crushed to fine-gravel consistency using a jaw crusher. The crushed pieces were pulverized to a fine powder in an aluminum-oxide shatter box. The powder was split into two vials. One vial was sent to MURR for chemical analysis, and the other was retained at the Department of Geological Sciences, University of North Carolina at Chapel Hill, for isotopic analysis.

For Sm-Nd isotopic analysis, approximately 200 mg of a mixed ^{147}Sm-^{150}Nd tracer solution (to determine absolute concentrations of Sm and Nd) was added to an equal mass of sample powder. The samples were dissolved with an hydrofluoric/nitric acid mixture in precleaned teflon high pressure dissolution vessels by heating in an oven for seven days at approximately 180°C. Conversion from fluoride to chloride solution is achieved by drying the hydrofluoric acid solution on a hot plate in a clean air environment and redissolution in 6M hydrochloric acid.

Sample preparation procedures for Phase 1 and Phase 2 samples deviate from one another slightly here, but this deviation has no impact on the final results. For Phase 1 samples, separation of bulk rare-earth elements followed standard cation exchange procedures. Rare-earth element separation was achieved by reverse-phase chromatography using 2-methyllactic acid on cation exchange resin. For Phase 2, the samples were dried and redissolved in nitric acid for separation of bulk rare-earth elements using RE-Spec™ resin. Rare-earth element separates were then dried and redissolved in hydrochloric acid for isolation of Sm and Nd using LN-Spec™ resin. Analytical procedural contamination is less than 20 pg for Sm and Nd, which is negligible considering the Sm and Nd concentrations of analyzed samples.

Isotopic analyses were performed on a VG Sector 54 magnetic sector, thermal ionization mass spectrometer with eight Faraday collectors operating in dynamic multicollector mode. Typical ^{144}Nd beam intensities were 5.0E^{-12} to 1.0E^{-11} volts relative to a 10E^{-11} ohm resistor. External precision is assessed by replicate analyses of the JNdi-1 standard (Tanaka et al. 2000) and yields ^{143}Nd/^{144}Nd = 0.512108 ± 0.000007 (n = 20). Neodymium isotopic compositions are normalized to ^{146}Nd/^{144}Nd = 0.7219 assuming exponential fractionation behavior. Internal run precision for the critical isotopic composition measurement, ^{143}Nd/^{144}Nd, is better than ± 0.000005, 1σ absolute. Internal run precision for measurement of ^{147}Sm/^{152}Sm is better than ± 0.00001, 1σ absolute. Total uncertainties in isotopic ratios are the quadratic sum of individual sample measurement errors, uncertainties in spike weight and concentration, sample weight, and the reproducibility of standards and are reported as 2σ, absolute (Table G.1).

Table G.1. Neodymium (Nd) and Samarium (Sm) Isotope Ratios.

	Measured Ratios [a, b]			
Sample [c]	^{147}Sm/^{144}Nd$_{(now)}$ [d]	^{143}Nd/^{144}Nd$_{(now)}$ [e]	eNd$_{(now)}$ [f]	^{143}Nd/^{144}Nd$_{(550\ Ma)}$ [g]
FBL001	0.1427	0.512570	-1.33	0.512056
FBL002	0.1466	0.512578	-1.17	0.512050
FBL003	0.1497	0.512595	-0.84	0.512056
FBL004	0.1455	0.512576	-1.21	0.512052
FBL005	0.1466	0.512586	-1.01	0.512058
FBL006 (1)	0.1452	0.512550	-1.72	0.512027
FBL006 (2)	0.1470	0.512568	-1.37	0.512038
FBL006 (3)	0.1472	0.512578	-1.17	0.512048
FBL007	0.1511	0.512594	-0.86	0.512050
FBL008	0.1522	0.512611	-0.53	0.512063
FBL009	0.1533	0.512604	-0.66	0.512052
FBL010	0.1534	0.512606	-0.62	0.512053
FBL011	0.1496	0.512599	-0.76	0.512060
FBL012	0.1516	0.512613	-0.49	0.512067
FBL013	0.1536	0.512607	-0.60	0.512054
FBL014	0.1430	0.512548	-1.76	0.512033
FBL015 (1)	0.1441	0.512548	-1.76	0.512029
FBL015 (2)	0.1440	0.512537	-1.97	0.512018
FBL016	0.1438	0.512544	-1.83	0.512026
FBL017	0.1451	0.512596	-0.82	0.512073
FBL018	0.1427	0.512553	-1.66	0.512039
FBL019	0.1430	0.512540	-1.91	0.512025
FBL020 (1)	0.1324	0.512484	-3.00	0.512007
FBL020 (2)	0.1323	0.512495	-2.79	0.512018
FBL021	0.1393	0.512689	0.99	0.512187
FBL022	0.1403	0.512685	0.92	0.512179
FBL023	0.1463	0.512518	-2.35	0.511990
FBL024	0.1388	0.512571	-1.31	0.512071
FBL025	0.1270	0.512458	-3.51	0.512000
FBL026	0.1282	0.512468	-3.32	0.512006
FBL027	0.1484	0.512244	-7.69	0.511709
FBL028	0.1320	0.512227	-8.02	0.511751
FBL029	0.1266	0.512197	-8.60	0.511741
FBL030	0.1576	0.512275	-7.08	0.511707
FBL031	0.1315	0.512623	-0.29	0.512149
FBL032	0.1270	0.512622	-0.31	0.512164
FBL033	0.1284	0.512613	-0.49	0.512150
FBL034	0.1331	0.512609	-0.57	0.512129
FBL035	0.1308	0.512601	-0.72	0.512130
FBL036	0.1289	0.512611	-0.53	0.512147
FBL037	0.1222	0.512560	-1.52	0.512120
FBL038	0.1272	0.512630	-0.16	0.512172
FBL039	0.1637	0.512783	2.83	0.512193
FBL040	0.1579	0.512655	0.33	0.512086
FBL041	0.1582	0.512618	-0.39	0.512048
FBL042	0.1689	0.512743	2.05	0.512134
FBL043	0.1189	0.512648	0.20	0.512220
FBL044	0.1354	0.512558	-1.56	0.512070
FBL045	0.1204	0.512652	0.27	0.512218
FBL046	0.1290	0.512640	0.04	0.512175

Table G.1. Neodymium (Nd) and Samarium (Sm) Isotope Ratios (continued).

Sample [c]	Measured Ratios [a, b]			
	^{147}Sm/^{144}Nd$_{(now)}$ [d]	^{143}Nd/^{144}Nd$_{(now)}$ [e]	eNd$_{(now)}$ [f]	^{143}Nd/^{144}Nd$_{(550\ Ma)}$ [g]
FBL047	0.1240	0.512621	-0.33	0.512174
FBL048	0.1227	0.512659	0.41	0.512217
FBL049	0.1123	0.512612	-0.51	0.512207
FBL050	0.1139	0.512616	-0.43	0.512206
FBL051	0.1213	0.512424	-4.17	0.511987
FBL052	0.1209	0.512398	-4.68	0.511962
FBL053	0.1231	0.512418	-4.29	0.511974
FBL054	0.1267	0.512412	-4.41	0.511955
FBL055	0.1417	0.512472	-3.24	0.511961
FBL056	0.1287	0.512372	-5.19	0.511908
FBL057	0.1282	0.512146	-9.60	0.511684
FBL058	0.1278	0.512602	-0.70	0.512141
FBL059	0.1330	0.512603	-0.68	0.512124
FBL060	0.1348	0.512666	0.55	0.512180
FBL061	0.1355	0.512683	0.88	0.512195
FBL062	0.1351	0.512654	0.31	0.512167
FBL063	0.1331	0.512699	1.19	0.512219
FBL064	0.1337	0.512689	0.99	0.512207
FBL065	0.1352	0.512675	0.72	0.512188
FBL066	0.1168	0.512606	-0.62	0.512185
FBL067	0.1217	0.512627	-0.21	0.512188
FBL068	0.1301	0.512474	-3.20	0.512005
FBL069	0.1247	0.512613	-0.49	0.512164
FBL070	0.1408	0.512668	0.59	0.512161
FBL071	0.1564	0.512696	1.13	0.512132
FBL072	0.1470	0.512553	-1.66	0.512023
FBL073	0.1472	0.512697	1.15	0.512167
FBL074	0.1294	0.512337	-5.87	0.511871
FBL075	0.1511	0.512687	0.96	0.512143
FBL076	0.1352	0.512431	-4.04	0.511944
FBL077	0.1326	0.512442	-3.82	0.511964
FBL078	0.1390	0.512489	-2.91	0.511988
FBL079	0.1400	0.512428	-4.10	0.511924
FBL080	0.1456	0.512549	-1.74	0.512024

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[a] All Nd data normalized to ^{146}Nd/^{144}Nd = 0.7219.

[b] Replicate analyses of JNdi-1 yield ^{143}Nd/^{144}Nd = 0.512108 ± 0.000007 (n = 20).

[c] Samples FBL006, FBL015, and FBL020 were each measured multiple times; the ratios for each measurement are listed separately.

[d] Error in measured ^{147}Sm/^{144}Nd is the quadratic sum of run precision, external reproducibility of the standards, and uncertainty in the Sm/Nd ratio of the spike. For the samples in this study, this error is consistently < 0.0010 in the measured ratio (absolute 2s).

[e] Error in measured ^{143}Nd/^{144}Nd is dominated by external reproducibility error and is estimated at ± 0.000010 (absolute 2s).

[f] eNd calculated using ^{143}Nd/^{144}Nd$_{ChUR}$ =0.512638 and ^{147}Sm/^{144}Nd$_{ChUR}$ = 0.1967.

[g] Error in the calculated ^{143}Nd/^{144}Nd at 550 Ma is a combination of errors in the measured ratios. For the samples in this study, this error is consistently < 0.000040 in the initial ratio (absolute 2s).

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