

***Carolina Geological Society
2008 Fieldtrip and Annual Meeting,
Little Switzerland, North Carolina
October 31-November 2, 2008***



***Co-leaders:
Alex Glover and Kenneth B. Taylor***

Carolina Geological Society (CGS)
2008 Field trip

Spruce Pine Mining District
North Carolina

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Gary Jensen of the Switzerland Inn

and

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Forward

The 2008 field trip and annual meeting of the Carolina Geological Society (CGS) was held in Little Switzerland, North Carolina on October 31-November 2, 2008. The meeting was convened by Alex Glover of the Attapulgit Division, Active Minerals, LLC, and staff of the North Carolina Geological Survey, in collaboration with CGS and sponsoring entities.

This meeting program contains the field trip road log, and technical papers given as part of the annual field trip. The annual meeting field trip provided glimpses of North Carolina's varied mineral industries including crushed stone and industrial minerals. The annual meeting field trip traversed areas from Little Switzerland on the Blue Ridge Parkway to the Spruce Pine Mining District and finally Mount Mitchell State Park.

It is our hope that this field trip guidebook provides useful information about this meeting.

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The Spruce Pine Mining District – A brief review of the history, geology, and modern uses of the minerals mined in the Spruce Pine Mining District, Mitchell, Avery and Yancey Counties, North Carolina

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ABSTRACT

The story of prospecting and mineral production of the Spruce Pine Mining District began before recorded time when Native Americans mined for glittering muscovite mica during the Woodland Age 2000 years ago. From Native American grave decoration to semi-conductor computer chips and tiles for the Space Shuttle, the Spruce Pine Mining District has been providing vital minerals for mankind. These minerals, including Feldspar, Quartz, and Mica are used in many applications of our daily life.

It took colliding continents, plutonic heat, and millions of years of cooling to place this rare geologic source in the once mighty and lofty Appalachian Mountains. These mountains, now worn and distinctly beautiful lie in western North Carolina within sight of the small town of Spruce Pine, North Carolina – nicknamed ‘The Mineral City’.

Glover, Alex, 2006, The Spruce Pine Mining District – A brief review of the history, geology, and modern uses of the minerals mined in the Spruce Pine Mining District, Mitchell, Avery and Yancey Counties, North Carolina, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

HISTORY

The story of prospecting and mineral production of the Spruce Pine Mining District began before recorded time when the "Ancients" mined for glittering mica during the Woodland age 2000 years ago. The Ancients, an early name given to the Native Americans by settlers of the area, mined mica for grave decoration and wampum, which they traded as money. The mica is known to have been traded as far away as the Ohio valley and is believed to have originated from Native American mines in the Spruce Pine area now known as the Clarissa, Ray, and Sinkhole mines. Legend is that this mining of mica led Hernando Desoto to the Spruce Pine area around 1540 in search of mineral wealth that he thought to be gold and silver. He found only silver mica better known as muscovite mica.

Later, around 1744, legend is that Cherokee Indians mined semi-weathered feldspar and kaolin from the Spruce Pine pegmatites and used oxen drawn sleds to transport it to the coast where it was loaded on ships bound for England. In England it was used as an ingredient for patented English ceramic wares.

From 1767 to 1911, mining of feldspar and mica occurred sporadically. Mica was mined to fuel the demand for the newly developed Edison electric motor in 1878. The motor required the electrical insulating properties of sheet mica.

Around 1910, gem prospector William E. Dibbell of Baltimore became interested in the large waste piles of feldspar discarded by early mica miners. He sorted material from the Flat Rock Mica mine near Penland and hand scrubbed it with steel brushes to enhance purity for trial shipment to the Golding Sons Ceramic Plant in East Liverpool, Ohio. Management of the Golding Sons Plant liked the ceramic grade feldspar so much that they contracted Dibbell to supply more. This led to Dibbell receiving bank backing to organize the Carolina Minerals Company of Penland. The first production load of feldspar was shipped from the Deer Park mine in 1911 and eventually supplied Golding Sons Ceramic Plants in Trenton, Wilmington, and East Liverpool, Ohio.

Three years later, in 1914, feldspar-grinding plants were built in Erwin, Tennessee by the Clinchfield Mineral and Milling Company. This plant was organized by Charles Ingram and financed by Blair and Company of New York. This same company financed building of the Clinchfield railroad, which was completed in 1908.

In 1917 North Carolina became the primary feldspar producer in the US and has continued to maintain that status ever since. Feldspar grinding continued in Erwin, TN along with new feldspar plants constructed in 1921 at Beaver Creek, NC and in 1923 at Micaville, NC. As the feldspar industry became more active and prosperous, many investors and producers were starting new companies and buying others. Feldspar and mica were being hand mined at hundreds of holes, pits, and mines throughout Mitchell, Avery, and Yancey counties, which make up the Spruce Pine Mining District.

Until 1949 most work, especially ore separation of minerals, was done by hand with crude machinery and hand tools. In 1949, the process of chemical separation of minerals was jointly developed by the Feldspar Mining Company, The North Carolina Feldspar Corp., The Tennessee Valley Authority, and The North Carolina State Mineral Research Laboratory of Asheville. This process led to the current large volume, high capacity process of separating the minerals of feldspar, mica, quartz, and garnet from the rock (ore).

GEOLOGY

The geologic history of Spruce Pine Mining District is as fascinating as its mining history. About 380 million years ago the African Continent was being forced toward the Ancestral Eastern North American Continent by plate tectonic force. The subduction, or forcing down of the Oceanic Crust underneath the North American Continent produced tremendous friction-generated heat from the two colliding continents.

This friction-generated heat in excess of 2000(F melted the surrounding rock 9-15 miles below the surface. This igneous molten rock was generated under intense pressure that forced the molten rock into cracks and fissures of pre-existing rock. This molten rock under pressure is similar to hot hydraulic fluid being forced into a chamber. Due to the pressure exerted on the molten fluid, it hydraulically pushed its way through the cracks of the host rock. This opened the rock up, along with melting contact areas of the host rock and sucking up rich mineral forming fluids. As these cooled, they crystallized and became a mineral rich buried treasure.

It then took an estimated 100 million years for this deeply buried (and insulated) mass to cool and crystallize. The slowly cooling mineral crystals grew within the Spruce Pine District to some of the largest feldspar and mica crystals in the world. After molten emplacement and cooling, it took millions of more years of Appalachian Mountain building and subsequent erosion to expose the deposits we see today.

TODAY'S USES

Modern day mining methods, research, plant production, and product development have enabled the use of these high purity natural resources from the earth to enhance our quality of life.

Feldspar

Feldspar is a major ingredient in the manufacture of many types of glass, from automobile windshields and computer screens to baby food bottles and electric light bulbs. Feldspar comprises about 65% of the rock from the Spruce Pine pegmatite and is a major source of aluminum, sodium, and potassium for glass manufacturing. Feldspar provides aluminum, which improves glass workability during forming, retards glass blooming, improves glass strength, and imparts resistance to thermal shock. About 110 pounds of feldspar is used to make a ton of container glass (bottles and jars) and about 100 pounds is used to make a ton of flat glass (auto windshields and window glass).

Feldspar is also a major ingredient in the manufacture of ceramic products. It acts as a flux to fuse (melt) other ingredients at lower temperatures; it cements the crystalline phases of other ingredients together; and it imparts strength, durability, and toughness to ceramic bodies. Feldspar's special qualities and glazing properties allow ceramic product manufacture of pottery, plumbing fixtures (sinks and toilets), electrical porcelain, ceramic tile, dinnerware, structural ceramics, art pottery, planters, and much more. The use of feldspar in the manufacture of ceramics has come a long way since its development during the Tang Dynasta of China around AD-621 to 945.

Mica

Mica, another ingredient from the rock of the Spruce Pine Mining District comprises about 10% of the rock mass. Once highly valued for wood and coal burning stove windows (often called isinglass) and for radio tube insulators during both world wars, it is now used as an industrial products special additive.

Muscovite, which is silver to white mica variety, is mostly ground to a fine particle size. It is valued for its flat particle shape. It is used mostly as a major ingredient of dry-wall joint compound or sheetrock joint cement. Muscovite's flat particle shape and light color allow it to serve as an anti-shrinking agent for the cement after it is applied to sheet rock joints. It applies as smooth damp putty, but because of muscovite mica's flat particle shape, it interlocks the mud as it dries, therefore reinforcing the mud as it dries-without shrinkage. It also acts as a fire retardant within the sheet rock joint.

Mica is also produced from the Spruce Pine Mining District for use as special electrical insulators, automobile metallic flake paint, women's make-up, and as a reinforcing additive in special plastics, and paints. It is used in oil well drilling fluids to seal and lubricate the borehole during drilling.

Quartz

Another major ingredient of the Spruce Pine rock is quartz. Through the years, quartz was always discarded as waste. Now it is recovered through froth flotation and is used as industrial sand in concrete and concrete mortar. It is also a highly valued white golf course trap sand and is sold across the country to the finest golf courses including, the Augusta National, the host for the Masters.

Comprising about 25% of the rock, the quartz has now become one of the most strategic minerals of the entire world. Because of its extreme purity, it is used in several critical process steps during the manufacture of computer semi-conductors (chips). At present, no other quartz in the world can match the processed quartz purity from the Spruce Pine District. As a matter of fact, every computer chip in the world uses Spruce Pine quartz in its' manufacturing process.

Also of high value to the lighting industry, the Spruce Pine quartz meets stringent purity requirements to serve as extreme high temperature light tubing required for light bulbs installed in automobiles, streetlights, and film projectors.

SUMMARY

It is amazing that this small 25 mile long by 10 mile wide pegmatite of the Spruce Pine Mining District (lying in Mitchell, Avery, and Yancey counties of North Carolina) is so important an ingredient for making products we use everyday. We often take for granted its role in the quality of life that we enjoy today.

The Spruce Pine District's importance has increased as mankind's need for minerals has progressed from early Native American burial decoration to space-age computer parts of today. Even more amazing is the fact that it took colliding continents to place this valuable resource in such a beautiful area as the Western North Carolina Mountains.

The Sink Hole at Bandana: A Blue Ridge mica mine reveals Its prehistoric past

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ABSTRACT

Aboriginal mining activity in the Blue Ridge Mountains during the Woodland period is a neglected aspect of North Carolina prehistory. Abundant evidence of such activity was still visible in the nineteenth and early twentieth centuries, before modern mining obliterated it. From published reports of this evidence, it appears that Woodland mining activity in the Blue Ridge was devoted largely, if not exclusively, to the extraction of a single mineral, mica, and its transport to centers of Adena and Hopewell culture in the Ohio Valley. Evidence for future study consists of tools and artifacts in museum collections. A cursory inspection of one such collection shows that much material is available, only awaiting renewed interest in the subject. A review of the literature and visits to a prehistoric mining site, the Sink Hole mica mine in Bandana, North Carolina, suggest future lines of inquiry, chief among these being the identity of the prehistoric miners.

Margolin, Peter R., 2006, The Sink Hole at Bandana: A Blue Ridge mica mine reveals its prehistoric past, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

INTRODUCTION

Intermittently, for a period of over two millennia, large clear sheets of mica—the isinglass of previous generations—have been extracted from deposits in North Carolina’s mountains. The prehistoric inhabitants of North America used sheet mica in ways very different from modern civilization. Whereas modern uses have been strictly utilitarian, ancestral Native Americans found ritual and ornamental uses for mica. Nevertheless, the aboriginal mining industry corresponded to its modern counterpart in two significant respects: (1) both prehistoric and modern miners invested large amounts of time and energy extracting sheet mica from the same deposits, excavating many tons of rock in the process; and (2) both transported their product hundreds of miles from mine to user.

In 1913, when the Smithsonian Institution’s William Henry Holmes came to Spruce Pine to investigate ancient mica mining in Mitchell County, evidence could still be seen where countless generations of prehistoric miners had extracted huge quantities of mica from the area’s many deposits. Although his discussion of this prehistoric industry betrays no awareness that Woodland period inhabitants of the region might have used mica themselves (Holmes 1919), later archaeological work at places such as the Warren Wilson site in Buncombe County and the Garden Creek site in Haywood County has resulted in the discovery of mica funerary objects (e.g., Dickens 1976; Wilson 1986), but in quantities that pale in comparison with those found in Ohio Valley mounds. Mica is soft but the large sheets that the miners prized, up to three feet in diameter, occur in the

form of thick, heavy crystals. Thus, preparing the mineral and transporting it hundreds of miles away required a great expenditure of time and effort.

This article was written in hopes of directing renewed interest in this neglected aspect of North Carolina prehistory. Toward that end, it: (1) records early speculations on the origins of ancient workers at a mica mine in Mitchell County; (2) describes two Ohio Valley burial mounds in which large quantities of mica from western North Carolina were discovered and the circumstances of its discovery; and (3) describes how the Woodland people of the Ohio Valley used this mica. A secondary aim is to present, in broad outline, the 2,000-year history of what may well be the oldest mine in the southern Appalachians.

Mica mining has a venerable history in the New World. Among the many mineral deposits exploited by prehistoric Native Americans, few were worked over a longer period than the mica veins of North Carolina. The State’s many historic mica mines, now abandoned, were first opened 2,000 years ago. By contrast, historic records of mica mining extend back barely two centuries, to 1803 when the mineral was first mined in New Hampshire.

Much of North Carolina’s prehistoric mining activity was centered in an area known in historic times as the Spruce Pine mining district. Until the 1950s, mica mining was an important industry in the district, supplying much of the domestic mica used in electrical and electronic applications. At the beginning of the twenty-first century, some 2,000 years after work began there, none of these mines offers better documentation of this vast span of history than the Sink Hole, located in the Mitchell County community of Bandana. Taking the period of prehistoric activity into account (and bearing in mind the distinction between mining minerals and quarrying rock), this may be among the oldest mines in North America. Its location is noted by an historical marker four miles northeast

of the site on U.S. 226, between Spruce Pine and Bakersville. The latter, the county seat, is six miles northwest of the mine.

EARLIEST DESCRIPTIONS

In 1868, rumors of Spanish silver mines gave General Thomas Lanier Clingman the idea to sink a shaft on the site of some ancient excavations in Bandana, located 15 mi upstream from where North Carolina's Toe River flows into Tennessee and becomes the Nolichucky River. He hoped to find silver ore there; instead, he found sheets of mica as large as any he had ever seen (Clingman 1877).

Clingman first visited Bandana in 1867 to investigate reports of ancient silver mines, according to William H. Holmes. Holmes was Chief of the Bureau of American Ethnology at the Smithsonian Institution from 1902 to 1909. His description of Clingman's work at Bandana was included in the earliest and possibly only comprehensive study of prehistoric Native American mining ever attempted (Holmes 1919) (Figure 1).

When General Clingman visited Bandana, evidence of mining there consisted of a series of overgrown pits dug into hillsides opposite what is now known as Sink Hole Creek. The diggings coincided with a band of outcrops of pegmatitic rock stretching a total distance of about 1,600 ft in a northeast-southwest direction and averaging 8–12 ft in width. (Pegmatite is an igneous rock, similar to granite in composition, consisting of uncommonly large crystalline masses of three minerals: feldspar, quartz, and mica.) Clingman thus became one of the first to record how the Bandana workings looked centuries after they had been abandoned, and before their disruption by nineteenth- and twentieth-century mining. On the north side of the creek, on land belonging to a farmer named William Silvers, Clingman observed a line of excavations that extended some 400 yards uphill onto a ridge crest. A similar but shorter line was visible on the south side, over the hilltop and about 1,000 feet away. As Clingman described the excavations, it appeared as though a large number of miners had been at work there for many years (Clingman, 1877). Although Clingman gave no estimate of the depth of the workings, Holmes, who saw them in 1913, described the diggings as having reached depths of 30 to 40 ft (Figure 2).

Clingman's first inclination, believing the stories that had brought him there, was to credit the men of De Soto's expedition with the mining. The conquistadors had trekked through the Carolinas looking for precious metals in 1540. Having studied mineralogy with Professor Elisha Mitchell at Chapel Hill 35 years previously, Clingman regarded the waste material lying in piles around the pits at Bandana as resembling "Mexican silver ore." Thus, in 1868, he decided to sink a shaft there and had two tunnels dug beneath the old excavations (Figure 3). Instead of silver, though, Clingman found an abundance of "large mica of good quality."

As Clingman observed, the size of the trees then growing on waste material heaped up around the pits suggested that the work had been done hundreds of years earlier. In a letter from Asheville, North Carolina, dated April 8, 1873, he speculated: "It does not seem improbable that a former race of Indians – possibly the 'Mound-Builder,' who used copper tools, made these excavations for the purpose of procuring the mica." Clingman was not alone in venturing a guess as to the origin of the prehistoric miners at the Sink Hole. In 1880, W. C. Kerr, State Geologist of North Carolina, wrote as follows concerning North Carolina's ancient mica mines: "I have stated elsewhere, several years

ago, that these veins were wrought on a large scale and for many ages by some ancient peoples, most probably the so-called Mound Builders” (Kerr 1880:457).

Kerr summarized his observations of aboriginal work at a number of mica mines in western North Carolina as follows:

They opened and worked a great many veins down to or near water level. . .as far as the action of atmospheric chemistry had softened the rock so that it was workable without metal tools. . . . Many of the largest and most profitable mines of the present day are simply the ancient Mound Builders’ mines reopened and pushed into the hard undecomposed granite by powder and steel. Blocks of mica have often been found half imbedded in the face of the vein, with the tool-marks about it, showing the exact limit of the efficiency of those prehistoric mechanical appliances [Kerr 1880:457].

Examples of the “appliances” Kerr referred to were illustrated by drawings that appeared in Holmes’ 1919 report (Figure 4). Kerr had also heard the stories of old Spanish silver mines. He visited the prehistoric diggings at Bandana in the same year that Clingman sank his shaft; however, his *Report of the Geological Survey for 1875* made no mention of Clingman’s presence or activities there. The geologist described “a dozen or more open pits 40 to 50 feet wide, by 75 to 100 long, filled up to 15 or 20 feet of depth” (Kerr 1875:300). He went on to relate that two years after his visit to Bandana (by 1870), he had learned that “mica was of common occurrence in the tumuli of the Mound Builders” and that “cut forms similar to those found in the mounds were occasionally discovered among the rubbish heaps about and in the old pits” (Kerr 1875:300). This latter piece of information Kerr (1875:300) took as revealing “unmistakably the purpose and date of these works [the pits at Bandana].” If it could be verified, it would have a direct bearing on the question of where the ancient miners originated. Among Kerr’s general comments on North Carolina mica mines in 1875 were the following observations regarding prehistoric work:

Since the development of mica mining on a large scale in Mitchell and adjoining counties, it has been ascertained that there are hundreds of old pits and connecting tunnels among the spurs and knobs and ridges of this rugged region; and there is no doubt that mining was carried on here for ages, and in a very systematic, skillful way. . . . The pits are always open “diggings,” never regular shafts, and the earth and debris often amounts to enormous heaps. . . . The tunnels are much smaller than such workings in modern mining, generally only three to three and a half feet in height and considerably less in width. Some have been followed for fifty and a hundred feet and upwards [Kerr 1875:300].

A year after Kerr’s visit and Clingman’s departure, two stove merchants from Tennessee, J. G. Heap and E. B. Clapp, began mining mica at what by then was known as the Sink Hole Mine. They established in Bandana the headquarters of what grew to be a large, profitable enterprise, producing mica from many properties within the district. The economic value of their product was based on its transparency, its resistance to fire and heat, and the ease with which it could be split into thin flexible sheets that could be trimmed to any size or shape. These qualities made mica eminently suited for stove and furnace windows, lanterns, and lampshades.

Within a few decades, by the turn of the century, it became apparent that mica would play an even more important role in industry. This new role depended upon an

additional quality, mica's dielectric properties, which made it a peerless electrical insulator. "Until a few years ago, almost the only commercial use of mica was in the doors or windows of stoves and furnaces. To a less extent it was used in lanterns and the portholes of naval vessels, where vibrations would demolish the less elastic glass. . . . Since the introduction of the present system of generating electricity, there has risen a considerable demand for it in the construction of dynamos and electric motors" (Merrill 1901:290).

THE HISTORICAL PERIOD OF MICA MINING

The workings at Bandana eventually grew to include over 30 shafts and 2,000–3,000 ft of drifts and stopes. The deepest shafts were connected below by a 900-ft tunnel which drained water that otherwise would have filled the underground workings. The tunnel extended under the paved road that is now N.C. Highway 80 (Figures 5 and 6). In the latter decades of the nineteenth century, the Sink Hole was known as a source of the highest grade of flat stove mica. In the twentieth century, when electrical and electronic applications overshadowed older uses, the Sink Hole became renowned as the source for a variety of reddish brown muscovite mica, known as "ruby" in the trade, that was regarded as possessing the highest dielectric properties and therefore preferred by industry.

Activity at the mine fluctuated over a 90-year period. When sheet mica was in demand, the selling price rose and fell depending on the amount imported from abroad (chiefly India) and the needs of the defense industry. After a 20-year interruption following the First World War, new shafts were sunk in 1941 a short distance southwest of Clingman's original shaft (see Olson 1944:Plate 5), as America prepared once more to go to war. In 1942, the U.S. Government established the Colonial Mica Corporation, headquartered in Asheville with an office in Spruce Pine, in order to encourage local miners by offering to buy all the mica they could produce and to help finance the purchase of mining equipment.

With peace, work came to a halt in 1945, only to be revived again by the Korean War. The buying program was reestablished in 1952, when the government began stockpiling mica to ensure against interruptions in overseas supplies. During the 10-year period from 1952 to 1962, the mine produced over 200,000 pounds of sheet mica (Lesure, 1968:68). When the federal buying program ended in 1962, so did activity at the Sinkhole Mine.

ANCIENT MINERS

When Clingman and Kerr visited Bandana, signs of prehistoric activity there consisted of deep pits and trenches with stone tools left lying in the bottom. The actual identity of Bandana's prehistoric miners is a matter of conjecture; however, questions about why the mica was mined, how it was used, and where it was used was solved by the excavation of burial mounds hundreds of miles away in the Ohio River Valley of Ohio, Kentucky, and West Virginia.

In 1913, some four decades after Clingman searched for silver there, W. H. Holmes visited Bandana to investigate reports of aboriginal tools found in mica mines of the Spruce Pine district. He arrived at a time when modern work had not quite obliterated the ancient diggings. Holmes appears to have been the second archaeologist to investigate

the diggings. In the report he published in 1919, Holmes mentioned a reconnaissance in 1893 by De Lancey Gill, also of the Smithsonian Institution's Bureau of American Ethnology, made under his direction. According to Holmes, the results of that work were never published. However, Gill may have collected some aboriginal mining tools in 1893, because Holmes mentions that by the time of his 1913 visit, the U.S. National Museum already had a dozen artifacts from the Spruce Pine area in its possession (Figures 7 and 8).

While Holmes did not do any digging in 1913, he did visit two mines in the vicinity of Spruce Pine (the Deake and an unnamed mine), one near Bakersville (the Clarissa mine), and the Sink Hole at Bandana. Judging from the information he published in 1919, Holmes devoted most of his time and attention to the workings at Bandana. Supplementing his description of the Sink Hole was a topographic map sketched in the field (see Figure 3). In addition to showing the locations of the various pits and trenches, the map indicates the sites of what he described as mica workshops. One, a wooded hummock situated on a ridge top immediately south of Sink Hole Creek, can still be seen. A review of the literature suggests that these are the only features in North Carolina that have ever been identified as such.

When Holmes reported the results of these and other investigations in 1919, he credited Clingman with having been the first to "bring to light. . .the sources of supply" of the mica found in Ohio Valley burial mounds. To Holmes, there was no question that mica unearthed in the graves of the Mound Builders came from deposits in North Carolina. This conclusion appears incontestable, for although they are hundreds of miles apart, North Carolina deposits are nearer to the mounds than any others available to the prehistoric miners. The identity of the miners themselves, however, remains open to conjecture.

NORTH CAROLINA MICA IN OHIO VALLEY BURIAL MOUNDS

The earliest Ohio Valley burial mounds are over 2,000 years old, firmly within the context of the Woodland period. Radiocarbon dating of organic remains found in the mounds indicates that they were constructed over a period of hundreds of years, beginning around 200 B.C., by a people in the early stages of adapting to a settled, agricultural existence. By the early nineteenth century, when the Ohio Valley was first being settled by people of European descent, the Native Americans whom the settlers found living there could shed no light on the identity of the people who had raised the mounds, people who had preceded them by more than a thousand years. The earthworks of these vanished people were excavated by amateurs as early as the 1840s (Squier and Davis 1848). In the decades that followed, professional archaeologists, faced with the necessity of attaching labels, assigned the names Adena and Hopewell to the Woodland people who built the mounds.

Archaeologists who excavated Adena and Hopewell burial mounds discovered an unusually rich array of artifacts, including images cut from tortoise shell, copper, and large smooth sheets of mica. The latter included stylized human torsos, hands, claws and talons, and geometric figures.

Other mica artifacts found in the mounds included large numbers of perforated disks as well as elliptical forms that may have served as mirrors. Several hundred mica disks were found in one of a group of two dozen mounds called Mound City, near Chillicothe, Ohio, in what is now Hopewell Culture National Historic Park (see Holmes

1919). Holmes and others have speculated that the disks and others like them were strung together to form part of the costume of a medicine man or shaman. Adena and Hopewell mica artifacts such as these now reside in the collections of the Museum of the Ohio Historical Society in Columbus, Ohio, and in the Smithsonian Institution.

The author visited the Smithsonian Institution's Museum Support Center (a storage and curatorial facility in Suitland, Maryland) in order to examine the stone tools and mica that Holmes and presumably Gill had collected from the Sink Hole and other mines in Mitchell County. This visit also served as an opportunity to examine some of the Smithsonian's collection of Hopewell and Adena artifacts made of mica, copper, and stone that came from various mounds in the Ohio Valley.

Holmes and Gill collected more than just stone mining tools at the Sink Hole. The Smithsonian collection of artifacts from Mitchell County also includes large elliptical sheets of mica, possibly retrieved from a cache left behind by the ancient miners. Discoveries by C. D. Smith at prehistoric mica mines in Macon County established that the miners commonly stored their mica in pits, especially dug for this purpose, until it was time to transport it westward (Smith 1877).

One of the conical mounds at Hopewell Culture National Historic Park was named the Mica Grave because of the great quantity of the mineral found when the mound was excavated in 1846 by amateur archaeologists Ephraim G. Squier and Edwin H. Davis (1848) (Figure 9). During a later, more systematic excavation by William C. Mills and Henry C. Shetrone in 1920 and 1921, workers uncovered 13 graves at a depth of 20 ft. One was decked with thick sheets of mica. Mills (1922) described the sheets as having been cut into rectangular shapes of up to 10 inches by 14 inches and completely covering an area 8 ft by 4 ft. Until 1997, when it was closed at the request of contemporary Native Americans, perhaps descendants of the Hopewell, the Mica Grave was on public display with a short tunnel providing entrance into the dimly lit interior.

At Seip Mound, located 20 mi west of Mound City, archaeologists unearthed the foundations of two workshops, the floors of which were littered with mica trimmings and blades used in the cutting process (Baby and Langlois 1979:18) (Figure 10). Here, presumably, Hopewell artisans cut mica sheets into designs of ritual significance, the sheets having been split from heavy books at mine sites such as the Sink Hole.

The oblong Seip Mound, originally 30 ft high and the focal point of a complex of mounds enclosed by a 10-ft high earthen embankment, was found to contain 122 burials when thoroughly excavated between 1926 and 1928 (Shetrone and Greenman 1931). In addition to mica from North Carolina and copper from Michigan, the graves contained thousands of freshwater pearls, estimated in 1960 to have been worth as much as \$2 million when new and in good condition (Woodward and McDonald 1986:93–95). Burial mounds such as Seip are characteristic of the Middle Woodland culture of the Ohio Valley which also produced large earthwork enclosures laid out in geometric designs, including squares, circles, and octagons.

What distinguishes the Woodland people of the Ohio Valley as much as monumental earthworks is the richness of their grave goods. These consist of artifacts crafted from a wide variety of materials, including not only mica but also copper, gold, silver, galena, flint, obsidian, pipestone, and saltwater shells. Such variety is remarkable considering that only flint is native to the valley region. The other materials were brought from sources hundreds of miles distant, without the aid of wheeled conveyances or beasts of burden. Copper, for example, came from aboriginal mines on the shores of Lake Superior, over 600 mi north of the Hopewell heartland. Were the Hopewell and Adena

exclusively traders, bringing flint and ceramics to North Carolina's mountains to exchange for mica, or could they have done some of the mining themselves?

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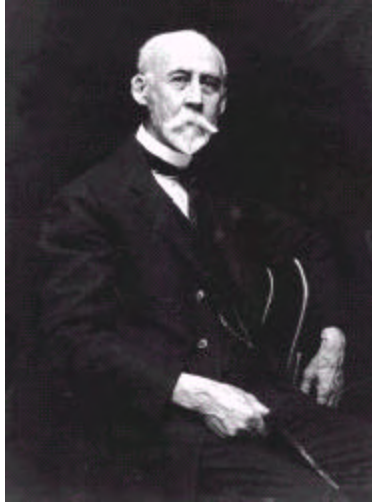


FIGURE 1 William H. Holmes, taken during the period when he was Chief of the Smithsonian Institution's Bureau of American Ethnology. Courtesy of the Smithsonian Institution.



FIGURE 2 Sketch map of the Sink Hole Mine in 1913 (from Holmes 1919:Figure 116): B and C – Sink Hole; A – Robinson; and D – aboriginal mica workshops. Sink Hole Creek meanders from east to west across the middle of the map area. (north to top)

Figure 3 – not available

FIGURE 3 Plan of openings at the Sink Hole Mine in 1940, including the location of Clingman's shaft (from Olsen 1944:Plate 5). [not available – oversize see Olsen, 1944)]



FIGURE 4 Drawings of prehistoric mining implements (one-fourth actual size) recovered from a deep pit near upper end of the Sink Hole Mine (from Holmes 1919:Figure 115).



FIGURE 5 The vicinity of the Sink Hole Mine in 1936 (view to south). The mine is to the right (not in picture). Photograph by Joffre L. Coe. Courtesy of the Research Laboratories of Archaeology.



FIGURE 6 View in 1936 of “ancient” workings at the Sink Hole Mine. Photograph by Joffre L. Coe. Courtesy of the Research Laboratories of Archaeology.



FIGURE 7 Stone mining implements recovered from the Sink Hole Mine and curated by the Smithsonian Institution.

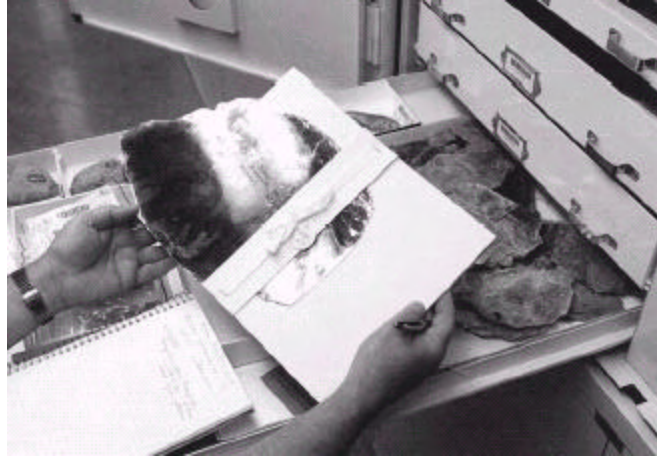


FIGURE 8 Green sheet mica mined by prehistoric Native Americans and collected by I. G. Heap from one of his mica mines in the Bakersville area of Mitchell County. Curated by the Smithsonian Institution.

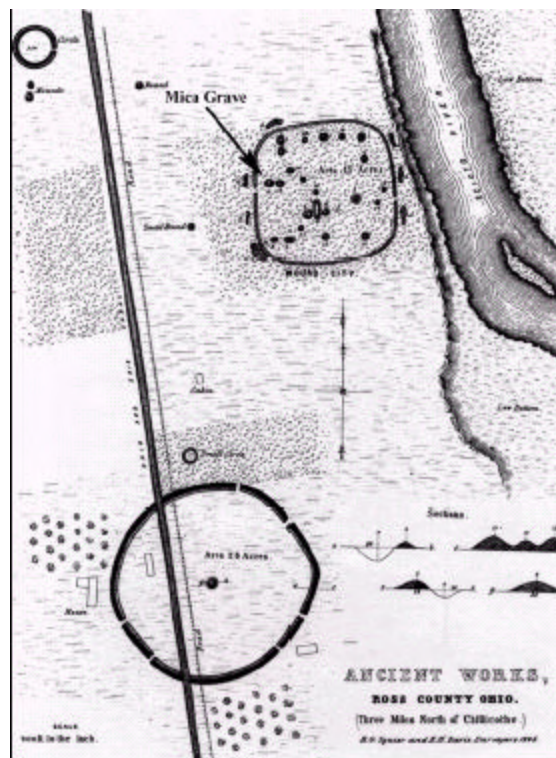


FIGURE 9 Map of the earthworks at Mound City, Chillicothe, Ohio, showing the location of the Mica Grave (from Squire and Davis 1848:Plate 19, label added).



FIGURE 10 View of the Seip Mound, Ross County, Ohio.

PETROGENESIS OF A SMALL SPRUCE PINE PEGMATITE: A MODEL FOR PETROGENESIS OF SPRUCE PINE GRANITOIDS

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ABSTRACT

Granitic rocks in the Spruce Pine Mining District consist of small plutons and numerous pegmatite bodies. Mining of the granitoid rocks produces feldspar, muscovite and quartz for various industrial applications. The Spruce Pine pegmatites are classified muscovite pegmatites. A small pegmatite (LUF1) provides a good model for crystallization of Spruce Pine granitic rocks. The LUF1 pegmatite is a small (about 1 m across) tabular body within the granite pluton just north of Minpro in the Spruce Pine District of North Carolina. The small dike was mapped and sampled in 1978, prior to its removal by the active mining operation. Feldspar and quartz proportions in the LUF1 pegmatite indicate a granodiorite bulk composition, similar to other estimates of the bulk composition of Spruce Pine granitic rocks. The dike is weakly zoned with a quartz core and a coarsening of graphic feldspar-quartz intergrowths toward the core. Muscovite and garnet are accessory phases in the pegmatite. Compositions of the LUF1 feldspar, muscovite, and garnet are similar to compositions in other Spruce Pine granitoids. Feldspar geothermometry combined with experimentally determined melting relations on Spruce Pine granitic rocks (taken from the literature) indicate a high pressure (8-12 kilobars; equivalent to a depth of 25-40 km) for the crystallization of the Spruce Pine magmas near the end of the peak regional metamorphic event. Post-magmatic cooling and recrystallization of the Spruce Pine granitic rocks went on for over 100 Ma. During this slow cooling, the granitic rocks were recrystallized to a wide-spread mortar structure of coarser-grained feldspars, quartz, muscovite, and garnet included in a finer-grained, recrystallized matrix. Local, hydrothermal alteration also accompanied the slow cooling of the granitic rocks.

INTRODUCTION

Granitic rocks of the Spruce Pine plutonic suite intrude schists and gneisses of the Ash Formation in the Blue Ridge of western North Carolina. The granitic rocks form dikes, sills and, in the vicinity of the town of Spruce Pine, small plutons. Contacts between the granitic rocks and the country rocks are sharp and generally parallel the regional foliation. However, locally Spruce Pine intrusions cross cut the dominant regional foliation and early folds (Butler, 1973).

Granitic and metamorphic rocks of the Spruce Pine area are part of the Spruce Pine thrust sheet, the structurally highest thrust plate in this part of the Blue Ridge. Ash Formation schists and gneisses preserve a polyphase metamorphic history (Figure 1) in mineral assemblages and structures (Butler, 1973, 1991; Abbott and Raymond, 1984; Adams et al., 1995). Peak metamorphism was assumed to be middle to upper amphibolite facies (Butler, 1973; Abbott and Raymond, 1984), but detailed mapping in the Spruce Pine thrust sheet revealed an earlier eclogite facies metamorphic event locally preserved near the base of the thrust sheet (Adams et al., 1995; Adams and Trupe, 1997). The earliest age determination on the Spruce Pine pegmatites was done on uraninite and yielded an age of 440 Ma (Aldrich et al., 1958) (Figure 1). Warner (this volume) shows the complex mineralogy of the uranium oxide minerals in the Spruce Pine pegmatites and this complexity makes the early U-Pb dates on uraninite questionable. Whole rock Rb-Sr ages for two Spruce Pine pegmatites are 404 and 392 Ma (Kish, 1983, 1989) while Johnson (et al., 2001) report a U-Pb zircon age of 377 Ma for a Spruce Pine pluton. Spruce Pine magmas were intruded near the end of the peak metamorphism (middle to upper amphibolite facies, dates on garnet and hornblende at 379-472 Ma, Goldberg and Dallmeyer, 1997) (Figure 1).

Spruce Pine granitic rocks are referred to as white rock or alaskite based on their low mafic mineral content. Spruce Pine granitic rocks contain more plagioclase than K-feldspar and lesser amounts of quartz and are best called granodiorite or quartz monzonite, depending on the classification used. Common accessory minerals include white mica (muscovite), biotite, and garnet along with minor amounts of epidote, apatite, zircon, and various U minerals (see Warner this volume). The granitic rocks are peraluminous, S-type granitic rocks.

Spruce Pine Granitoid Rocks

Granitic rocks of the Spruce Pine plutonic suite are coarse-grained, light-colored white mica granite and granodiorite that contain more plagioclase than K-feldspar. Common accessory minerals include garnet and epidote and, less commonly, biotite. Less common are rare U-oxide minerals (see Warner, this volume), beryl (including the green variety, emerald) and apatite. Spruce pine granitic rocks are characterized by larger grains of quartz, feldspar, white mica and garnet surrounded by a thin fine-grained matrix of these same phases resulting in a mortar structure. The fine-grained matrix is often just a few grains wide, but is common around many of the larger grains. Some feldspar and mica grains show evidence of deformation (bent and broken twin and cleavage planes). Large quartz grains have undulose extinction. Variations in grain size produces a foliation in some of the granitic rocks that is roughly parallel to the regional foliation in the country rocks (London, 2008).

Mining of feldspar and mica from Spruce Pine granitic rocks started over 100 years ago and continues today (Olson, 1944; Brobst, 1962; Lesure, 1968). Native Americans

exploited Spruce Pine minerals. White mica from archaeological sites in the midwest is attributed to the Spruce Pine deposits. Historically, mining activity was concentrated in the pegmatitic rocks that are common in the Spruce Pine Mining District. The very coarse grain size (cms to 10's of cms) of some feldspar and mica allowed for hand separation of these phases. The need for mica during World War II focused attention on the mica-bearing pegmatites in the United States. Hundreds of mica mines operated in the Spruce Pine District during WWII (Lesure, 1968). The search for mica prompted an intensive geologic mapping program in the Spruce Pine District by the U.S. Geological Survey (USGS) aimed at increasing the production of mica for the war effort. Dick Jahns, a pioneer in the modern studies of pegmatites, headed the USGS effort in the Spruce Pine District for nearly two years. The author was fortunate to spend several days visiting Spruce Pine pegmatites with Dick during this study (1978) and his guidance and experience was invaluable. Development of flotation techniques for separation of feldspars, mica and quartz in the 1940's resulted in a shift in mining from pegmatitic granitoids to open pit mining of the coarse-grained granitic plutons, a practice that continues today.

Quartz was initially a waste product at Spruce Pine. The high purity and coarse grain size of quartz from Spruce Pine allowed for some specialized uses, such as production of high-purity glass used for the 200 inch mirror for Mt. Palomar telescope (Olson, 1944), but most of the quartz was not used. The white sand traps at the Augusta National Golf Course in Georgia were filled with quartz sand from Spruce Pine. Ultra high purity quartz from Spruce Pine is currently used in the production of silica glass used in the processing of silicon chips for the electronics industry.

Spruce Pine Pegmatites

Granitic rocks of the Spruce Pine plutonic suite are typically coarse-grained. Pegmatitic granitic rocks at Spruce Pine are very coarse-grained. Jahns (1955) applied the term pegmatite to rocks that are “at least in part very coarse grained ... (with) extreme textural variations, especially in grain size”. Using this definition, there are two types of pegmatite bodies in the Spruce Pine District based on the nature of the pegmatite - host rock contact. Dikes, lenses and sills of pegmatitic granitoid rock that have sharp contacts with the metamorphic rock intrude parallel to the foliation of the host rock. Dikes vary in width from 10's of cm to 10's of m. Individual dikes can be traced for 3 km along strike (Olson, 1944). Irregular pegmatitic pods and dikes with gradational contacts to the host granitic plutons represent the second type of Spruce Pine pegmatite. Dimensions (diameter or thickness) vary from one to 100's of meters. Pegmatitic and coarse-grained granitoid rocks have very similar chemical and mineralogic compositions suggesting a genetic link (Olson, 1944).

Most of the Spruce Pine pegmatites are unzoned (Lesure, 1968). Those with zoning have a fine-grained margin of quartz, plagioclase, and K-feldspar; an intermediate zone of

these same minerals with variable (mm's to m's) grain size, and a massive quartz core. When present, zoning is equally well displayed in the large and small pegmatites at Spruce Pine. Fine-grained (aplitic) equigranular granitic rock is a rare part of the Spruce Pine plutonic suite. Dikes of aplitic granite cross cut pegmatitic rocks and form irregular elongate masses that parallel some of the pegmatite dikes. Mineral layering, so called line rock occurs in some of the aplitic granite. Dick Jahns suggested, based on his years of mapping in the Spruce Pine District, that small Spruce Pine pegmatites should be a good model for crystallization of the Spruce Pine magmas (Jahns, personal communication, 1978).

Textures in Spruce Pine pegmatites are dominated by magmatic features. The large grain size and skeletal and dendritic crystal forms pictured in Maurice (1940) and Raymond (1995, pp. 196, 225, 226, 232) and discussed by Swanson (1978a, 1978b, and Fenn, 1986) are all features of magmatic crystallization (London, 2008). Pegmatites also contain, post-magmatic features, such as the exsolution and deformation in the feldspar, related to post-magmatic recrystallization.

The purpose of this study is to determine the crystallization history of a Spruce Pine pegmatite and to use this history to model crystallization of Spruce Pine magmas. Despite a long mining history and a rich legacy of geologic information, relatively little is known about the Spruce Pine pegmatites (London, 2008). Spruce Pine pegmatites are mica pegmatites (Černý, 1991) and relatively little is known about this type of pegmatite. This study adds to the general understanding of crystallization processes in mica pegmatites, and specifically to crystallization of Spruce Pine magmas.

METHODS

A small pegmatite (LUF1) in the old Lawson United Feldspar quarry was selected for study in 1978. The quarry is still active today (KT Feldspar) and the LUF1 pegmatite and enclosing granite is long gone. The quarry is about 1.5 km north of the community of Minpro in the Spruce Pine District (Figure 2). Feldspar is produced from a very coarse grained garnet muscovite granitoid pluton that is typical of the Spruce Pine intrusions. The quarry is located near the margin of the pluton and the granitoid rocks are foliated parallel to the contacts with the country rock. A number of pegmatitic and aplitic dikes and elongate pods oriented subparallel to the foliation of the host granitoid rock occur in the quarry. Contacts between the pegmatitic and aplitic rocks and the host granitoid are typically gradational, suggesting the granite was still partially molten when pegmatitic and aplitic rocks crystallized. Some of the pegmatites show crude zoning with a core of quartz (\pm K-feldspar).

The LUF1 dike was exposed on a steep working face of the open pit quarry, about 5 meters above the quarry floor. Access to the pegmatite was provided by debris at the base of the quarry wall. The pegmatite had a sharp contact with the host granite and an

irregular quartz core (Figure 3). Width of the dike was variable, but averaged about 1 m. K-feldspar from the dike is light pink, plagioclase is white, quartz is dark gray, muscovite is greenish-gray, garnet is dark red, and epidote is dark green. Individual feldspar crystals exceed 40 cm in length. Crystals of muscovite and graphic intergrowths of K-feldspar and quartz were distributed around the quartz core (Figure 3). Graphic textures were not found in feldspar immediately adjacent to the quartz core (Figure 3). Spacing between the rods of the quartz in the graphic texture increased toward the quartz core until the quartz formed individual grains not intergrown with the feldspar to form the graphic texture.

Modal Analysis

Modal analysis of the pegmatite was done using photographs of the pegmatite and a 5 cm grid. Mineralogy of each grid point was checked by taking the photographs and grid to the outcrop. Over 1500 points were analyzed representing an area of almost 4 square meters. The technique worked well for the coarser grained feldspars, muscovite, and quartz core. The modal analysis could not distinguish fine-grained minerals (garnet, quartz in graphic intergrowths) and underestimated these phases in the pegmatite. Modal composition of the pegmatite was (in volume percent): 57.8% plagioclase, 33.6 % K-feldspar, 7.5 % quartz, and 1.1 % muscovite. These are reasonable estimates of the relative proportions of feldspar and muscovite, but underestimate the fine-grained quartz and garnet. The coarse scale of the modal analysis could easily have underestimated the fine-grained quartz content by a factor of two or three. The pegmatite is a granite (verging on granodiorite) based on the proportion of feldspars (Streckeisen, 1976). Several chemical analyses of Spruce Pine pegmatites are available in the literature (Olson, 1944; Parker, 1952; Burnham, 1967), all in the granite to granodiorite range.

Modal analysis of individual, coarse-grained feldspar crystals was done on thin sections from several samples. Exsolved and host feldspars were determined using a point spacing of 0.3 mm. Modal proportions of feldspars, combined with the composition of the feldspar phases were combined to estimate the pre-exsolution composition of the feldspar (Table 1).

Samples

Large hand samples were collected from various positions within the pegmatite and from the immediately adjacent granitic rocks during 1978. Mining activity within the quarry subsequently removed the pegmatite and host granitic rock. Many of the hand samples contained portions of very coarse-grained feldspar crystals, but an effort was made to include other mineral phases in each sample. Polished thin sections were prepared when the grain size was small enough to provide a representative sample on a thin section scale. Very coarse-grained samples were sub-sampled by hand picking and microprobe analyses were done on grain mounts.

Microprobe Analyses

Electron microprobe analyses of some feldspars were done by W. C. Luth at Sandia National Laboratory using a ARL electron microprobe. Other microprobe analyses were done at the Department of Geology at the University of Georgia using a JEOL-8600 Superprobe. Machine conditions were: accelerating voltage of 15kV and a sample current of 5 nA. Beam diameter varied with mineral phase analyzed: 10 μm for mica and feldspar and 2 μm for garnet. Synthetic and natural minerals were used for standards. Data were reduced using standard techniques.

X-Ray Diffraction

X-ray diffraction studies of K-feldspar of the LUF1 pegmatite was done at Stanford University using a Phillips X-ray diffractometer. Samples were powdered in a corundum mortar. The feldspar powder was mixed with a internal standard (annealed CaF_2) and placed on a glass slide. A solution of acetone and glue was mixed with the powder and the slurry was spread on the glass slide. X-ray procedures followed the method of Wright (1968).

MINERALOGY OF THE LUF1 PEGMATITE

Feldspars and quartz grains in the LUF1 pegmatite are variable in size, ranging from less than a mm to 10s of cms. Muscovite forms subhedral to euhedral crystals ranging from less than a mm to 10 cm in diameter. Anhedral to euhedral garnet crystals up to 5 cm in diameter occur in LUF1, but most garnet is less than one cm in diameter. The margins of some of the larger feldspar and quartz grains are surrounded by a narrow zone of fine-grained recrystallized quartz, feldspar, and muscovite that forms a mortar structure. Bent and broken feldspar twin planes and undulose extinction in quartz also support post-magmatic deformation in the LUF1 pegmatite.

Feldspar

Plagioclase is more abundant than K-feldspar in the LUF1 pegmatite (Figure 3). Albite twinning is well developed in the plagioclase and is often bent and broken. The plagioclase is antiperthitic with stringers of K-feldspar included in the plagioclase. Much of the plagioclase contains graphic quartz intergrowths (Figure 3). Plagioclase grains are unzoned and there is no compositional variation with position within the LUF1 pegmatite. Average plagioclase composition is $\text{Ab}_{91}\text{Or}_1\text{An}_8$. Exsolved K-feldspar in the plagioclase is also uniform at $\text{Ab}_{50}\text{Or}_{95}\text{An}_0$ (Table 1).

K-feldspar forms large, slightly pink crystals in the LUF1 pegmatite (Figure 3). Graphic intergrowths of quartz and K-feldspar are common in the pegmatite, especially in feldspar crystals away from the quartz core (Figure 3). Most of the K-feldspar is perthitic

with albite ($\text{Ab}_{98}\text{Or}_1\text{An}_1$) exsolution in a K-feldspar ($\text{Ab}_6\text{Or}_{94}\text{An}_0$) host (Table 1). Compositions of the K-feldspar do not vary within the LUF pegmatite. X-ray analysis of the K-feldspar following the method of Wright (1968) shows the structural state of the K-feldspar is near maximum microcline throughout the pegmatite.

Modal proportions of exsolved feldspar phases, combined with composition of the feldspars yield pre-exsolution estimates of magmatic feldspar compositions (Table 1).

Estimates of pre-exsolution K-feldspar compositions range from Ab_9 to Ab_{16} . Estimates of pre-exsolution plagioclase compositions are uniform at Ab_{91} (Table 1).

Muscovite

Muscovite is a widespread, minor component in the LUF1 pegmatite (Figure 3). Grain size ranges from 0.1 to 40 mm, most of the mica is medium to very coarse-grained. Most of the larger mica grains are subhedral and is often terminated by finer grained skeletal mica

The white mica in Spruce Pine granitoid rocks is referred to as muscovite, but it contains 5-6 weight percent Fe and about one percent Mg (Table 2). Minor amounts of Ti and Na are also found in the “muscovite”. Muscovite compositions are uniform (Figure 4) within the LUF1 pegmatite and generally similar to the muscovite in the host granite. Some of the fine grained muscovite in the Spruce Pine rocks is very low in Fe, approaching ideal muscovite in composition (Figure 4) and some of the fine-grained muscovite in LUF is probably near ideal muscovite. The LUF1 muscovite plots in or near the field for igneous white mica in granitic rocks (Figure 5).

Garnet

Garnet is more abundant in the inner parts of the LUF1 pegmatite (Figure 3). Subhedral to euhedral deep red garnet crystals range from 0.1 to 20 mm in diameter. Most of the garnet is clear and free of inclusions, but a few grains have turbid cores.

The garnet is essentially an almandine - spessertine solid solution with only 8-12 mole percent pyrope + grossular components (Figure 6, Table 3). The limited range of garnet compositions in the LUF1 pegmatite mimics the compositional range of garnet in other Spruce Pine intrusions (Figure 6). Interdiffusion of Fe-Mn in garnet is slow relative to diffusion of major components in feldspar or mica (Freer, 1981). Thus garnet is the most likely phase in LUF1 to preserve magmatic compositions.

Epidote

Euhedral to anhedral grains of epidote are found in the LUF1 pegmatite. The anhedral grains are fine-grained and occur with fine-grained white mica in the matrix mortar

structure. Euhedral epidote is fine to medium-grained and is included in coarse-grained muscovite. Experiments show epidote is a stable phase in granitic magmas at high pressures (e.g., Naney, 1983). The occurrence of epidote in the Spruce Pine granite suggests a high pressure for crystallization of the Spruce Pine magmas.

DISCUSSION

The LUF1 pegmatite provides a reasonable model for crystallization and recrystallization of the Spruce Pine granitic rocks. The mineralogy and texture of the LUF1 pegmatite is identical to that of other Spruce Pine granitic rocks and pegmatites. Many early workers suggested a similar origin for the granitic rocks and pegmatites of the Spruce Pine District (Olson, 1944; Brobst, 1962). However, the most compelling argument to use the LUF crystallization model for the Spruce Pine system is the garnet compositional data. Garnet is the most refractory phase in the Spruce Pine granitic rocks and shows a similar range of compositional variation in the LUF1 pegmatite as in a suite of Spruce Pine granitic rocks (Figure 6). Compositions of muscovite and feldspar from LUF1 are also similar to the compositional variation of these phases in the Spruce Pine plutonic suite, but the range in the LUF pegmatite is more restricted than the range in the Spruce Pine plutonic suite (Swanson, 1998). It appears that the recommendation of Jahns (personal communication, 1978) is correct, small Spruce Pine pegmatites are good models for crystallization in the larger Spruce Pine system.

Compositions of coexisting feldspars allow an estimate of temperature of crystallization. Following the method of Whitney and Störmér (1977), P-T paths for crystallization of coexisting feldspars are calculated based on the structural state of the K-feldspar. For most granitic rocks the authors suggest (Whitney and Störmér, 1977) K-feldspar probably crystallizes from the magma as orthoclase and they use a combination of sanidine (Störmér, 1975) and microcline models for feldspar geothermometry. This approach was adopted in the current study.

P-T paths for the magmatic crystallization of LUF1 feldspars were calculated using the estimates of pre-exsolution compositions of feldspars in Table 1. Results of those calculations are shown on Figure 7. The feldspar P-T models intersect the experimentally determined solidus for Spruce Pine granitoids (Vaughn, 1963; Fenn, 1986, and unpublished) between 8 and 12 kilobars at a temperature of 650-700 degrees C (Figure 7). These pressure estimates translate to a depth of 25 to 40 km, suggesting a mid- to lower crust site for crystallization of the Spruce Pine magmas. These conditions correspond to the estimates of regional metamorphism in the Spruce Pine thrust sheet (Adams and Trupee, 1997) and are near the upper limits of regional metamorphism estimated by Abbott and Raymond (1984) and McSween (et al., 1987) for the Spruce Pine thrust sheet northeast of the Spruce Pine area. Goldberg and Dallmeyer (1997) reported Sm-Nd and Rb-Sr ages for hornblende from amphibolites with ages of 379-472 Ma and this age is consistent with the 377 Ma age for solidification of the Spruce Pine magma (Johnson et al., 2001).

Feldspar geotherms (Figure 7) indicate a very high pressure for the liquidus of the Spruce Pine magmas. Errors on the intersections of the feldspar geotherms and the liquidus are high due to the shallow intersection of these lines (Figure 7), but the pressure of the intersection is clearly high on the order of $12 \pm$ kilobars. High pressures (13-17 kilobars) and moderate temperatures (625-790 degrees C) were attributed to the formation of eclogite at the base of the Spruce Pine thrust sheet (Adams and Trupe, 1997). These conditions are above the liquidus of the Spruce Pine magmas (Figure 7) suggesting that the thrusting and accompanying thickening initiated melting to form the Spruce Pine magmas.

Muscovite and garnet compositions in the LUF pegmatite are similar to compositions of these phases in other Spruce Pine granitic rocks (Figures 5 and 6) and probably represent magmatic compositions. Euhedral epidote included in large crystals of Fe-bearing muscovite may also represent a magmatic phase. Experiments at 8 kilobars by Naney (1983) showed epidote is a stable magmatic phase in granodioritic compositions, but epidote was not a magmatic phase at 2 kilobars. The apparent stability of epidote in the LUF magmas is consistent with their crystallization at high pressure.

Evidence for subsolidus, post-magmatic recrystallization is widespread in the Spruce Pine granitic rocks. The common feldspar exsolution forms during subsolidus cooling. The fine-grained, low-Fe muscovite probably reflects crystallization from either a late stage magmatic or post-magmatic hydrothermal fluid. Open-space veins of pumpellyite-zoisite reported from a Spruce Pine pegmatite (Wood and Abbott, 1995) crystallized a hydrothermal fluid at subsolidus temperatures.

Geochronology of Spruce Pine granitic rocks also reflects subsolidus cooling. Whole rock and muscovite Rb-Sr and zircon U-Pb ages (Figure 1) reflect magmatic crystallization ages. Muscovite K-Ar ages are lower (Figure 1), similar to muscovite ages in the country rocks, and reflect cooling ages. The K-Ar ages reflect about 100 Ma of cooling from magmatic conditions to the 350 degrees C blocking temperature for Ar in muscovite. This long cooling period is consistent with a tectonic setting of thickened continental crust related to thrusting in the Blue Ridge.

Butler (1973) indicated a third deformation-metamorphic event in the Spruce Pine area at about 250 Ma (Figure 1) This event is not reflected in any of the geochronology either in the granitic rocks or the country rocks (Figure 1). The alteration phases (low Fe muscovite, pumpellyite-zoisite) may be related to this later event.

CONCLUSIONS

The LUF1 pegmatite and, by analogy, the Spruce Pine magmas, crystallized at high pressure, near the end of the peak regional metamorphic event. Mineral assemblages and compositions of the LUF1 pegmatite mimic those of other Spruce Pine granitic rocks.

The weak zoning, presence of a quartz core, and the gradual coarsening of the graphic feldspar-quartz intergrowths toward the core of the LUF1 pegmatite are features of many Spruce Pine pegmatites (Olson, 1944; Lesure, 1968). Post-magmatic deformation; deformed quartz and feldspar, and the mortar structure found in the LUF1 pegmatite are common in other Spruce Pine granitic rocks. Overall, the LUF1 system appears to be a good model for the Spruce Pine granitic rocks and pegmatites.

Muscovite class pegmatites, such as LUF1 and other Spruce Pine pegmatites, crystallize at moderate to high pressure from magmas generated by anatectic melting (Černý, 1991; London, 2008). Cooling of these deep-seated mica pegmatites is slow, resulting in a range of cooling ages and post-magmatic deformation and recrystallization.

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The late Dick Jahns was a friend of Spruce Pine pegmatites and his guidance in the early stages of this study is acknowledged. Alex Glover was a valuable guide to many of the Spruce Pine pegmatites during later stages of this study. Chris Fleisher aided with the electron microprobe analyses at the University of Georgia and W. C. Luth did the feldspar analyses at Sandia National Laboratory. The Geology Department of the University of Georgia and the Geology Department at Appalachian State University supported this study. Brian Veal worked with the author on studies of Spruce Pine pegmatites and was a valuable colleague.

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FIGURE CAPTIONS

Figure 1. Geochronology of the Spruce Pine area. The histogram is based on work by Goldberg and Dallmeyer (1997) on amphibolite, mica schist and gneiss; the country rocks for the Spruce Pine plutonic suite. Garnet ages are by Nd-Sm, hornblende ages are by Rb-Sr and Ar-Ar, muscovite dates are by Ar-Ar. Ages of the Spruce Pine granitic rocks are shown by arrows over the top of the histogram and include U-Pb ages on uraninite (Aldrich et al., 1958) and zircon (Johnson et al., 2001), Rb-Sr whole rock isochrons on pegmatites (Kish, 1983, 1989), and K-Ar dates on muscovite as compiled by Lesure (1968). Below the histogram is the model for deformation (F1, F2, F3) and metamorphism (M1, M2, M3) in the Spruce Pine area as proposed by Butler (1973).

Figure 2. General geology (modified from Brobst, 1962) of the Minpro pluton and the location of the LUF1 pegmatite (Luf).

Figure 3. Geologic map of a portion of the LUF1 pegmatite.

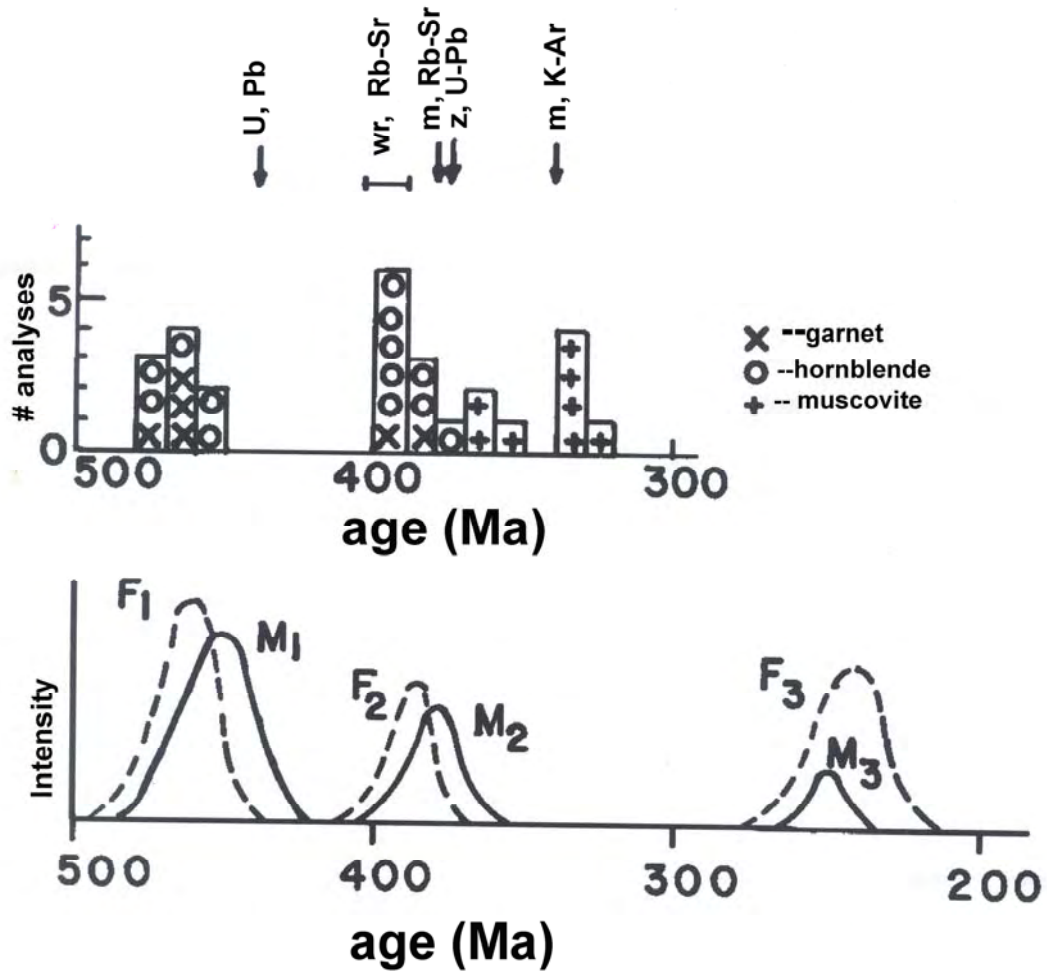
Figure 4. Composition of muscovite from the LUF1 pegmatite compared to muscovite from other Spruce Pine pegmatites.

Figure 5. Compositions of muscovite from the LUF1 pegmatite and other Spruce Pine granitic rocks compared to the field for igneous white mica from granitic rocks (Miller et al., 1981).

Figure 6. Composition of garnet from the LUF1 pegmatite compared to garnet from other Spruce Pine granitic rocks. The other Spruce Pine granitic rocks include samples from Deer Park pegmatite (DP), Crabtree Creek Falls pegmatite (CTCF), McKinney Mine pegmatite (MP), Sink Hole pegmatite (SH), and Day Book pegmatite (DB).

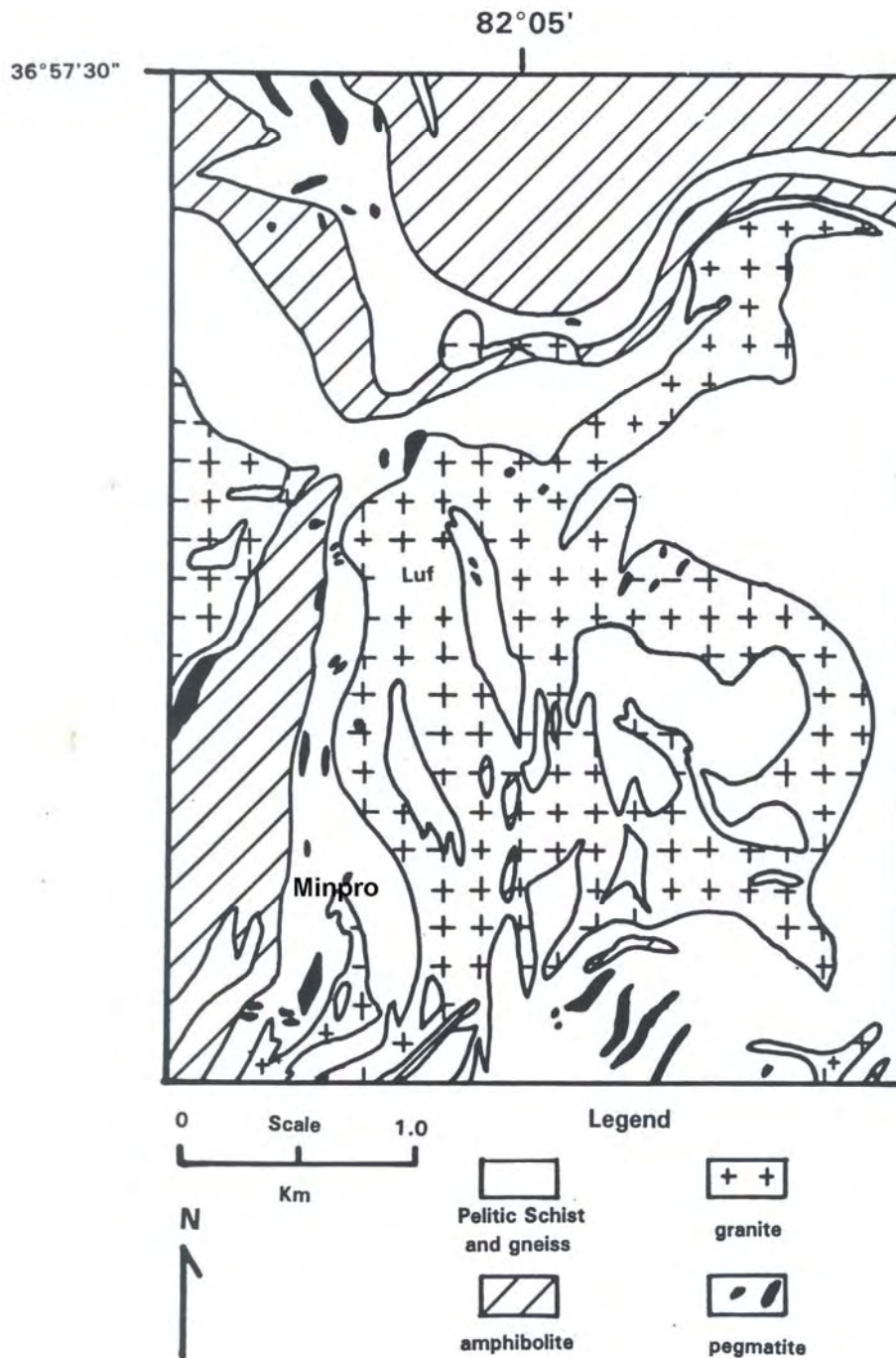
Figure 7. Melting relations of the Spruce Pine granite taken from Vaughn (1963) and Fenn (unpublished data). Cooling paths for LUF feldspars (LUF Fs) are based on estimates of pre-exsolution feldspars following the methods of Whitney and Stormer (1977). See text for details.

Age and Deformation at Spruce Pine

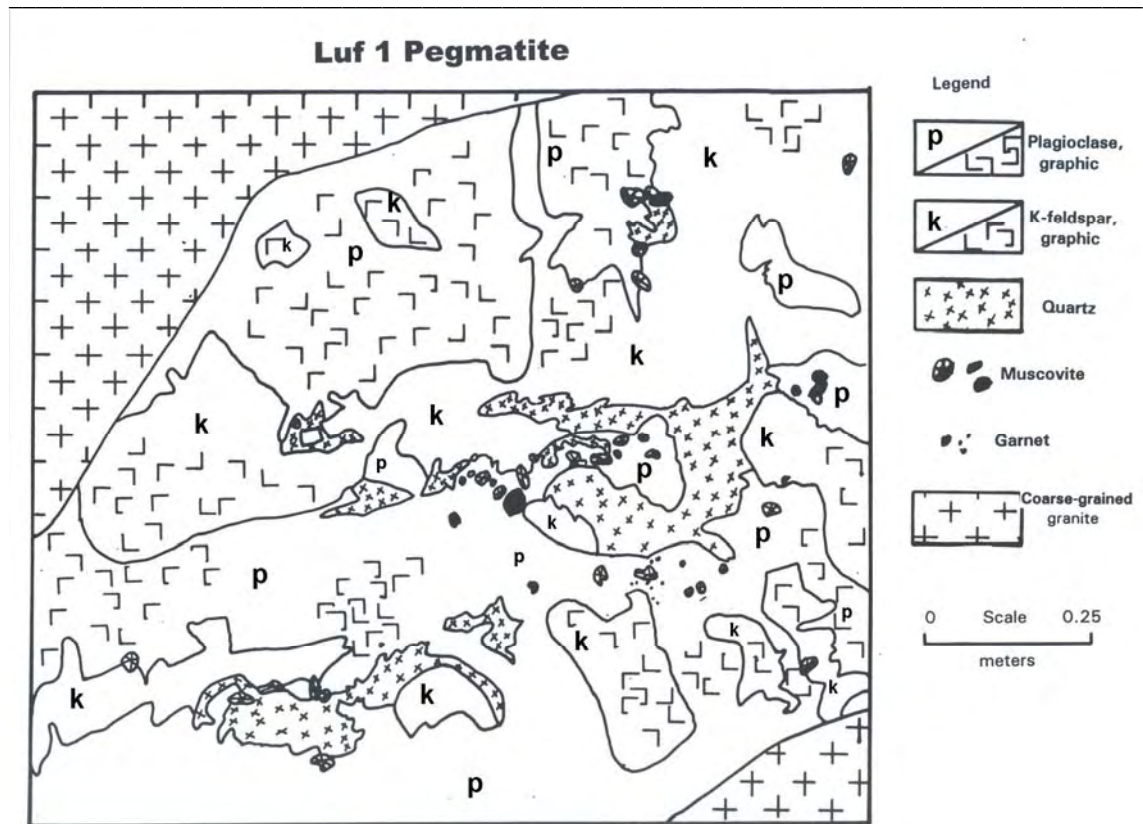


Swanson – Figure 1.

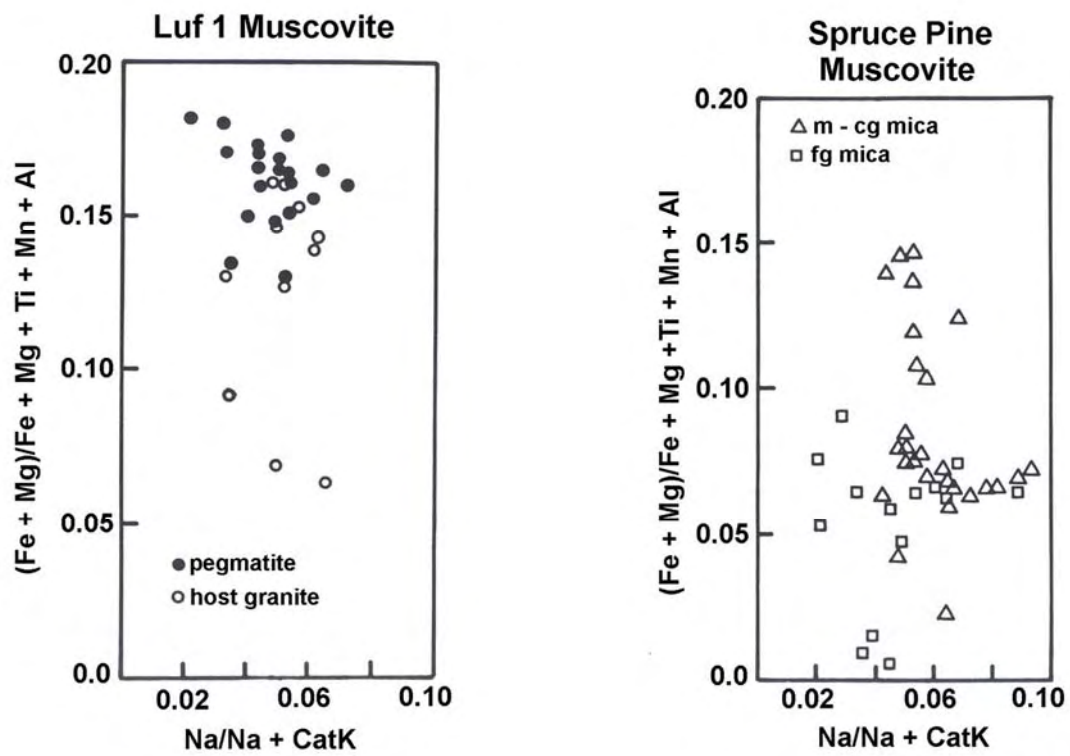
Location of the Luf Pegmatite



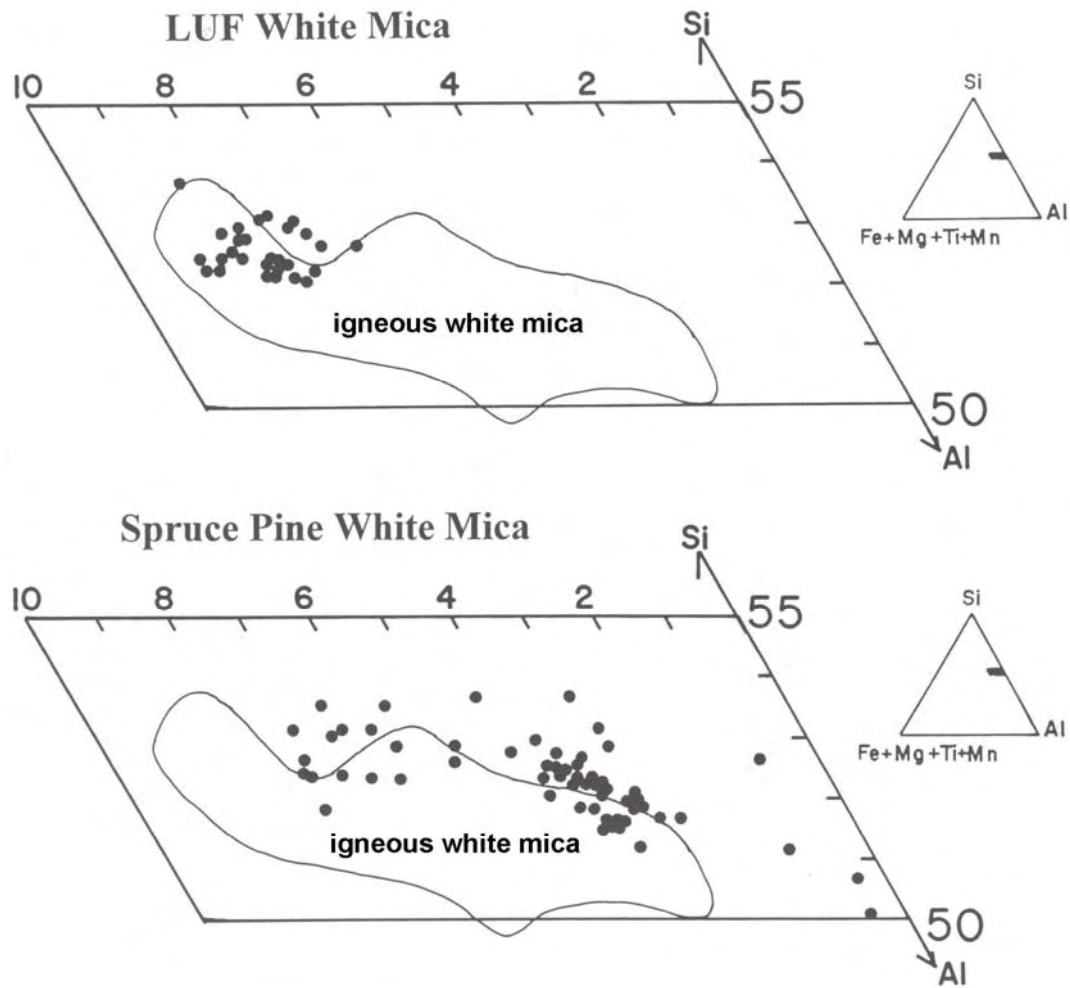
Swanson – Figure 2.



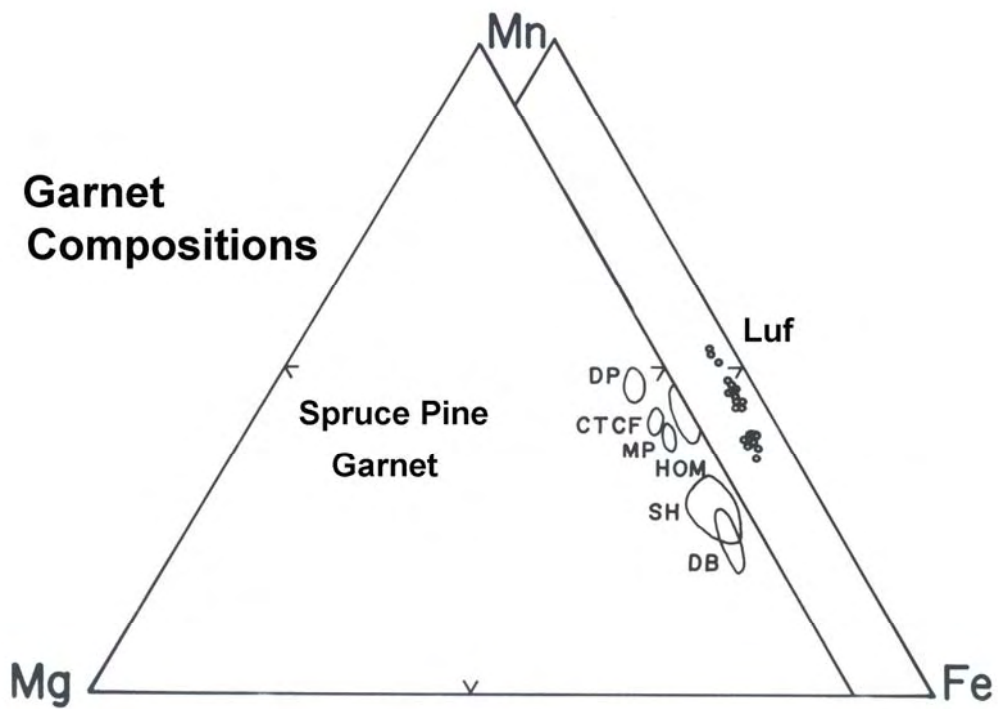
Swanson – Figure 3.



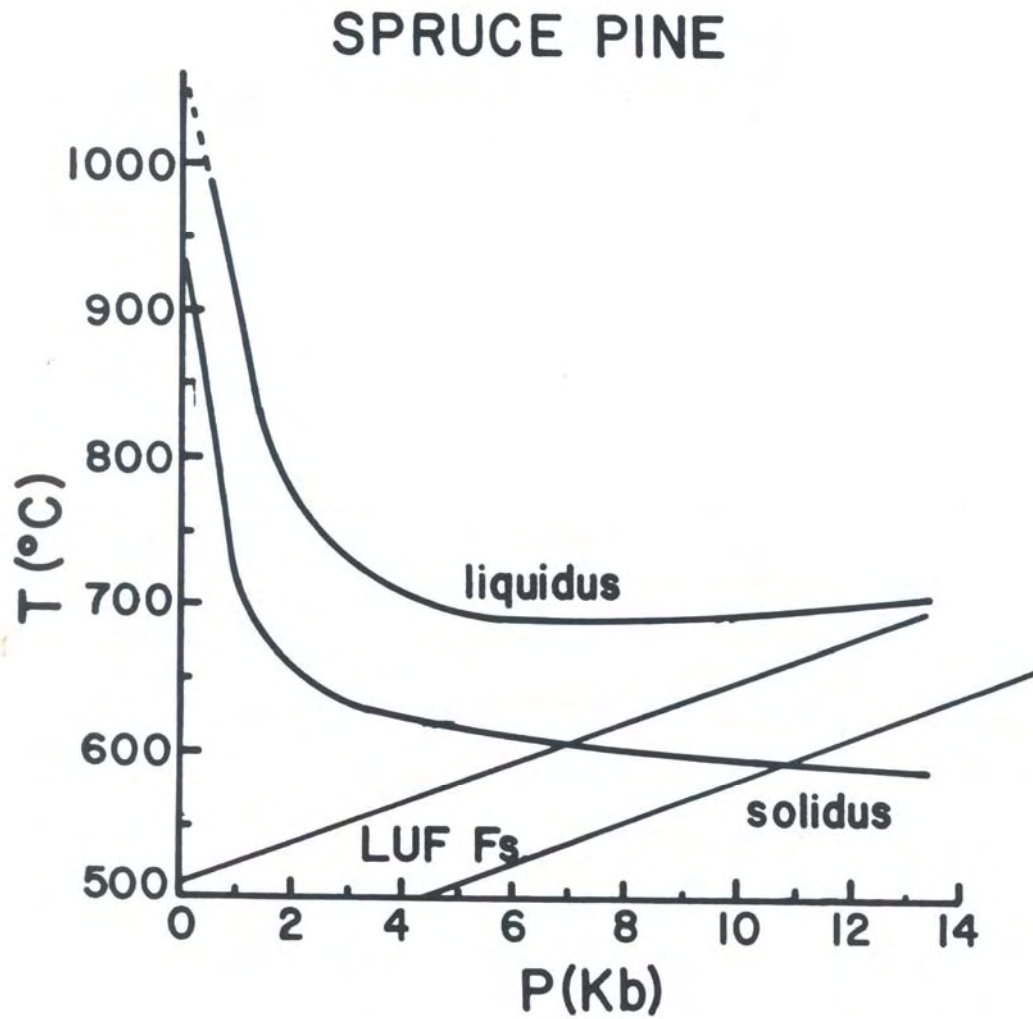
Swanson – Figure 4.



Swanson – Figure 5.



Swanson – Figure 6.



Swanson – Figure 7.

Table 1. Modal and chemical composition of coexisting plagioclase and K-feldspar in samples of LUF1 pegmatite.

Plagioclase Crystals

sample	plagioclase host		exsolved K-feldspar		pre-exsolution bulk composition
	modal %	mole % Ab	modal %	mole % Ab	mole % Ab
2	98.7	90.2	1.3	4.6	89.1
8	99.0	90.2	1.0	4.6	89.2
10	96.6	90.7	3.4	4.6	87.8
16A	100	91.3	0	nd	91.3

nd = not determined

K-Feldspar Crystals

sample #	K-feldspar host		exsolved plagioclase		pre-exsolution bulk composition
	modal %	mole % Ab	modal %	mole % Ab	mole % Ab
2	98.0	7.1	2.0	98.1	9.0
8	89.8	6.0	10.2	98.2	15.4
10	89.1	6.0	10.9	98.2	16.0
16A	95.3	5.9	4.7	98.1	10.2

Table 2. Representative white mica compositions from the LUF1 pegmatite.

sample number and texture*										
	1 cg*	1 fg	7 cg	7 fg	10 cg	12cg	17 cg	17 mg	17 fg	18 cg
SiO ₂	45.47	47.93	45.40	46.14	45.78	45.75	45.66	45.85	46.66	46.06
Al ₂ O ₃	29.77	28.79	29.15	27.59	28.61	28.83	30.06	29.77	30.28	29.74
TiO ₂	0.42	0.01	0.16	0.12	0.18	0.15	0.12	0.13	0.41	0.09
FeOt	5.93	3.96	6.08	6.33	6.05	6.53	5.86	6.20	4.76	6.14
MgO	0.98	1.19	1.01	1.27	1.08	1.14	1.04	1.07	1.24	1.08
MnO	0.05	0.07	0.05	0.03	0.07	0.12	0.10	0.06	0.09	0.05
CaO	0.00	0.11	0.00	0.00	0.00	0.00	0.01	0.00	0.03	0.01
Na ₂ O	0.35	0.31	0.33	0.24	0.40	0.32	0.43	0.39	0.34	0.37
K ₂ O	11.01	8.17	10.46	10.69	10.68	10.71	10.82	10.79	10.49	10.89
F	0.18	0.16	0.25	0.36	0.29	0.30	0.23	0.27	0.22	0.24
Total	93.86	90.70	92.89	92.77	93.16	93.85	94.32	94.53	94.53	94.67
Cations based on 11 oxygens										
Si	3.1740	3.3465	3.1969	3.2639	3.2208	3.2036	3.1686	3.1800	3.1990	3.1876
Al	2.4493	2.3691	2.4196	2.3002	2.3721	2.3791	2.4587	2.4331	2.4467	2.4258
Ti	0.0064	0.0006	0.0084	0.0065	0.0098	0.0078	0.0062	0.0065	0.0210	0.0049
Fe	0.3459	0.2312	0.3582	0.3744	0.3560	0.3823	0.3400	0.3594	0.2731	0.3551
Mg	0.1018	0.1237	0.1061	0.1338	0.1135	0.1188	0.1071	0.1105	0.1272	0.1117
Mn	0.0032	0.0042	0.0032	0.0017	0.0039	0.0069	0.0060	0.0034	0.0049	0.0030
Ca	0.0000	0.0080	0.0000	0.0000	0.0000	0.0000	0.0005	0.0000	0.0024	0.0010
Na	0.0474	0.0415	0.0446	0.0325	0.0550	0.0438	0.0575	0.0531	0.0457	0.0493
K	0.9802	0.7281	0.9395	0.9646	0.9587	0.9566	0.9581	0.9543	0.9179	0.9612
F	0.0395	0.0358	0.0558	0.0800	0.0608	0.0675	0.0488	0.0595	0.0484	0.0516

* fg = fine grained, mg = medium grained, cg = coarse grained

Table 3. Representative garnet compositions from the LUF1 pegmatite.

	Sample # and analysis location					
	7 core	7 rim	10 core	12 core	17 core	17 rim
SiO ₂	35.51	35.53	35.64	36.06	35.36	35.80
Al ₂ O ₃	19.83	19.70	20.05	20.79	19.45	20.42
TiO ₂	0.06	0.00	0.03	0.00	0.07	0.00
FeOt	17.37	24.22	19.54	23.45	22.34	22.90
MnO	20.66	15.96	19.04	15.72	15.68	15.58
MgO	0.58	0.81	0.68	0.93	0.97	0.98
CaO	3.01	2.16	2.79	1.97	2.40	2.37
Total	97.01	98.38	97.77	98.91	96.26	98.05
Cations based on 12 oxygens						
Si	2.9952	2.9775	2.9856	2.9778	3.0054	2.9805
Al	1.9709	1.9457	1.9799	2.0230	1.9484	2.0035
Ti	0.0036	0.0000	0.0019	0.0000	0.0044	0.0000
Fe	1.2253	1.6971	1.3685	1.1690	1.5878	1.5944
Mn	1.4758	1.1328	1.3510	1.0991	1.1285	1.0990
Mg	0.0726	0.1016	0.0844	0.1149	0.1226	0.1217
Ca	0.2720	0.1943	0.2508	0.1739	0.2184	0.2116

A NOTE ON URANIUM MINERALS FROM THE SPRUCE PINE AREA, NORTH CAROLINA

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INTRODUCTION

Uranium minerals are often found in granitic pegmatites, where they nearly always occur as minor constituents of insufficient quantity to be mined (Page, 1950). Their occurrence in this geologic setting is a consequence of the fact that uranium behaves as an incompatible element in magmatic systems. The size and charge of uranium ions make their substitution for major ions in common silicate minerals difficult, with the result that uranium is concentrated at the felsic (e.g., granitic) end of magmatic differentiation series (Rogers and Adams, 1969; Krauskopf and Bird, 1995). Thus, the mean uranium content of igneous rocks ranges from 0.8 ppm in mafic rocks to 4.0 ppm in granite (Rogers and Adams, 1969; Plant and others, 1999). The separation of a water-rich fluid phase both promotes the growth of exceptionally coarse crystals, characteristic of pegmatites, and further concentrates uranium, such that some pegmatites eventually crystallize one or more uranium-rich minerals.

The uranium minerals occurring in pegmatites include both primary (i.e., magmatic) minerals and various secondary minerals. Chief among the primary uranium minerals is the simple oxide, uraninite (UO₂). It typically is associated with muscovite-rich pegmatites (Page, 1950). Also important are uranium-bearing multiple oxide minerals (Fron del, 1958): these are principally niobate-tantalate minerals and often contain significant amounts of the rare earth elements (REE). Samarskite is the most common example, and may contain 10-20 weight percent UO₂. Other primary uranium-bearing minerals include the REE-phosphate, monazite, and silicate minerals such as zircon and allanite. The latter minerals, though more abundant in pegmatites, generally contain much less uranium (usually far below 1 weight percent UO₂). A wide variety of secondary minerals, of variable water content, are derived from the partial or complete alteration of uraninite and other primary uranium minerals. Gummite, uranophane, autunite and torbernite are but a few of the many secondary minerals that can be formed (Page, 1950; Fron del, 1958).

Pegmatites of the Spruce Pine mining district have long been known to host uraninite and related uranium minerals and constitute one of the principal occurrences of such minerals in the eastern United States (Ross and others, 1931). Allen (1877) reported chemical analyses of samarskite and hatchettolite (a niobate-tantalate mineral belonging to the

pyrochlore group) from Mitchell County, North Carolina. Kerr (1877) and Genth (1879) examined uranium minerals from the Flat Rock mine in Mitchell County and found them to consist of uraninite and a mixture of alteration products. Hidden (1881) noted the occurrence of uraninite and its alteration products at Flat Rock and two other mica mines in Mitchell County. An analysis of uraninite from the Flat Rock mine was included by Hillebrand (1891) in his general survey on the composition of uraninite. Sterrett (1923) noted four mines from the Spruce Pine area (Flat Rock; Deer Park; Deake; W. W. Wiseman) from which uranium minerals were found; with reference to the W. W. Wiseman mine, the uraninite alteration minerals pitchblende, gummite and uranophane were identified, and also rare-earth minerals (e.g., samarskite). The new mineral name clarkeite was proposed by Ross and others (1931) for a sodic uranyl oxide associated with uraninite, gummite and uranophane and originally found at Spruce Pine. These authors surmised that clarkeite formed during a late hydrothermal stage whereby alkali-bearing solutions caused its alteration from primary uraninite.

Maurice (1940) included uraninite and several of its alteration products (clarkeite, gummite, uranophane, autunite, and torbernite) plus samarskite and other less common niobate-tantalate minerals such as columbite, euxenite, fergusonite, hatchettolite, and microlite among the accessory minerals characteristic of Spruce Pine district pegmatites. Additional listings of the various uranium minerals known to occur in the Spruce Pine area were published by Parker (1952) and Brobst (1962), along with information on specific mines where they have been found. However, by far the most thorough compilation of uranium mineral localities in the Spruce Pine area was published by Lesure (1968) in his exhaustive compendium of mica deposits in the Blue Ridge of western North Carolina. Of more than 700 mica mines described from the Spruce Pine district, eight (a little over 1 percent of the mines) were noted as containing uraninite. Another dozen mines were indicated to host unspecified uranium minerals, while samarskite was noted to occur at eight mines. About half of the latter were stated to contain uraninite or uranium minerals as well, yielding a total of 25 mines at which uranium containing minerals have been identified.

Because many of the previous studies either focused on samples from a single locality or emphasized the occurrence of secondary uranium minerals, and very few microprobe mineral analyses have been published in the literature, we have undertaken a mineralogical characterization study of uranium minerals from selected mine localities in the Spruce Pine district. Based on the mine description summaries catalogued by Lesure (1968), specific pegmatites were chosen to visit and collect samples for study. Our efforts for the most part have been directed towards the primary uranium mineralogy of the pegmatites, with the goal of ascertaining how much compositional variability exists, both within a single deposit and from one pegmatite to another, in the various uranium minerals.

METHODS OF INVESTIGATION

Samples of uranium minerals were collected with the aid of an Exploranium Model GR-110 portable scintillometer. This instrument measures the intensity (in counts per second) of gamma-ray emissions from radioactive minerals. By placing the scintillometer on or close to the ground surface, areas yielding gamma-ray intensities considerably higher than background were easily identified and targeted for further exploration. Subsequent digging usually resulted in increasingly higher gamma-ray counts and the eventual discovery of a radioactive, uranium-bearing sample.

Selected samples were transferred to the University of Georgia. Here, representative pieces were broken from the samples, mounted in one-inch diameter epoxy plugs, and then polished. Final polishing was done using a Buehler Minimet micropolisher with 5 μm , 1 μm and 0.3 μm Al_2O_3 polishing powders.

Microprobe analyses were performed at the University of Georgia with a JEOL 8600 microprobe using wavelength dispersive spectrometers automated with Geller Microanalytical Laboratory's dQANT automation system. Data were acquired using an accelerating voltage of 15 KV and a 15 nA beam current. Fe, Nb, Ta, Ti, U, and Y were analyzed using 10 second counting times on peak and background; all other elements were analyzed using 60 second counting times, except for Pb in uraninites, for which 90-second count times were utilized. Analyses were compared to natural and synthetic mineral standards and the NMNH REE phosphate standards (Jarosevich and others, 1980; Jarosevich and Boatner, 1991). Matrix corrections were calculated using the phi-rho-Z approach of Armstrong (1988). Backscattered electron images were obtained using the dPICT imaging software, also from Geller Microanalytical Laboratory.

X-ray powder diffraction data were collected at Clemson University using a Scintag XDS 2000 diffractometer with a germanium detector. Processing and presentation of the data used the Scintag DMSNT program.

URANIUM MINERALOGY

The principal uranium minerals in our samples from the Spruce Pine district are uraninite (and its various alteration products) and samarskite. In addition to samarskite, several other niobate-tantalate minerals (fergusonite and two members of the pyrochlore group) were also found to contain substantial uranium. A number of other minerals (e.g., zircon, monazite, columbite) occur in which uranium is present but at concentrations of less than one weight percent; the latter minerals are not discussed in this paper.

Uraninite

Samples of uraninite were collected from eight mines, including three (Deake; Deer Park; Carolina Mineral Co. No. 20) described by Lesure (1968) as hosting "uranium

minerals”. The Pink mine was noted to be a locality for samarskite (Parker, 1952; Lesure, 1968), but had not previously been reported to contain uraninite. The Goog Rock mine also had no prior report of uraninite being present.

In appearance, uraninite crystals typically are subequant to equant with a dull to vitreous luster, black color and black streak. Their hardness is 5½, roughly the same as glass. Individual grains of uraninite range from 0.5 cm to a little more than 2 cm long; at some localities (e.g., Goog Rock mine), these may be concentrated to form much larger masses of uraninite. Alteration of the uraninite is widespread and locally results in yellowish-colored flakes or orange-red to reddish brown banded masses. Insofar as possible, we avoided these alteration products, focusing instead on what was most likely primary uraninite.

Backscattered electron images (Figure 1) reveal a variety of textures in uraninite. Although some grains appear homogeneous (e.g., Figure 1A), most are not. On a very fine scale there are patchy variations in brightness related to small heterogeneities in composition. The brighter areas in Figure 1B, for example, are slightly richer in uranium than adjacent areas. In some grains there is also a distinct, broad banding (Figure 1C); the darker bands usually give lower totals, possibly due to incipient oxidation and/or hydration of the uraninite. Such areas are more susceptible to beam damage, which may be caused by the presence of water. In other cases, the banding is clearly compositional, as evidenced in Figure 1D, where the image brightness is related to the extent of calcium substitution for uranium (discussed below).

Representative electron microprobe analyses of uraninite from Spruce Pine pegmatites are given in Table 1. Many of the analyses are characterized by low totals (more than half of the analyses sum to less than 98 weight percent). There are several possible reasons for this. First, the uraninite may be partially oxidized. That is, some U^{4+} may have been oxidized to U^{6+} . According to Janeczek and Ewing (1992), uraninite of ideal UO_2 composition probably never occurs in nature; instead, the structural formula for uraninite is better represented as UO_{2+x} ($0 < x < 0.25$), where $x = U^{6+}/(U^{4+} + U^{6+})$. The relative amounts of U^{4+} and U^{6+} cannot be directly determined from our analyses because the electron microprobe measures only total uranium. To the extent that uranium is present as U^{6+} , the analyses in Table 1 will be low because not enough oxygen will have been assigned to make uranium oxide. A second possibility is hydration of the uraninite. Alteration of primary uraninite leads to the formation of a variety of hydrous uranyl minerals collectively referred to as gummite (Fronzel, 1956). Although we deliberately avoided samples with obvious alteration products, some of the material we analyzed may have experienced incipient alteration and hydration. This would be consistent with the beam damage occasionally observed. Still another possibility is that radioactive decay may have disrupted the crystal structure of uraninite, causing it to become metamict or partially metamict. X-ray diffraction patterns of two randomly selected uraninite samples reveal well-defined x-ray peaks identifiable as uraninite (Figure 2), so we conclude that

the uraninite crystal structure has remained generally intact and metamictization has been minimal.

The principal cation impurities in the Spruce Pine uraninites are Th, Pb (radiogenic), Ca and Y (Table 1). Uraninites typically contain measurable Th, and the Spruce Pine uraninites are no exception: ThO₂ contents vary from less than one weight percent (analysis #3) to more than 7 weight percent (sample from the Field mine). Both Ca and Y may also substitute in the uraninite structure, inasmuch as their ionic radii are similar to that of U⁴⁺. Inspection of the data in Table 1 reveals that most uraninites contain small but measurable amounts of CaO, but samples from the Goog Rock and Deake mines contain areas (analyses #3 and #11) exceptionally high in CaO (10.56 weight percent and 12.07 weight percent, respectively). These are comparable to the highest (11 weight percent CaO) values documented in the literature for uraninite chemical analyses (Janeczek and Ewing, 1992). Figure 3 shows several broad areas in uraninite from the Deake mine that are Ca-rich and contrast sharply with adjacent Ca-poor uraninite (analysis #12 in Table 1). The Ca-rich uraninites also contain substantial (> 2 weight percent) F. Yttrium (as Y₂O₃) is generally present in amounts < 2 weight percent. However, uraninite from the Carolina Mineral Co. No. 20 mine contains almost 7 weight percent Y₂O₃ (analysis #10). In contrast, Y is below the limit of detectability in the Ca-rich uraninites. Lead in uraninite analyses is of radiogenic origin and likely occupies interstitial sites (Janeczek and Ewing, 1992).

Uraninite Alteration Products

Although not a major focus of this study, several secondary uranium minerals, derived by alteration of primary uraninite, were encountered. They include clarkeite, uranophane, and a hydrated oxide of lead and uranium that we tentatively identify as fourmarierite. Representative analyses of these minerals are given in Table 2. Clarkeite was named by Ross and others (1931) for a “dark brown to brownish black material” found in association with uraninite, gummite and uranophane in pegmatites from Spruce Pine. Spruce Pine remains one of only two localities in the world (the other being in India) at which clarkeite occurs (Fron del, 1958; Finch and Ewing, 1997). The mineral is Na rich and often contains admixed Ca-rich material (Finch and Ewing, 1997). Clarkeite is interpreted to have formed during late-stage pegmatite crystallization from the action of hydrothermal Na-bearing solutions (Ross and others, 1931). During this process uranium in primary uraninite was oxidized to U⁶⁺ (Finch and Ewing, 1997). The Pb contained in clarkeite is attributed to radiogenic origin (derived from decay of U and Th).

Uranophane, a Ca-rich hydrated uranyl silicate, is one of the commonest secondary uranium minerals and a typical alteration product of uraninite in pegmatites (Fron del, 1958). It frequently occurs in the outer zone of material derived by oxidation-hydration of uraninite in Spruce Pine district pegmatites. The uranophane analyses reported in Table 2 have low totals, due to the presence of water in the crystal structure. They are also characterized by low concentrations of Pb, indicative of later replacement of earlier

formed secondary uranium minerals by the action of meteoric waters containing silica and calcium (Fron del, 1958).

Intermediate between primary uraninite and the outer silicate zone containing uranophane is a zone composed chiefly of hydrated lead uranyl oxides (Fron del, 1958). At least two different Pb-rich minerals have been reported from pegmatites in the Spruce Pine district: fourmarierite and vandendriesscheite. According to analyses presented in Fron del (1958), vandendriesscheite contains 8.86-11.25 weight percent PbO (theoretical formula has 9.14 weight percent PbO), whereas fourmarierite analyses range from 12.11 to 18.31 weight percent PbO (theoretical, 15.31 PbO). The two analyses given in Table 2 have PbO concentrations within the fourmarierite range, hence we identify the material as such. The sample from the Fanny Gouge mine probably has admixed clarkeite, as evidenced by higher Na₂O and CaO. Fourmarierite typically contains 6-10 weight percent H₂O (Fron del, 1958), which largely accounts for the low totals.

Samarskite

Samarskite was identified in samples from four Spruce Pine mines, including one (Polly Randolph) at which it had not previously been reported. Individual crystals up to 4 cm long were obtained in this study, but according to Sterrett (1923), masses of samarskite “weighing many pounds were mined during the early days” at the W. W. Wiseman mine. Samarskite crystals appear massive and have vitreous luster. They are brittle, with hardness of 6-6½ and prominent conchoidal fracture. The color is black and streak is brown.

Compositionally, samarskite is a complex multiple oxide consisting of niobium and tantalum and a host of other elements including Ti, Fe, Y, and various rare earth elements (REE). It is one of several niobate-tantalate minerals that are known to contain relatively large amounts of uranium (Fron del, 1958; Finch and Murakami, 1999). Representative samarskite analyses are presented in Table 3 (this table includes other niobate-tantalate minerals also found at Spruce Pine). The data indicate that most Spruce Pine samarskites are enriched in Nb₂O₅ relative to Ta₂O₅. Substantial amounts of uranium occur, with UO₂ in many cases exceeding 10 weight percent (the highest is nearly 20 weight percent). Yttrium and rare earth elements are also abundant. In order to simplify the results presented in Table 3, we record only total REE (as trivalent oxides, REE₂O₃). The most abundant REE is gadolinium (Gd₂O₃ in samarskite ranges from 3.4 to 6.4 weight percent), while Sm₂O₃, Dy₂O₃, and Ho₂O₃ usually are each present in amounts between 1 and 2 weight percent.

Structural formulas for samarskite were calculated on the basis of the general formula ABO₄ (Warner and Ewing, 1993). Nb and Ta are the principal B site occupants, whereas the A site contains U, Th, Y, REE, Ca, Fe, and other cations; Ti usually occurs in the B site, but may exist in either site. In Table 3, all Ti was assigned to the B site; the resulting B site totals for samarskite are all greater than 1, suggesting that some of the Ti

occupies the A site. The specific name given to samarskite minerals is based on the A-site occupancy. Hanson and others (1999) proposed a three-fold subdivision: samarskite-(Y), wherein the A site is dominated by Y+REE; ishikawaite, in which the A site is dominantly U+Th; and calciosamarskite, which contains predominantly Ca in the A site. A ternary diagram (Figure 4) can be employed to distinguish among these three members. The samarskites from Spruce Pine analyzed in this study all plot in the samarskite-(Y) field. The sample from the Polly Randolph mine (last analysis in Table 3) contains the highest proportion of U+Th and plots very close to the ishikawaite field. The filled star corresponds to the samarskite from Mitchell County analyzed by Allen (1877); it plots at the yttrium-rich end of the samarskite-(Y) compositions found in this study. Also shown in Figure 4 is the composition of calciosamarskite from Mitchell County (star) reported in Hanson and others (1999). All of the samarskites we have analyzed contain very little Ca and, consequently, are clearly distinct from the Ca-rich sample studied by Hanson and others (1999).

Fergusonite

Fergusonite was identified in samples from the McKinney mine, where it occurs in association with samarskite and a Ta-rich member of the pyrochlore group (Figure 5A), and the W. W. Wiseman mine, where it is intergrown with a Pb-rich pyrochlore and uraninite (Figure 5B). Fergusonite is Y- and REE-rich (see analyses #5,8,9 in Table 3). Heavy REE such as Gd, Dy, Ho, and Er were found to have the highest concentrations. Fergusonite is further characterized by high Nb₂O₅ relative to Ta₂O₅, very low TiO₂ concentrations, and FeO below the limit of detectability. Uranium concentrations (roughly 5 weight percent UO₂) are lower than those found in samarskite. The structural formula for fergusonite is ABO₄ (Finch and Murakami, 1999), identical to that of samarskite. Like samarskite, the B site is occupied by Nb, Ta and Ti. However, the A site in fergusonite is larger, excluding smaller cations such as Fe and Mn that occur in samarskite.

Pyrochlore group

Samples from the McKinney and W. W. Wiseman mines also contain niobate-tantalate minerals belonging to the pyrochlore group. The latter are intergrown with fergusonite and, in the case of the McKinney mine, samarskite (Figure 5). Three analyses are given in Table 3 - analyses #3 and #4, both from the McKinney mine, are Ta-rich, while analysis #10 (W. W. Wiseman mine) is Nb- and Pb-rich. In addition to their Ta-rich nature, the McKinney mine pyrochlores contain appreciable CaO and TiO₂ and modest amounts of Na₂O, but little or no Y or REE. Most relevant to this study, UO₂ concentrations (approximately 10-15 weight percent) are comparable to samarskite. The Pb-rich material from the W. W. Wiseman mine has lower UO₂, but higher ThO₂ and FeO; it also contains appreciable SiO₂ (> 3 weight percent).

The general formula for pyrochlore group minerals is $A_{1-2}B_2O_6(O,OH,F)$, with Nb, Ta, and Ti occupying the B site and all other cations housed in the A site. According to Hogarth (1977), members of the pyrochlore group are subdivided on the basis of B-site cations: those with Nb > Ta belong to the pyrochlore subgroup, whereas those with Ta > Nb are assigned to the microlite subgroup; betafite is characterized by having $2Ti > (Nb+Ta)$. A ternary Nb-Ta-Ti plot (Figure 6) shows that the McKinney mine analyses plot in the microlite field but the W. W. Wiseman analysis plots as pyrochlore. Further subdivision can be made according to the A-site occupancy. Where Ca+Na dominate, the subgroup names are retained, but if another A-site cation exceeds 20 percent of the total occupancy, the species is named according to that cation (Hogarth, 1977). Thus, with Pb constituting more than 50 percent of A-site cations, the W. W. Wiseman analysis (#10 in Table 3) is properly designated as plumbopyrochlore. Microlite from the McKinney mine does not have sufficient uranium to be called uranmicrolite according to the Hogarth (1977) scheme, but since it does contain more than 10 weight percent UO_2 , we prefer to designate it uranoan microlite. The star in Figure 6 indicates the composition of uranoan pyrochlore from Mitchell County, North Carolina (Fron del, 1958; the original analysis was published by Allen (1877), who called the mineral hatchettolite, a name no longer used in the pyrochlore-group classification of Hogarth (1977).

DISCUSSION

The most striking aspect of the compositional data for uraninites from the Spruce Pine area pegmatites is the very high Ca content found in some samples from the Goog Rock and Deake mines. A similar occurrence of highly calcic uraninite - from biotite granite near Simpsonville, South Carolina - was reported by Warner and others (2004). Like the Spruce Pine uraninites described in this study, the Ca-rich uraninite from Simpsonville was marked by having an appreciable amount of F. Since uraninite is isostructural with fluorite, we attribute the presence of fluorine to solid solution between UO_2 and CaF_2 . Even so, the amount of Ca far exceeds that which is required to be bound with F in a fluorite component. Thus, we conclude that these Ca-rich areas are mostly the result of unusually extensive substitution of Ca for U in the uraninite crystal structure. Radiogenic lead contents appear consistent with this hypothesis, as the Ca-rich areas have lower PbO relative to more U-rich adjacent areas (cf., analysis #3 vs #2 and #11 vs. #12-13 in Table 1). The substitution of Ca for U in uraninite implies a certain amount of oxidation whereby U^{6+} substitutes for U^{4+} to compensate for the lower charge of Ca^{2+} (Janecz ek, 1991; Janecz ek and Ewing, 1992).

Under the assumption that all of the lead present in uraninite is derived from the decay of uranium and thorium, it is possible to date the ages of formation (chemical ages) of individual uraninite grains from electron microprobe analyses (Bowles 1990). The relevant equation is

$$Pb = U[0.99276(e^{\lambda_1 t} - 1) + 0.007196(e^{\lambda_2 t} - 1)] + Th(e^{\lambda_3 t} - 1)$$

where Pb is the total amount of radiogenic lead produced by the decay of ^{238}U (99.276% of modern uranium), ^{235}U (0.7196% of modern uranium) and ^{232}Th , and λ_1 , λ_2 , and λ_3 are the decay constants for ^{238}U ($0.000155125 \text{ Ma}^{-1}$), ^{235}U ($0.00098485 \text{ Ma}^{-1}$), and ^{232}Th ($0.000049475 \text{ Ma}^{-1}$), respectively. Results of such determinations have been shown to yield valid ages when compared with ages derived from isotopic measurements (Bowles, 1990).

In order to obtain more accurate age estimates, counting times of 90 seconds were used for Pb, longer than for other elements. Table 4 summarizes the chemical ages determined from our microprobe analyses. Most Spruce Pine uraninites date approximately between 350 Ma and 400 Ma; the Pink mine yields the oldest (443 Ma) age. These results are in good agreement with published U-Pb age dates for Spruce Pine district pegmatites. For example, Aldrich and others (1958) report uraninite ages from the Chestnut Flats mine of 370-420 Ma, as compared to 378-411 Ma in this study. Uraninites from other Spruce Pine localities have been dated between 340 Ma and 370 Ma (Rodgers, 1952), while Alter and McColley (1942) reported ages ranging from 358 Ma to 382 Ma from a zoned single crystal of uraninite from Mitchell County. Clarkeite from the Fanny Gouge mine yields chemical ages of 360-375 Ma, comparable to those obtained from primary uraninite and virtually identical to the clarkeite formation ages (360-380 Ma) determined by Finch and Ewing (1997). These ages are consistent with late-stage pegmatite crystallization of clarkeite as originally proposed by Ross and others (1931).

Several niobate-tantalate minerals containing significant amounts of uranium (5-20 weight percent UO_2) were identified in this study: samarskite, fergusonite, uranoan microlite, and plumbopyrochlore. Our data (Table 3) indicate that Spruce Pine samarskites are enriched in Y plus REE, so are classed as samarskite-(Y). We consistently find very little Ca in samarskite-(Y), and therefore conclude that calciosamarskite, although it has been reported from Mitchell County (Figure 4), is rare. Instead, a trend from the Y-rich sample analyzed by Allen (1877) towards, but not quite reaching, the ishikawaite field is apparent. Our data further suggest greater compositional variability in pyrochlore-group minerals than heretofore recognized. The only previously published analysis from the Spruce Pine district that is known to us is of uranoan pyrochlore (hatchettolite of Allen, 1877; Frondel, 1958). Uranmicrolite has been reported from the Sullins Wiseman mine (Wilson and McKenzie, 1985), but no published analysis exists. We confirm the presence of microlite containing substantial uranium (uranoan microlite), albeit not enough to be called uranmicrolite according to Hogarth (1977). We have also identified a Pb-rich variety of pyrochlore, plumbopyrochlore (Table 3; Figure 6), not previously reported from the Spruce Pine pegmatite district.

A similar assemblage of uranium-bearing niobate-tantalate minerals was recently described from a pegmatite in the Inner Piedmont belt of northwestern South Carolina (Warner and Fleisher, 2004). At this site (Maw Bridge pegmatite) samarskite-(Y) and fergusonite occur together with the betafite member of the pyrochlore group. Table 5 compares the compositions of the above minerals and shows that there is a remarkable

similarity between the Maw Bridge pegmatite and the Spruce Pine pegmatites. The pyrochlore-group mineral at Maw Bridge is more Ti-rich, hence analyses plot in the betafite field rather than the microlite or pyrochlore fields (Figure 6). Concentrations of uranium in the niobate-tantalate minerals are roughly comparable at the two sites, the largest difference being that betafite from the Maw Bridge pegmatite has notably higher uranium than uranoan pyrochlore from McKinney mine (Table 5).

CONCLUSIONS

The results of our study indicate that pegmatites in the Spruce Pine district contain, in order of decreasing uranium content, the following uranium minerals: uraninite, clarkeite, fourmarierite, uranophane, samarskite-(Y) and uranoan microlite, plumbopyrochlore, and fergusonite. Clarkeite, uranophane and fourmarierite are alteration products of primary uraninite, whereas samarskite-(Y), uranoan microlite, plumbopyrochlore and fergusonite are primary niobate-tantalate minerals. The chemical signature of the uranium minerals analyzed in this study reinforces the affiliation of the Spruce Pine district pegmatites with the NYF (niobium, yttrium plus REEs, and fluorine) family of granitic pegmatites (Černý, 1991; Ercit, 2004). That is, the niobate-tantalate minerals taken as a whole are characterized by $Nb > Ta$ and high Y+REE, while appreciable amounts of F are present in Ca-rich uraninite. Under the recent pegmatite classification scheme of Černý and Ercit (2005), the Spruce Pine pegmatites belong to the muscovite – rare-element (MSREL) class, specifically, subclass MSREL-REE. Muscovite, of course, is one of the two principal economic minerals of the Spruce Pine district. Other minerals typical of this subclass are fergusonite, samarskite, and monazite, while the minor elements Be, Y, REE, Ti, U, Th, and Nb-Ta characterize its geochemical signature (Černý and Ercit, 2005). The metamorphic environment typical for this subclass is moderate to high P, amphibolite facies, consonant with the Paleozoic metamorphism experienced by the Blue Ridge of western North Carolina (Adams and Trupe, 1997).

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FIGURE CAPTIONS

Figure 1. Backscattered electron images of uraninites from Spruce Pine pegmatites. Scale is given by bars below each image. A) Relatively homogeneous uraninite from Deake mine. B) Higher magnification image showing small-scale heterogeneities in uraninite, Deer Park mine. Brighter areas have higher uranium. C) Broad-scale banding in uraninite from Pink mine. Darker area (bottom) yielded lower analysis totals and is more prone to damage from the electron beam. D) Compositional banding in uraninite from Goog Rock mine. Darker area (lower right) is Ca-rich; brighter areas have higher uranium.

Figure 2. X-ray diffraction patterns of uraninite from Goog Rock mine (top) and Carolina Mineral Co. No. 20 mine (bottom). The scans show diffraction peaks with the background removed. Beneath are the peaks located from the scans and, below that, matching uraninite peaks from a data file.

Figure 3. A) Backscattered electron image of inhomogeneous uraninite from Deake mine (bar gives scale). B) X-ray map of Ca distribution in same field of view. Note that brighter areas are higher in Ca (and also yield higher analysis totals).

Figure 4. Ternary plot of A-site cations in samarskite-group minerals. Subdivision into samarskite-(Y), ishikawaite, and calciosamarskite is based on relative dominance of (Y+REE), (U+Th), and Ca, respectively (Hanson and others, 1999). Open triangles, data from this study; filled star, samarskite-(Y) analysis reported by Allen (1877); open star, calciosamarskite analysis reported in Hanson and others (1999).

Figure 5. Backscattered electron images of uranium-bearing niobate-tantalate minerals in Spruce Pine pegmatites. Scale is given by bars below each image. A) Sample from McKinney mine consisting of intergrown uranoan microlite (brightest phase), samarskite-(Y) (intermediate brightness), and fergusonite (dark phase). Note burn marks (from electron beam damage) in fergusonite (near center of image and toward right side above uranoan microlite). B) Fergusonite (darker, inhomogeneous phase on left side of grain) and plumbopyrochlore (bright, on right side of grain) from W. W. Wiseman mine. Tiny, very bright material included in fergusonite and in plumbopyrochlore is uraninite. Separate grain at lower right is samarskite-(Y).

Figure 6. Ternary plot of B-site cations in pyrochlore-group minerals. Fields for betafite, pyrochlore, and microlite are based on Hogarth (1977) classification. Symbols: open triangles, uranoan microlite from this study; filled triangle, plumbopyrochlore from this study; open star, uranoan pyrochlore from Mitchell County (Allen, 1877; Frondel, 1958); plusses, betafite from Maw Bridge pegmatite, South Carolina (Warner and Fleisher, 2004).

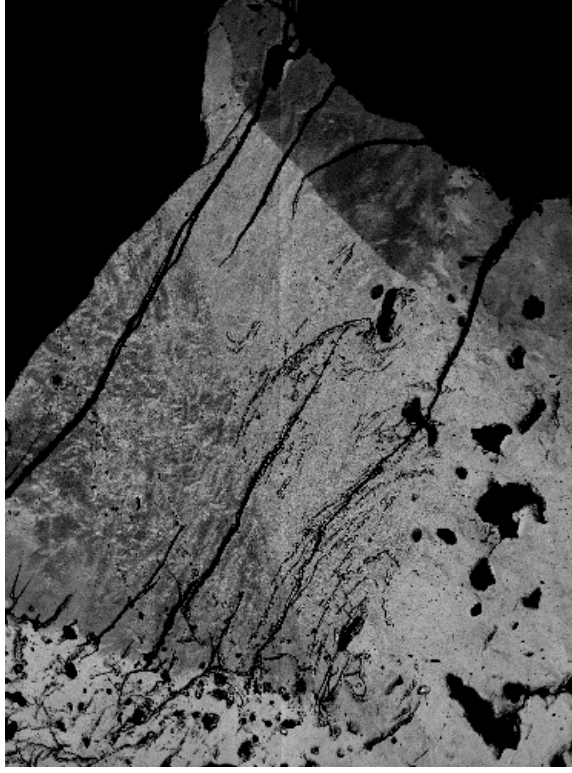
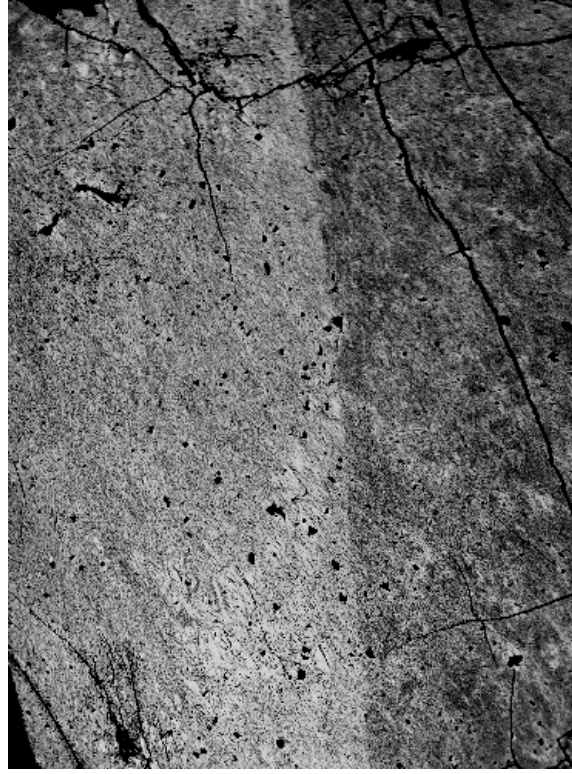
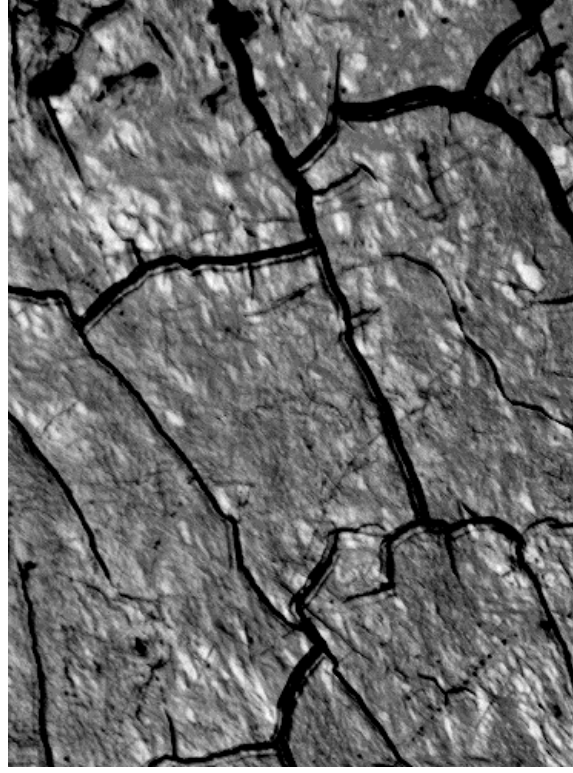
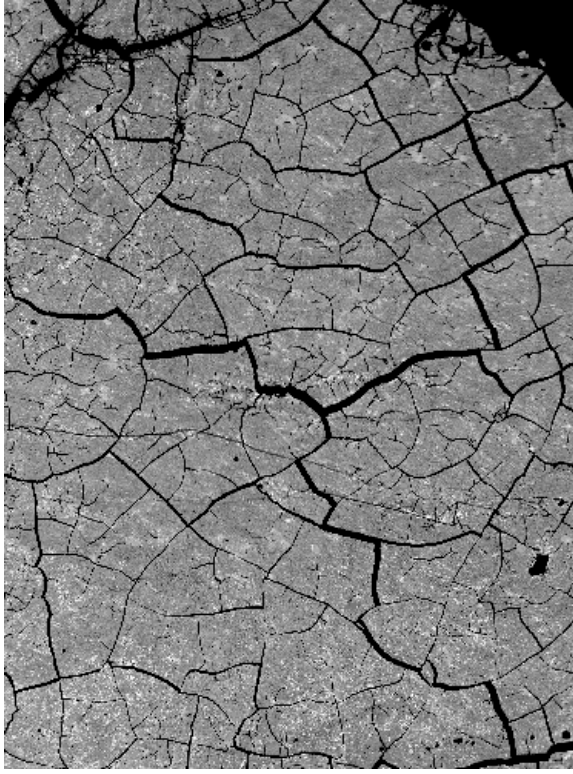


Figure 1 Warner and others (2008)

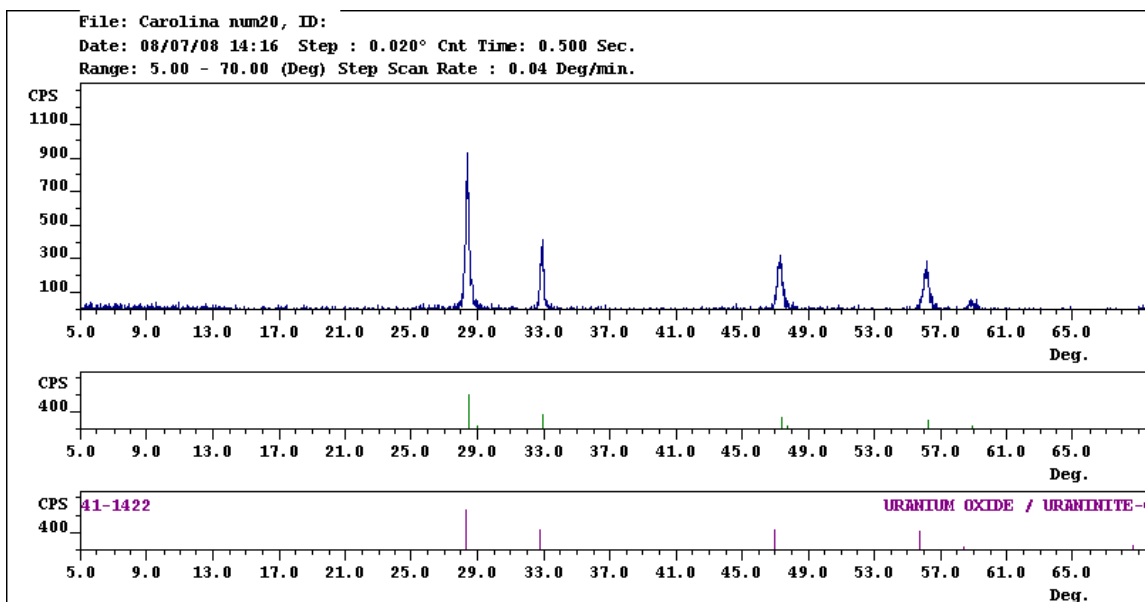
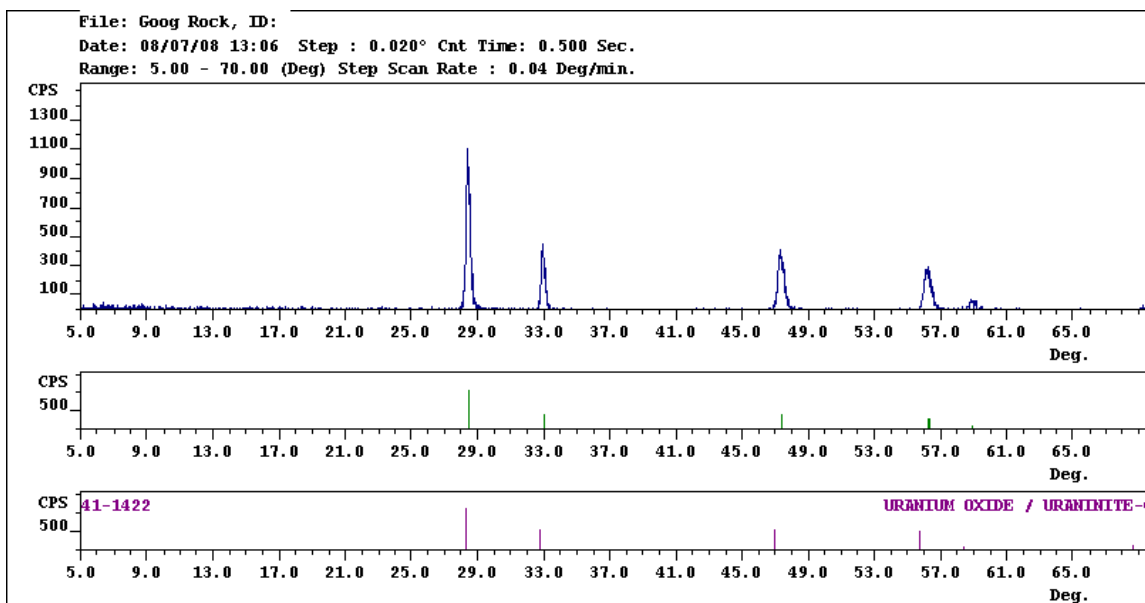
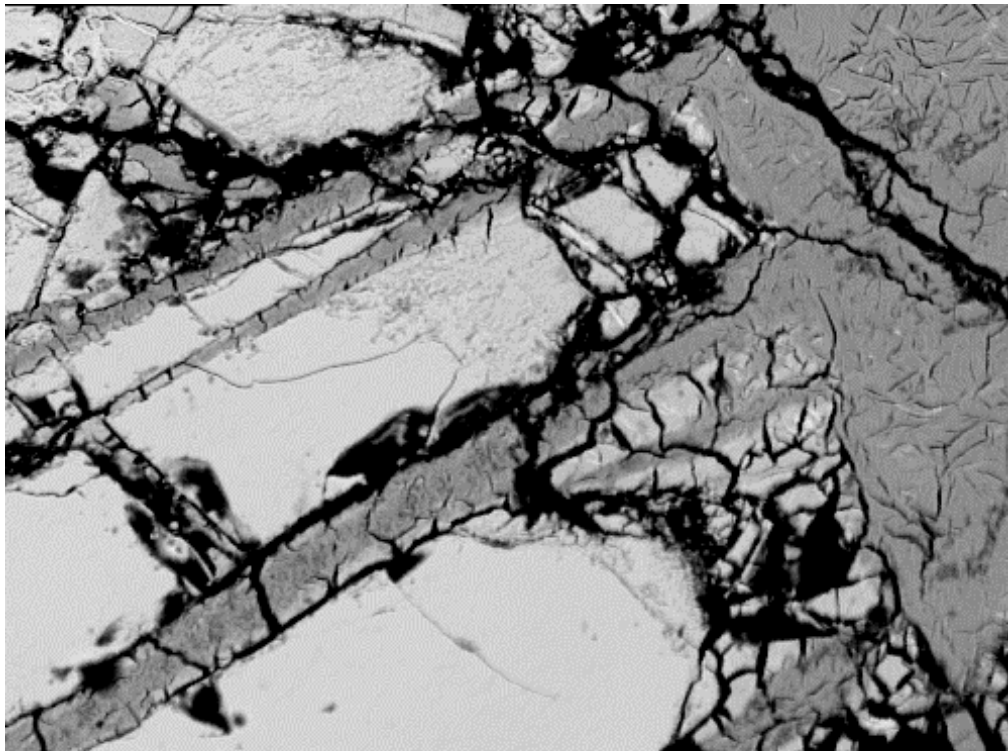
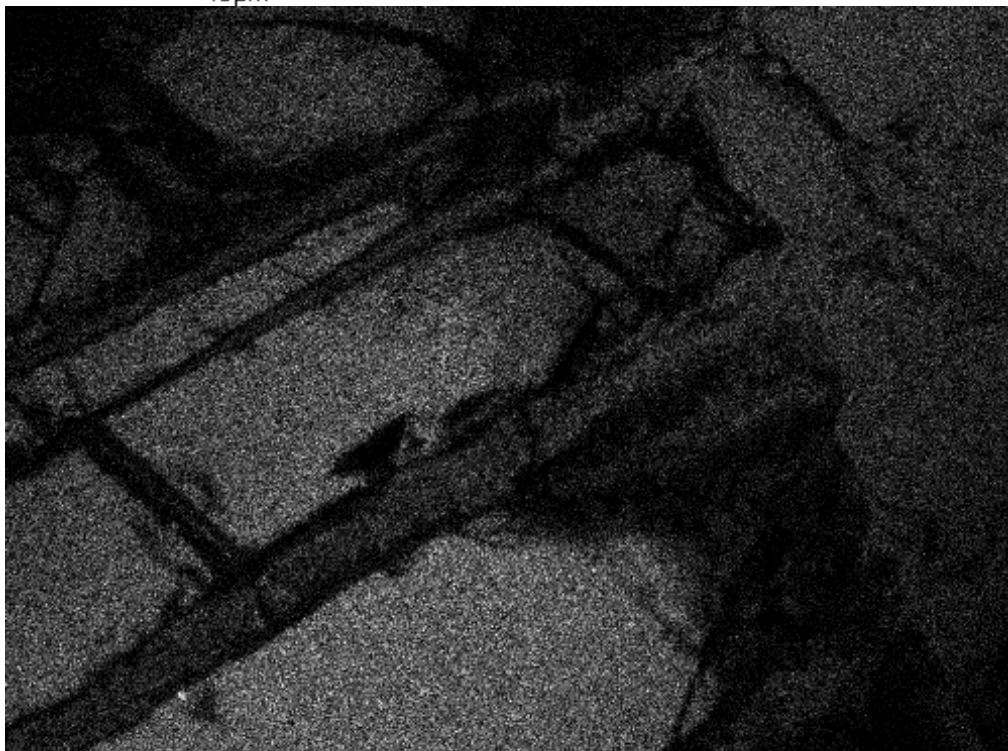


Figure 2 Warner and others (2008)



40µm



40µm

Figure 3 Warner and others (2008) page 44

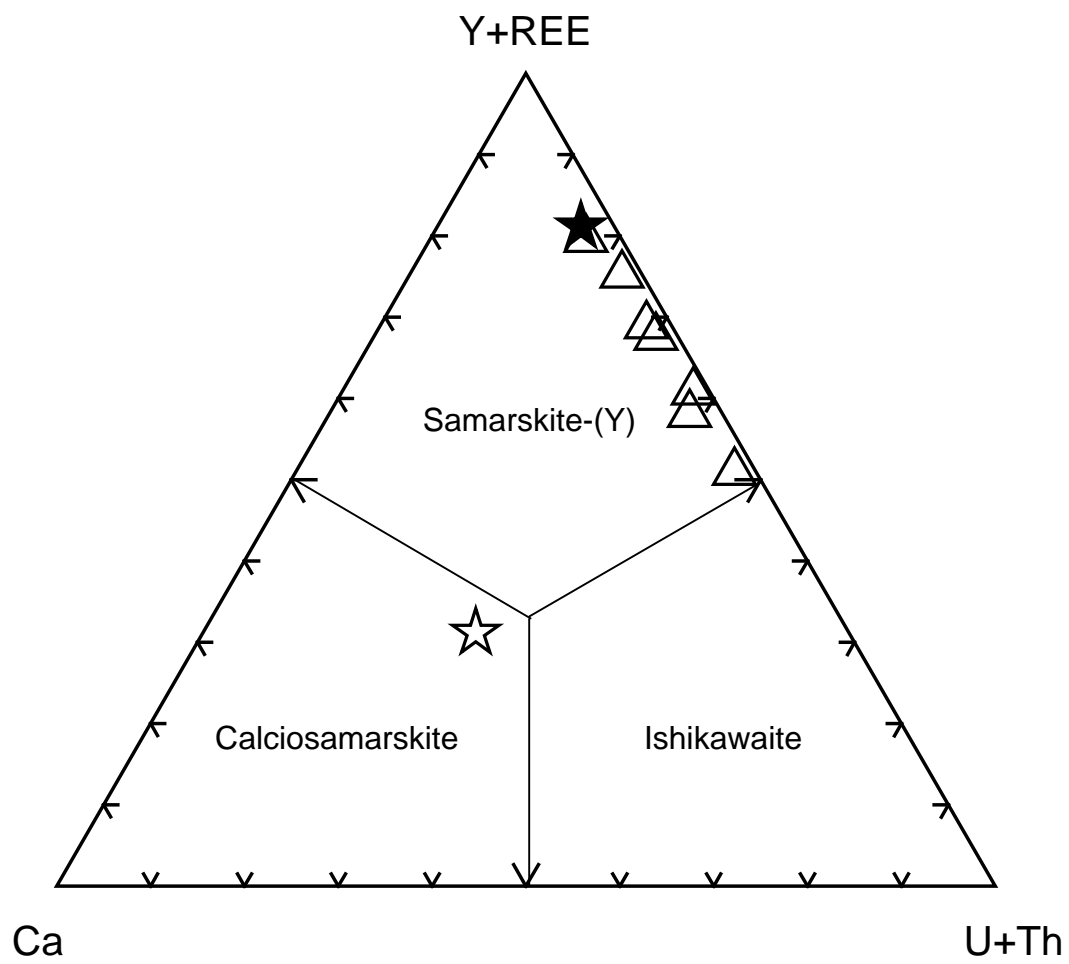


Figure 4 Warner and others (2008)

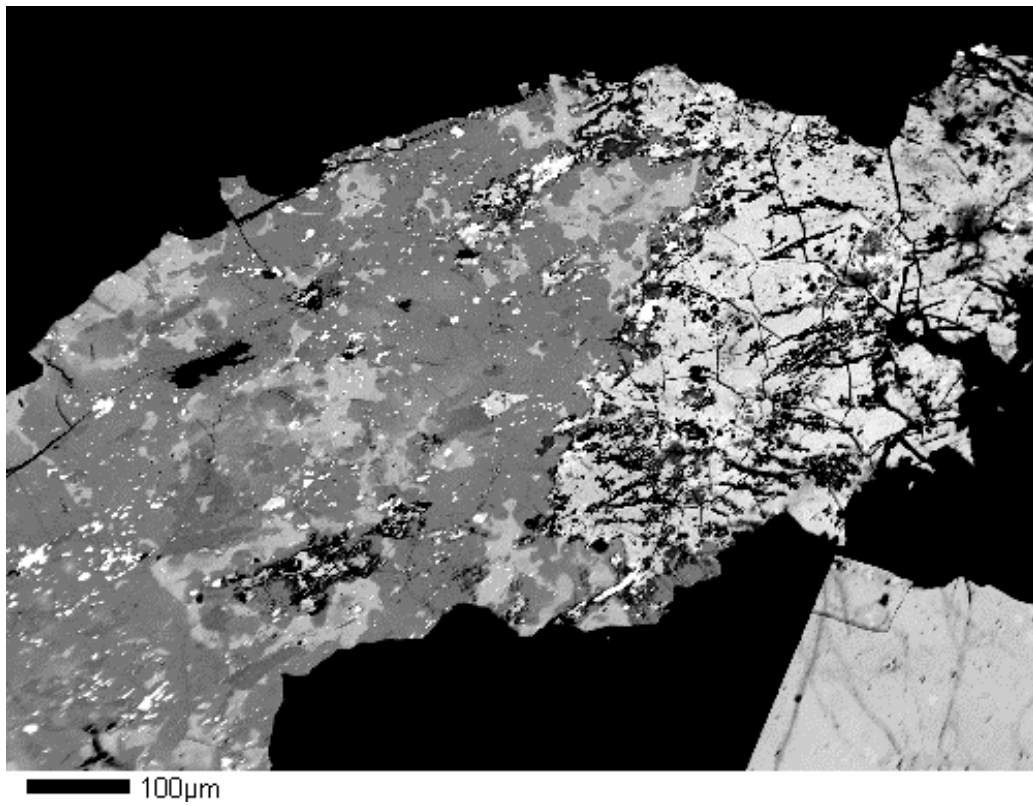
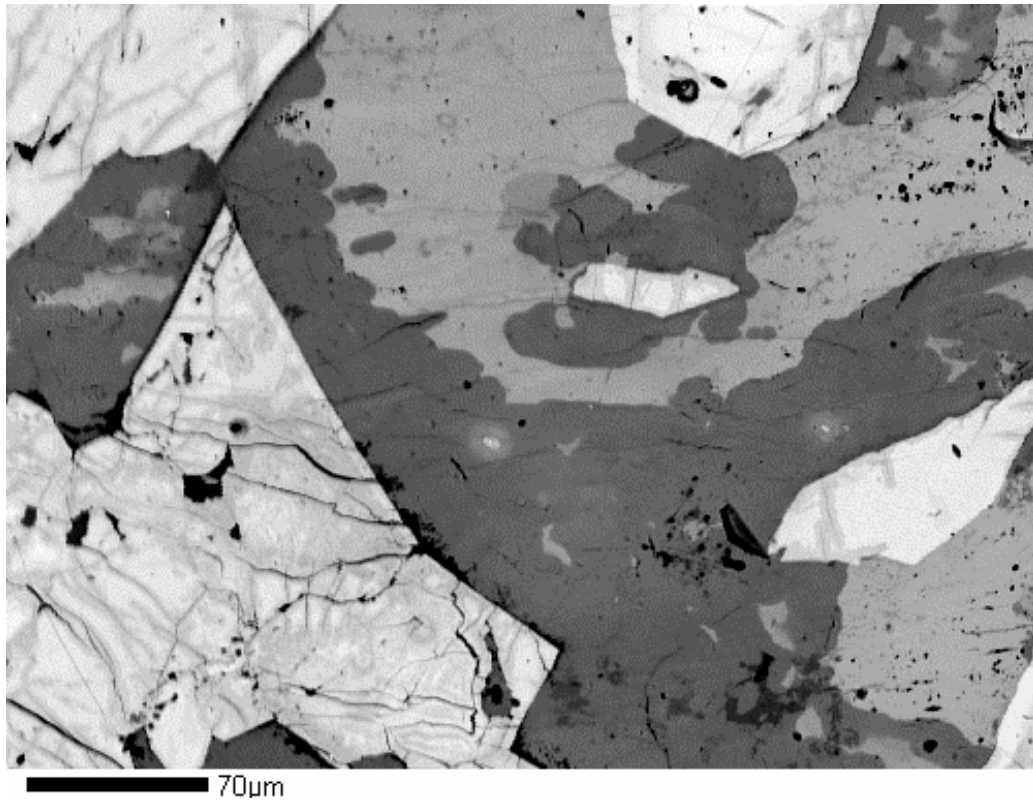


Figure 5 Warner and others (2008) page 46

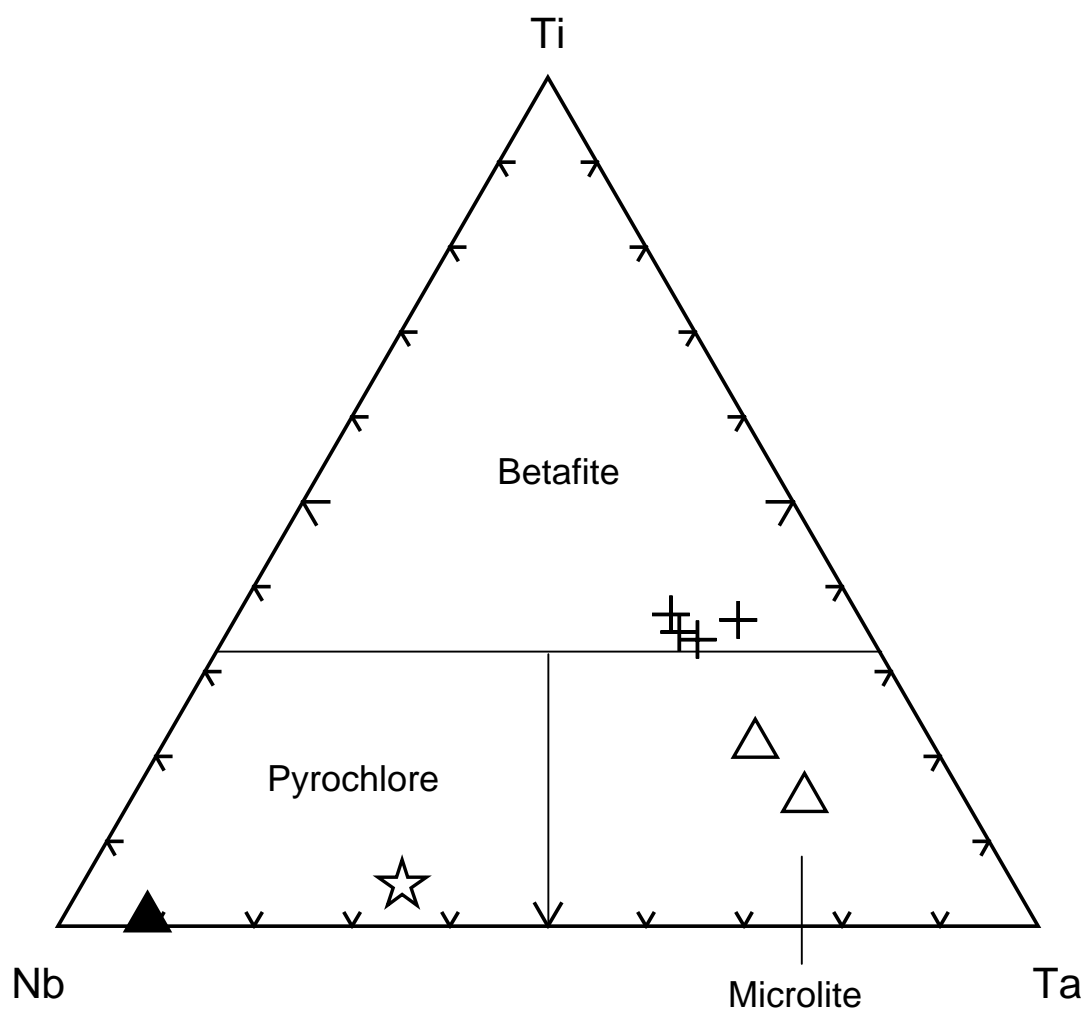


Figure 6 Warner and others (2008)

Table 1 Representative Electron Microprobe Analyses of Uraninite from Spruce Pine Pegmatites

	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO ₂	0.11	0.08	0.38	0.33	0.27	0.06	BDL	0.12	0.15	BDL	0.30	0.31	BDL
ZrO ₂	0.22	BDL	BDL	0.18	BDL	BDL	0.54	0.20	BDL	BDL	BDL	BDL	BDL
UO ₂	88.20	85.12	80.21	88.18	91.79	92.30	80.68	81.93	82.66	83.20	79.60	87.12	91.45
ThO ₂	2.86	1.50	0.78	4.42	1.54	2.63	6.04	7.23	4.35	1.59	1.53	2.31	2.47
PbO	4.65	4.54	3.64	4.69	4.35	5.52	4.15	4.51	4.58	3.84	3.64	3.92	4.98
CaO	0.23	2.82	10.56	0.19	0.30	0.05	0.45	0.18	0.25	0.33	12.07	0.38	0.07
Y ₂ O ₃	1.31	0.62	BDL	1.38	0.48	0.25	1.95	1.11	1.68	6.81	BDL	BDL	BDL
F	BDL	0.49	2.86	BDL	BDL	BDL	BDL	BDL	BDL	0.21	2.43	BDL	BDL
Total	97.58	95.17	98.43	99.37	98.73	100.81	93.81	95.28	93.67	95.98	99.57	94.04	98.97
O=F		-0.21	-1.20							-0.09	-1.02		
		94.96	97.23							95.89	98.55		

Cations on basis of 2 oxygens

Si	0.005	0.004	0.014	0.015	0.012	0.003	0.000	0.006	0.007	0.000	0.011	0.015	0.000
Zr	0.005	0.000	0.000	0.004	0.000	0.000	0.012	0.005	0.000	0.000	0.000	0.000	0.000
U	0.902	0.856	0.666	0.879	0.929	0.931	0.848	0.858	0.878	0.825	0.650	0.925	0.941
Th	0.030	0.015	0.007	0.045	0.016	0.027	0.065	0.077	0.047	0.016	0.013	0.025	0.026
Pb	0.058	0.055	0.037	0.057	0.053	0.067	0.053	0.057	0.059	0.046	0.036	0.050	0.062
Ca	0.011	0.137	0.422	0.009	0.015	0.002	0.023	0.009	0.013	0.016	0.475	0.019	0.003
Y	0.032	0.015	0.000	0.033	0.012	0.006	0.049	0.028	0.043	0.161	0.000	0.000	0.000
F	0.000	[0.070]	[0.337]	0.000	0.000	0.000	0.000	0.000	0.000	[0.030]	[0.282]	0.000	0.000
Sum	1.043	1.082	1.146	1.042	1.037	1.036	1.050	1.040	1.047	1.064	1.185	1.034	1.032

Columns: 1 - Deer Park; 2,3 - Goog Rock; 4 - Pink; 5 - Chestnut Flats; 6 - Polly Randolph; 7 - Wiseman (inclusion in samarskite-(Y)); 8,9 - Field; 10 - Carolina No. 20; 11-13 - Deake

BDL = below limit of detectability

Table 2 Analyses of Uraninite Alteration Products in Spruce Pine Pegmatites

	1	2	3	4	5	6
SiO ₂	BDL	BDL	16.79	12.79	BDL	BDL
ThO ₂	0.55	0.40	0.85	BDL	BDL	1.79
UO ₃	86.39	87.00	69.77	67.95	79.25	75.34
Y ₂ O ₃	0.67	0.74	0.77	0.29	BDL	BDL
Al ₂ O ₃	BDL	0.05	0.20	0.82	BDL	NA
PbO	4.21	4.08	0.28	0.37	13.09	14.44
CaO	0.69	2.69	5.35	6.08	1.45	0.06
Na ₂ O	3.65	3.71	BDL	NA	3.74	BDL
P ₂ O ₅	BDL	BDL	BDL	0.42	0.05	NA
Total	96.16	98.67	94.01	88.72	97.58	91.63

Columns: 1,2 - Clarkeite, Fanny Gouge; 3 - Uranophane, Fanny Gouge;
4 - Uranophane, Goog Rock; 5 - Fourmarierite, Fanny Gouge;
6 - Fourmarierite, Deake

BDL = below limit of detectability NA = not analyzed

Table 3 Representative Electron Microprobe Analyses of U-bearing Niobate-Tantalate Minerals in Spruce Pine Pegmatites

	1	2	3	4	5	6	7	8*	9*	10#	11	12	13
Nb2O5	28.70	23.08	8.79	8.89	37.25	42.31	38.73	43.20	36.85	37.74	30.20	42.11	36.55
Ta2O5	27.78	34.73	56.58	49.25	6.62	6.42	13.19	6.73	13.77	6.02	23.27	11.31	11.40
TiO2	1.31	2.20	4.45	6.29	0.13	2.07	1.33	0.23	0.16	0.23	1.54	1.46	2.03
ZrO2	BDL	0.24	BDL	BDL	BDL	0.26	0.43	BDL	BDL	BDL	0.12	0.08	0.14
UO2	11.53	7.34	10.29	15.45	5.38	13.07	9.95	4.86	5.82	6.74	15.53	16.16	19.56
ThO2	0.30	0.44	BDL	BDL	1.17	0.95	1.62	1.56	0.40	2.91	1.15	1.20	1.80
Y2O3	0.04	0.09	0.14	0.13	BDL	BDL	0.03	BDL	0.05	BDL	0.19	0.35	0.07
Y2O3	6.26	9.46	BDL	BDL	21.13	6.66	7.58	28.67	26.54	BDL	5.80	6.25	4.30
REE2O3	9.39	9.85	0.28	BDL	24.23	10.55	13.82	8.62	9.05	BDL	8.92	7.68	8.81
CaO	0.23	0.38	13.46	11.74	1.60	0.23	0.24	1.51	1.51	0.42	0.17	0.33	0.22
FeO	10.37	11.59	0.32	0.66	BDL	11.22	10.51	BDL	BDL	4.39	9.05	10.64	10.27
MnO	0.41	0.31	0.21	0.23	BDL	0.80	1.13	BDL	BDL	0.07	0.35	0.52	0.60
PbO	1.02	0.51	0.52	0.83	0.49	1.64	0.68	0.62	0.65	30.95	1.08	1.09	1.00
Na2O	BDL	BDL	1.01	1.90	BDL	0.05	BDL	BDL	BDL	BDL	0.15	BDL	BDL
Total	97.39	100.22	96.05	95.37	98.00	96.23	99.24	96.40	95.20	92.80	97.52	99.18	96.75

Oxygens

	4	4	7	7	4	4	4	4	4	7	4	4	4
Nb	0.667	0.523	0.325	0.348	0.838	0.919	0.839	0.914	0.818	1.688	0.700	0.901	0.834
Ta	0.388	0.474	1.365	1.158	0.090	0.084	0.172	0.086	0.184	0.162	0.324	0.146	0.156
Ti	0.051	0.083	0.297	0.409	0.005	0.075	0.048	0.008	0.006	0.017	0.059	0.052	0.077
Zr	0.000	0.006	0.000	0.000	0.000	0.006	0.010	0.000	0.000	0.000	0.003	0.002	0.003
U	0.132	0.082	0.203	0.297	0.060	0.140	0.106	0.051	0.064	0.148	0.177	0.170	0.220
Th	0.004	0.005	0.000	0.000	0.013	0.010	0.018	0.017	0.004	0.066	0.013	0.013	0.021
Sc	0.002	0.004	0.011	0.010	0.000	0.000	0.001	0.000	0.002	0.000	0.008	0.014	0.003
Y	0.171	0.253	0.000	0.000	0.560	0.170	0.193	0.714	0.694	0.000	0.158	0.157	0.115
REE	0.159	0.163	0.008	0.000	0.397	0.166	0.218	0.130	0.144	0.000	0.150	0.119	0.147
Ca	0.013	0.020	1.297	1.088	0.085	0.012	0.012	0.076	0.079	0.044	0.009	0.017	0.012
Fe	0.446	0.486	0.024	0.048	0.000	0.451	0.421	0.000	0.000	0.363	0.388	0.421	0.433
Mn	0.018	0.013	0.016	0.017	0.000	0.033	0.046	0.000	0.000	0.006	0.015	0.021	0.026
Pb	0.014	0.007	0.012	0.019	0.007	0.021	0.009	0.008	0.009	0.824	0.015	0.014	0.014
Na	0.000	0.000	0.174	0.319	0.000	0.005	0.000	0.000	0.000	0.000	0.015	0.000	0.000

A	0.959	1.039	1.745	1.798	1.122	1.014	1.034	0.996	0.996	#1.781	0.951	0.948	0.994
B	1.106	1.080	1.987	1.915	0.933	1.078	1.059	1.008	1.008	1.867	1.083	1.099	1.067
Sum A+B	2.065	2.119	3.732	3.713	2.055	2.092	2.093	2.004	2.004	3.648	2.034	2.047	2.061

Columns: 1,2 - Samarskite, McKinney; 3,4 - Uranian Microcline, McKinney; 5 - Fergusonite, McKinney; 6,7 - Samarskite, W. W. Wiseman; 8,9 - Fergusonite, W. W. Wiseman; 10 - Plumbopyrochlore, W. W. Wiseman; 11,12 - Samarskite, Peterson; 13 - Samarskite, Polly Randolph

BDL = below limit of detectability

*Contains 0.40 F

#Contains 3.33 SiO2 (Si = 0.330)

Table 4 Uraninite Age Determinations

Mine	Chemical Age (Ma)	
	Average	Range
Carolina No. 20	356	326-401
Deake	358	326-391
Goog Rock	364	322-393
W.W. Wiseman	365	NA
Deer Park	389	369-409
Polly Randolph	393	332-427
Chestnut Flats	394	378-411
Field	401	389-432
Pink	443	418-460

NA = not applicable (single analysis)

Table 5 Comparison of niobate-tantalate minerals at Maw Bridge and Spruce Pine

	Samarskite-(Y)		Fergusonite		Pyrochlore Group	
	1	2	*3	4	5	6
Nb ₂ O ₅	42.11	40.23	36.85	35.77	8.89	6.12
Ta ₂ O ₅	11.31	11.45	13.77	13.70	49.25	41.71
TiO ₂	1.46	1.70	0.16	1.19	6.29	10.59
ZrO ₂	0.08	0.39	BDL	BDL	BDL	BDL
UO ₂	16.16	14.62	5.82	7.50	15.45	25.93
ThO ₂	1.20	1.51	0.40	1.19	BDL	BDL
Sc ₂ O ₃	0.35	0.87	0.05	0.08	0.13	0.12
Y ₂ O ₃	6.25	9.29	26.54	26.46	BDL	BDL
REE ₂ O ₃	7.68	7.71	9.05	12.04	BDL	BDL
CaO	0.33	0.12	1.51	0.84	11.74	12.09
FeO	10.64	10.34	BDL	BDL	0.66	0.25
MnO	0.52	0.68	BDL	BDL	0.23	0.06
PbO	1.09	0.45	0.65	0.31	0.83	0.84
Na ₂ O	BDL	NA	BDL	NA	1.90	2.11
Total	99.18	99.36	95.20	99.08	95.37	99.82

Columns: 1 - Samarskite-(Y) from Peterson mine, Spruce Pine; 2 - Samarskite-(Y) from Maw Bridge pegmatite; 3 - Fergusonite from W. W. Wiseman mine, Spruce Pine; 4 - Fergusonite from Maw Bridge pegmatite; 5 - Uranoan microlite from McKinney mine, Spruce Pine; 6 - Betafite from Maw Bridge pegmatite

BDL = below limit of detectability

NA = not analyzed

*Contains 0.40 weight percent F

Spruce Pine analyses are from this study (Table 3); Maw Bridge pegmatite data are from Warner and Fleisher (2004)

ROAD LOG – DAYS 1 and 2

CGS Road Log for Saturday, November 1, 2008 Spruce Pine Mining District – Day 1

- **Busses LOAD at 7:00 a.m. and LEAVE at 7:15 a.m.**
- Leave Switzerland Inn (Parkway Mile Marker 334) and travel North on the Parkway (toward Boone) for 3.1 miles.
- Turn left off of the Blue Ridge Parkway and into the **North Carolina Museum of Minerals for field trip STOP No. 1.**

STOP No. 1 – North Carolina Museum of Minerals – 7:30 a.m. to 8:30 a.m.

- 8:30 a.m. depart Museum
- Leave the North Carolina Museum of Minerals and travel NC Highway 226 North toward Spruce Pine (left from leaving the museum).
- Travel 4.6 miles to Highway 19/226 North and take a left onto 19/226N.
- Travel 0.7 mile on 19E/226N and take a right continuing on 226N (Spruce Pine Bypass) toward Bakersville.
- Proceed 0.3 mile to Meadowlark Drive on right for **stop 2 (Spruce Pine Mines Overlook).**

STOP No. 2 – Spruce Pine Mines Overlook – 8:30 a.m. to 9:30 a.m.

- 9:30 a.m. depart overlook
- Leave Meadowlark Drive (right) onto Highway 226 North toward Bakersville (cross North Toe River).
- Travel 3.1 miles to Bear Creek Road (follow signs to Vulcan Materials -- Spruce Pine Quarry).
- Travel 0.4 mile and take right at the Y.
- Travel 0.7 miles to **Vulcan/Spruce Pine Quarry Entrance on right.**

**STOP No. 3 – Vulcan Materials – Spruce Pine Quarry –
10:15 a.m. to 11:15 a.m. (Coffee break also part of this stop)**

- 11:15 a.m. depart quarry
- Leave Vulcan (left on Bear Creek Road) and travel 0.7 mile and take left at stop sign.
- Travel 0.4 mile to Highway 226
- Left (South) onto Highway 226
- Travel 3.4 miles on Highway 226 to 19 E.
- Right onto 19 E (toward Burnsville) and travel 3.6 miles to Crabtree Road or left at Mitchell/Yancey County Line.
- Left on Crabtree Road and travel 0.6 mile and stay left at Y across bridge (follow signs to Emerald Village).
- Continue for another 4.1 miles to McKinney Mine Road or left.
- Left onto McKinney Mine Road for 2.3 miles to Chestnut Grove Road.
- Right on Chestnut Grove Road and travel toward the Blue Ridge Parkway for 0.9 mile.
- Circle left onto the Blue Ridge Parkway
- Travel South on the Parkway (toward Asheville) for 6.5 miles to left turn into **Crabtree Meadows picnic area.**

**STOP No. 4 – Crabtree Meadows picnic area –
LUNCH STOP -- 12 noon to 1:00 p.m.**

- 1:00 p.m. depart Crabtree Meadows picnic area
- Leave Crabtree Meadows picnic area by taking a right (North) on Blue Ridge Parkway.
- Travel 6.5 miles to Little Switzerland exit (at Little Switzerland Inn) and circle right to Chestnut Grove Church Road.
- Travel 0.9 mile and take a left onto McKinney Mine Road.
- Travel 3.1 miles on McKinney Mine Road to **entrance into Emerald Village on left.**

STOP No. 5 – Emerald Village – 1:30 p.m. to 3:30 p.m.

- 3:30 p.m. depart Emerald Village
- Leave Emerald Village parking lot and exit left onto McKinney Mine Road.
- Travel McKinney Mine Road for 0.2 mile to Crabtree Road.
- Right onto Crabtree Road and travel 4.7 miles to Hwy 19E.

- Turn right onto Hwy 19E (toward Spruce Pine) and travel 1 mile to Hoot Owl Road on right.
- Travel Hoot Owl Road for 0.4 mile to unmarked paved road on right (there is a NO OUTLET sign on the unnamed road).
- Travel 0.7 mile to cul-de-sac at end of road (where bus unloads).

STOP No. 6 – Hoot Owl Mine – 4:00 p.m. to 6:00 p.m.

- **Continue on foot onto dirt road for approximately 0.5 - 0.75 mile to Hoot Owl Mine entrance** (take right at y-intersection to cross small creek at half-way mark).
- 6:00 p.m. depart cul-de-sac
- Leave bus stage area and continue 0.7 mile to Hoot Owl Road.
- Left onto Hoot Owl Road and continue 0.4 mile to Hwy 19E.
- Left onto Hwy 19E (toward Burnsville) for 1 mile to Crabtree Road on left (at Mitchell/Yancey county line).
- Travel Crabtree Road for 4.7 miles to McKinney Mine Road on left (be sure to take left at y-intersection 0.6 mile from Hwy 19E across bridge).
- Take McKinney Mine Road 3.3 Miles to Chestnut Grove Road.
- Take right onto Chestnut Grove Road. And travel 0.9 mile to **Switzerland Inn on left (for banquet)**.

STOP No. 7 -- Switzerland Inn for banquet. – 6:45 p.m. to 8:00 p.m.

- 8:15 p.m. depart for Emerald Village and fluorescent minerals walk
- Leave Switzerland Inn and take right onto Chestnut Grove Church Road.
- Travel 0.9 mile on Chestnut Grove Church Road to McKinney Mine road on left. Take McKinney Mine Road 3.1 miles to parking area on the left at **Emerald Village**.

**STOP No. 8 – Emerald Village fluorescent minerals walk –
8:20 p.m. to 9:20 p.m.**

- 9:20 p.m. depart Emerald Village to return to Switzerland Inn
- 9:30 p.m. arrive at Switzerland Inn.

End of Field Trip Day 1

CGS Road Log for Sunday, November 2, 2008 Spruce Pine Mining District – Day 2

- **Busses LOAD at 7:00 a.m. and LEAVE at 7:15 a.m.**
- Leave Switzerland Inn and take Blue Ridge Parkway North toward Boone.
- Travel 17.6 miles to **Linville Falls entrance on right.**
- Travel 0.3 mile and take left (between the two bridges) into River Bend parking lot.

STOP No. 1 – Linville Falls Fault – 8:00 a.m. to 9:00 a.m.

- 9:00 a.m. depart River Bend parking lot.
- Leave River Bend parking area and turn right out of parking area, travel 0.3 mile back to Blue Ridge Parkway.
- Take left on Blue Ridge Parkway and travel 23.1 **miles to the slide area**, park at Crabtree parking area on right at 23.3 miles.

STOP No. 2 – Crabtree Meadows Rock Slide – 9:30 a.m. to 10:15 a.m.

- 10:15 a.m. depart from the Crabtree parking area.
- Leave Crabtree parking area and travel South (right) onto Blue Ridge Parkway 16 miles to Mt. Mitchell State Park entrance on right. Take Mt. Mitchell Road 4.6 miles to **Summit parking area.**

STOP No. 3 – Mt. Mitchell State Park – 10:45 a.m. to 12 noon

- 12:00 noon - leave summit parking area.
- Leave Mt. Mitchell parking area and travel 4.6 miles to the Blue Ridge Parkway. Turn Left (North) onto Blue Ridge Parkway. Travel 21.4 miles and take right at Little Switzerland exit to the Switzerland Inn (headquarters).
- 12:30 p.m. arrive at Switzerland Inn

End of Field Trip Day 2 and the 2008 CGS Annual Field trip

STOP No. 1 – The Sink Hole at Bandana: A Blue Ridge mica mine reveals Its prehistoric past

By: Peter R. Margolin

Please see paper located in front part of this guidebook.

STOP No. 2 – Spruce Pines mines – Overlook and handout

*By: Samuel E. Swanson, Department of Geology, University of Georgia
Athens, GA 30602*

Please see paper located in front part of this guidebook.

STOP No. 3 -- Vulcan Materials Company -- Spruce Pine Quarry

By: Jim Stroud and Marion Wiggins, and Jeff Panther

Vulcan Materials Company's Spruce Pine Quarry in Spruce Pine, North Carolina was originally called the Bear Creek Quarry or Mayland Stone and was opened in 1978. It is located in the Blue Ridge Mountain Province. The topography at Spruce Pine Quarry consists of relatively steep terrain with high relief, typical of the Blue Ridge Province of North Carolina.

Spruce Pine Quarry is underlain by the Late PreCambrian Ashe Metamorphic Suite of the Spruce Pine thrust sheet. This thrust sheet is part of the Blue Ridge thrust complex and consists of amphibolite facies metasedimentary rocks. These rocks are described as amphibolite, biotite schist, biotite-amphibole gneiss, and biotite-amphibole schist. Quartz veining is widespread.

The major minerals observed in these rocks are feldspar, amphibole, biotite, and quartz. Garnet and pyrite are also evident in trace (<1 to 1%) to accessory amounts (1 to 5%). These rocks are relatively hard and competent. Metamorphic foliations or trends in the quarry area consistently strike northwest and dip to the southwest.

The major geologic structure, which is a dominate foliation, causes unstable highwall conditions. Average strike and dip are N43W, 45SW. The rocks in the highwall bounding the east side of the old pit structurally dip into the pit. The combination of the direction of mining along strike of the deposit with the rock dipping into the pit and the lack of benching on the east side previously created a dangerous, unstable highwall

situation. Vulcan turned the bench orientation approximately east-west or perpendicular to the major structure in order to minimize hazardous mining conditions.

This rock is produced to provide quality construction stone (aggregate) to be used as the major ingredient to make asphalt and concrete. It is also used extensively in other construction projects such as base for highways and roads and as an erosion control material.

STOP No. 4 – Lunch stop

STOP No. 5 -- Emerald Village and the Seven Mines

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Emerald Village is a fascinating collection of mines buildings and attractions nestled into the beautiful Blue Ridge Mountains near Little Switzerland, North Carolina. Seven large abandoned mines dot the mountainsides at Emerald Village and offer evidence of man's long search for buried treasures. One of the mines, the Bon Ami Mine, is now home to The North Carolina Mining Museum, offering visitors the opportunity to go underground into a real mine. Another mine, the Big McKinney Mine, was once the world's largest Feldspar mine and today the abandoned mine is quite spectacular. The other five mines each offer a unique glimpse into our earth. Together these mines tell the historic story of mining, miners and minerals in this important part of the Spruce Pine Mining District.

Feldspar mining began at the Big McKinney mine around 1923 and continued steadily through the 1950's. The development of flotation separation for mixed ores spelled the end of these massive underground mines, although they were far from worked out. Vast underground operations were risky and expensive. Today, more than 54 gems, rocks and minerals have been documented from these seven mines, and the area remains a rockhound treasure chest. Other minerals sold from these mines over the years included mica, columbite, and beryl. Many minerals found here are extremely rare, such as Samarskite, Torbernite and the exquisite crystals of Pumpellyite documented in 1996 in the Mineralogical Record. The McKinney Mine is the only place in the Carolinas where this mineral has been found.

The mines were owned or worked by various companies over the years, and in some cases workers in different mines mined within a few feet of each other. Sometimes only a thin wall remained between the workings. During depression years the mines offered some of the only work available in the area, and old-timers recalled lines of would-be workers on the road, just waiting for someone to get hurt or quit. Average wages at that time were 10 cents an hour for 10 long hard hours a day.

The mines were abandoned in the early 1960's and allowed to fill up with water. Today the old mines offer mute evidence to the fierce determination and work ethic of previous generations of mountain people. Bob Schabilion of Flora, Mississippi, purchased the property in 1979. Bob was well known for his preservation of the Mississippi Petrified Forest, and later for developing Gem and Lapidary Wholesalers and their "cover the country" schedule of annual wholesale gem shows.

One of his first actions was to blast a drainage ditch through solid rock to lower the water level of the Bon Ami Mine by 14 feet, to make the mine accessible today. After draining the mine, antique mining equipment was brought in and tracks were laid again. Historic steam engines, ore cars, air compressors, drills, winches, elevators and other almost-lost

pieces of equipment were placed in the Bon Ami Mine. Over the years the Bon Ami mine produced Feldspar for the Bon Ami Company. The well-known Bon Ami scouring powder is made up of 94% feldspar and 6% soap.

By the mid-1920's the Crabtree Railroad had been extended to within a couple of miles, but could come no closer due to the steep mountainous terrain. In early days, ore was carried by horse-drawn wagons to aerial tram-cars to be sent down the mountain to the waiting railroad. The entire valley rang with the steady sound of drills, trucks, winches, steam shovels, compressors and dynamite blasts. The combined work of hundreds of men along with powerful hoists and steam shovels steadily ate into the mountain. The process went on for decades. A few men made a lot of money but in truth most of the workers barely survived. Some miners walked for miles just to get to work every day. Gradually mining activity tapered off but sporadic mining continued into the early 1960's.

At a mine dynamite blasts were generally set off at the end of the day, to let the air clear and the dust settle overnight. In 1965, the "Big Boom" spelled the end of mining at the Big Deal Mine, another one of the 7 mines. Already reduced to a small operation, all of the mining equipment and trucks at this mine were buried by a misplaced huge dynamite blast. One of the miners recalled, "At least a million tons of rock came down that night." Soon after that, the mines were abandoned and a quiet stillness settled over the region.

Now, 28 years after opening, Emerald Village has grown to major tourist attraction status. Tens of thousands of visitors take the underground mine tour every year, and many more thousands of school children visit on group outings. The important history of this vital part of our mountain heritage is well-preserved and being shared with new generations. New exhibits have been added and plans call for an evolution and expansion of recreational and educational activities. A popular addition this year is the addition of night-time "Black-Light" tours in the underground Bon Ami mine. Equipped with shortwave ultraviolet lamps, visitors marvel at the vivid fluorescent colors of Hyalite Opal and other minerals in the darkened ceiling and walls of the mine.

Today, 90 years after the first load of Mica and Feldspar left these mountains, visitors still come from all over with visions of buried treasures. Most take home rocks and gemstones but the greatest treasures for many are fond memories of adventures shared in these beautiful and ancient mountains!

STOP No. 6 Hoot Owl Pegmatite Mine.

Park at school bus turn. The private road leading to the mine continues straight ahead. Note it is surfaced with pegmatite gravel. Walk along the trail a few hundred feet past the dumps to the mine.

The Hoot Owl mine, one of the larger pegmatite mines in the district, yielded feldspar and mica. It was worked chiefly from 1937 through World War II. It has been reported that sheet mica have been mined intermittently to as late as 1962. The connected cut and stopes at this site are about 500 feet long and up to 250 feet wide; workings went as deep as 150 feet. The mine is now abandoned and partly flooded.

Country rock comprises Alligator Back Metamorphic Suite (ABMS) metagraywackes, schists and amphibolites (Rankin et al., 1973; Raymond et al., 1989). These rocks represent Neoproterozoic to Early Cambrian rifted margin sedimentation and volcanism. Regional Ordovician to Silurian-aged Taconic metamorphism produced the prominent foliation and fold patterns seen within the country rock. The ABMS was later intruded by Devonian-aged granites and pegmatites that make up the Spruce Pine Plutonic Suite (Brobst, 1962; Kish, 1983; Rankin et al., 1991; Johnson et al., 2001; Trupe et al., 2003).

At the Hoot Owl Mine, the foliation of the enclosing muscovite-biotite gneiss, schist and minor amphibolite is cross cut by the pegmatite. A few country-rock inclusions or xenoliths are visible in the pegmatite body.

Based on information averaged from pegmatite mines in this district, it is estimated that of the total rock mined about 1.6% was recovered as block mica. Sheet mica pieces larger than 1.5 by 2 inches probably made up only about 10 percent of the block mica, or less than 0.2 % of the total rock mined. Feldspar recovery from the mined rock usually averaged from 20 to 30%. About 2 man-hours of labor were required to mine and handle each ton of pegmatite at the site.



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Stop No. 7 – Banquet stop (return to Little Switzerland for dinner then reboard buses for night fluorescent mineral Stop 8).

Stop No. 8 – Night fluorescent mineral viewing – Emerald Village.

DAY TWO

STOP No. 1 – New Exposure of the Linville Falls Fault

By: Peter R. Margolin, petermargolin@hotmail.com and Alex Glover

Four years ago, thanks to catastrophic flooding during hurricanes Ivan and Frances, which destroyed the Park Service's Linville Falls Visitor Center, scientists were provided with a new exposure of the Linville Falls Thrust Fault. At the west edge of the Grandfather Mountain window, less than a mile above Linville Falls, the Linville River cut a new but temporary channel across an ox-bow meander at a place called River Bend, less than a mile from the Blue Ridge Parkway. Although the channel was abandoned in less than a day--the time that elapsed for the river's floodwaters to subside--the effects of this event are still quite evident, and no attempt has been made to undo them. The chief effect was removal of a vast accumulation of soil, loose rock and vegetation as the temporary riverbed was scoured down to bedrock. The bedrock here is a sheet of Precambrian gneiss that is highly jointed as a result of its emplacement over Cambrian quartzite during a major episode of late Paleozoic thrust faulting. Thanks to the joint pattern in the gneiss, the river plucked out large angular blocks of gneiss during the several hours it flowed through its new channel. When the waters subsided, the newly scoured bedrock surface revealed substantial exposures of fissile mylonitic rock, a much larger exposure of the thrust fault mylonite than had ever been available before.



STOP No. 2 -- Crabtree Meadows Rock Slide – June 15, 1999 rock slide in interlayered metagraywacke and schist of the Alligator Back Formation near Crabtree Meadows.

By: Rick Wooten, Rebecca Latham, and Bart Cattanach.

Leaders: Rick Wooten, Bart Cattanach

Location: GPS latitude 35.81442 N, longitude 82.13971 W; approximately 0.2 mi (0.3 km) northeast of Crabtree Meadows.

PURPOSE: To observe lithologic and structural features in bedrock related to rock slope instability in a road cut through interlayered metasedimentary rocks of the Alligator Back formation.

WARNING: Be extremely careful around the rock cut. Rock slides and rock falls may occur suddenly without warning.

Background. The June 15, 1999 rock slide at this location blocked the Blue Ridge Parkway (the Parkway) for several days (Fig. 1). Rockslide debris included one intact block estimated to have weighed about 800-1,000 tons (725-907 metric tons) (A.Glover, personal communication). Periodic slope movements, primarily rock slides and embankment failures that make the Parkway impassable are costly to repair, and adversely affect communities that depend on income from tourism along the Parkway. Figure 2 shows the stop location on the Parkway, and other mapped slope instability features in the vicinity.

Identification and analysis of rock slope stability was a major part of the geologic and geohazards studies recently completed by the North Carolina Geological Survey (NCGS) along the North Carolina segment of the Parkway. That inventory identified 172 past-active or active slope movements including rock slides, rock falls, weathered-rock slides, embankment failures, and debris flows, as well as 138 locations (57 of which are also active or past active and 81 that have no known history of failure) that have the potential for future rock slides and rock falls. Rock slope failures occur for the most part along cut slopes and are generally confined to the Parkway corridor. Some of the inventoried embankment failures are subsiding roadway segments marked by arcuate cracks in the pavement. Other embankment failures, however, mobilized into debris flows triggered by rainfall from the remnants of Hurricane Frances in September 2004. A number of these roadway failures traveled down slope significant distances causing damage on land administered by the U.S. Forest Service (Collins, 2007).

Description. Figure 3 shows the current slope configuration along with structural and lithologic features that relate to the rock slope stability. Rock slope data were provided to the National Park Service in this format with the image and explanatory data hot linked to ArcGIS data layers showing point locations of observed instability features. Other examples of these rock slope stability assessments along the Parkway are given in Latham and Wooten (2005). Here, an undulatory dominant foliation parallels

compositional layering and dips generally about 30-45 degrees to the southeast out of the cut face. This surface forms the basal slip surface of the rock slide along thin schistose layers within metagraywacke and schistose metagraywacke. Northwest-striking fracture sets that dip steeply northeast form planar segments of the left-lateral release surfaces of the rock blocks along the northeast side of the slide scar.

The degree of weathering of rock masses relates to their strength and permeability; therefore, rock weathering classifications (in accordance with Williamson, 1984) are provided. Most of the rock at this location is weathered to the stained state. Exposed along the middle of the scar is a partly- to completely-decomposed graphitic, quartz, muscovite schist interlayer that is remoldable with hand pressure. A line of vegetation marks this zone of preferential weathering and seepage (Fig. 3). Seepage from this zone probably contributed to destabilizing pore-water pressure along the basal failure surface of the rock slide.

Acid-Producing Potential. Acid-producing rocks are common in the western and central Blue Ridge. Bryant and others (2003) summarize many of the geotechnical problems associated with acid-producing rocks. Acid runoff can occur when these rock types are freshly exposed accelerating the weathering and hydrolysis of sulfide minerals such as pyrite and pyrrhotite. Acid-producing rocks can also be a factor contributing to slope instability. Schaeffer and Clawson (1996), and Douglas and others (2007) reported means to identify and treat acid-producing rock types encountered in road construction. Bogucki (1976) and Clark and Ryan (1987) reported debris slides and flows, and Wooten and Latham (2004) reported embankment failures that mobilized into debris flows related to acid-producing rocks.

NCGS studies along the Parkway included identification of sulfide-bearing lithologies that are potentially acid producing. Selective sampling and testing of rock exposures suspected of having acid-producing potential helped quantify the range of acid-producing potential. Results of net neutralization potential (NNP) testing (Fig. 4) show lithologies within the major map units identified as having acid producing potential. A metagraywacke layer exposed at the northeast part of the outcrop at this stop (Fig. 5, CER-002 in Fig. 2) was tested because the iron-oxide staining and gypsum blooms on the weathering surface are characteristic of weathering sulfide minerals, chiefly pyrite and/or pyrrhotite. The graphitic muscovite schist exposed in the slide scar was not tested because of its advanced weathering state; however, it is likely that it contains significant sulfide minerals in the stained and visually fresh weathering states as do several other graphitic schist units exposed along the Parkway (Fig. 4). The advanced weathering, and hence the permeability of the schist layer here, may be due in part to the presence of sulfide minerals.

Summary. Here as in many rock slope failures along the Parkway, several factors combine to result in rock slope instability: Ductile structural features like foliation and compositional layering that define the slide surface dip toward the roadway and are

undercut by the cut slope. Brittle features like fractures form the back and lateral release surfaces allowing the rock block to detach from the rock mass. In this case, accelerated weathering enhanced the permeability of the of the sulfidic, graphitic schist layer surface contributing to excess pore-water pressure that probably triggered the rock slide.

Acknowledgements. Funding for the geologic inventory of the North Carolina segment of the Blue Ridge Parkway was provided in part by the National Park Service. The Asheville Geotechnical Unit of the N.C. Department of Transportation is gratefully acknowledged for providing essential technical support by conducting the net neutralization potential testing. Tom Collins with the U.S. Forest Service provided much useful information on landslides affecting National Forests in North Carolina, and many thought-provoking discussions on landslide hazard mapping and loss prevention.

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Figure 1. Photograph of the July 15, 1999 rockslide blocking the Blue Ridge Parkway. Photograph courtesy of Alexander Glover, Active Minerals Inc.

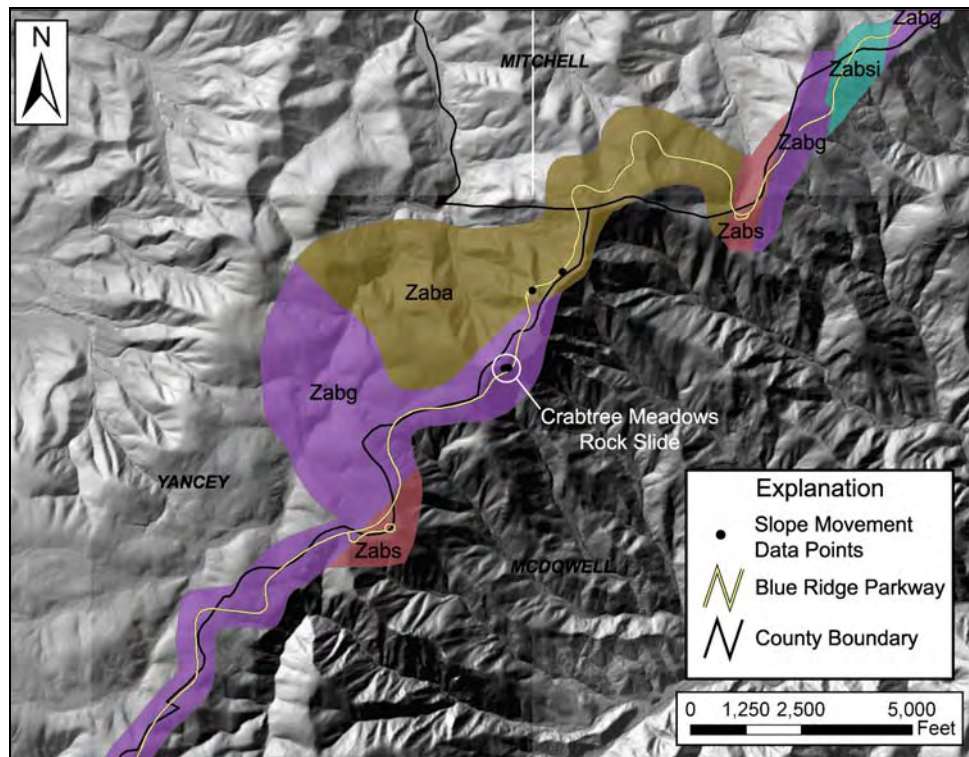


Figure 2. Map showing the location of this stop on the Blue Ridge Parkway, bedrock map units, and other slope movements cataloged during the geologic and geohazards inventory of the Parkway. Rock units within the Alligator Back Metamorphic Suite: Zabs – mica schist interlayered with metagraywacke and amphibolite; Zabg – muscovite, biotite metagraywacke interlayered with mica schist, amphibolite and metasiltstone; Zaba – amphibolite interlayered with metagraywacke and mica schist; Zabsi – muscovite, biotite, schistose metagraywacke interlayered with metagraywacke and mica schist. Map base is a shaded relief map developed from a 6m pixel resolution, Light Detecting And Ranging (LiDAR) digital elevation model.

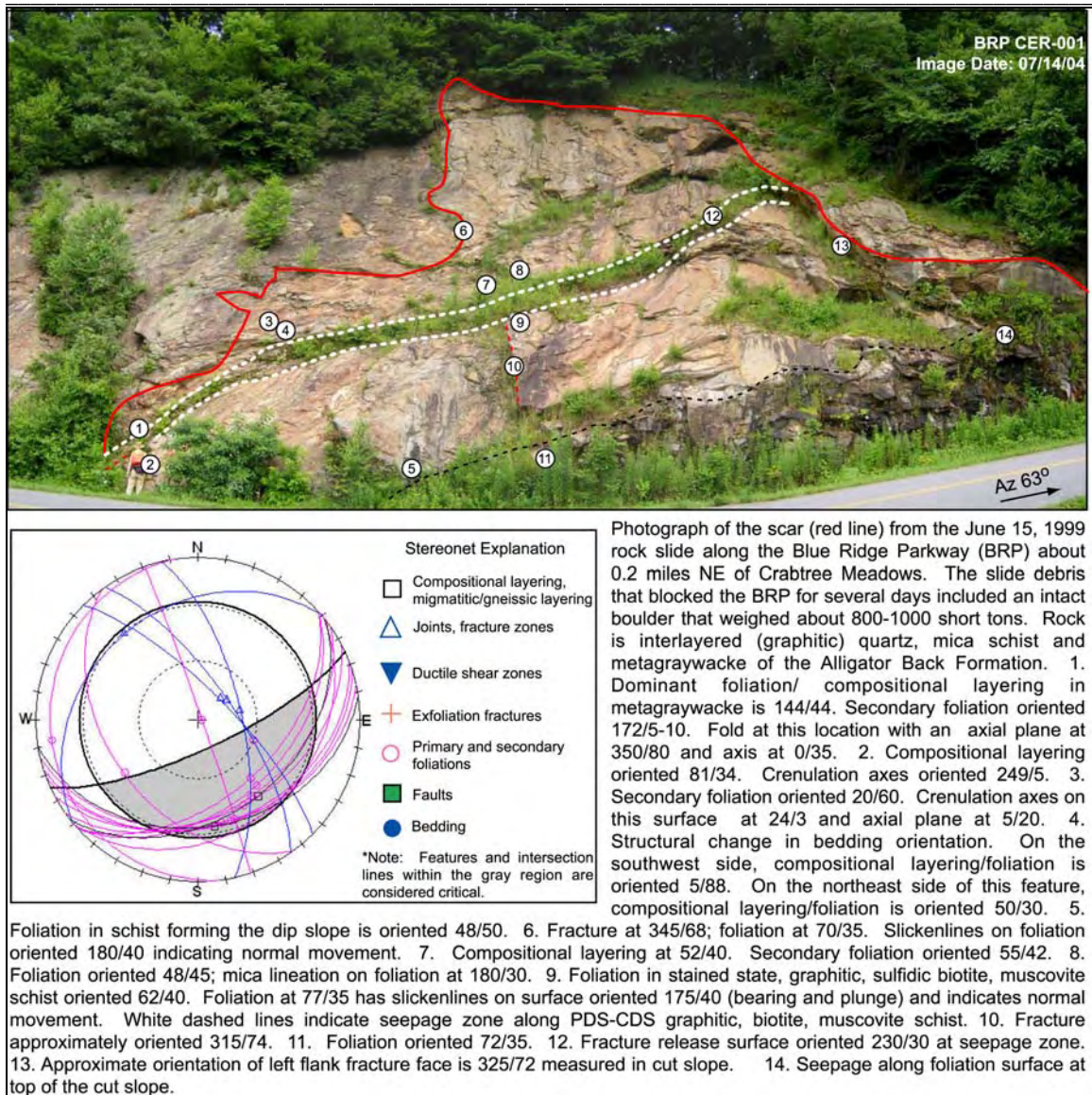


Figure 3. Lithologic and structural details on the rock slope exposed by the June 15, 1999 rockslide. Rock slope data were provided to the National Park Service in this format are hot linked to ArcGIS™ data layers giving point locations for observed instability features. The stereonet kinematic analysis (Watts and others, 2003) confirms that the potential exists for additional rock slope failures at this location. The dip vectors and intersections of great circles that plot within the gray region defined by the assumed friction angle and the azimuth of the cut slope are considered the critical planar structural elements susceptible to sliding.

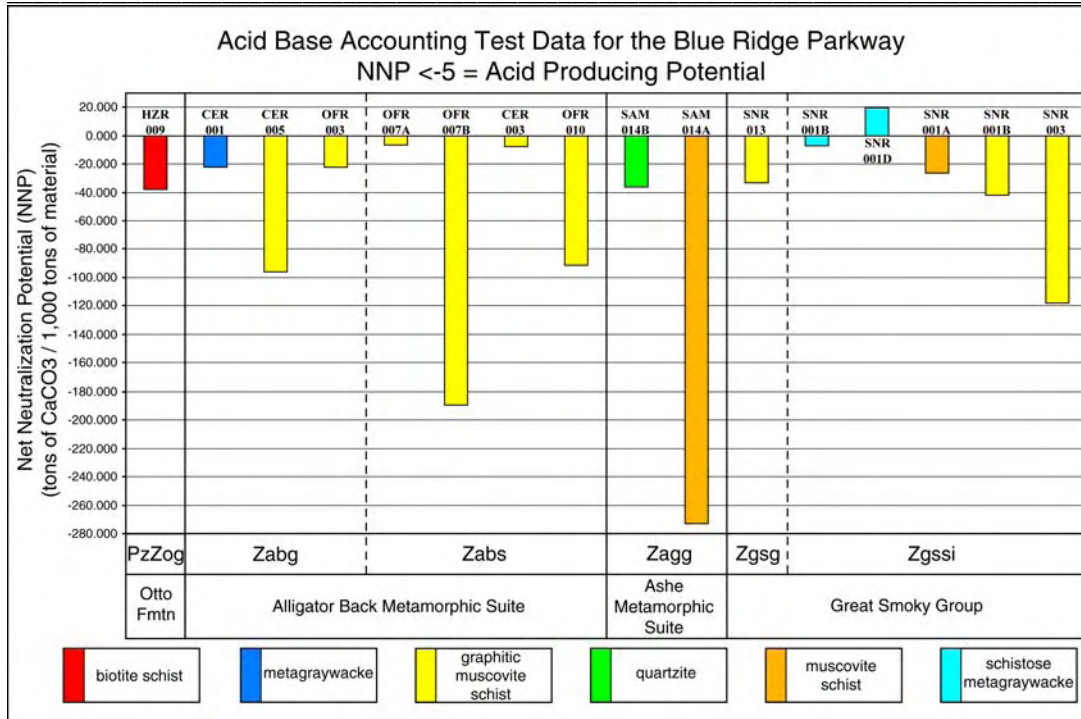


Figure 4. Chart showing the Net Neutralization Potential (NNP) test results for sixteen samples categorized by rock types and grouped within mapped bedrock units along the BRP. Data point numbers for outcrop locations are shown for each color bar. Letters after the same data point numbers indicate different samples tested from one data point location (e.g., OFR-007A, OFR-007B). Sample CER-001 is the metagraywacke in the Alligator Back Metamorphic Suite sampled at this field trip stop location.



Figure 5. White gypsum blooms, yellow (jarosite?), and dark orange oxide coatings on sulfidic metagraywacke exposed adjacent the June 15, 1999 rockslide (CER-001) near Crabtree Meadows. The NNP test value for this rock was -22.02 as shown on Figure 4.

Stop No. 3 – Day 2 – Mount Mitchell State Park and Return to Little Switzerland and end of field trip.