SEGSA Guidebook article:

The Petrogenesis and Tectonic Implications of Blue Ridge Mafic-Ultramafic Rocks: The Buck Creek and Carroll Knob complexes, and rocks of the Addie-Willets region

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INTRODUCTION

Isolated mafic and ultramafic rock units are scattered throughout the central Blue Ridge from Alabama to Maryland (Misra and Keller, 1978; Misra and McSween, 1984; Misra and Conte, 1991). The petrogenesis of some of these bodies is well documented (i.e., the Bakersville metagabbro, and mafic volcanic rocks of the Mt. Rogers and Grandfather Mountain Formations: Goldberg et al., 1986; Rankin, 1993), but most are poorly understood. A primary scientific goal of the WCU-USF Blue Ridge Research Experiences for Undergraduates (REU) Site research program has been to document the origins and tectonic significance of these units through careful, detailed field, petrologic, and geochemical characterization. For each of 4 summers, 12 undergraduate researchers, mentored by WCU and USF faculty conducted detailed field mapping and sampling and geochemical and petrologic characterization of all mafic and ultramafic rock types encountered. Students participated in field-based geophysical studies of the ultramafic bodies during the last two years of the project. The Buck Creek ultramafic body within the Chunky Gal Mountain mafic complex provided the research target for the 1997 and 1998 field seasons (Stonesifer et al., 1998; Collins et al., 1998; Slusser et al., 1998; McCoy et al., 1999; Thomas et al., 1999; Morman et al., 1999). The extensive geochemical database tied to detailed field observations that resulted from our work at Buck Creek provided the context to explore other mafic and ultramafic rocks in the region, including the Carroll Knob complex (Bierly et al., 2001; Dean et al., 2001; Meyer et al., 2001) in the 2000 field season and in 2001, the ultramafic and mafic rocks in and around the hamlets of Addie (Webster-Addie complex), Willets, and Balsam Gap (Soraruf et al., 2002a; Primm et al., 2002; Doughty et al., 2002). Several individual post-summer student research projects contributed to our understanding of these bodies including expanded geochemical characterization of the amphibolites at Buck Creek (Simons et al., 1998;

Slusser et al., 1998), REE analysis of Buck Creek rocks (Berger et al., 2001), petrologic studies of the metamorphic reaction textures in Buck Creek rocks (Lang et al., 2004), detailed analysis of pyroxenitic horizons in the Addie dunites (McIlmoil et al., 2002) and rare-earth element characterization of Addie-Willets amphibolites (Soraruf et al., 2002b).

GEOLOGICAL SETTING

The Blue Ridge of the Southern Appalachians has been broadly subdivided into Western and Eastern provinces (Rankin, 1975; Hatcher, 1978) (Fig. 1). The Western province is dominated by Late Proterozoic metasedimentary rocks that have been interpreted as slope and rise sediments deposited along the proto-North American continental margin, and by Grenville-age (~ 1 b.y.) basement massifs. The Eastern province includes metasedimentary, meta-volcanic, and meta-ultramafic rocks of oceanic affinity. In southwestern North Carolina and northeastern Georgia, the pre-metamorphic Hayesville Fault (Fig. 1) separates Late Proterozoic rocks of the Tallulah Falls Formation (Hatcher, 1971) and Coweeta Group (Hatcher, 1979) in the eastern Blue Ridge from rocks of the Ocoee Supergroup in the western Blue Ridge (Hatcher, 1978). Ultramafic bodies are present in both Eastern and Western Blue Ridge; however in southwestern North Carolina they lie predominantly east of (above) the Hayesville Fault (Hatcher et al., 1990; Misra and Keller, 1978). Peak Taconic metamorphic conditions within the Eastern Blue Ridge reached amphibolite and locally granulite facies (Absher and McSween, 1985; Abbott and Raymond, 1984; Goldberg and Dallmeyer, 1997) with locally preserved eclogites (Willard and Adams, 1994; Abbott and Raymond, 1997; Abbott and Greenwood, 2001) and other high pressure assemblages (Tenthorey et al., 1996; Emilio, 1998).

Meso- to macro-scale block-in-matrix structures are common throughout the North Carolina Blue Ridge (Raymond et al., 1989). Because of the ambient amphibolite to granulite grade metamorphism preserved in the Eastern Blue Ridge of southwestern North Carolina, the most easily recognized blocks are of mafic, ultramafic, or carbonate composition. Raymond et al., (1989) have identified two belts of rocks containing widespread block-in-matrix structures, the Toe and Cullowhee terranes (Fig. 1), interpreting each as part of a tectonic mélange formed within an accretionary complex. Hatcher et al. (2004) and Hatcher and Merschat (2005) map these two belts as parts of the Cowrock and Cartoogechaye Terranes, and the Dahlonega Gold Belt, based primarily on zircon dating results. Our field areas all fall within the Cartoogechaye Terrane of Hatcher et al. (2004).

Most of the ultramafic bodies within the Cullowhee/Cartoogechaye Terrane are small, and are dominated by metadunite with locally significant modal enstatite (bronzite) (Yurkovich, 1977; Honeycutt, 1978). Among the larger bodies, the Buck Creek and nearby Lake Chatuge bodies comprise recrystallized dunites interlayered with metamorphosed troctolite (e.g. Hadley, 1949; Hartley, 1973) while the Webster-Addie body, by contrast, appears to be a domed layer of dunite with interlayers of pyroxenite and/or websterite. Isotopic studies on mafic rocks from the Buck Creek, Lake Chatuge, and Webster-Addie complexes (Shaw and Wasserburg, 1984) point to depleted mantle sources for Buck Creek and Lake Chatuge while Webster-Addie preserves nearly chondritic ($\varepsilon Nd \approx -1$) isotopic signatures.

RESEARCH PROGRAM AND APPROACH

The data and interpretations presented here derive from the mentored research of 48 undergraduate participants in an NSF-funded Research Experiences for Undergraduates (REU)

Site program over 4 years (1997-1998, 2000-2001). During each summer of the project, 12 students worked together during a 7-8 week summer program on a common research goal. Approximately the first half of the summer program was field-based at Western Carolina University and the second half, based at the University of South Florida in Tampa, focused on geochemical, petrographic, and geophysical analysis and data interpretation. All students participated in compilation of results, which they presented at the GSA Southeastern Section Meeting following their summer activities.

Approach to field observation. Existing geologic maps were used as a framework for focused mapping to better understand the character of the different lithologies and the nature of the contacts between them. The maps used most extensively were Hadley's (1949) 1:6000 scale map of the Buck Creek body, along with several more detailed maps of specific parts of the body; maps of the Chunky Gal complex (Fig 2a) (McElhaney and McSween, 1983; Lacazette and Rast 1989); for the Carroll Knob complex, the 1:24:000 scale map of the Prentiss, NC Quadrangle (Hatcher, 1980) that includes a 1:14,400 scale geologic map of the Coweeta Hydrologic Station; the 1:24:000 mapping in the vicinity of the Webster-Addie complex by Quinn (1991); and maps of the Balsam Gap body in Honeycutt (1978). Mapping, field observations and sampling were completed by teams of three students with ongoing mentoring by faculty. Detailed maps linked to geochemical and petrographic samples were developed each field season. Standard hand-sample and microscopic petrography was done during the summer program to confirm mineralogy and map unit distinctions, and to identify interesting textures. More extensive petrographic studies, including microprobe studies, were conducted by individual students as part of post-summer independent research.

Geochemical Sample Selection: Initial selection of samples for geochemical analysis was based on student mapping results, with the paired goals of characterizing the major mapped units, and the examination of contacts between units. Samples were also taken of unusual rock types discovered during fieldwork, and to test hypotheses developed by participants in previous years. Between 50 and 90 samples were collected and analyzed each year for bulk chemical and lithophile trace element abundances, using the Direct Current Plasma Emission Spectrometry facility in the Department of Geology at the University of South Florida. The undergraduate participants prepared and analyzed all samples under faculty oversight. Post-summer efforts by several REU participants led to a geographically more detailed sampling of some units or rock types.

During post-Summer research efforts by several REU participants, subsets of our sample suites (primarily amphibolites) were analyzed for Zr, Y, P and rare earth elements (REE) (see Berger et al., 2001). The REE results in particular became a very effective tool for identifying different amphibolite compositional types, and for constraining the igneous petrogenesis of these rocks.

FIELD AND GEOCHEMICAL RESULTS

THE BUCK CREEK COMPLEX

Map Units: The lithologic characteristics of our map units build on previous work, and are defined by a combination of field and petrographic descriptions, refined and interpreted using geochemical signatures. Like Hadley (1949), we identify two separate mapped areas of ultramafic rock within the complex. The main body is separated by a thin septum of amphibolite along its northern and eastern margins from the northeastern body (Figs. 2a, 2b). Our contacts are generally similar to those of Hadley (1949). The most notable exception is in the southeastern part of the complex, an area with few outcrops in and near the floodplain of Buck Creek (Fig. 2b). Hadley shows interlayered troctolite, troctolite amphibolite and dunite. We saw no bedrock exposure of troctolite in this area, and our experience is that troctolite is a ridge or knob-former. For this reason we modified Hadley's map to show this area as primarily underlain by dunite and amphibolite.

Dunite. Deformed and variably altered dunite constitutes approximately 90% of the Buck Creek body (Fig. 2b). When fresh, the dunite is dominated by equigranular, light-green olivine grains, 0.1 to 2.0 mm in diameter (Kuntz, 1964; Warner, 2001) with variably annealed textures, and up to 5 % chrome spinel (Warner, 2001). Alteration minerals, produced during metamorphic hydration of the dunite, include chlorite, serpentine, magnetite, talc, calcic amphibole and carbonates (Kuntz, 1964; Warner, 2001). Serpentine alteration follows olivine grain boundaries, fractures within grains, and larger veins and fracture fillings and is more resistant to weathering than the host dunite. Highly serpentinized dunite appears black and dense in the field, and is typically magnetic due to the presence of secondary magnetite. Chlorite alteration is nearly ubiquitous in dunite samples (see also Warner, 2001), but varies from spotty to complete. Chlorite-schist alteration of dunite is persistent along its contacts with meta-troctolite or amphibolite.

Metatroctolite. Metatroctolite within the Buck Creek body has a varied field appearance and mineralogy but a consistent troctolite chemistry (see below, also Emilio, 1998; Tenthorey et al., 1996). Three map units with troctolite chemistry are recognized (Figs. 2b, 2c) -- anhydrous metatroctolite, edenite-margarite schist, and actinolite-chlorite schist. Anhydrous metatroctolite and edenite-margarite schist are spatially associated and are particularly well exposed together in the vicinity of Corundum Knob (Fig. 2c; **STOP 1**). Most of the actinolite-chlorite schist is present in the separate northeastern ultramafic body (Fig. 2b; **STOP 3**).

Our **Anhydrous Metatroctolite** is generally equivalent to the 'troctolite' or 'troctolite-amphibolite' of Hadley (1949) and 'central troctolite' of Tenthorey et al., (1996). In many places fresh surfaces of the anhydrous metatroctolite have a distinct blue-gray color and fine microcrystalline texture. In coarser-grained samples, gray to white plagioclase, up to 15 mm, and pale green olivine, up to 2 mm, are visibly intermixed with and separated by bluish microcrystalline material. Hadley (1949) recognized the blue microcrystalline material as zoned coronas with enstatite adjacent to olivine and a pale blue symplectite adjacent to plagioclase. The fine-grained symplectite includes clinopyroxene-spinel, amphibole-spinel, and clinopyroxene-sapphirine intergrowths and formed at ≥850º C and <9-10 kbar under anhydrous conditions (Tenthorey et al., 1996; Lang et al., 2004). Clear reddish-brown, Cr-bearing spinel, a common minor constituent, contains sub-equal proportions of [MgAl] and [FeCr] spinel components. In the field, a bright green halo surrounding many spinel grains reflects Cr diffusion into surrounding minerals. Thus, it is probable that these spinel grains began as igneous chromites that re-equilibrated with surrounding olivine and plagioclase during metamorphism. In a few places troctolitic rocks have a greenish rather than bluish hue, presumably due to diffusion of Cr from spinel.

The anhydrous metatroctolite possesses several distinct field attributes. Not only does the microcrystalline coronal material lend a bluish hue, but it also makes the rock extremely hard, dense, and resistant to weathering. Thus, anhydrous metatroctolites are ridge-formers with weathered surfaces that have a characteristic knotty texture. Outcrops of anhydrous metatroctolites also commonly display a layered appearance. Distinct ~1-30 cm thick compositional layers can be identified within this map unit based on variations in modal plagioclase relative to olivine. Layers of nearly pure plagioclase or anorthosite occur, as well as thin layers of deep red-brown spinel. In many cases foliation, defined by preferred orientation of elongate plagioclase grains, closely parallels compositional layering, enhancing the appearance of layering on a weathered surface.

Our **edenite-margarite schist** unit (**EMS**) is generally equivalent to Hadley's (1949) edenite amphibolite and the 'marginal troctolites' of Tenthorey et al. (1996). This schistose unit is dominated by pale to bright emerald green edenitic to pargasitic amphibole ± silvery margarite (Emilio, 1998; Tenthorey et al., 1996; Hadley, 1949). Proportions of these two minerals are quite variable, so that locally the rock may be dominated by either phase. Plagioclase may also be volumetrically significant in the rock. Minor constituents visible in the field include red-pink to blue-clear corundum, purplish zoisite, and chromite. Emilio (1998) identifies the equilibrium assemblage preserved in these rocks as edenitic amphibole + plagioclase ± spinel ± corundum ± kyanite ± zoisite with secondary margarite and chlorite. The EMS assemblage formed during hydration of the troctolite near peak pressure conditions (~825º C and 12-14 kbar), following prograde anhydrous formation of the coronal symplectites. Corundum, the target of present-day ruby prospecting and historical mining at Buck Creek, originates from the EMS unit and from corundum-bearing veins. Strong coloration in the corundum is due to diffusive inputs of Cr from spinel.

The **actinolite-chlorite schist** (**ACS**) unit forms most of the narrow northeastern belt of ultramafic rock, north of the main body (Fig. 2b), that was originally identified by Hadley (1949) as talc-chlorite schist. Petrography and field observations indicate that actinolite and chlorite are the dominant minerals with minor and variable serpentine, carbonate, talc, and iddingsite

(Thomas et al., 1999). In the field the rock is soft and friable. Where fresh the rock has a well-developed schistosity. More commonly, the rock is relatively poorly exposed and deeply weathered with a splotchy rusty to red-brown appearance. Within the ACS unit, remnant olivine and chromite are present locally. Lenses of anhydrous metatroctolite are preserved in the northeast, where exposure of the unit is at its widest (**Optional STOP 3**).

Amphibolite. The Chunky Gal amphibolite (**STOP 2**) encloses the Buck Creek ultramafic rocks, isolating them from the surrounding metasedimentary country rock and separating the main body of ultramafic rock from the northeastern body (Figs. 2a, 2b). In addition, very small and previously unmapped outcrops of amphibolite are present near the top of Corundum Knob (**STOP 1**) in the midst of the main ultramafic body (Fig. 2c). Amphibolite texture varies from 'salt-and-pepper' to schistose to locally more gneissic. The amphibolite in the vicinity of the Buck Creek body contains black hornblende + plagioclase ± epidote ± pyroxene ± scapolite with accessory quartz, titanite, ilmenite, garnet, apatite, and rutile; and displays variably foliated poikiloblastic textures (Morman et al., 1999). Plagioclase abundance, relative to hornblende, varies from ~ 20% to 90% with the more plagioclase-rich rocks in close proximity to the ACS unit in the north. Plagioclase contents in the amphibolites vary from ~ An 25-45. Scapolite and epidote appear to replace plagioclase and hornblende, respectively, and titanite locally rims or occurs in symplectic intergrowths with ilmenite.

Amphibolite samples from this study did not fall neatly into Type I (pyroxene-scapolite-rutile bearing) and Type II (garnet-epidote-titanite bearing) categories defined by McElhaney and McSween (1983). Epidote and titanite are present in all amphibolite samples from this study, and relict clinopyroxene, while uncommon, occurred across the outcrop area. Scapolite seemed confined to samples collected to the north and west of the Buck Creek ultramafic body, but was also prominent in plagioclase-rich amphibolites. Garnet was not observed in any of the amphibolites mapped. No clear metamorphic distinctions were evident from our observations, as all the amphibolites included both prograde and "retrograde" metamorphic mineral assemblages, as well as relict ilmenite and pyroxene from original mafic igneous protoliths.

Pale green amphibolite. The pale green color of the amphiboles in the field and in thin section distinguishes this unit from the other amphibolites. The rock is typically well foliated and populated by roughly equal proportions of pale green amphibole and white plagioclase (~ labradorite), with minor but locally coarse zoisite. The rock is present in map-scale lenses associated with the northeastern ultramafic body along both the eastern and northern margins of the complex (Fig. 2b) and appears to grade into the darker Chunky Gal amphibolites in the field.

Contact relations: Sub-meter to map-scale interlayering of olivine-plagioclase rocks, varying from dunite through troctolite into anorthosite, is present throughout the Buck Creek complex, and is particularly well exposed on Corundum Knob. Outcrop-scale layering is evident within the metatroctolite. Centimeter scale rhythmic layering of metatroctolite and dunite is preserved in one of the northern trench outcrops on Corundum Knob. Map-scale interlayering is evident in Figure 2.

Hydration characterizes the contacts between the dunite and troctolite, suggesting that contacts served as pathways for hydrous fluids. Along exposed contacts, dunite is altered to chlorite schist. In several places on and near Corundum Knob, more hydrated edenite-margarite schists are marginal to anhydrous troctolite, separating it from dunite (Fig. 2c). Tenthorey et al., (1996) referred to EMS as 'marginal troctolite' for this reason. On the southern lobe of Corundum Knob, thick bands of EMS separate anhydrous metatroctolite from dunite along its entire margin. Elsewhere, map-scale lenses of edenite-margarite schist follow along at least one contact of most of the anhydrous metatroctolites (Fig. 2).

Contacts between the anhydrous metatroctolite and EMS or ACS appear sharp to gradational. Typically the contact between the more resistant anhydrous troctolite and its schistose, hydrated equivalent is distinct. However, the anhydrous rocks may display evidence for minor to moderate hydration near these contacts. On Corundum Knob, several samples of the anhydrous metatroctolite contain minor to moderate amounts of bright green edenitic amphibole. In thin section the amphibole appears to be replacing the coronal minerals. The contact between Chunky Gal amphibolite and Buck Creek ultramafic rocks varies from sharp and well defined to gradational and more difficult to pinpoint. Most commonly, amphibolite contacts with dunite appear to be sharp and contacts with troctolitic rocks are more gradational. In a few places a mineralogic and textural gradation from EMS to Chunky Gal amphibolite is preserved in outcrop.

Geochemistry: All of the lithologies of the Buck Creek complex are silica-poor (<52% SiO_2), very low in potassium (K_2O << 1% wt) and span wide ranges in MgO, Fe_2O_3, CaO, and Al_2O_3 concentrations. Most are silica under-saturated, based on their CIPW norms.

Table 1 includes compositional analyses for typical Buck Creek lithologies. Figure 3 plots of MgO vs. Al_2O_3 for the various Buck Creek rock types. Also plotted on this diagram are ranges in composition for the minerals olivine, plagioclase, and clinopyroxene, based on relict mineral compositions reported by Tenthorey et al. (1996), and on mono-mineralic rock samples analyzed in this study.

Dunite: The Buck Creek dunites examined in this study span a range in MgO concentration, consistent with the observations of Warner (2001), though most possess Mg numbers between 87 and 89. Minor variations in Al_2O_3 and CaO content appear to reflect trace normative or modal mineralogical differences. A number of ostensibly mono-mineralic dunites contained small, but significant CaO and Al_2O_3 concentrations, and preserve Al_2O_3:CaO ratios of ~2.0, consistent with plagioclase proportions. These dunite samples yield plagioclase in their CIPW norms, consistent with the presence of minor plagioclase in cumulate dunite protoliths. A smaller subset of our analyzed dunite samples show excess Al and little or no Ca, and generally contain significant modal spinel. These samples may represent original cumulate dunites with abundant chromite. Most of the dunite we examined had LOI values in excess of 5% wt., indicating considerable serpentinization.

Troctolite and related rocks: The map units anhydrous meta-troctolite, edenite-margarite schist, and actinolite-chlorite schist, all have geochemical characteristics consistent with olivine+plagioclase (troctolite) protoliths. Most of these rocks are characterized by an approximate 2:1 Al_2O_3/CaO abundance ratio. The troctolite-EMS-ACS rocks form a single linear trend running from the composition of relict troctolite olivine to relict troctolite feldspar (Fig. 3), suggesting these rocks all represent simple cumulates of olivine + plagioclase crystals in varying proportions. The anhydrous metatroctolites fall at the plagioclase-rich end of this array, while the ACS rocks fall toward the olivine rich end; EMS rocks overlap with both.

A small subset of the troctolitic rocks has Al_2O_3/CaO ratios <2, which generates pyroxene in CIPW norms, and indicates the probable presence of clinopyroxene in the protolith. These “gabbroic” troctolites populate the center of the compositional “cumulate triangle” (Fig. 3), and thus may represent plagioclase-rich gabbroic protoliths.

Amphibolite: Buck Creek amphibolites have compositional ranges of 45-52% SiO_2, 7-18% MgO, and 14-24% Al_2O_3. CIPW norms for amphibolites suggest gabbroic protoliths, and the fact that many are silica-undersaturated may imply a significant role for olivine. Na_2O contents for the amphibolites vary widely, from 0.6 – 4.5% wt., and do not vary regularly with other major elements, suggesting metasomatic additions of Na at some stage: K_2O contents, by contrast, are low, between 0.06 and 0.93%, with most samples <0.3% K_2O. We did not observe geographic variations in amphibolite compositions as suggested by MacElhaney and McSween (1983) or Lacazette and Rast (1989); however, amphibolite compositions do vary with proximity to Buck Creek dunite and troctolite. This variation is best seen in the abundances of immobile trace elements, particularly TiO_2. We identify two geochemically distinct amphibolite groupings, low-Ti and high-Ti amphibolites (Table 1).

High-Ti amphibolites have >0.8% TiO_2 (typically 1-2%) and span limited ranges in MgO, Fe_2O_3, CaO, and Al_2O_3. These rocks plot as a tight cluster (Fig. 3) partly outside of the "cumulate triangle", and occur at a greater map distances from Buck Creek dunite and troctolite exposures than Low-Ti amphibolites. The High-Ti amphibolites have overall higher incompatible trace element abundances, higher overall REE contents (10-15x chondrite levels) and distinctive, light rare-earth depleted REE patterns similar to those of modern mid-ocean ridge basalts (Berger et al. 2001; Fig. 4a)

Low-Ti amphibolites have <0.8% wt. TiO_2, show large variations in MgO, Fe_2O_3, Al_2O_3, and CaO, and plot within the "cumulate triangle" on Figure 3. Low-Ti amphibolites are found in close proximity to Buck Creek dunite and troctolite, and may grade into troctolite/EMS rocks (see below). Our one sample from the Pale Green Amphibolite map unit plots with the low-Ti amphibolites. Low-Ti amphibolites show overall low abundances of incompatible trace elements, and variably high concentrations of Ni, Cr, and Sr, elements compatible in olivine, pyroxene, and plagioclase, respectively. Rare-earth element abundances in these rocks are typically < 10x chondrite levels, and the REE patterns are variable in slope, with strong, positive Eu anomalies (Berger et al. 2001; Fig. 4b).

CARROLL KNOB COMPLEX

The Carroll Knob complex is the largest and most lithologically diverse of the amphibolite/ metagabbro bodies exposed ENE of Buck Creek (Fig. 1). Earlier work on the Carroll Knob complex by Hatcher (19810) and Hatcher et al., (1984) documented the existence of lenticular bodies of altered dunite within extensive amphibolite exposures (Fig. 5a). The Carroll Knob Complex is enclosed in metasedimentary rocks of the Tallulah Falls Formation and Coweeta Group (Hatcher, 1980). Our work in the Carroll Knob complex focused on two small areas, the type Carroll Knob (CK) area and the Jones Creek (JC) area (Fig. 5), both of which included multiple lithologies in outcrop. As rock exposures are limited across the Carroll Knob complex, geophysical surveys using multiple methods (magnetic, refraction seismic, resistivity, electromagnetic, and ground penetrating radar) were conducted toward trying to recognize unit contacts in areas of poor exposure. Similar geophysical studies were undertaken at our Addie-Willets-Balsam Gap field sites the following summer, informed by our Carroll Knob experiences.

Map Units: We identified four mapable mafic/ultramafic lithologies within our focus areas in the Carroll Knob complex: altered dunite (including anthophyllite-talc schists), metapyroxenite, metagabbro, and amphibolite. In addition, small outcrop-scale lenses of metatroctolite and pale green amphibolite are present locally. Evidence of pervasive mid- to upper-amphibolite facies metamorphic conditions includes amphibole, Ca-plagioclase, garnet, and epidote in mafic rocks, anthophyllite and talc in ultramafic rocks, and staurolite and garnet in metasedimentary rocks.

Amphibolite. Amphibolite, the dominant rock type present in the Carroll Knob complex, ranges from massive to compositionally banded and foliated with amphibole and plagioclase plus variable epidote, sphene, garnet, quartz, biotite, and opaques. Amphibole is generally in greater or equal proportions to plagioclase and appears black in hand sample. Garnet, when present, ranges from fine pink grains to larger red grains.

Metagabbro and Metapyroxenite. Rocks defined as metagabbro and metapyroxenite are distinguished from amphibolites by coarser grain sizes, a lack of strong foliation, and the presence of pyroxene (or pseudomorphic amphibole after pyroxene). What appear to be relict cumulate textures were observed in a few large blocks. These rocks occur as isolated lenses (Fig. 5) or are found in close proximity to the metaultramafic rocks, particularly the anthophyllite-talc schists.

Altered Dunite. Rock assemblages interpreted to be altered dunite are present in elongate lenses (Fig. 6) of single rock types or mixed lithology. In some places the altered dunite is massive to foliated, preserving primary olivine and chromite, with locally extensive alteration to serpentine, talc, anthophyllite, and chlorite. Elsewhere, the unit is an anthophyllite-talc schist with variable chlorite, serpentine, and opaques, reflecting more complete hydrothermal alteration. Weathering of the chlorite-rich exposures yields a distinct bright red-orange soil coloration and localized saprolites.

Metatroctolite. Thin, outcrop-scale exposures of rock similar in appearance and geochemistry to Buck Creek metatroctolite are associated with and appear gradational to the altered dunites. Where freshest, these metatroctolites are massive to foliated and contain olivine, plagioclase and locally minor pyroxene. Coronal reaction rims between olivine and plagioclase are observed, similar to those seen at Buck Creek. Local outcrops of Pale Green Amphibolite, similar in appearance to that described at Buck Creek, are found in close proximity to metatroctolite.

Calcsilicate Unit. A hard, slabby, weakly foliated, quartz-rich calc-silicate unit with lesser plagioclase, diopside, hornblende, and locally garnet forms a discontinuous layer within the amphibolite and to the south of Carroll Knob.

Field Relations: Altered dunite, metapyroxenite, metagabbro and associated rocks form elongate, NE-trending, outcrop to map-scale lenses with foliation parallel to that in the dominant amphibolite near its southern contact (Fig. 5c). Contacts among the ultramafic units appear to be gradational, and lithologies are often interlayered on the meter scale. Petrographic and field relations suggest that the rocks observed in the Carroll Knob complex are similar to those found in the Buck Creek complex to the southwest.

Geochemistry: Elemental abundances of Carroll Knob amphibolites (Fig. 3, Fig. 4c; Table 1) are similar to those of Buck Creek amphibolites, and to modern oceanic gabbros. Carroll Knob dunites, amphibolites and troctolitic rocks overlap compositionally with samples from Buck Creek in Figure 3, but verge toward the plagioclase-pyroxene side of the "cumulate triangle". The Carroll Knob samples that have been analyzed for REE systematics possesses LREE-depleted, low abundance signatures consistent with pyroxene-rich gabbroic cumulates (Figure 4c). To a first order, igneous protoliths at Carroll Knob are similar to those at Buck Creek in that they represent an oceanic crust cumulate sequence. The more pyroxene-rich nature of Carroll Knob rocks may relate to origins in an active oceanic magmatic system, in which mixing of primitive and evolved lavas in a ridge-crest magma chamber results in the early crystallization of clinopyroxene (see Walker et al., 1979).

THE ADDIE, WILLETS, AND BALSAM GAP AREAS

Primary field targets of the 2001 Summer Program were the mafic and ultramafic rocks in and around the hamlets of Addie and Willets, NC, along with the Balsam Gap ultramafic body (Figs. 1, 6). Field areas targeted for detailed mapping, geophysical studies and geochemical characterization included the northeastern part of the Webster-Addie body from Addie to Chestnut Gap, the dominantly mafic rocks of the Willets area, and the Balsam Gap dunite body (Figs. 6, 7 - Soraruf et al., 2002a; Primm et al., 2002; Doughty et al., 2002).

Earlier maps of the Addie/Willets area were produced as part of broader field campaigns focused on characterizing the Webster-Addie ultramafic deposits (Madison, 1968; Condie and Madison, 1969; Cronin, 1983; Quinn, 1991). The Webster-Addie ultramafic body, with its distinctive ring-shaped map pattern, was mined extensively for olivine at several sites, most notably at Webster, Addie, and Chestnut Gap (Madison, 1968; Cronin, 1983; Quinn, 1991) (Fig. 6 and 7). Highly recrystallized, metamorphosed dunite is the most common rock type, but pyroxenites (orthopyroxenites, clinopyroxenites, and websterites) occur locally throughout the body. Podiform pyroxenite bodies within the dunite vary from 1-2 cm to several meters long. Hydrothermal fluid/melt exchanges, associated with cross-cutting trondhjemitic dikes, have locally altered the ultramafic rocks into mineralogically zoned hydrous assemblages that include talc, anthophyllite, vermiculite, Mg-chlorite, and locally magnesite and tremolite and a green Mg-rich hornblende.

Amphibolite and ultramafic bodies are locally in contact, but are more typically enclosed within variably migmatitic, metasedimentary biotite and/or muscovite schists and gneisses. The amphibolites are also present as lenticular outcrop- to map-scale bodies. The most pervasive amphibolite exposures are in and around the Willets community along US Highway 23/74 (Figs. 6, 7a; **STOP 8**). These and the associated metasedimentary rocks preserve evidence of polyphase, high temperature metamorphism with migmatite development: typically, the amphibolites consist of coarse-grained amphibole ± biotite± garnet melanosomes enclosed in coarse to spidery feldspathic leucosomes, while metasedimentary rocks show pervasive ptygmatic folding, a finer interleaving of leucosome and melanosome materials, and locally entrained blocks of amphibolite, granitoid rocks, and other lithologies **(STOP 5; STOP 10)** Cross-cutting pegmatitic dikes within the migmatitic amphibolite may represent coalesced leucosome.

Madison (1968) and Condie and Madison (1969) were the first to report on the structure and lithology of the Webster-Addie deposit in significant detail. Subsequent quadrangle-scale mapping studies by Cronin (1983) and Quinn (1991) refined the field geometry and outcrop pattern. Current structural interpretations suggest emplacement of the Webster-Addie dunite as a solid sheet, followed by deformation to produce a dome structure with a ring-shaped exposure pattern (Madison, 1968; Quinn, 1991). The dunite is poorly exposed on the eastern and western margins, but significant exposures are preserved elsewhere along the ring. Recent work suggests that rocks of the Cartoogechaye Terrane within the Webster-Addie "ring" are largely similar to those outside, although a window of Dahlonega Gold Belt rocks has also been mapped inside the ring (Cronin, 1983; Quinn, 1991; Hatcher and Merschat, 2005). Previous isotopic data from the Webster-Addie complex, mostly studies of Webster pyroxenites, point to a non-depleted mantle source (i.e., εNd ~ 0; Shaw and Wasserburg, 1984).

Map Units: Detailed mapping, typically at 1:6000 or finer scale in some quarries, resulted in a slightly revised map pattern of the northeastern region of the Webster-Addie body and Willets area (Fig. 7).

Ultramafic rocks. Our mapping indicates an even more dismembered and lenticular character in the ultramafic rocks than was observed by Quinn (1991) or others in this area. REU field results show the fairly thick ultramafic body exposed in Addie pinching out southward with several small lenses defining the arc of the Webster-Addie ring to the south toward Chestnut Gap (Fig. 7b). In the Chestnut Gap area, some small ultramafic lenses are offset from and oblique to the arcuate trend of the Webster-Addie map pattern (Fig. 7c).

Dunite is the most common rock type encountered in the Addie and Chestnut Gap deposits. The dunite has been variably altered to serpentine, shows classic annealed polygonal textures in some samples, and contains scattered grains and/or stringers of chromite. Hydrothermal fluid interactions with the dunite produced serpentine-rich vein assemblages consisting largely of coarse antigorite. The most common metasomatic assemblage in the Addie dunites relates to the intrusion of trondhjemitic dikes, and the dramatic chemical exchange reactions that occur in response to these intrusions. The contact assemblage is anthophyllite + talc + chlorite + vermiculite, grading from chlorite-rich assemblages near the dunite, through anthophyllite + talc and into vermiculite-bearing assemblages nearest the intrusion. The intruding igneous rocks are typically completely reacted with the enclosing dunite, and consist of feldspar + hornblende assemblages. Exposed walls at the Chestnut Gap quarry preserve numerous dike reaction coronas, and large zones of dunite in this locality have been pervasively altered to a magnesian amphibole + chlorite granofelsic rock.

Pyroxenite occurs as lenses in the dunite, ranging from a few cm to several meters across. Most of the smaller pyroxenite lenses are comprised of bronzitic enstatite, while the largest lenses contain significant diopsidic clinopyroxene, grading into websterite, which preserves an almost gneissic banding of diopside and bronzite. Pyroxenite lenses are sheathed in a tremolite + talc hydration assemblage, and pinch out into talc-rich stringers, defining a pervasive foliation in the dunite that follows the regional patterns.

Amphibolites. An extensive body of amphibolite is exposed in and around the Willets community. Smaller map- to outcrop-scale lenses and pods of amphibolite are exposed adjacent to the Webster-Addie ultramafic rocks or enclosed by metasedimentary country rocks in the Addie-Chestnut Gap region. (Fig. 7). The rocks consist of hornblende + feldspar ± biotite ± garnet ± quartz, locally, with minor titanite. The rocks are variably migmatitic, with amphibole + biotite + titanite melanosomes and feldspar + quartz leucosomes. The best migmatite development is observed in a large roadcut along US 23/74 in Willets and in the surrounding area (Fig. 7c). Amphibolite typically preserves the same regional folding and foliation patterns as the metasedimentary country rocks. Dikes and veins crosscut the amphibolites. Some ptygmatically folded dikes appear to be spatially associated with the migmatites and may represent anatectic melts.

Geochemistry

Typical Addie-Willits-Balsam Gap rock compositions may be found in Table 1. The amphibolites are typically more siliceous than those of Buck Creek or Carroll Knob. Plotted on a K_2O vs. SiO_2 classification diagram (after Gill, 1981; Fig. 8), Addie-Willets amphibolite compositions are generally more consistent with basaltic andesites and andesites, or their intrusive equivalents. By contrast, the amphibolites from Buck Creek and Carroll Knob plot as basalts, consistent with a mafic cumulate origin. Addie-Willets-Balsam Gap mafic rocks follow a distinctly calc-alkaline trajectory in an AFM diagram, in contrast to the definitive tholeiitic trajectory of the Buck Creek and Carroll Knob suites (Fig. 9). While it is possible to derive calc-alkaline and tholeiitic melts from similar mantle sources (Miller et al., 1992), dramatically different differentiation histories are required, pointing to different depths of melting and crystallization, and different mean volatile concentrations in the protolith melts. In Fig. 3, most samples from the Addie-Willets-Balsam Gap sites fall outside the "cumulate triangle": dunites and pyroxenites trend along the MgO axis at relatively low Al_2O_3 contents, while all but two of the amphibolites examined cluster at a relatively uniform Al_2O_3 content, consistent with lava compositions. The rare earth element (REE) patterns of Addie-Willets amphibolites range from flat to modestly light REE enriched at >10x chondrite abundance levels (Fig 4d), and contrast markedly with those of Buck Creek complex amphibolites. The overall abundances and patterns of the Addie-Willets suite are similar to a first order to those observed in amphibolites further NE in the Blue Ridge by Misra and Conte (1991). Webster-Addie clinopyroxenite preserves a "V" shaped REE pattern at the ~1x chondrite level (Fig. 4e), similar in shape and abundance level to an orthopyroxenite from Balsam Gap and one from the Moores Knob dunite to the SW. A Buck Creek clinopyroxenite sample shows a MORB-like LREE depleted pattern at ~10x chondrite levels, indicating a very different igneous origin, as a magmatic mafic cumulate. The similarity of the Webster-Addie, Balsam and Moores Knob samples point to similar igneous origins, if not similar source regions, for the protoliths of these dunite bodies, origins distinct from those of the Buck Creek and Carroll Knob complexes.

PETROGENETIC AND TECTONIC IMPLICATIONS

Our REU mapping and analytical results indicate that two different kinds of mafic-ultramafic rock associations are present in the southern Blue Ridge, reflecting different, but related tectonic environments.

Buck Creek, Carroll Knob: Buck Creek and Carroll Knob show similarities both in lithology and in rock chemistry. Fig. 3 offers a simple way to assess a possible mafic cumulate origin for both Buck Creek and Carroll Knob samples, assuming that their protoliths would be composed of minerals chemically similar to the relict mafic phases found in the samples (troctolites/ pyroxenites). From this diagram, most Buck Creek dunites, metatroctolites and EMS rocks can be explained as variable mixtures of magnesian olivine and calcic plagioclase. Low-Ti Buck Creek amphibolites, and many Carroll Knob amphibolites and metagabbros are consistent with cumulates of plag+cpx±ol. High-Ti Buck Creek amphibolites show similarities to a subset of Carroll Knob amphibolites examined in previous studies (i.e. Walter, 1990; Figure 3). Carroll Knob metatroctolite and altered dunite samples plot within the field of oceanic mafic cumulates, but differ from Buck Creek dunites and troctolitic rocks in that they likely had significant pyroxene in their protoliths.

The abundances of key compatible trace elements are also consistent with a cumulate origin for Buck Creek and Carroll Knob lithologies. Ni and Cr are elevated in Buck Creek dunites, and variably high in the metatroctolite lithologies; while Cr is somewhat more elevated than Ni in low-Ti amphibolites, indicating the involvement of pyroxene. Markedly elevated Sr contents in the metatroctolite lithologies indicate primary plagioclase, as does the presence of positive europium anomalies in amphibolite rare-earth element patterns (see Berger et al., 2001).

The high-Ti Buck Creek amphibolites plot as a distinct cluster in Fig. 3, along with some Carroll Knob amphibolites. All these rocks contain higher concentrations of the incompatible elements Ti and Zr, but markedly lower Ni and variably low Cr contents. The major element compositions of these rocks are not generally consistent with those of basaltic lavas, but they are not simple cumulates either. It is probable that these rocks represent gabbroic protoliths that include variable percentages of melt along with some cumulate crystals, or that they represent "isotropic gabbros" such as are found near the top of the gabbroic sequences in ophiolites. These rocks probably afford the closest approximations to the composition of the magmas parental to the Buck Creek and Carroll Knob suites, but are nonetheless gabbroic crustal rocks.

Based on norms and elemental characteristics, we infer that the protoliths of the different Buck Creek and Carroll Knob lithologies include cumulate dunites, troctolites, and gabbros, including gabbros with at least a partly non-cumulate character. These cumulate rocks are fully gradational in terms of their chemistries, suggesting continuously variable protolith assemblages.

Field constraints on Petrogenesis: Several field observations support an interpretation that the Buck Creek lithologies formed as part of a common cumulate assemblage. The thin, pervasive cm- to m-scale and locally rhythmic interlayering of dunite and metatroctolite along with thin, intercalated layers of spinel most likely formed as cumulate horizons in a magma chamber, as the preserved textures and igneous mineral associations are not consistent with tectonically-induced compositional banding. Competence differences between the amphibolites, dunites and metatroctolites in the Buck Creek complex may have focused deformation along unit contacts, as attested to by the apparent map scale disaggregation of metatroctolites along these contacts. However, the gradational changes from edenitic metatroctolites to hornblende amphibolites apparent in the field are paired with regular geochemical gradations, suggesting a genetic linkage.

Geochemical Constraints: Rare earth element systematics of Buck Creek amphibolites and the one Carroll Knob metagabbro examined also suggest a mid-oceanic origin. High-Ti amphibolite REE patterns of Berger et al. (2001) mimic those of MORBs, and the Low-Ti amphibolite patterns are consistent with pyroxene-plagioclase cumulates gabbros from ocean crust sections (Figure 4). Nd isotopic data on Buck Creek amphibolites suggest an εNd of +5 or higher, also indicative of a depleted, MORB-like, mantle source (Shaw and Wasserburg, 1984). All the major and trace element data available for the metamafic and ultramafic rocks at Buck Creek point to an igneous origin as a layered mafic/ultramafic sequence of mid-oceanic affinities, perhaps representing a sliver of ocean crust from Layer 3 and deeper. The mafic and ultramafic rocks of the Carroll Knob complex, while less well-preserved than those at Buck Creek, also point to ocean crust protoliths.

The Buck Creek and Carroll Knob complexes also show strong similarities to the Lake Chatuge mafic-ultramafic complex in northernmost Georgia. All three lie within the westernmost part of the Cullowhee olistostromal terrane of Raymond et al. (1989) and include interlayered mafic and ultramafic rocks that are similar lithologically (dunite-metatroctolite-amphibolite/gabbro), geochemically (signatures consistent with ultramafic/mafic crustal portions of "high Ti" ophiolites, see Fig. 4c), and in terms of metamorphic P-T trajectories (deep burial at >12 kbars, ~800C). Hatcher et al. (2004) include the Buck Creek and Carroll Knob complexes within the Cartoogechaye Terrane and the Lake Chatuge complex in the Cowrock Terrane. The Buck Creek and Lake Chatuge complexes lie in close proximity to the Hayesville thrust and may represent fragments of deeply subducted ocean crust uplifted during collision. The Carroll Knob complex lies further east of the Hayesville thrust and is dominated by amphibolites with much less extensive ultramafic rock occurrences. As well, the regional mid-amphibolite facies Taconic (?) metamorphic event has pervasively altered rocks at Carroll Knob, while at Buck Creek and Lake Chatuge this event is largely preserved as a later overprint on the predominant granulite facies assemblages. Although the Carroll Knob complex is lithologically less diverse than the other two associations, the rocks preserved are nonetheless consistent with an oceanic Layer 3 origin. Thus, all the major mafic and ultramafic bodies in this part of the Cartoogechaye - Cowrock terranes appear to be ophiolitic in character.

Tectonic environment of Addie-Willets mafic-ultramafic rocks: Mineral chemistry data indicating olivine Mg numbers >90 (Madison, 1968; Cronin, 1983; Doughty et al., 2002), and our bulk chemical data for the ultramafic rocks in the Addie-Willets area point to a residual mantle origin. However Addie-Willets amphibolites record bulk chemical and trace element signatures consistent with igneous rocks of intermediate, calc-alkaline composition (i.e., andesites and diorites; see Fig. 4c, 8,9). The mafic rocks of ophiolites are primarily basaltic/gabbroic in character. Even in “arc ophiolites” such as Troodos or Thetford-Mines, the mafic rocks are more silica-poor than seen in Addie or Willets (Robinson et al., 1983; Olive et al., 1997). The geochemical signatures of the mafic and ultramafic rock units argue against any direct petrogenetic connection between them; the andesitic protoliths of Willets amphibolites are not melts derived from the source that produced the residual ultramafic rocks at Addie. The lack of regular contact relationships between mafic and ultramafic rocks in the field provides support for this contention. While amphibolites are in contact with ultramafic rocks at several locations in the area, these rocks are equally likely to occur as small pods within mica schists, or as larger bodies with no associated ultramafic rock. It is likely, however, that both units represent the outcomes of magmatism in the same overall tectonic environment, i.e., both were most likely produced in a convergent plate boundary setting, as is typical of calc-alkaline igneous rocks today. Modern-day accretionary sequences, such as the Franciscan Complex or the Catalina Schist may include well-preserved blocks of ultramafic rocks (dunites and pyroxenites) in close proximity to volcanic and sedimentary rocks, all reflecting different portions of a disaggregating upper plate. The country rocks of the Addie-Willets area are distinctively olistostromal, typical of the Cullowhee olistostromal terrane as defined Raymond et al., (1989). Amphibolite, ultramafic and metasedimentary blocks are enclosed in metasedimentary matrix in several described Cullowhee terrane exposures to the south and east of Addie-Willets, along US 23/74 (Raymond et al., 1989). While more recent tectonic syntheses place the Addie-Willets units in the Cartoogechaye terrane, and other similar olistostromal rocks in the Dahlonega Gold Belt (Hatcher et al., 2004; Hatcher and Merschat, 2005), unquestionably the rocks of the Addie-Willets region are different in look and probable history from those enclosing the Buck Creek and Carroll Knob complexes.

Our favored working hypothesis for the petrogenesis of mafic and ultramafic rocks in the Addie-Willets area follows on the observations of Willard and Adams (1994) and Abbott and Greenwood (2001) to the northeast, and on the inferences of Raymond et al., (1989). These rocks and their surrounding metasediments, like those of the Ashe Metamorphic Suite, represent the blocks and matrix of an ancient subduction-related accretionary sequence. The high P/T metamorphic signatures characteristic of such sequences have been pervasively overprinted at Addie and Willets by several of the high-temperature collisional metamorphic events of the Blue Ridge, which provoked the development of migmatites and felsic dikes, domed and disaggregated the Webster-Addie ultramafic body, and produced the ductile deformation features observed pervasively in the Addie dunites and nearby schists and gneisses. Whereas the petrogenesis of the Buck Creek and Carroll Knob complexes point to a lower plate origin during the subduction and collisional events of the Taconic orogeny, rocks of the Addie-Willets are best explained as accreted fragments from the upper plate.

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Figure Captions

Article Figures:

Figure 1. Regional geologic map of the Blue Ridge province southwestern North Carolina and northeastern Georgia, as modified from Hatcher et al (2005). Numbered shaded areas show division into eastern (1), central (6) and western Blue Ridge (5), Grenville-age rock (2), and map-scale mafic (3) and ultramafic (4) bodies. The Cullowhee (6) and Toe (5) terranes (Raymond et al., 1989) generally correspond with the areas of the central and eastern Blue Ridge, respectively. Labeled features include the Hayesville thrust faults, and the Buck Creek, Webster-Addie, and Lake Chatuge ultramafic bodies. The Blue Ridge in this region is bounded to the west by the Great Smoky Mountain- fault and to the east by the Brevard Fault zone (not shown).

Figure 2. Geologic maps of the Chunky Gal and Buck Creek complexes 1 = amphibolite of the Chunky Gal Mountain complex; 2= dunite; 3 = metatroctolites; 4 = actinolite-chlorite schist + pale green amphibolite; 5 = metasedimentary rocks. a) Geologic map of the Chunky Gal Mountain complex (modified from Hatcher and Butler, 1979; and McElhaney and McSween, 1983), including the Buck Creek complex. Lettered boxes are STOPS 1-3. Box shows location of Figure 2b. b) Geologic map of the Buck Creek Complex modified from Hadley (1949). Box shows location of Figure 2c. c) Detailed geologic map of a portion of the Buck Creek Complex in the vicinity of Corundum Knob (STOP 1). In this figure 3a = anhydrous metatroctolites; 3b = hydrous metatroctolites.

Figure 3. Plot of MgO vs. Al_2O_3 Buck Creek, Carroll Knob, and Addie-Willets area rocks. Symbols and colors are as described on the diagram. "Cumulate triangle" is defined based on the compositions of relict olivine and plagioclase in Buck Creek anhydrous metatroctolites (Tenthorey et al. 1996), and the composition of clinopyroxenite samples from Buck Creek and Carroll Knob.

Figure 4. REE abundance patterns for a) High-Ti and b) Low Ti amphibolite subgroups for the Buck Creek complex, and c) for selected Carroll Knob and Lake Chatuge gabbroic rocks from Berger et al. (2001). c) REE patterns for Addie-Willets amphibolites, and d) for pyroxenites from Webster-Addie, Balsam Gap and the Moores Knob dunite, from Soraruf et al (2002), along with the REE pattern for Buck Creek pyroxenite BC98SM-11.

Figure 5. Geologic maps of Carroll Knob complex. a) Geologic map from the Prentiss Quadrangle (Hatcher, 1980) showing the distribution of mafic rocks (gray shading) and ultramafic rocks (black shading). Box outlines location of Fig. 5b and area of STOP 4. Star shows location of Carroll Knob. Cross near center of figure is 35^o 05' N, 83^{o}27'30"W. b) Detailed mapping from the Summer 2000 REU program in the area of Jones Creek Road ultramafic rocks (STOP 4). Shaded area shows the extent of ultramafic rocks. Several geophysical traverses (resistivity, seismic, ground-penetrating radar) were conducted along the road in this area. c) Detailed mapping from the Summer 2000 REU program in the area south of Carroll Knob showing interlayering of rock units near the amphibolite contact with the enclosing

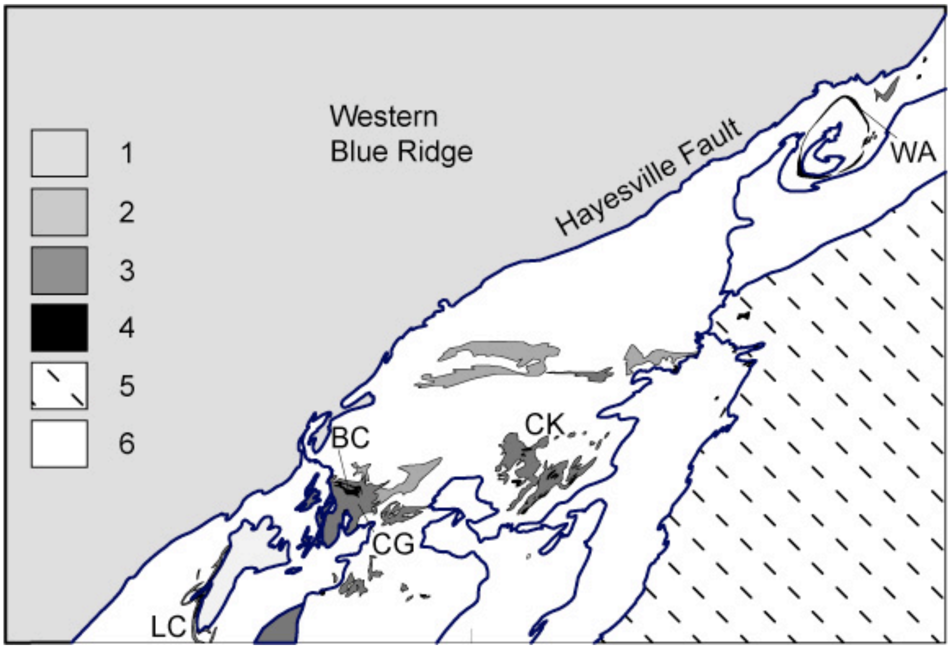
metasediments. Amphibolite (AM) = white; Metasediments (MG) = light gray; Ultramafic rocks (DNA) = intermediate gray; Metagabbro (PX) = darkest gray.

Figure 6. Schematic geologic map of the Webster-Addie Ultramafic body and associated mafic and ultramafic deposits. Addie-Willets field areas lie within the square. Modified from Brown et al., 1995 (NC State Geologic Map) and Quinn, 1991. BG: Balsam Gap dunite; DR: Dark Ridge dunite; WA: Webster-Addie ultramafic body.

Figure 7. (a) Close-up of the northern part of the Addie-Willets field area. Ultramafic and amphibolite unit exposures based on detailed mapping results from the 2001 Blue Ridge REU Site research program. (b) Close-up of segment of the Webster-Addie ultramafic deposit in and around Blanton Branch Road. Note adjacent amphibolite, and the discontinuous nature of the ultramafic units. (c) Webster-Addie ultramafic and mafic exposures at Chestnut Gap.

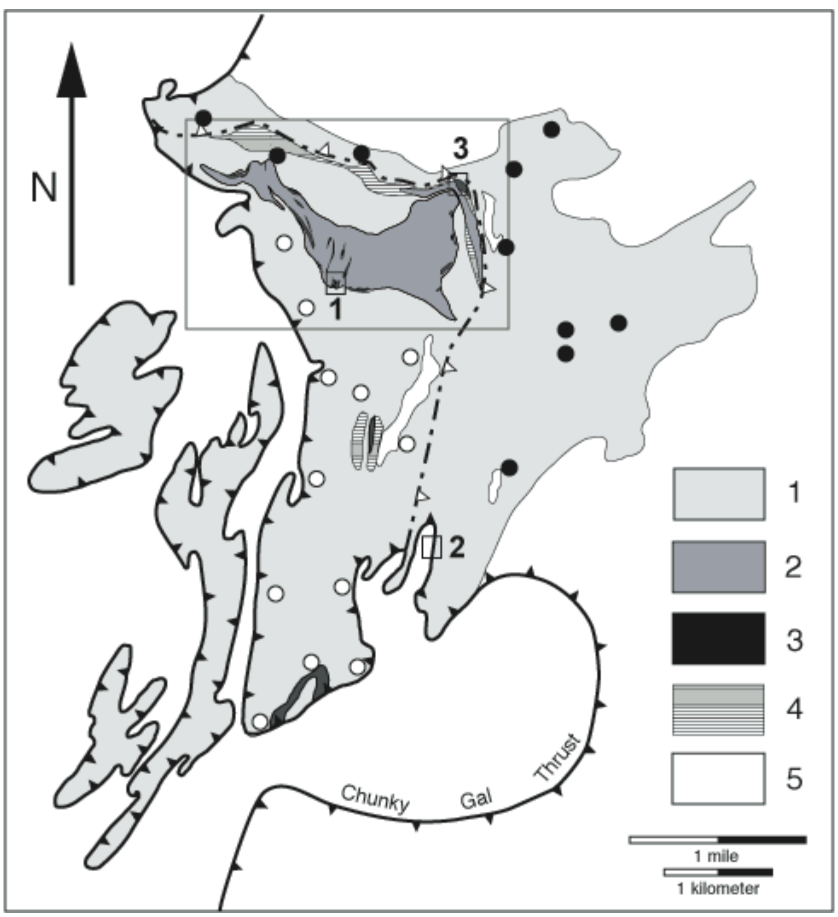
Figure 8. Plot of K_2O vs. SiO_2 for Addie-Willets, Buck Creek, and Carroll Knob amphibolites. Symbols and colors as in Figure 3

Figure 9. AFM diagram for Addie/Willets amphibolites, again with Buck Creek and Carroll Knob samples for comparison. Symbols and colors as in Figure 3.



1
2
3
4
5
6
Western
Blue Ridge
Hayesville Fault
WA
BC
CK
CG
LC

Figure 1



N
3
1
2
Chunky
Gal
Thrust
1
2
3
4
5
1 mile
1 kilometer

Figure 2a

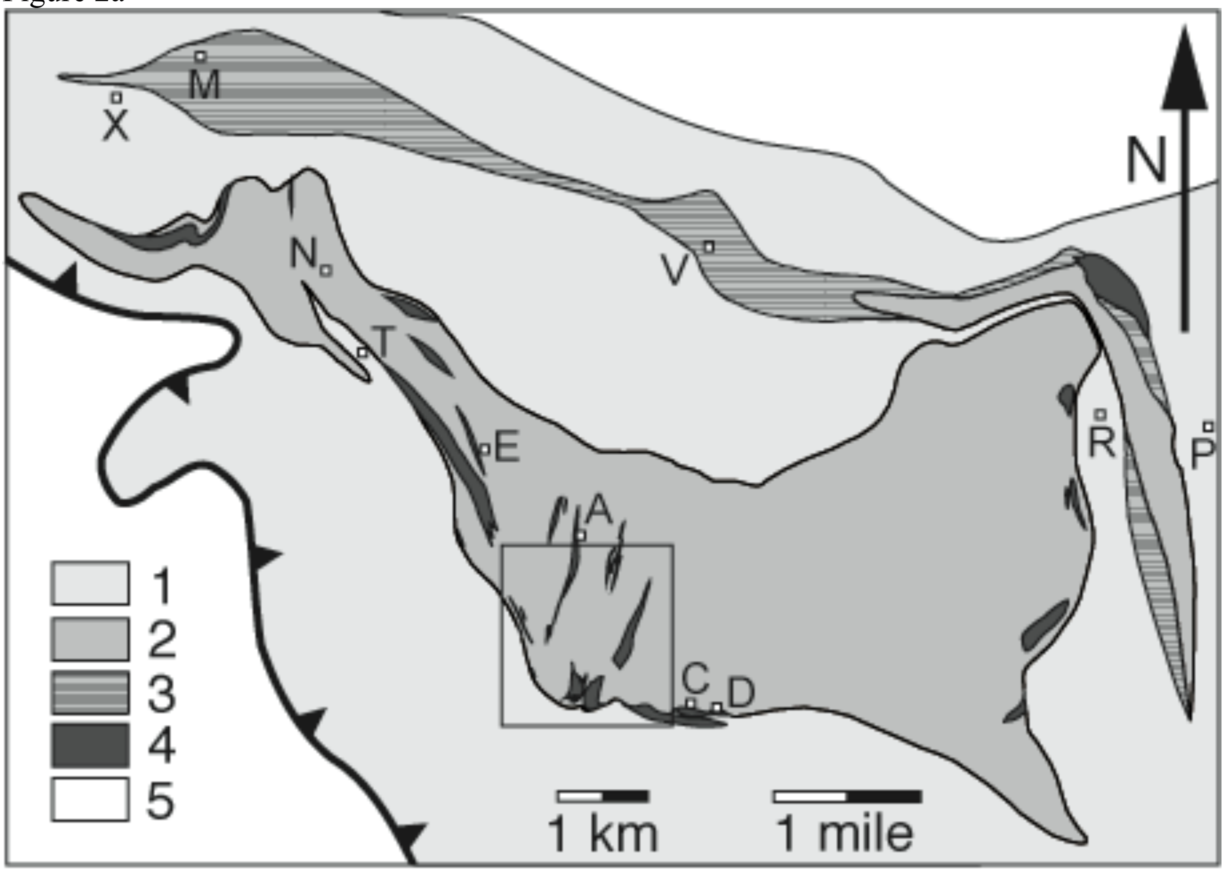


Figure 2b

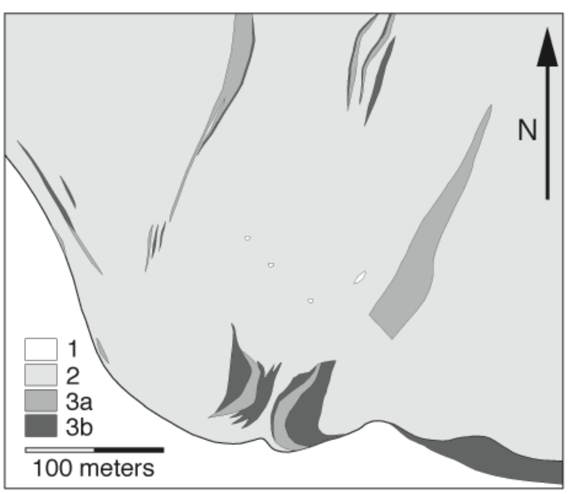
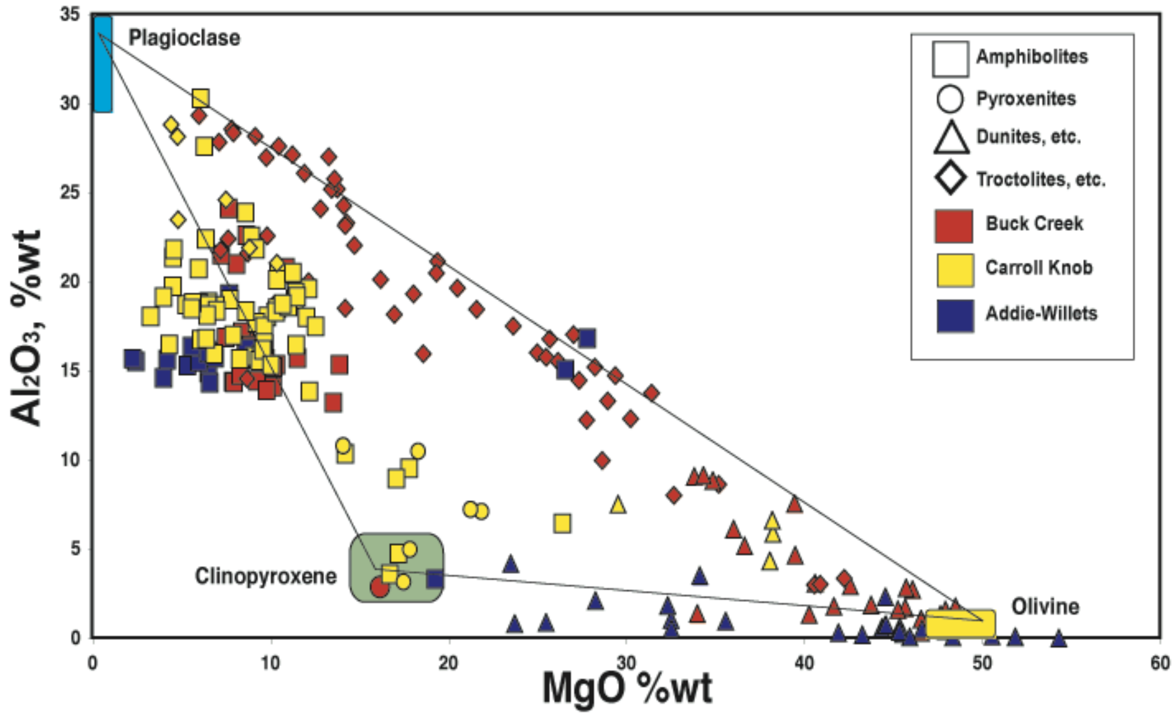


Figure 2c



Plagioclase
Clinopyroxene
Olivine
Amphibolites
Pyroxenites
Dunites, etc.
Troctolites, etc.
Buck Creek
Carroll Knob
Addie-Willets
Al2O3, %wt
MgO %wt
0
5
10
15
20
25
30
35
0
10
20
30
40
50
60

Figure 3

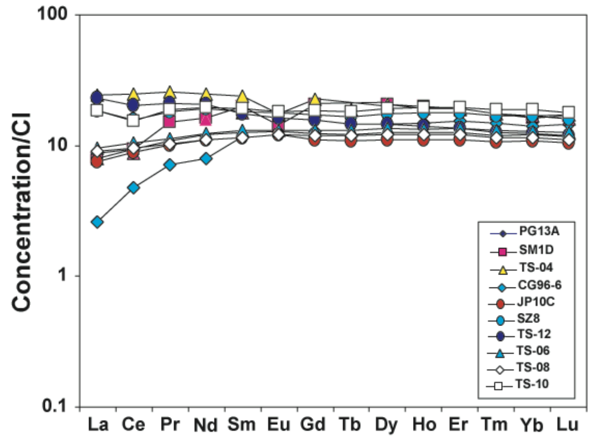


Figure 4a

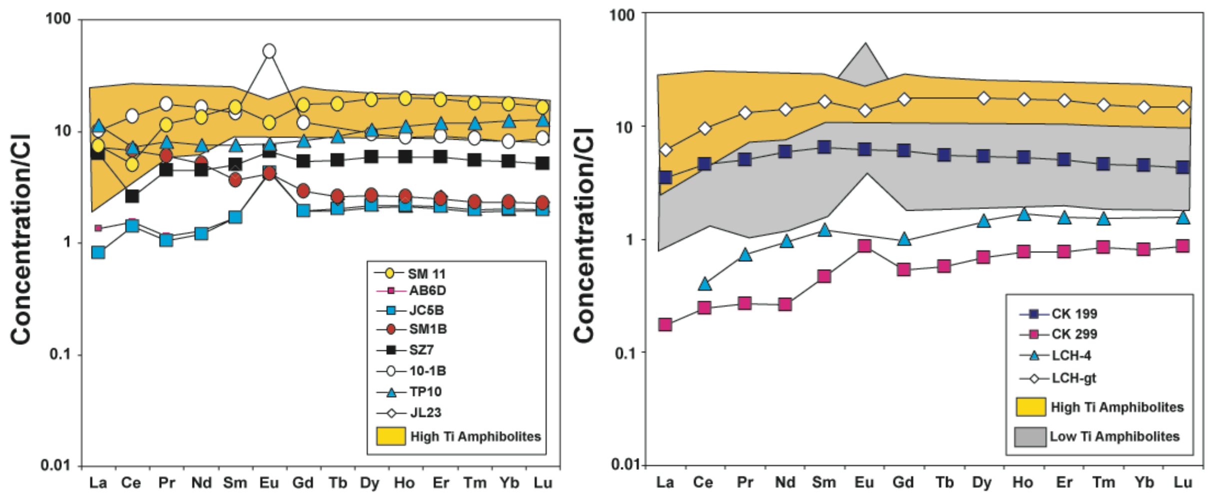


Figure 4b, 4c

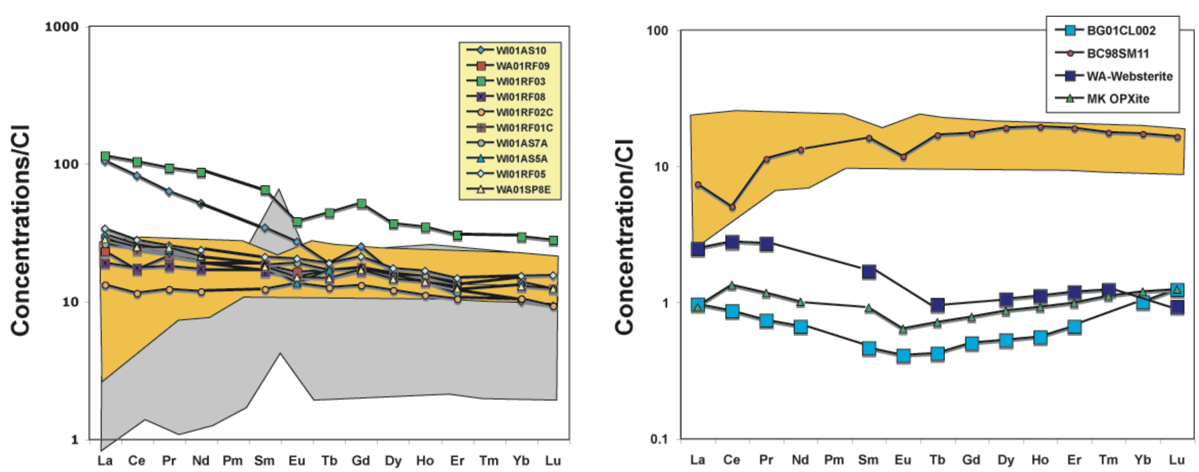


Figure 4d, 4e

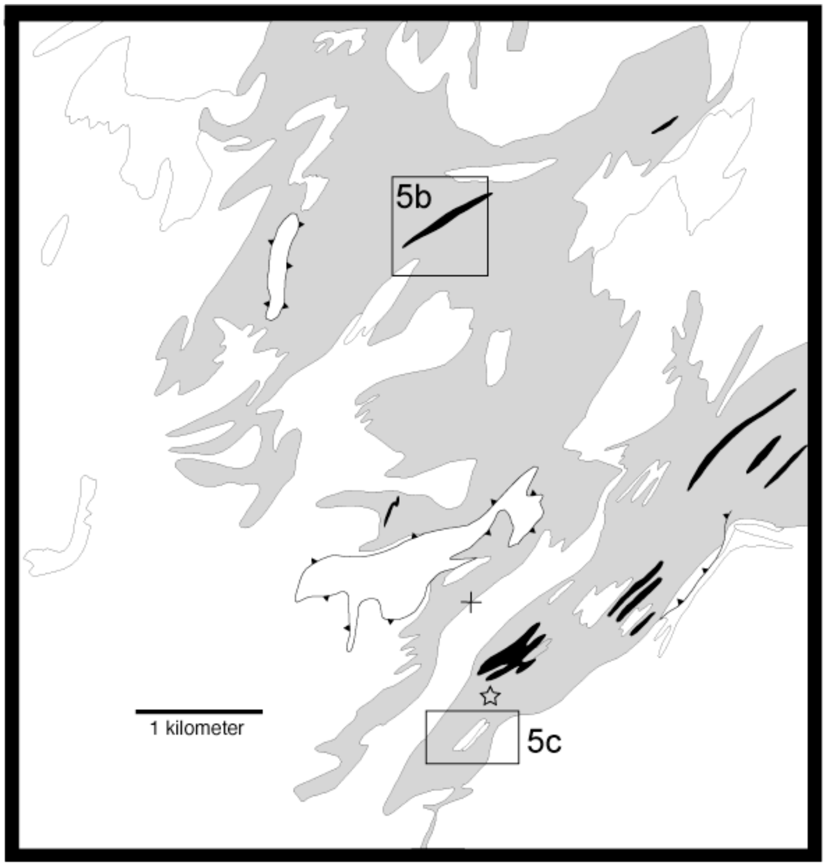


Figure 5a

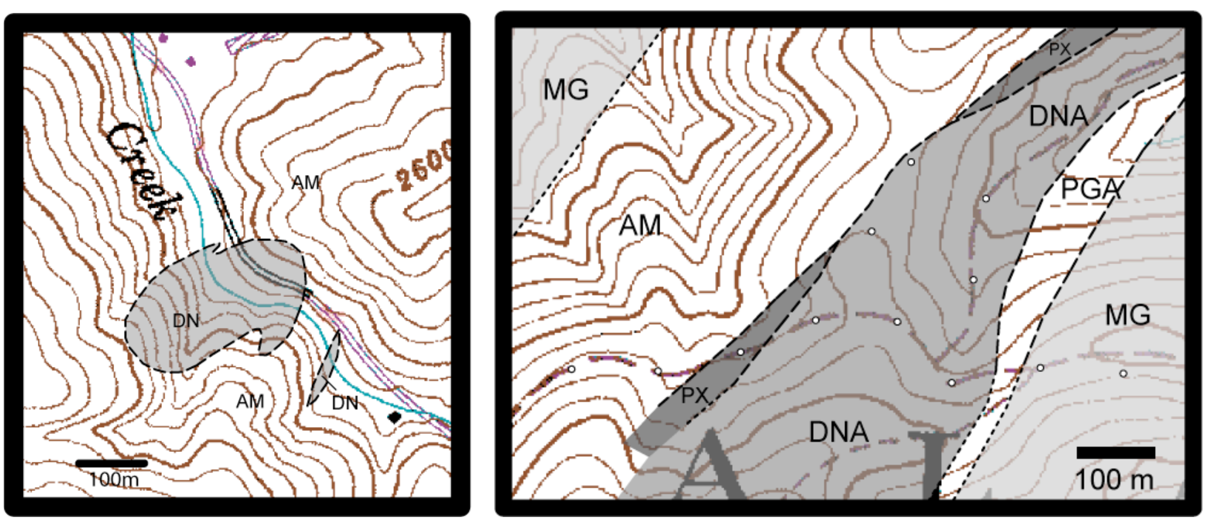


Figure 5b, 5c

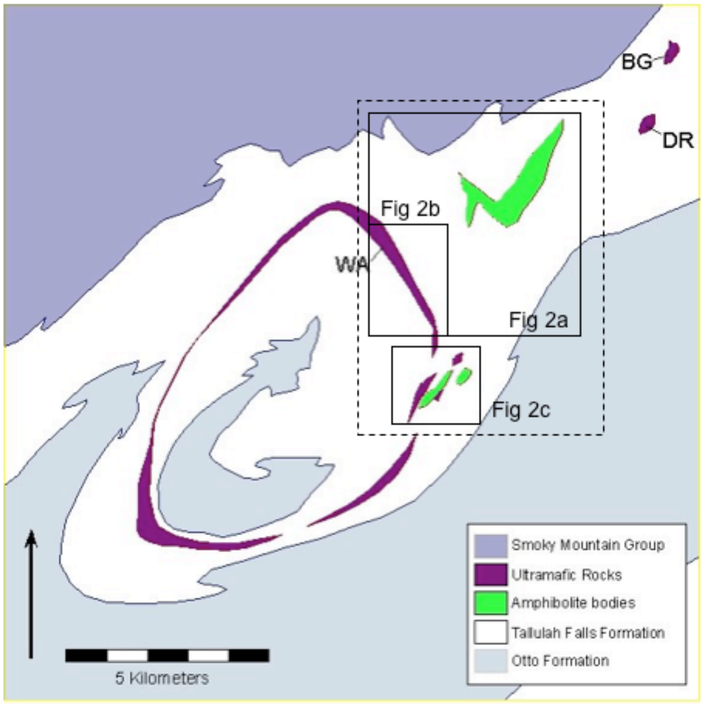


Figure 6

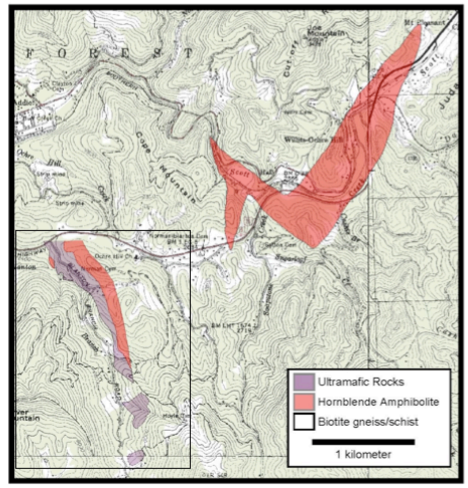


Figure 7a

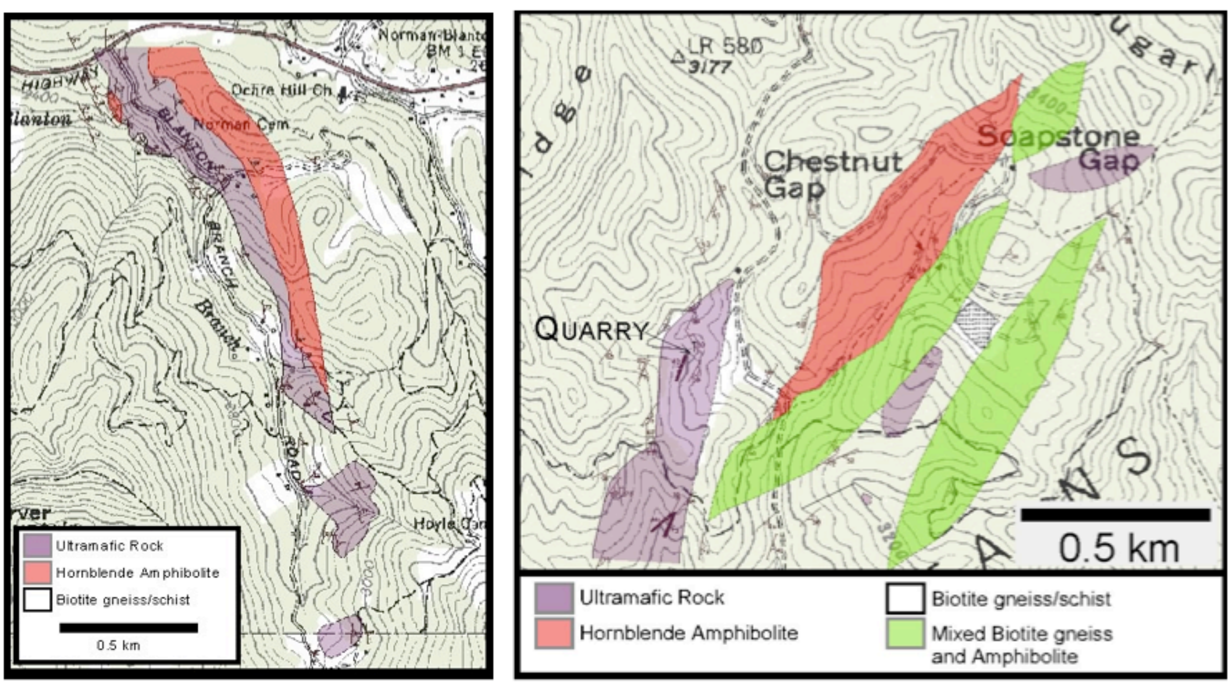


Figure 7b, 7c

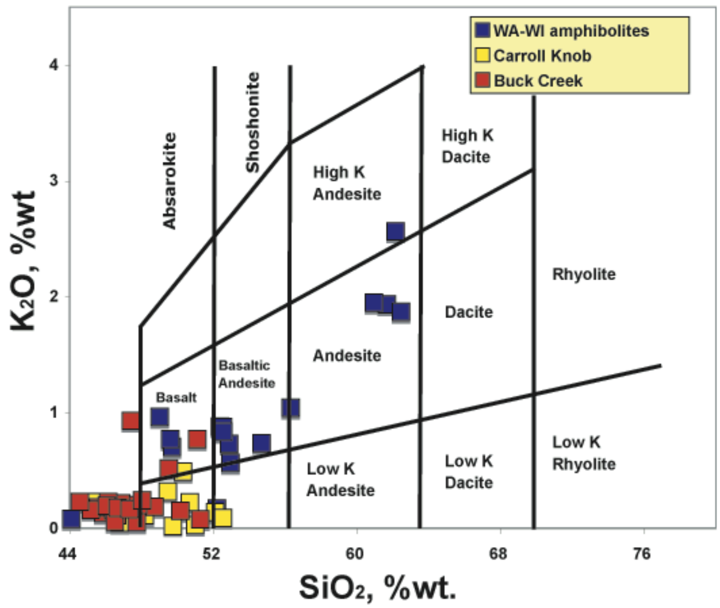


Figure 8

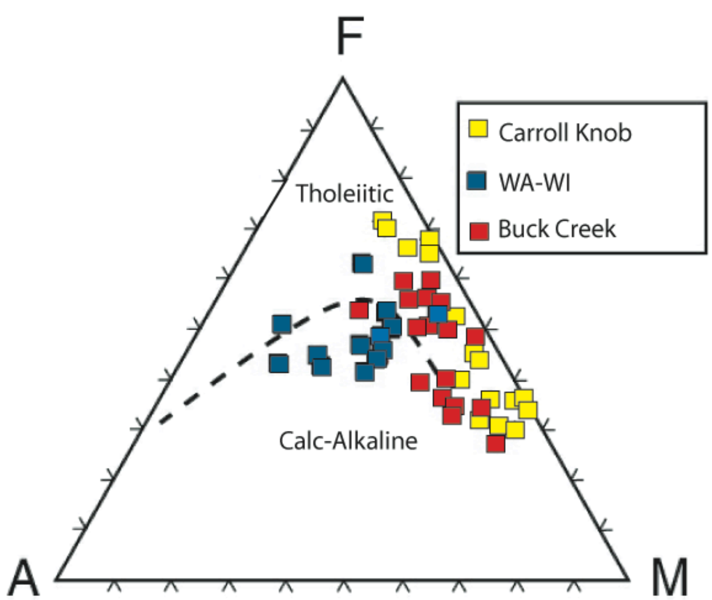


Figure 9

Road Log

Saturday March 25, 2006

Mileage	Description
0.0	Comfort Inn, Sylva, NC. Turn Right onto US 23/74 Westbound. 35º 23.517'N, 83º 11.020'W
5.2	Take Exit 81 to US 441 South
5.9	Cross trace of the Hayesville Fault in Dillsboro
23.6	US 64/NC 28 from Highlands merges with US 441 here in Franklin
26.1	Exit US 441 to US 64 West in Franklin
32.3	West Old Murphy Road, SR 1448 to Carroll Knob outcrops
36.4	Winding Stair Gap, elevation3820, Granulite Facies metamorphism. 35º 07.294'N, 83º 32.707'W
38.2	Wallace Gap Road (old US 64) to Standing Indian intersects US 64. Continue west on US 64.
43.9	Turn right on Old US 64 then take an immediate left onto USFS Road 6236
45.0	**STOP 1.** Follow road to Parking Area on right side of road. Trail to Buck Creek Dunite is to the left of the kiosk. 35º 04.810'N, 83º37.683'W

Follow the trail to the summit of Corundum Knob. In this location, most of the major mapped lithologies of the Buck Creek ultramafic body are exposed, as outcrops and in exploration trenches dating from the1940's that have been substantially expanded since then by mineral collectors. Primary structural elements in the Buck Creek body are evident at the summit and along its eastern face.

Metatroctolites and edenite-margarite schists (EMS) are the primary ridge-forming units, and outcrop prominently at the crest of the hill. The metatroctolites are dense, knobby, bluish-gray rocks consisting of calcic plagioclase, relict olivine, and a very fine grained bluish or greenish symplectic matrix consisting of orthopyroxene and a symplectic intergrowth of Mg-rich clinopyroxene and Fe-bearing spinel +/- sapphirine (see Tenthorey et al 1996; Lang et al 2004). The rock shows a strong foliation defined by oriented plagioclase grains, and includes layers of pure anorthosite. Edenite-Margarite Schist is evident on the margins of the meta-troctolites, varying from a massive green edenitic amphibole+plagioclase ±zoisite±kyanite±corundum rock to horizons rich in pale green margarite. Locally EMS weathers into zones of kaolinite, which have been excavated for possible corundum. Massive, sugar-textured Buck Creek dunite is exposed at the ends of some of the exploration trenches as boulders in the forest, or in small pavement outcrops along trails.

The summit area is supported by two large, extensively excavated metatroctolite/EMS bodies. Both show evidence for extensive folding, and the hinge of a NE trending fold is preserved in EMS margarite schists on the western side of the summit. Smaller metatroctolite lenses trend to the NE down the gentle northern slopes of Corundum Knob. Traversing down slope to the east from the summit, one passes into dunite, and along the edge of a lower bench another metatroctolite body, which is in contact with Chunky Gal amphibolite further down slope. As well, between the two large troctolite exposures at the summit lies a small body of amphibolite, enclosed in dunite.

The observed outcrop and foliation patterns in the troctolites reflect a two-stage folding event: a major isoclinal F1 fold that dips to the NE and trends NW is refolded in a gentler F2 north-trending event. The brittle metatroctolites pinch into lenses during these folding events, while dunites and amphibolites experience ductile deformation around the troctolites and thus end up in tectonic contact in numerous places along the margins of the ultramafic body and (in a few instances) across the summit.

Figure A: Topographic map showing locations of Stops 1, 2, and 3.
Figure B: Photographs from Corundum Knob showing a) slabby nature of troctolite outcrops. b) Foliation in troctolite layers on Corundum Knob – weathered symplectite produces knotty appearance. c) Troctolite with thin anorthosite layer (~ 4 cm thick).

46.1 Return to US 64 and turn right towards Andrews .

47.3 **STOP 2.** Chunky Gal Mountain Fault. Parking area on right side of highway. 35º 03.471'N, 83º 37.185'W.

The parking lot here provides a spectacular view to the west. The long outcrop across the highway is written up in the Centennial Field Guide (Hatcher, 1986) and exposes the Chunky Gal Fault. This stop provides easy access to amphibolites of the Chunky Gal complex, exposed near the southern end of the outcrop. The amphibolites are well foliated hornblende-plagioclase gneisses with abundant retrograde epidote, described as Type 2 amphibolites by MacElhaney and McSween (1983), but identified as High Ti amphibolites by our REU participants. The amphibolites are separated from quartz-feldspar-biotite metasandstones by the Chunky Gal Mountain fault. The fault is interpreted as a syn-metamorphic thrust (Hatcher, 1986).

Return to US 64 and turn left.

48.6 Old US 64/USFS 6236

49.8 From US 64 turn left on Buck Creek Road. Go to end of road bear right then take a left onto Buck Creek Road.

50.5 **Optional STOP 3.** Exposures of the smaller northeastern Buck Creek ultramafic body. Pull off at gated road on right. Walk along the dirt road which heads up hill and then parallels the creek which should be downhill to the left. When it crosses a small saddle, walk up to the small knob to the south at 35º 05.012'N, 83º 36.730'W

This small ridge exposes rocks of the northern body of ultramafic rocks within the Buck Creek complex. Most of the rocks within the northern body are significantly hydrated under retrograde metamorphic conditions to actinolite-chlorite-talc schists (Thomas et al., 1999). These rocks dominate the knob at this stop, but locally less hydrated rocks are preserved, particularly near the top of the knob. Interesting samples at this site are dominated by fine-grained, partially hydrated olivine with rounded plagioclase grains up to a centimeter in diameter. These plagioclase grains are separated from the enclosing olivine-rich matrix by a thin blue corona, visible in hand sample and characterized in thin section by symplectites similar to those observed at corundum knob. This northern body of ultramafic rocks is separated by the main body by a thin septum of amphibolite.

51.2 Return to US 64 and take a left towards Franklin.

55.8 Old US 64 to Standing Indian.

61.7 Exit right from US 64 onto West Old Murphy Road (SR 1448)

63. 2 Turn Left onto North Jones Creek Road.

63.3 Altered gabbro with mineralization on left side of road.

64.1 **STOP 4.** Amphibolite of the Carroll Knob Complex. 35º 06.594'N, 83º 27.677'W

The amphibolites are at this station are typical of the relatively coarse grained, foliated hornblende-plagioclase schists and gneisses that are the dominant rock type of the Carroll Knob complex. Garnet is observed to occur in Carroll Knob amphibolites at several localities.

64.5 **Stop 4A** Walk south along Jones Creek road to the crest of the hill.
35º 06.593'N, 83º 27.677'W

The exposures along this road give a good sense of some of the variety within the Carroll Knob complex. Near the crest of the hill, cross into a small ultramafic body with thin inclusions of more troctolitic composition. The ultramafic rock varies from talc-anthophyllite-chlorite schist to variably hydrated dunite. Metatroctolite is rare in the Carroll Knob complex and is locally recognized by the chert-like appearance of fine symplectites, which are similar to those observed at Buck Creek.

Figure C: Topographic map of stop 4 location

67.8 Turn around and return to US 64. Turn right.

74.0 US 64 merges onto US 441 North

98.6 Exit US 441 onto US 64E and NC 28

89.9 **STOP 5.** Block and matrix structure at Savannah Church, Tathams Creek. 35º 17.565'N, 83º 16.546'W.

The migmatitic biotitic gneiss at this exposure was given a Middle to Late Proterozoic age by Brown et. al. (1985). Several name changes have occurred and most recently Hatcher et. al. (2004) have assigned these rocks to the Dahlonega Gold Belt Terrane consisting of the Otto Formation (pelitic schists), metasandstones (containing biotite, muscovite and two feldspars), and mafic and ultramafic rocks. The Dahlonega Gold Belt Terrane is bounded on the east by the Chattahoochee-Holland Mountain Fault (Hatcher et. al., 2004) and metamorphosed to amphibolite grade assemblages. Detailed discussion of the terranes can be found in Hatcher and Merschat (2005).

Raymond et. al. (1989) included these Tathams Creek rocks into their discussion of block-in-matrix structures found in the Central Blue Ridge. They suggested these rocks might be part of a mélange that extends from Franklin, NC northeastward towards Boone, NC. In this exposure the matrix is porphyroblastic biotite migmatite and biotite schists. The blocks include amphibolite, biotite –quartz feldspar gneiss, and calcsilicate hornblende metaquartzites. On a larger regional scale ultramafic rocks may be other blocks/pods that occur within the postulated mélange.

Figure D: Topographic map showing stop 5 location.

97.1 Follow US 441 North until it intersects with US 23/74. Merge right onto US 23/74 East.

102.3 Comfort Inn, Sylva, NV.

Road Log for Sunday March 26, 2006

0.0 Comfort Inn, Sylva, NC. Turn Left onto US 23/74 Eastbound. 35º 23.517'N, 83º 11.020'W

The rock exposures we will see today were described as Middle to Late Proterozoic Biotite Gneiss on the North Carolina Geologic Map by Brown et. al. (1985). Quinn (1991) did large scale structural and petrologic mapping around Sylva and included these rocks as part of the Tallulah Falls Formation. Recently, Hatcher et. al. (2004) placed these into their Cartoogechaye Terrane. The Cartoogechaye Terrane contains rocks metamorphosed to upper amphibolite to granulite facies mineral assemblages that include metasedimentary gneisses and schists interbedded with amphibolites, granulites, ultramafic rocks and some basement rocks (Hatcher and Merschat, 2005). The Terrane is bounded on the west by the Hayesville Fault which is located only a few kilometers to our west.

We will examine several exposures of metamorphosed dunites (Balsam Gap and Webster-Addie) and mafic units. These mafic/ultramafic units are different from those observed earlier in the field trip. The mafic/ultramafic complexes seen yesterday were intimately associated and in contact with each other. The units today lie close to each other but are not is direct stratigraphic contact.

1.5 Turn right on Blanton's Branch Road
1.9 Eclipse Drive

3.3 Pavement ends; Blanton's Branch Road becomes gravel

4.0 **STOP 6.** Entrance road to Chestnut Gap Quarry in the Webster- Addie Dunite. 35º 21.926'N,
83º 09.016'W

The Webster-Addie Ultramafic Complex is a discontinuous series of ultramafic rocks, sheet-like in nature, that is folded into a dome shape and is conformably enclosed by gneissic metagraywackes and amphibolites (Madison, 1968 and Condie and Madison, 1969) of the Tallulah Falls Formation (Quinn, 1991) now called the Cartoogechaye Terrane by Hatcher et. al., 2004. The outcrop pattern is ring-shaped with a diameter of about 10 km. Dunite is the principal rock type within the body, but harzburgite and pyroxene-rich rocks (websterite, orthopyroxenite) are locally abundant.

The Chestnut Gap Quarry sits in the eastern-most side of the Webster-Addie dunite. Dunite is the principal rock type. It is surrounded by biotite gneisses and a large amphibolite pod is located a few hundred meters to the east of it (Quinn, 1991). The dunite has been mined for olivine here and also at the Addie Quarry, approximately 4 km NNW of this stop. As you enter the quarry look at the rocks to the east (left) and then the west (right) of the mine workings.

Rocks exposed within the quarry are primarily dunite and its metamorphosed alteration products. Dunite mineralogy is represented by olivine, orthopyroxene, serpentine, chlorite, and chromite. Olivine occurs in the dunite most commonly as granoblastic polygonal aggregates of equant to subequant grains ranging in size from 0.5-1.0 mm (Cronin, 1983). Orthopyroxene occurs in lens-like bodies 1-10 cm in diameter enclosed in the dunite. Serpentine occurs as and alteration product of the olivine, as veins that surround and/or cross cut olivine, and as concentrated masses along joint or foliation surfaces (Cronin, 1983). Many vein forming minerals indicate the addition of H_2O and CO_2 rich fluids during metamorphism producing minerals such as anthophyllite, talc, tremolite, and magnesite. Talc also occurs along the contact of the body with the country rock and adjacent to intrusions of more felsic rocks here where veins of chlorite, anthophyllite, and talc are seen.

On the western side of the quarry the ultramafic rocks have been intruded by a tonalitic (dioritic) dike. A zoned mineral assemblage, including talc, anthophyllite, vermiculite and chlorite, reflects the metasomatic exchanges between the intrusion and the surrounding dunite.

Figure E: Topographic Map showing stop 6 location:
Figure F: Photographs from Chestnut Gap Quarry, showing a) lenticular pyroxenite in a boulder, and b) Reaction zonation around trondjhemite dike.

6.6 Return to US 23/74 and turn right.

6.8 Mineral Springs Road to Addie Quarry

9.2 Highway exposure of block and matrix structure in amphibolite

12.7 Turn right onto Candlestick Lane then take an immediate right onto Cabin Flats Road.

13.1 Bear right onto Old Balsam Depot Road and pass entrance to Balsam Mountain Inn. Stay left at next road intersection.

13.8 **STOP 7.** Pull off on right into Balsam Gap Dunite. 35º 25.558'N, 83º 05.607W

The Balsam Gap dunite was investigated by Honeycutt (1978) and Honeycutt and Heimlich (1979), who concluded that the dimensions of the body were 240 by 390 meters, with the long axis parallel to regional foliation. The dunite is enclosed within regional biotite and hornblende gneisses. Magnetic modeling (Honeycutt and Heimlich 1979) suggest the dunite was podiform in shape with a maximum depth of 150-170 meters. The dunite is composed of olivine (Fo93), chromite ± orthopyroxene that has undergone varying degrees of alteration. Like many of the dunites in western North Carolina the olivine grains meet at 120º triple-point junctions suggesting annealing of the unit has occurred. Grain size of the olivine varies from 0.5 mm to 2 cm.

The Balsam Gap dunite is very typical of most of the dunites found in southwestern North Carolina. They are usually small pods or sheets with elongated axes parallel to foliation, have little to no mafic material associated with them, lack clinopyroxenes, and possess varying amounts of metamorphic alteration. The olivine is always very magnesium rich, often possesses recrystallization textures, may show strain bands, and may have preferred crystallographic orientation. Alteration products include minerals such as anthophyllite, talc, serpentine, chlorite, tremolite, vermiculite and magnesite. In one of the upper mine workings a tonalite dike cuts through the dunite producing a metasomatic zone with anthophyllite, talc and chlorite separating it and the dunite.

Recent work by Warner and Hepler (2005) on the nearby Dark Ridge dunite with associated harzburgite indicate that body underwent upper amphibolite/lower granulite facies metamorphism at temperatures of 705 ± 35º C and a pressure ≈ 11 kb.

Figure G: Topographic map showing Stop 7 location.

14.9 Backtrack to US23/74. Turn left.

19.0 Turn right onto Skyland Drive

19.1 Turn right onto Willets Road and follow until gated blockade.

19.8 **STOP 8.** At gate walk onto old US 19A/23 to the block and matrix texture outcrop in amphibolite. 35º 24.345'N, 83º 07.533'W.

This outcrop is part of an extensive amphibolite body northeast of the Webster-Addie ultramafic body near the community of Willets. Quinn (1991) mapped these rocks as part of the Tallulah Falls Formation and they are now included in the Cartoogechaaye Terrane. (Hatcher et.al., 2004)

Raymond et. al. (1989) state "The distinctive block-in matrix structure here consists of blocks of fine- to medium- grained garnet amphibolite … in a granitoid to pelitic leucosomal matrix." They describe the structures as breccia to raft with layered structures also present and suggest these are late structures developed as an injection complex produced by intrusion of a leucosomal melt. The block-in matrix structures here have amphibolite blocks enclosed within leucosomal material, producing a structure very different from that at Tathams Creek.

Ryan et. al. (2005) describe the geochemistry of this unit and present data that indicate the amphibolites are enriched in silica and potassium. Their resulting compositions are more akin to andesites or basaltic andesites or their plutonic equivalents.

Figure H: Topographic map showing Stop 8 location.

20.6 Return to US23/74, turn right.

22.2 Turn right onto Mineral Springs Road.

23.1 **Optional STOP 9.** Turn right into housing development Green Gables and pull to right into the dunite quarry at Addie. 35º 23.988'N, 83º 09.593'W.

The Addie Quarry sits on the northern tip of the Webster-Addie ultramafic complex. Rocks exposed within the quarry are primarily dunite and its metamorphosed alteration products. Dunite mineralogy is represented by olivine, orthopyroxene, serpentine, chlorite, and chromite. Olivine occurs in the dunite most commonly as granoblastic polygonal aggregates of equant to subequant grains ranging in size from 0.5-1.0 mm

(Cronin, 1983). Anthophyllite, talc, Ca-amphibole, and magnesite may also be found. The northeast face of the quarry illustrates the compositional layering common in this body. Serpentine occurs as alteration products of the olivine, as veins that surround and/or cross cut olivine, and as concentrated masses along joint or foliation surfaces (Cronin, 1983). Many vein forming minerals indicate the addition of H_2O and CO_2 rich fluids during metamorphism producing minerals such as anthophyllite, talc, tremolite, and magnesite. Talc also occurs along the contact of the body with the country rock and adjacent to intrusions of more felsic rocks (pegmatite here) where veins of chlorite, anthophyllite, and talc are seen.

This is one of several original quarries in the Addie area that was mined for olivine. Production ended here in the early 1980s.

Figure I: Topographic map showing Stop 9 location.

24.0 Return to US 23/74 turn right.

27.3 **STOP 10.** Parking Lot of Food Lion Supermarket. 35º 22.970'N, 83º 12.259"W.

Quinn (1991) mapped these rocks as Tallulah Falls Formation. At this location (immediately to the west of the Webster-Addie body) we are about 1.5 km NW of the Soque River Fault and less that 3 km SE of the Hayesville Fault. The rocks here dip steeply to the NW and vary from biotite gneisses, to migmatites, to the block-in-matrix structures similar to those seen at Tathams Creek. Quinn and Wright (1993) analyzed zircons from the Middle Proterozoic basement rocks (biotite-hornblende orthogneiss) a few kilometers north of this stop. The U/Pb concordia plot gave a magmatic age of 1147 ± 8 Ma and a 334 ± 15 Ma age of metamorphic overgrowths.

Figure J: Topographic map showing Stop 10 location.

28.8 Return to Comfort Inn, Sylva.

Roadlog Figures:

Figure A. Topographic map showing locations of Stops 1, 2, and 3.

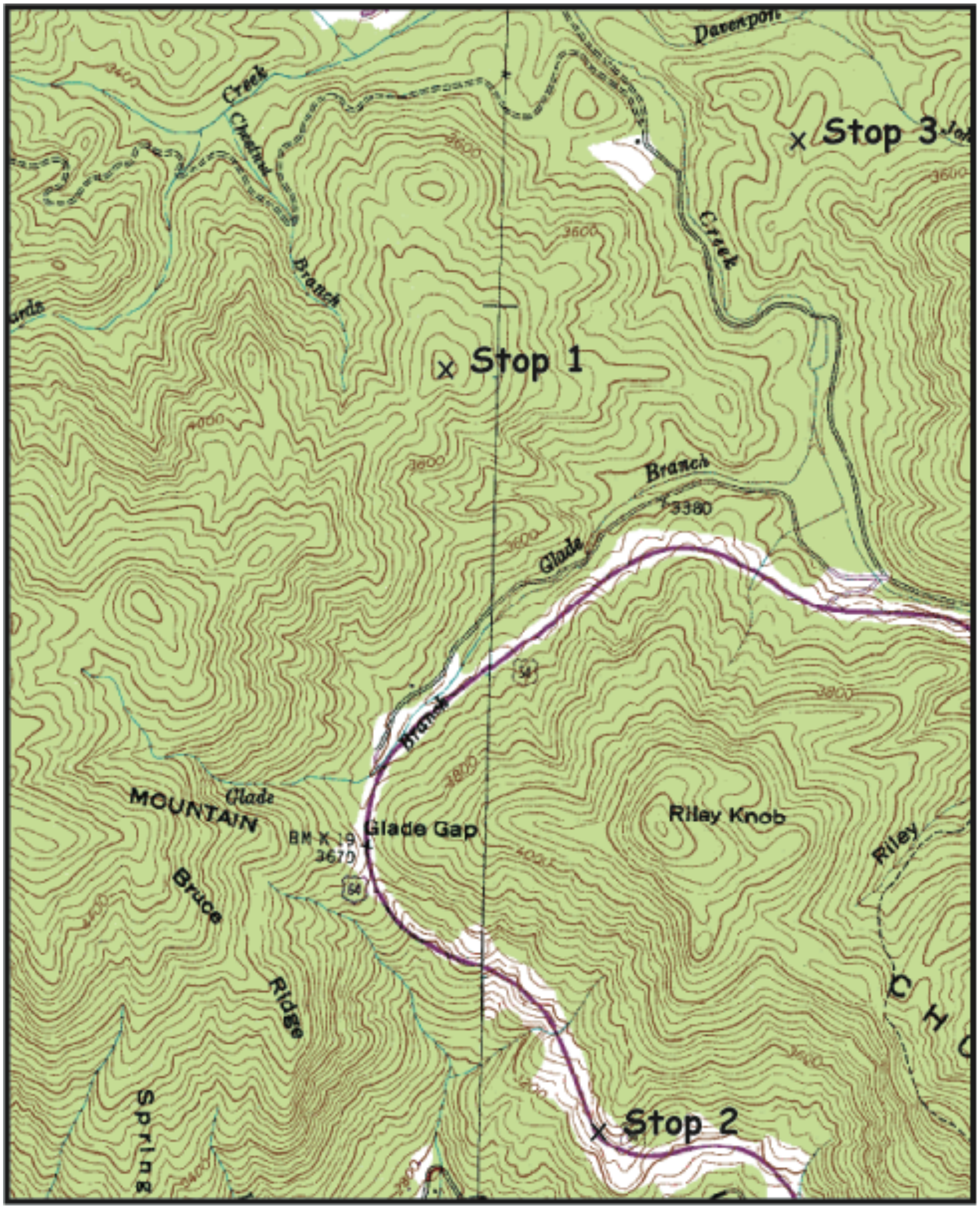


Figure B. Photographs from Corundum Knob showing a) slabby nature of troctolite outcrops. b) Foliation in troctolite layers on Corundum Knob – weathered symplectite produces knotty appearance. c) Troctolite with thin anorthosite layer (~ 4 cm thick).

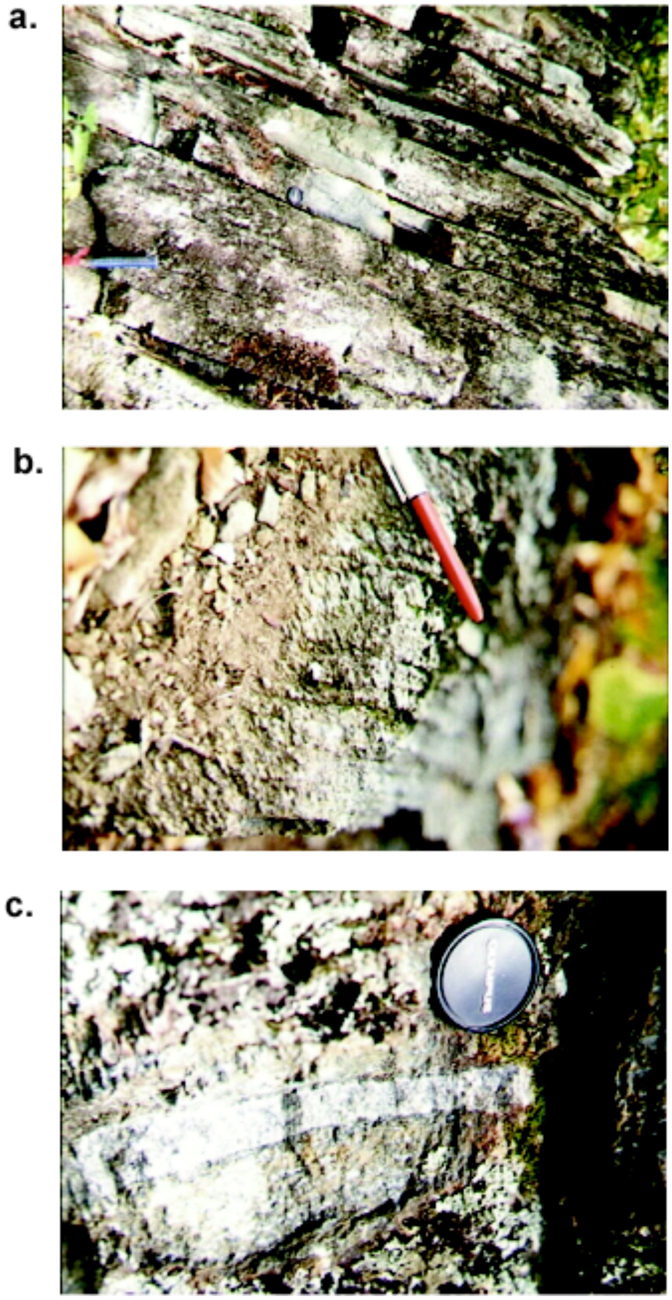


Figure C. Topographic map of stop 4 location.

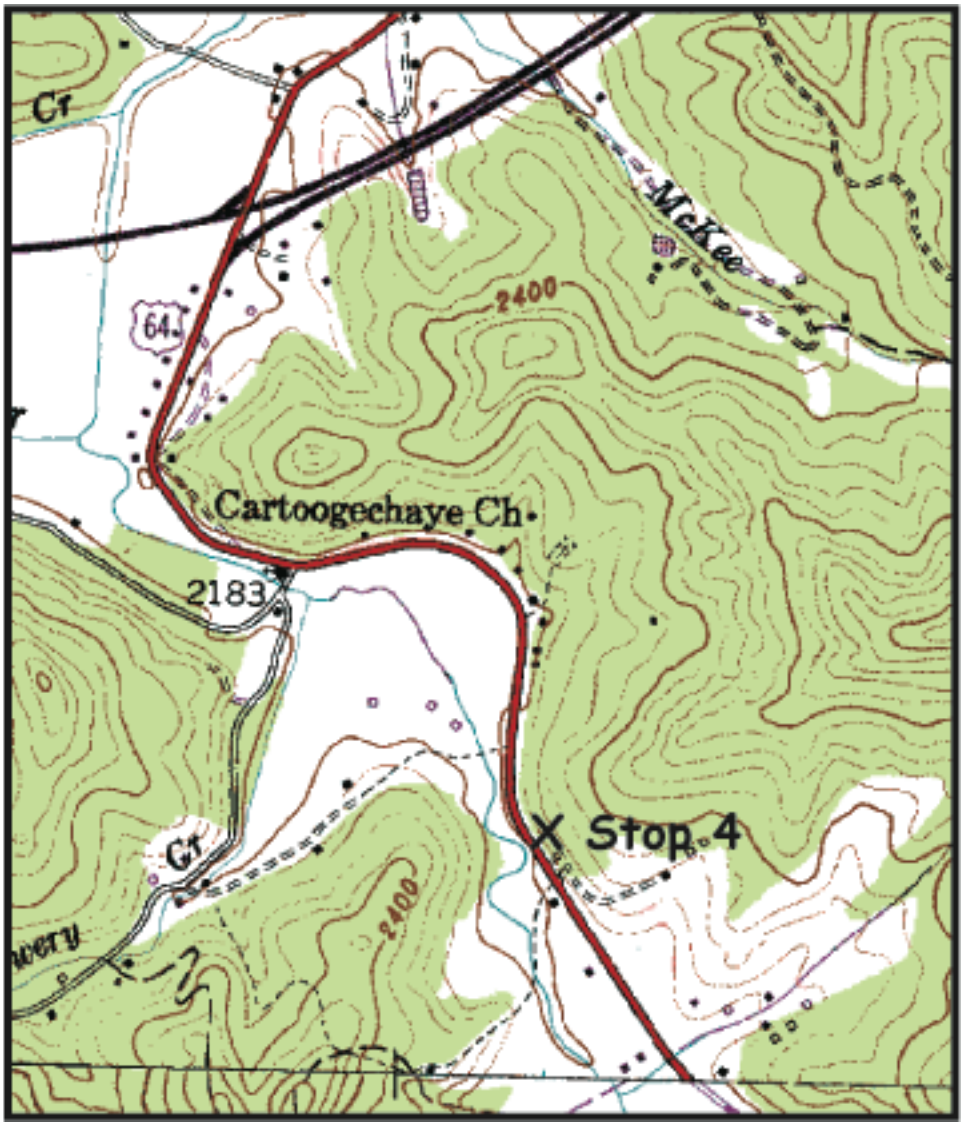


Figure D. Topographic map showing stop 5 location.

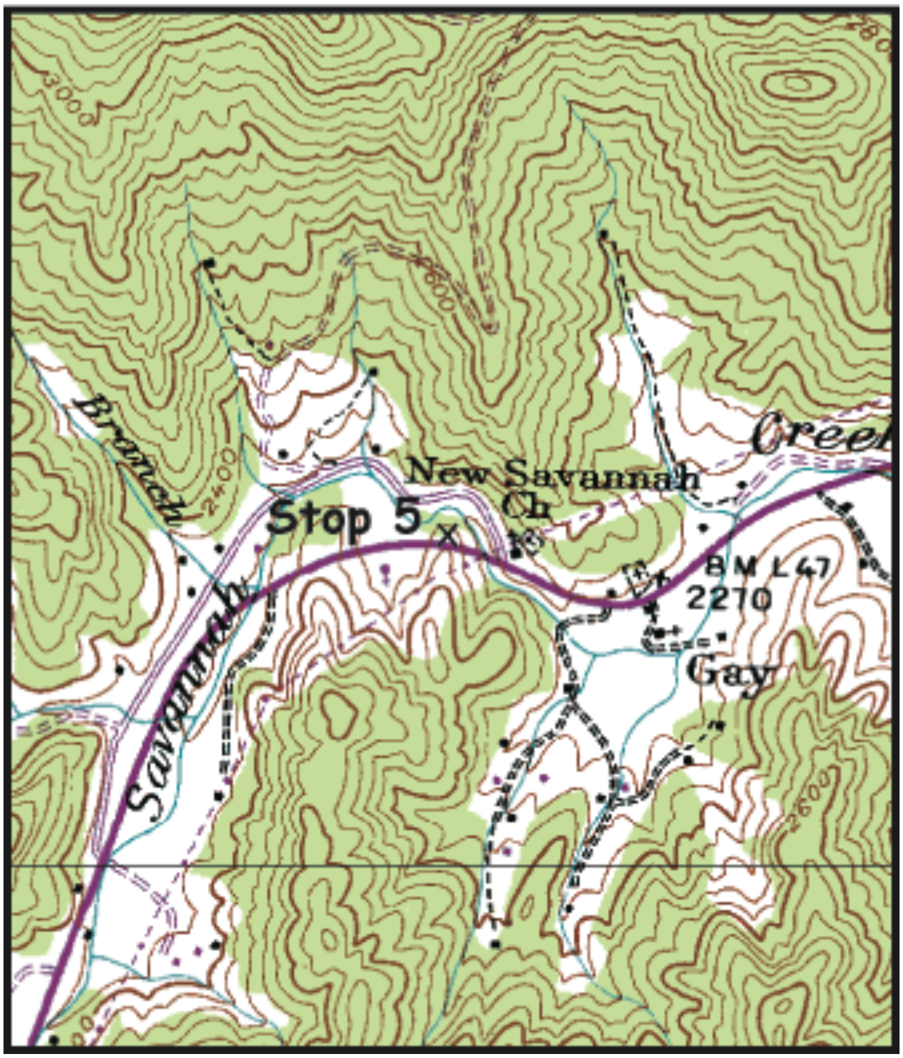


Figure E. Topographic Map showing stop 6 location:

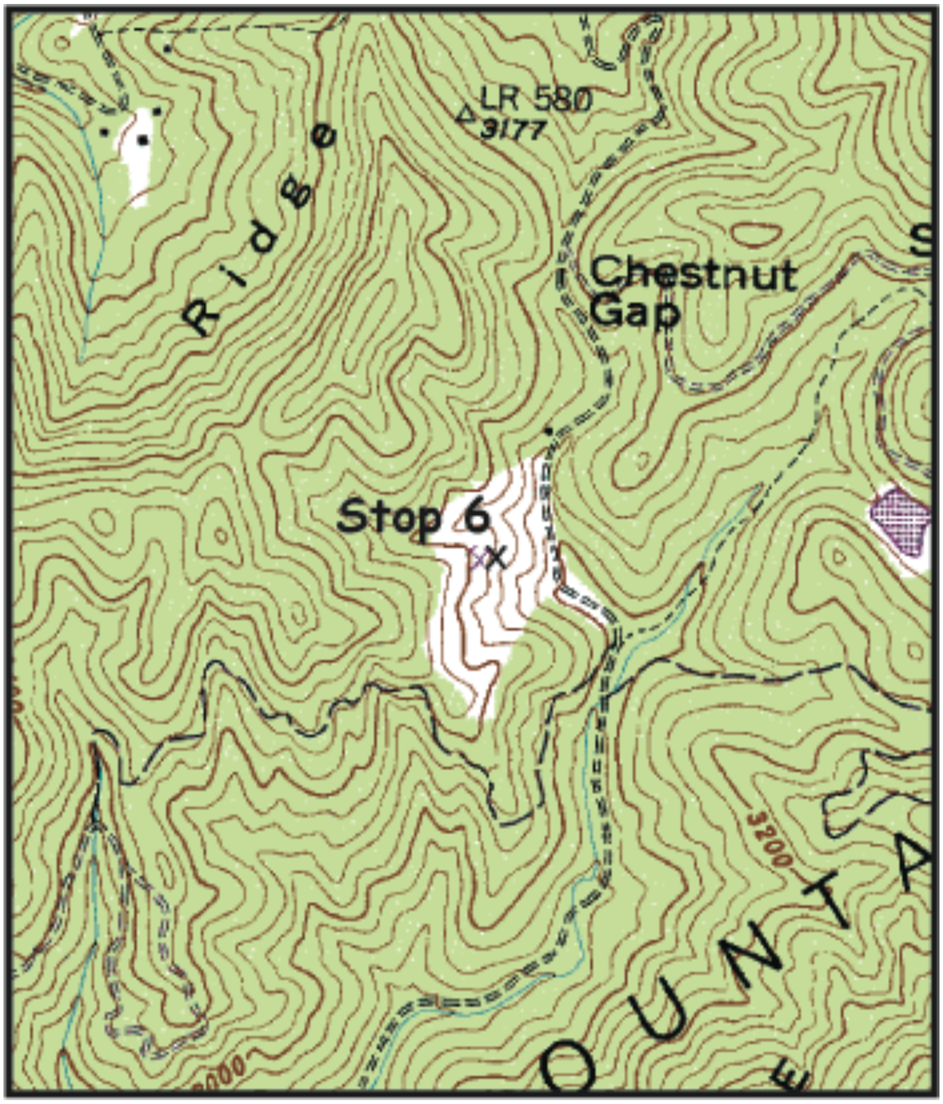


Figure F. Photographs from Chestnut Gap Quarry, showing a) lenticular pyroxenite in a boulder, and b) Reaction zonation around trondjhemite dike.

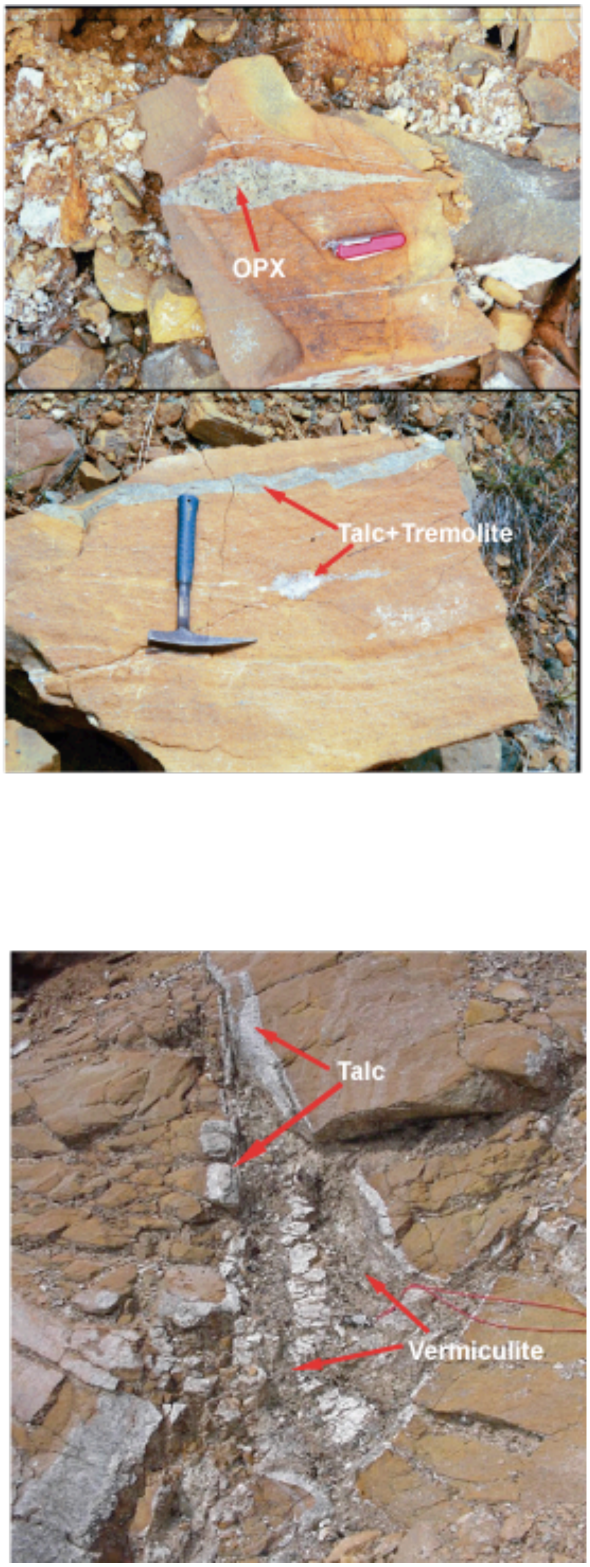


Figure G. Topographic map showing Stop 7 location.

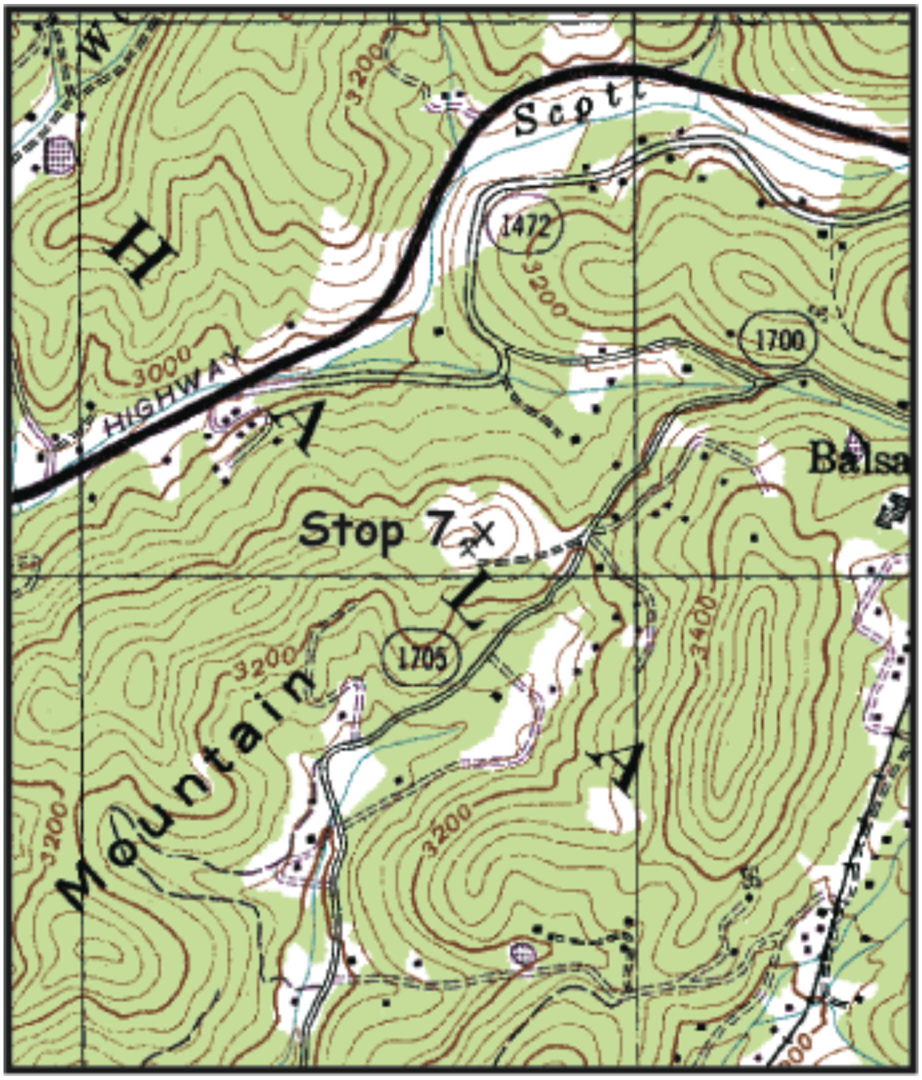


Figure H. Topographic map showing Stop 8 location.

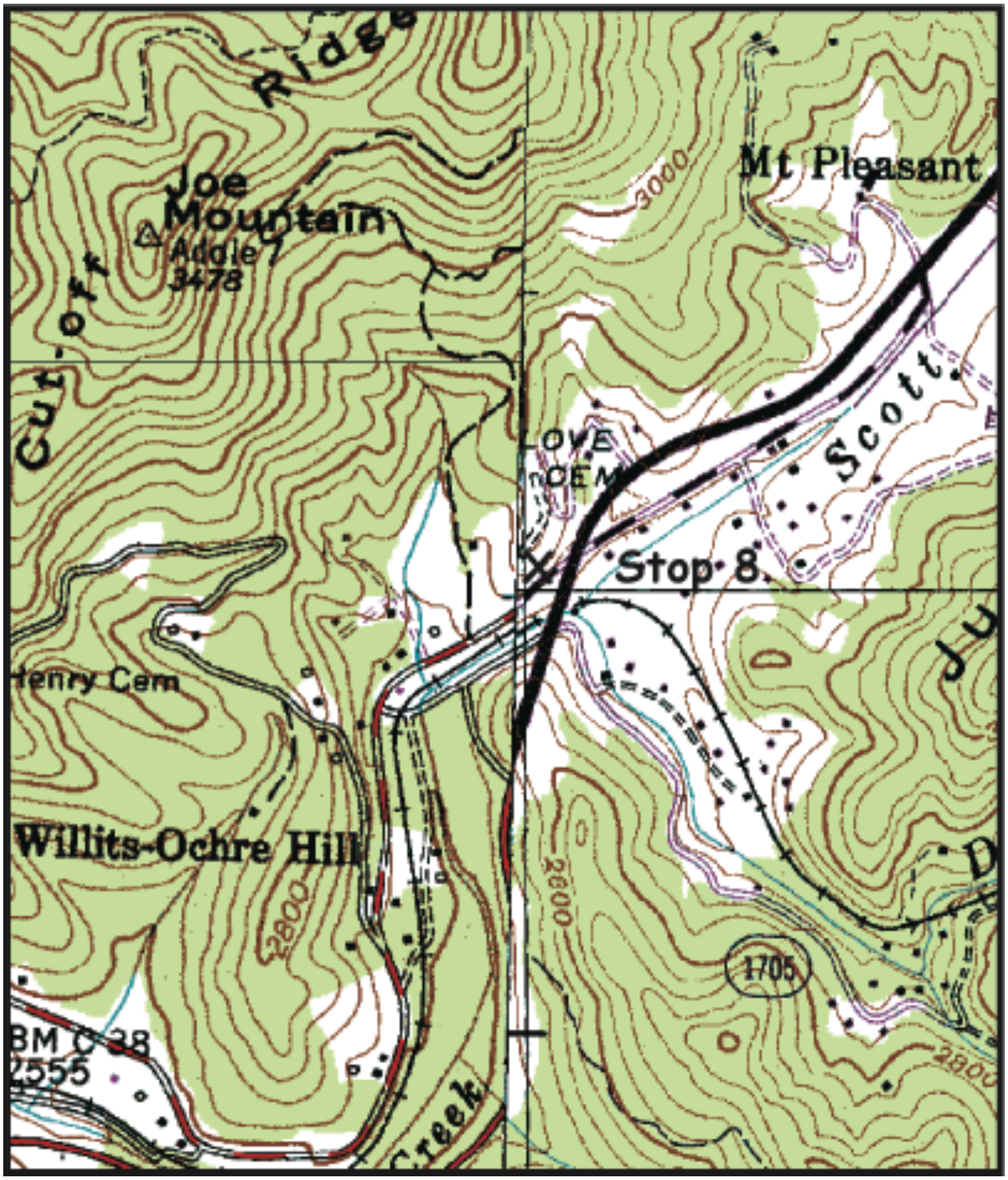


Figure I. Topographic map showing Stop 9 location.

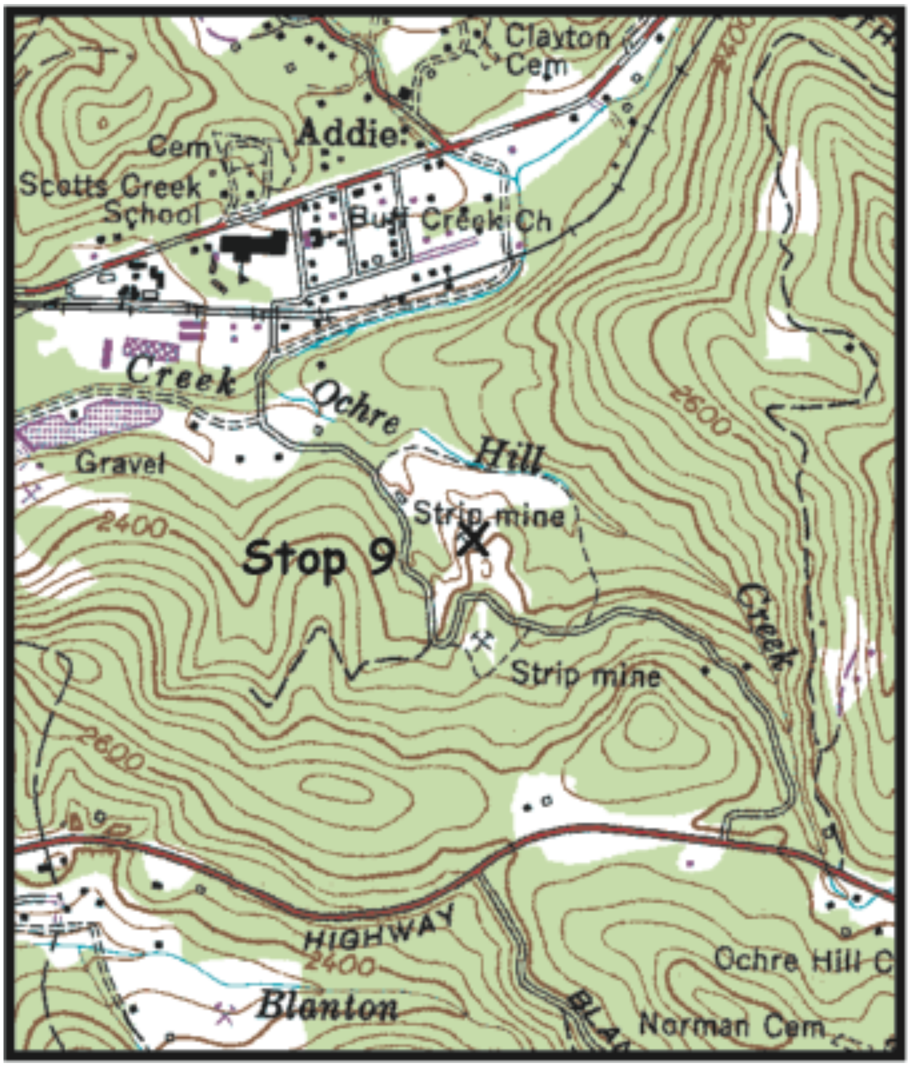


Figure J. Topographic map showing Stop 10 location.