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Stacked Crystalline Thrust Sheets and Episodes of Regional Metamorphism in Northeastern Georgia and Northwestern South Carolina—A Reinterpretation

By ARTHUR E. NELSON

Thrust sheets that underlie the Greenville quadrangle in northeastern Georgia and in northwestern South Carolina have been selectively metamorphosed and deformed during several Paleozoic prograde metamorphic events

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By Arthur E. Nelson

Abstract

Parts of three major allochthonous terranes underlie the Greenville 1°×2° quadrangle, Georgia and South Carolina. From northwest to southeast, they are the eastern part of the Blue Ridge terrane, the Inner Piedmont, and the Charlotte terrane. The Brevard zone forms the tectonic boundary between the Blue Ridge terrane and the Inner Piedmont, and the Lowndesville shear zone forms the boundary between the Inner Piedmont and the Charlotte terrane. A total of eleven and possibly twelve westward-transported crystalline thrust sheets compose these terranes in the Greenville quadrangle. The Blue Ridge terrane consists of a stack of five thrust sheets; the Inner Piedmont is underlain by four and possibly five thrust sheets, and two thrust sheets compose the Charlotte terrane.

A variety of metasedimentary, igneous, and metaigneous rock assemblages compose the various thrust sheets. Some adjoining thrust sheets have metasedimentary units that are formed from sediments laid down in different depositional environments, and some thrust sheets contain distinctly different proportions and types of igneous and metaigneous rocks.

Various Paleozoic prograde metamorphic or thermal events are recorded in the rocks of thrust sheets underlying the Greenville quadrangle. These events occurred at the following times: between 470 and 430 Ma, possibly between 430 and 410 Ma, about 365 Ma to possibly 344 Ma, and 338 to 312 Ma. Generally the oldest metamorphic events are recorded in rocks of thrust sheets underlying the northwestern part of the quadrangle; successively younger metamorphic events are recorded in rocks of thrust sheets exposed to the southeast. These metamorphic events represent intense thermal-deformation pulses that are recorded in the rocks that were subjected to episodes of major westward thrusting. This thrusting emplaced a series of thrust sheets onto the North American Continent during the middle and late parts of the Paleozoic Era.

INTRODUCTION

Previously, workers showed that thrust sheets transported toward the west are the dominant structural feature in the Valley and Ridge province of the southern Appalachian orogen (fig. 1). Recent work has shown that the same structural style also dominates much of the crystalline terrane east of the Valley and Ridge. Regional geologic investigations show that all the metamorphosed crystalline rocks underlying the Greenville 1°×2° quadrangle are allochthonous. Assemblages of these rocks form thrust sheets that were emplaced by tectonic transport toward the west. Recent seismic-reflection studies, the Consortium for Continental Reflection Profiling (COCORP) line (Cook and others, 1979), and the U.S. Geological Survey seismic lines (Harris and Bayer, 1979; Harris and others, 1981) present seismic profiles across different parts of the southern Appalachians. Each of these studies shows southeast-trending seismic profiles across several segments of the southern Appalachian Mountains. When taken together, these seismic profiles cross the major lithotectonic units that form the southern Appalachian Mountains from the Appalachian Plateaus in the northwest to the Coastal Plain in the southeast. These seismic studies clearly support the allochthonous nature of the crystalline rocks from the Blue Ridge to the Coastal Plain as suggested by geologic mapping. The studies also suggest that Paleozoic sedimentary rocks in several thrust sheets continue from the Valley and Ridge beneath the crystalline rocks of the Blue Ridge and under a part of the western Inner Piedmont. Harris and Bayer (1979) suggest 179 km of westward transport for the crystalline rocks of the Blue Ridge.

Previous Work

Many geologic studies have been made within the Greenville quadrangle over a considerable time span.

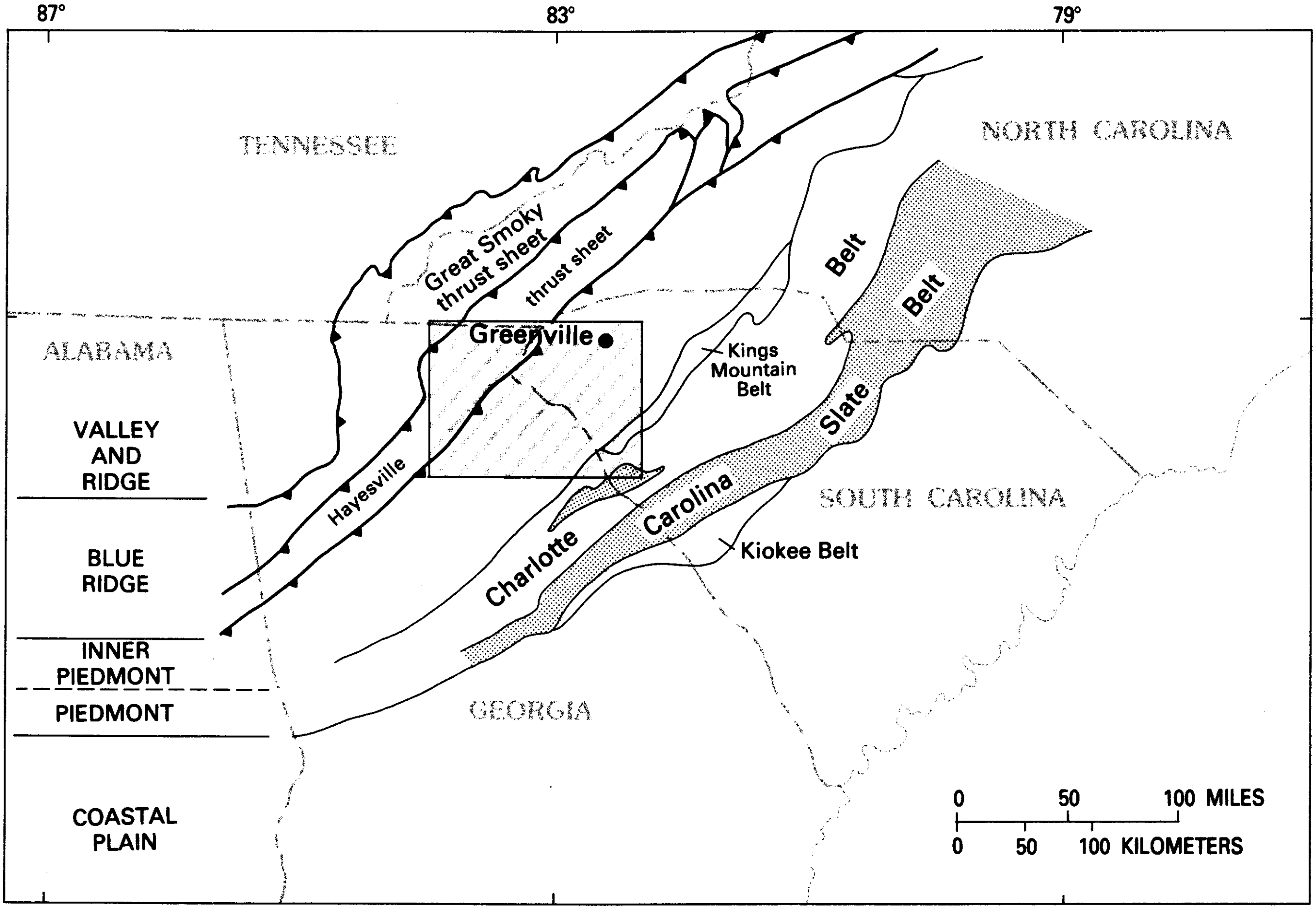

Figure 1. Previous interpretations of terranes of the southern Appalachian Mountains. The Greenville 1°×2° quadrangle is striped. Physiographic provinces discussed in the text are shown to the left.

Yeates and McCallie (1896) and Park (1953) described some of the gold deposits and mining properties of Georgia. One of the major gold producing zones, the Dahlonega gold belt, extends northeast from Dahlonega and forms part of the Helen thrust sheet, defined on page 5 in this report. Hopkins (1914) described soapstone, and Furcron and Teaque (1943) reported on mica-bearing pegmatites within the Greenville quadrangle. Crickmay (1952) and Hurst (1973) described rocks in this area as part of their general descriptions of Blue Ridge crystalline rocks. Hartley (1973) reported on the ultramafic rocks present in the northern part of the area, and Hatcher (1971) described the geology of Rabun and Habersham Counties, Ga. Hatcher also reported on various aspects of the tectonic history of northern Georgia (1974, 1976, 1978a,b). Dupuis (1975) and Wooten (1980) mapped adjoining areas to the west and north, respectively, of the Greenville quadrangle, and Shellebarger (1980) and Gillon (1982) mapped areas in the northwestern part of the quadrangle. German (1985) mapped the Dahlonega gold belt, and Nelson (1982, 1983a,b, 1985) and Nelson and Koeppen (1986) mapped areas in the northwestern part of the Greenville quadrangle. In the Inner Piedmont and southeast of the Brevard zone, Griffin (1967, 1973, 1974, 1975, 1977, 1978, 1979, 1981) mapped a large part of the Greenville quadrangle in South Carolina. Grant (1958) mapped Hart County, Ga., and Hatcher (1969) mapped southeast of the Brevard zone. Nelson and others (1986) compiled a tectonic map of the Greenville quadrangle.

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GENERAL GEOLOGY OF THE BLUE RIDGE

The distribution and the stacking order of the thrust sheets that form the allochthonous rocks underlying the Greenville quadrangle are shown in figure 2 (Nelson and others, 1986). Parts of three major allochthonous terranes underlie the Greenville quadrangle. From northwest

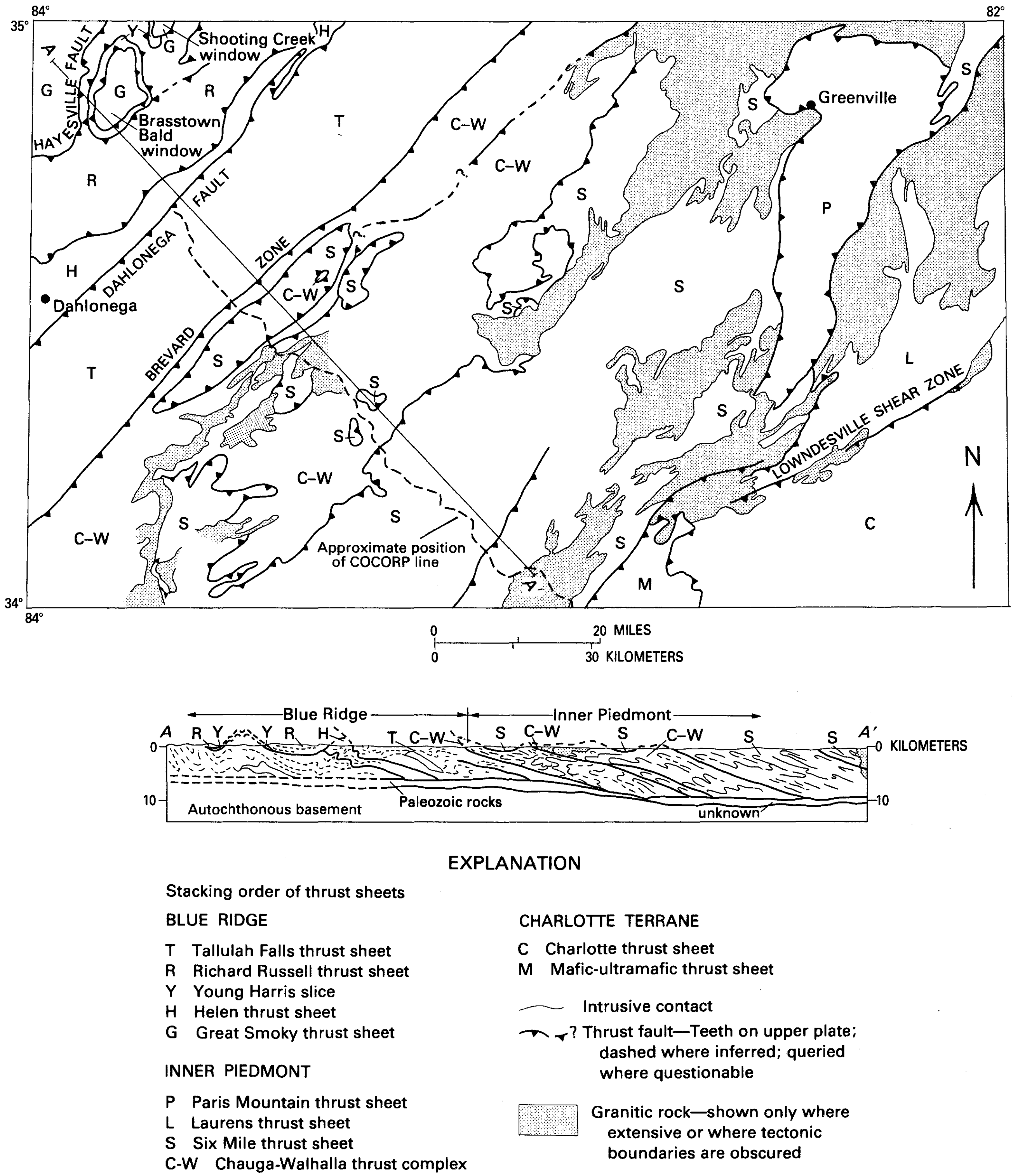

Figure 2. Generalized tectonic map and cross section of the Greenville 1°×2° quadrangle.

to southeast, they are the eastern part of the Blue Ridge Mountains, the Inner Piedmont, and the Charlotte terrane. Each of the terranes consists of a series of westward-transported stacked thrust sheets. The Brevard zone forms the tectonic boundary between the Blue Ridge and the Inner Piedmont, and the Lowndesville shear zone forms the boundary between the Inner Piedmont and the Charlotte terrane. A stack of five crystalline thrust sheets underlies the Blue Ridge terrane; a stack of four (possibly five) thrust sheets forms the Inner Piedmont. Two additional thrust sheets compose the Charlotte terrane in the Greenville quadrangle. In ascending order, the thrust sheets that form the Blue Ridge thrust stack are the Great Smoky thrust sheet, the Helen thrust sheet, the Young Harris slice, the Richard Russell thrust sheet, and the Tallulah Falls thrust sheet. The ascending stacking order for the Inner Piedmont thrust sheets are the Chauga-Walhalla thrust complex, the Six Mile thrust sheet, the Laurens thrust sheet, and the Paris Mountain thrust sheet. A mafic-ultramafic thrust sheet and the overlying Charlotte thrust sheet compose the Charlotte terrane.

The metamorphosed stratified rocks of the Great Smoky thrust sheet include rock assemblages of the Late Proterozoic Ocoee Supergroup together with some minor Cambrian age rocks of the Murphy syncline. The ages of metasedimentary rock units in other thrust sheets, however, are uncertain, but the ages are thought to range from Late Proterozoic(?) to Ordovician(?). Two bodies of Middle Proterozoic (Grenville age, 1,200 Ma, Fullagar and others, 1979) basement rocks are present in the Tallulah Falls thrust sheet, but Middle Proterozoic basement has not been observed elsewhere in the Greenville quadrangle. In the adjoining Knoxville quadrangle to the north, Middle Proterozoic plutonic rocks and variably layered paragneisses are exposed in the eastern part of the Great Smoky thrust sheet (Hadley and Nelson, 1971; Nelson and Zietz, 1983). Where the basement rocks have been dated in the Blue Ridge province, the ages range from 1,000 to 1,300 Ma—ages typical of the Grenville province of eastern Canada and elsewhere in the Appalachian orogen (Rankin, 1975, p. 304). It is uncertain whether the Middle Proterozoic rocks represent detached fragments of the Grenvillian North American craton or possibly parts of an accreted terrane (Hatcher, 1978b; Zen, 1981; Nelson and Zeitz, 1983).

The allochthonous rocks underlying the eastern Blue Ridge were previously divided into two major thrust sheets, the Hayesville sheet to the southeast and the Great Smoky sheet to the northwest (Hatcher, 1978b; Williams, 1978; Nelson and Zietz, 1983). Nelson and Zietz (1983) divided the Hayesville thrust sheet into three major lithotectonic units, each of which has tectonic borders and contains distinctive rock assemblages juxtaposed along thrust faults. The two largest units were referred to as the east and west parts, and a third unit in the middle was called the Helen-Coweeta terrane. In this report, the east part of the Hayesville thrust sheet is named the Tallulah Falls thrust sheet; the west part is called the Richard Russell thrust sheet, and the terrane in the middle is called the Helen thrust sheet.

Griffin (1970, 1971, 1974, 1977, 1978) divided the Inner Piedmont, extending from the Chauga belt (Hatcher, 1969) southeast of the Brevard zone to the Lowndesville shear zone, into a central core of sillimanite schist and gneiss that is flanked on either side by zones rich in amphibolite and granitoid gneiss. These zones are separated from each other by faults and tectonic slides. Griffin (1975) named the Walhalla, Six Mile, and Antreville nappes as parts of his core and flank complex and proposed a tectonic stockwork model for the Inner Piedmont. While many of the geologic interpretations are similar to those presented by Griffin, I have integrated the more recent COCORP seismic data and have interpreted the stacking order of the thrust sheets differently than was shown in the stockwork model. The Inner Piedmont has been divided into four and possibly five thrust sheets (Nelson and others, 1986).

THRUST SHEETS OF THE BLUE RIDGE—DESCRIBED IN ASCENDING STRUCTURAL POSITION

Great Smoky Thrust Sheet

The lowest crystalline thrust sheet in the Blue Ridge thrust stack is the Great Smoky thrust sheet (fig. 3). Seismic reflection surveys (Harris and Bayer, 1979; Harris and others, 1981; Cook and others, 1979) support surface observations that the Great Smoky thrust sheet in the eastern Blue Ridge of Georgia was emplaced westward along the Great Smoky fault upon Paleozoic sedimentary rocks. These rocks may be an oceanward extension of the lower Paleozoic section in the Valley and Ridge province to the northwest, in eastern Tennessee. The other westward-directed thrust sheets overlie the Great Smoky thrust sheet that is succeeded structurally to the southeast by the Richard Russell thrust sheet, the Young Harris slice, the Helen thrust sheet, and the Tallulah Falls thrust sheet (fig. 2).

Middle Proterozoic (Grenville) basement rocks and rock assemblages of the Ocoee Supergroup, the Chilhowee Group, and the Murphy Group of Hatcher (1972), as used by Dallmeyer and others (1978), consti-

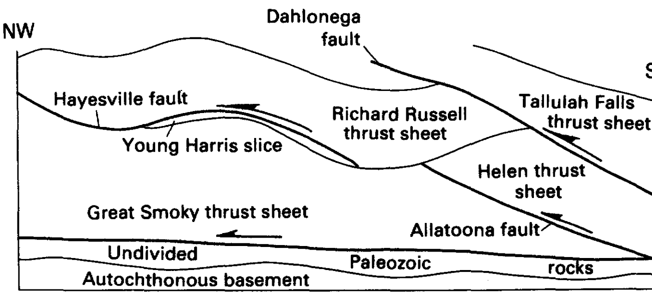

Figure 3. The thrust sheet stacking order northwest of the Brevard zone. Arrows show the direction of fault movement.

tute the Great Smoky thrust sheet. Metamorphosed Late Proterozoic conglomerate, sandstone, quartzite, siltstone, and shale of the Ocoee Supergroup make up most of the Great Smoky thrust sheet in the Greenville quadrangle. Rocks of the Ocoee Supergroup in northeastern Georgia are interpreted as shallow water deposits in a fluviatile coastal-plain environment (Dupuis, 1975; Price, 1977; Shellebarger, 1980) that were probably deposited along the western side of a rift basin along the eastern margin of the North American craton. These rocks of the Ocoee do not contain volcanic deposits and are believed to have formed from sediments derived from the North American craton.

The Great Smoky thrust fault defines the base of the Great Smoky thrust sheet, but this fault is not exposed in the Greenville quadrangle. Farther west in Georgia and to the north in Tennessee, however, the Great Smoky thrust sheet rests on Paleozoic sedimentary rocks of the Valley and Ridge along the Great Smoky fault (Hadley and Goldsmith, 1963). The Hayesville thrust fault marks the upper boundary of the Great Smoky thrust sheet in the northwestern part of the Greenville quadrangle (figs. 1 and 2).

Helen Thrust Sheet

Rocks of the Helen Group (Nelson and Gillon, 1985) form the Helen thrust sheet that is exposed in the northwestern part of the Greenville quadrangle. This thrust sheet has a variable width and is overlain on the west by the Richard Russell thrust sheet and on the east by the Tallulah Falls thrust sheet. The Helen thrust sheet includes a variety of interlayered metagraywacke, including some very thinly laminated units that are distal turbidites, quartzite, graphite-bearing garnet-muscovite-biotite schist, metasiltstone, phyllite, feldspathic metasandstone (locally conglomeratic), thin muscovite-schist beds, some garnet-diopside-plagioclase-quartz granofels, and chemical metasediments (Stanton, 1976) represented by banded iron formation, manganiferous schists, and quartz magnitite rocks. Thin to thick layers of amphibolite are also present. Granitic and granodioritic gneisses interpreted to be intrusive rocks are included in the Helen thrust sheet, and numerous discontinuous pegmatite veins and pods of various sizes are also widely dispersed. The Helen Group, which constitutes most of the Helen thrust sheet, has been interpreted by Gillon (1982) to represent a rock sequence derived from sediment deposited in a moderate- to low-energy rift basin that has associated marine-pelitic and volcanic deposits. The volcanic rocks are believed to be the results of volcanism on the ocean floor.

The Helen thrust sheet rests on the Great Smoky thrust sheet along the Allatoona fault, which is not exposed in the Greenville quadrangle but is exposed to the southwest. The Richard Russell thrust sheet rests on the Helen thrust sheet along the Hayesville thrust fault (fig. 2), which, along with the Allatoona fault, forms the northwest border of the Helen thrust sheet. The Dahlonega fault, which forms the southeast border of the Helen thrust sheet, places the Tallulah Falls thrust sheet on top of the Helen thrust sheet (figs. 2 and 3).

Young Harris Slice

All thrust sheets overlying the Great Smoky thrust sheet contain a wide variety of ultramafic and mafic rocks that form small discontinuous pods, as well as some large mappable units (Hadley and Nelson, 1971; Nelson, 1982, 1983a,b; Nelson and Zietz, 1983). These rocks are chiefly serpentinite, dunite, pyroxenite, eclogite, troctolite, gabbro, and amphibolite. Some of these rocks are rich locally in magnetite. A separate thrust slice of ultramafic and mafic rocks, named the Young Harris slice in this report, lies between the Great Smoky and the Richard Russell thrust sheets around the Brasstown Bald and Shooting Creek windows. At least parts of the Young Harris slice are a melange. The ultramafic rocks of the Young Harris slice have chemical affinities with mantle rocks (Hartley, 1973, p. 59), and additional geochemical studies suggest a midocean ridge or island-arc origin for them (Long and Miller, 1983). Shaw and Wasserburg (1984) analyzed a sample from the Young Harris slice and suggested that it represents oceanic crust. The Young Harris slice and other smaller mafic-ultramafic bodies may represent fragments of oceanic crust emplaced within the various thrust sheets during or before their westward transport.

Richard Russell Thrust Sheet

The Richard Russell Formation (Nelson and Gillon, 1985) structurally overlies a previously unnamed rock assemblage, informally labeled in this report the schist of Crooked Creek. These two units form most of the Richard Russell thrust sheet, formerly the western part of the Hayesville thrust sheet. Intrusive rocks include granitic and dioritic gneisses along with variably layered granitic rocks; pegmatites, quartzofeldspathic segregations, and migmatitic biotite gneiss are locally abundant. The Richard Russell Formation consists primarily of thinly layered migmatitic garnet-biotite gneiss that is gradational to garnetiferous-feldspathic-argillaceous metasandstone interlayered with thin garnet-sillimanite-biotite schist. Smaller amounts of mica schist, quartzite, and small, discontinuous, thinly layered calc-silicate bands and minor amphibolite are present. The interlayered metasandstone and mica schist of the Richard Russell Formation resemble some of the metasandstone of the Ridgepole Mountain and Coleman River Formations of the Coweeta Group (Hatcher, 1979) and may correlate with them (R.D. Hatcher, oral commun., 1986). In a few places, some interlayered, thin psammitic and pelitic horizons with thicker and locally graded metasandstones of the Richard Russell suggest that these rocks most likely formed as deep-water turbidite deposits (Gillon, 1982).

The schist of Crooked Creek lies between the western part of the Richard Russell Formation and the Hayesville fault. This unit is composed of an irregularly layered sequence of reddish-weathering schist, fine-grained quartz-feldspar gneiss, thinly to thickly layered amphibolite, hornblende gneiss, calc-silicate rocks, argillaceous to feldspathic metasandstone and (or) metagraywacke, and minor diamictite. The Crooked Creek contains a more heterogeneous rock assemblage and is generally more variably layered than the Richard Russell.

The Crooked Creek has a higher metavolcanic and schist component and smaller amounts of feldspathic metasandstone and metagraywacke than does the Richard Russell Formation, which is characterized in this terrane by its low amphibolite content, by its high percentage of fine-grained, garnetiferous, biotite gneiss that is locally migmatitic, and by gneissic metasandstone that is interlayered with very thin pelitic horizons. To the northeast along strike, however, numerous amphibolite bodies are present in rocks that probably correlate with the Richard Russell. These lithologic differences between the Crooked Creek and the Richard Russell suggest that they may have formed in different environments, in different parts of a large depositional basin, or in a basin that had a large influx of volcanic material during deposition of the Crooked Creek. In the northern part of the quadrangle, a fault separates the Richard Russell from the Crooked Creek, but elsewhere the nature of the contact between the two rock units is obscure, and it is difficult to determine if it is tectonic or depositional. Within the Crooked Creek and the Richard Russell, bedding is rarely preserved; instead, a discontinuous compositional layering is the most prevalent structure. This results from metamorphic differentiation and transposition of bedding into the regional foliation (Nelson, 1983a,b).

Geologic field evidence at hand does not support the subdivision of the Richard Russell thrust sheet. The Crooked Creek underlying the western part of the Richard Russell thrust sheet is lithologically similar to and might correlate with the rocks of the Zebulon thrust sheet (Higgins and others, 1984).

Tallulah Falls Thrust Sheet

Several metamorphosed sedimentary rock assemblages, a variety of intrusive rocks, pegmatites, and some Grenville basement plutonic rocks (Fullagar and others, 1979), make up the Tallulah Falls thrust sheet. The Tallulah Falls sheet overlies the Helen thrust sheet along the Dahlonega fault. To the southeast, the Tallulah Falls thrust sheet is bounded by the Brevard zone. The Tallulah Falls Formation of Galpin (1915), as used by Hatcher (1971), forms a large part of the thrust sheet and consists of the following members: (1) a lower metagraywacke-schist-amphibolite, (2) an aluminous schist, (3) a metagraywacke-schist, and (4) an upper quartzite-schist (Hatcher, 1976). The Union Grove sequence (Gillon, 1982) of metagraywacke, biotite schist and gneiss, amphibolite, calc-silicate granofels, and some epidote quartzite is present along the southeast side of the Dahlonega fault. These rocks correlate with the lower metagraywacke-schist-amphibolite member of the Tallulah Falls Formation. Gillon (1982) considered the metasedimentary rock assemblages of the Union Grove sequence to represent sediments deposited in a fluvial-delta to distal-turbidite environment. Intrusive rocks include granitic, granodioritic, quartz monzonitic, and tonalitic gneisses and pegmatite.

THRUST SHEETS OF THE INNER PIEDMONT—DESCRIBED IN ASCENDING STRUCTURAL POSITION

Chauga-Walhalla Thrust Complex

The Chauga River and the Poor Mountain Formations of Hatcher (1969), together with rocks of the Walhalla nappe (Griffin, 1974), form the Chauga-Walhalla thrust complex. This thrust complex includes button phyllonites, graphite phyllonite, carbonate rocks, considerable amphibolite, granitoid, hornblende gneiss, quartzite, feldspathic quartzite, various types of biotite gneiss, migmatite, and mica gneisses. These rocks probably originated from sediments derived from a deeply weathered source and deposited both on a shelf and in an associated rift basin that also received considerable ocean-floor volcanic deposits.

Griffin (1974) interpreted the contact between the rocks of the Chauga belt and his Walhalla nappe to be a tectonic slide; elsewhere, Hatcher and Acker (1984) interpreted this contact as a metamorphic gradient. Our work suggests that there is a structural discontinuity locally between these lithotectonic units but that in other places the contact appears to be a metamorphic gradient. The Chauga-Walhalla thrust complex overlies the Tallulah Falls thrust sheet along the Brevard zone.

Six Mile Thrust Sheet

In this thrust sheet, the mapped units are unnamed and consist of varying assemblages of many rock types. In order of decreasing abundance, they are mica schist, red-weathering biotite schist, sillimanite schist and gneiss, amphibolite, various biotite gneisses (some of which are porphyroblastic), felsic gneiss, metagraywacke, some manganiferous schist, and gondite. The layering varies from thin to thick, and some is massive; the rocks are commonly deeply weathered. These rocks probably formed from sediments deposited in an environment that also received considerable volcanic materials.

The Six Mile thrust sheet is believed to rest on the Chauga-Walhalla thrust complex along a tectonic slide (Griffin, 1973). This tectonic slide is difficult to trace in the field, but lithologic and structural discontinuities along the contact and the higher metamorphic grade of the rocks forming the Six Mile sheet contrast with the lower grade rocks of the adjoining Chauga-Walhalla thrust complex. A low-angle thrust fault separating these sheets has been seen but is difficult to map. Numerous variably sized klippen of the Six Mile thrust sheet are present in the Chauga-Walhalla thrust complex.

Laurens Thrust Sheet

The principal rock type of the Laurens thrust sheet is a layered biotite gneiss. Individual layers are very noticeable in large outcrops. Amphibolite, hornblende gneiss, some biotite schist, and locally, considerable granitoid are also present. These rocks appear to be mostly metavolcanic rocks that were probably deposited in an island-arc environment. The Laurens thrust sheet overlies the Six Mile thrust sheet along an unnamed fault.

Paris Mountain Thrust Sheet

Sillimanite schist is the predominant rock type in the Paris Mountain thrust sheet. Amphibolite is present locally near the western margin; elsewhere, metasiltstone, quartzite, garnet-sillimanite schist, sillimanite-bearing felsic gneiss, and a marker bed of garnet-quartz granulite are present. Granite plutons are present throughout the terrane, composing about half of the thrust sheet's volume. The Paris Mountain thrust sheet overlies both the Six Mile and Laurens thrust sheets along an unnamed fault.

THRUST SHEETS OF THE CHARLOTTE TERRANE

Mafic-Ultramafic Thrust Sheet

An assemblage of ultramafic, mafic, and fragmental mafic rocks, together with some variably sized granitic bodies, composes a terrane on the southeast side of the Lowndesville shear zone near the southern border of the Greenville quadrangle. To the northeast, this terrane is overlain by the Charlotte thrust sheet. The boundary between the two terranes has not been observed but is inferred to be a thrust fault.

The mafic-ultramafic terrane is deeply weathered to a saprolite, and the distribution of fresh rock exposures is sparse. Some of the saprolite is derived from a fragmental rock that had a hornblende-rich matrix. The fragments in the saprolite were originally gabbro, ultramafic rock, and some siliceous rock. Because of the deep weathering, the distribution of much of the rock types within the terrane is uncertain. However, since this terrane is along strike with the Macon melange (Higgins and Crawford, 1985) to the southwest, it is probably also a melange. Like the Young Harris slice, these rocks are probably derived from ocean crust or a midocean ridge.

Charlotte Thrust Sheet

Formations and unnamed rock units that compose the Kings Mountain belt, Charlotte belt, and Carolina slate belt make up the Charlotte thrust sheet. These rocks include phyllite, greenstone, metamorphosed intermediate volcanic tuffs and lava flows, amphibolite, metasandstone, metagraywacke, metasiltstone, various biotite gneiss and mica schist units, and intrusive rocks. Granite, granodiorite, pyroxenite, and variably interlayered and textured gabbro form the principal intrusive rocks. The Charlotte thrust sheet and the mafic-ultramafic terrane overlie rocks of the Six Mile and Laurens thrust sheets along the Lowndesville shear zone.

DEFORMATION

All the thrust sheets and some rocks within fault zones have experienced several episodes of deformation. Detailed studies in the northwestern part of the Greenville 2° quadrangle have shown that the rocks have been deformed by folding at least four and possibly six times (Nelson, 1985). Small interference folds are commonly seen at rock exposures, and the present outcrop patterns of large structural features, such as the the large Chattahoochee basin (Nelson, 1985) and the Tallulah Falls dome (Hatcher, 1971), have resulted from superposed folding (Dallmeyer and others, 1978; Hatcher, 1974; Nelson, 1985). The first generation folds are represented by intrafolial, rootless, and recumbent isoclinal folds in transposed layers. Second generation folds (F_2), which form the major folds, are steeply inclined to recumbent. The limbs of F_2 folds have been folded into two sets of tight to open, upright to overturned flexure folds. These later folds form conjugate fold pairs. All the above mentioned folds have axial planar cleavages. A later folding event gently folded the flanks of some late flexure folds, but axial plane cleavage has not been identified with these later folds.

Most of the major folds (F_2) trend northeast, and their axes plunge gently northeast or southwest. These folds range from upright to inclined to recumbent, and although some of them verge southeast, most verge northwest. Regional F_2 folds in the Great Smoky thrust sheet are mostly overturned to the northwest, and their axial surfaces are steeply inclined. In the Richard Russell sheet, most of the F_2 folds are reclined to recumbent and, depending on their location with reference to the Chattahoochee basin, have variable orientations reflecting considerable F_3 (northwesterly and northeasterly) strain. In contrast, in both the Helen thrust sheet and the Tallulah thrust sheet west of the Tallulah Falls dome, the F_2 folds generally have steeply dipping axial surfaces overturned to the southeast, and their axes generally plunge northeast or southwest. These fold attitudes are believed to result from later superposed folding associated with development of basins and domes in this part of the Greenville quadrangle (Nelson, 1985). Table 1 summarizes the types of folds characteristic of each fold phase.

In many places, the rocks display multiple sets of planar surfaces—foliation, cleavage, metamorphic layering, and bedding (table 1). The first foliation (S_1) is considered to have formed during a regional metamorphic event and was later deformed during regional folding (F_2) that probably occurred after the high temperature peak of metamorphism (Nelson, 1985). Moderate temperatures may have continued through a third episode of folding (F_3). This is indicated by biotite that has grown

Table 1. Summary of fold phases observed in the northwestern part of the Greenville quadrangle, northwest of the Tallulah Falls thrust sheet

Fold phases	Characteristics of phases
F_1........	Rootless recumbent to reclined isoclinal folds that trend northeasterly; may be coplanar with F_2 folds and lie in the transposed S_1 foliation.
F_2........	Steep to recumbent isoclinal folds; form major folds and fold S_1 foliation; probably are post-peak metamorphism; rarely have well-developed axial-plane S_2 foliations.
F_3........	Upright to slightly inclined conjugate fold pairs that have axial-planar crenulation cleavage in pelitic units; probably late metamorphic; conjugate fold sets trend northeasterly and northwesterly.
F_4........	Poorly developed, gentle, upright folds and warps that have east-northeast- and north-northeast-trending axes; axial-plane cleavage has not been observed with these later folds.

along the axial-plane cleavage of third-generation folds. This later folding event may also represent a separate thermal pulse.

Regional relations suggest that the Richard Russell thrust sheet was emplaced in a westward direction over the Great Smoky thrust sheet along the Hayesville fault. This fault is probably pre- to synmetamorphic but formed before the regional metamorphic peak (Shellebarger, 1980; Wooten, 1980). North of the Greenville quadrangle, Wooten reported that the fault is folded by F_2 folds; it does not appear to offset the sillimanite isograd or to juxtapose rocks of different metamorphic grade. In the Greenville quadrangle or in an area to the north, the first generation foliation attitudes in rocks on either side of the fault do not appear to be deflected (Wooten, 1980). At a few places along the fault, however, some rocks of the Richard Russell thrust sheet have small zones where blastomylonite and mylonite textures are preserved (Shellebarger, 1980).

The northwestern side of the Helen thrust sheet is bounded by an unnamed fault. Foliation attitudes appear to be parallel in rocks on both sides of the fault; however, local discordances of foliation attitudes between the Helen and the Richard Russell thrust sheets suggest some post-S_1 foliation movement along at least part of the fault. From the Georgia-North Carolina boundary, the unnamed fault extends southwestward toward Dahlonega (Gillon, 1982), where it appears to join the Hayesville fault west of the Greenville quadrangle. If the Hayesville and the unnamed fault are the same, as the present interpretation suggests, then the Hayesville fault does not continue southwestward through Georgia as depicted by Williams (1978). Southwest of the Greenville quadrangle, McConnell and Costello (1980) correlated the Allatoona fault with the Hayesville fault, but Higgins and others (1984; 1988) mapped the Allatoona fault as the northwesternmost boundary of the Ropes Creek thrust sheet.

The Dahlonega fault (Crickmay, 1952) juxtaposes the southeastern part of the Helen thrust sheet, whose rocks are nonmigmatitic, with highly migmatitic rocks of the Tallulah Falls thrust sheet. Early ductile deformation along the fault formed mylonites and blastomylonites, but later brittle deformation formed button schists and intensely fractured the rocks (Bowen, 1961; McConnell and Costello, 1980; Gillon, 1982). Ductile deformation along the Dahlonega fault probably began near the metamorphic peak, and later brittle deformation probably occurred after temperatures had cooled to near the lower temperature boundary of greenschist facies conditions (Sibson, 1977).

Although a detailed structural study has not been completed southeast of the Brevard zone, preliminary work shows that these rocks were also polydeformed. Similar styles of superposed folds are present and the major folds also trend northeast. Rock exposures also display planar structures such as metamorphic layering, foliation, schistosity, and cleavage. In places, several of these planar fabrics are displayed in the same exposure.

Rocks in both the Brevard zone and the Lowndesville shear zone are also polydeformed. Early ductile and later brittle deformation fabrics are common (Nelson, 1981), and several generations of folding are evident, as are several generations of cleavage.

The Lowndesville shear zone closely follows a major gravity gradient that trends northeast across the eastern United States (American Geophysical Union, 1964; Bouguer gravity map compiled from data on file at the Defense Mapping Agency). The significance of this gravity gradient and its relations to the Lowndesville shear zone are unknown. The gravity gradient probably reflects a major change in the deeply buried basement. Griffin (1970) suggested that northwestward thrusting and development of the mobile Inner Piedmont core was related to underthrusting of the continental crust by an oceanic plate. The gravity gradient may reflect the juxtaposition of continental basement to the northwest and oceanic crust to the southeast (Hatcher and Zeitz, 1980; Nelson, 1981).

METAMORPHISM

Metamorphic gradients exist within some thrust sheets, and some thrust faults juxtapose terranes of differing metamorphic grade (figs. 4 and 5). Northwest of the Brevard zone in the Blue Ridge, the Great Smoky thrust sheet has regional metamorphic zones ranging from chlorite (in the northwest) to sillimanite (in the southeast) (Hadley and Nelson, 1971). In the Greenville quadrangle, however, the rocks of the Great Smoky sheet range from garnet to sillimanite-muscovite zones (Shellebarger, 1980; Gillon, 1982). In the overlying Richard Russell thrust sheet, the rocks appear to be mostly in the sillimanite-muscovite zone (Gillon, 1982; Nelson and Zietz, 1983), although to the northeast, beyond the quadrangle boundary, some of the rocks are in the granulite facies of regional metamorphism (Eckert and Mohr, 1985). The Helen thrust sheet is exposed in a relatively narrow zone and generally contains lower grade rocks than does the adjoining Richard Russell thrust sheet to the northwest or the Tallulah Falls thrust sheet to the southeast. Rocks in the Helen thrust sheet range from the garnet to staurolite and kyanite zones (Gillon, 1982; Nelson, 1982, 1983a). To the southeast, the Tallulah Falls thrust sheet includes rocks ranging from the kyanite to sillimanite-muscovite zones (Hatcher, 1976; Roper and Dunn, 1970).

Southeast of the Brevard zone, the Chauga-Walhalla thrust complex of the Inner Piedmont contains prograde metamorphic rocks ranging from the greenschist facies to the kyanite zone of the amphibolite facies. Most of the rocks in the Chauga part of the complex are in the greenschist facies. To the southeast, the metamorphic grade gradually increases to kyanite in the Walhalla part of the thrust complex (Griffin, 1967, 1975; Hatcher, 1969). To the southeast, the Six Mile thrust sheet is mostly in the sillimanite-muscovite zone, but locally it is in the kyanite zone (Griffin, 1975). The Paris Mountain and Laurens thrust sheets farther to the east are in the sillimanite-muscovite zone.

Southeast of the Lowndesville shear zone, highly weathered and altered mafic and ultramafic rocks of the mafic-ultramafic terrane are poorly exposed, and, although metamorphic data are sparse, the rocks appear to be at medium grade. Adjoining the mafic-ultramafic terrane to the northeast is the Charlotte thrust sheet that includes rocks of the Carolina slate belt that are in the biotite-chlorite zone of the greenschist facies. Also included are rocks of the Kings Mountain belt and the Charlotte belt that are in the amphibolite facies.

Retrograded metamorphic rocks are exposed in and near the Brevard zone and the Lowndesville shear zone. In addition, retrograded metamorphic rocks are also associated with some smaller shear zones elsewhere in the quadrangle.

Much radiometric whole rock and mineral age dating has been done on samples from the southern Appalachian Mountains (Long and others, 1959; Kulp and Eckelmann, 1961; Butler, 1972; Odom and Fullagar, 1973; Dallmeyer, 1975, 1978; Fullagar and Butler, 1979; Harper and Fullagar, 1981; Fullager and Kish, 1981; Whitney and others, 1976; Odom and others, 1976; Medlin, 1968). This radiometric dating includes the U-Pb zircon, K-Ar, ^{40}Ar-^{39}Ar, and Rb-Sr methods. The oldest period of regional metamorphism recorded in the southern Appalachian Mountains occurred about 1,000–1,200 Ma (Hadley and Goldsmith, 1963; Rankin and others, 1969), but there was also a thermal peak about 800–900 Ma. In the Blue Ridge thrust sheet, mostly Great Smoky thrust sheet of this report, Butler (1972) indicates that a Paleozoic Barrovian-type prograde metamorphism occurred between 430 and 470 Ma, probably during the Taconic orogeny; a possible period of metamorphism also occurred about 380 Ma (Acadian) when the Spruce Pine pegmatites originated. In addition, he indicated an episode of retrograde metamorphism that was particularly intense along the Brevard zone and along other faults but which was sporadically developed elsewhere. This retrograde metamorphism appears to be associated with late Paleozoic deformation and thrust faulting but could also be the result of uplift and cooling and not necessarily a separate thermal event (Shellebarger, 1980). Dallmeyer (1975) also concluded that the Blue Ridge was regionally metamorphosed about 480 Ma. Butler (1972) considered the Inner Piedmont to have been metamorphosed about

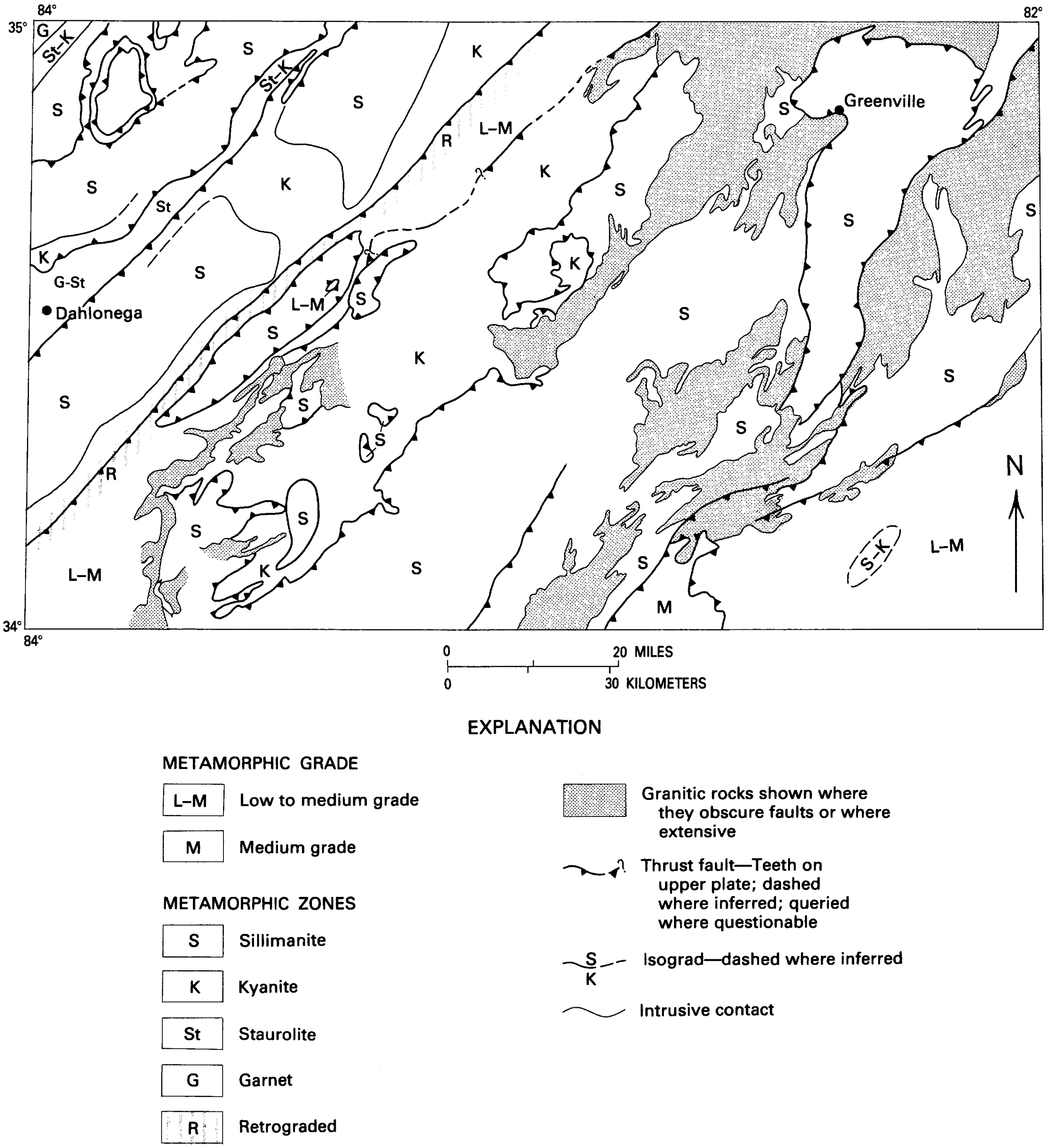

Figure 4. Generalized tectonic map of the Greenville 1°×2° quadrangle showing metamorphic grade and metamorphic zones.

410–430 Ma and that belts to the southeast were metamorphosed about 380–420 Ma.

Odom and others (1976) indicated that a part of the southern Appalachians in Alabama and Georgia that corresponds to the Tallulah Falls thrust sheet was regionally metamorphosed about 370 Ma. Dallmeyer (1978) gave evidence to support a regional metamorphic event in the Inner Piedmont of Georgia at about 365 Ma.

Shearing and recrystallization and tectonism in the Brevard zone have been dated around 356 Ma (Odom and Fullagar, 1973). The minimum age for mylonite formation in the Lowndesville shear zone is reported as

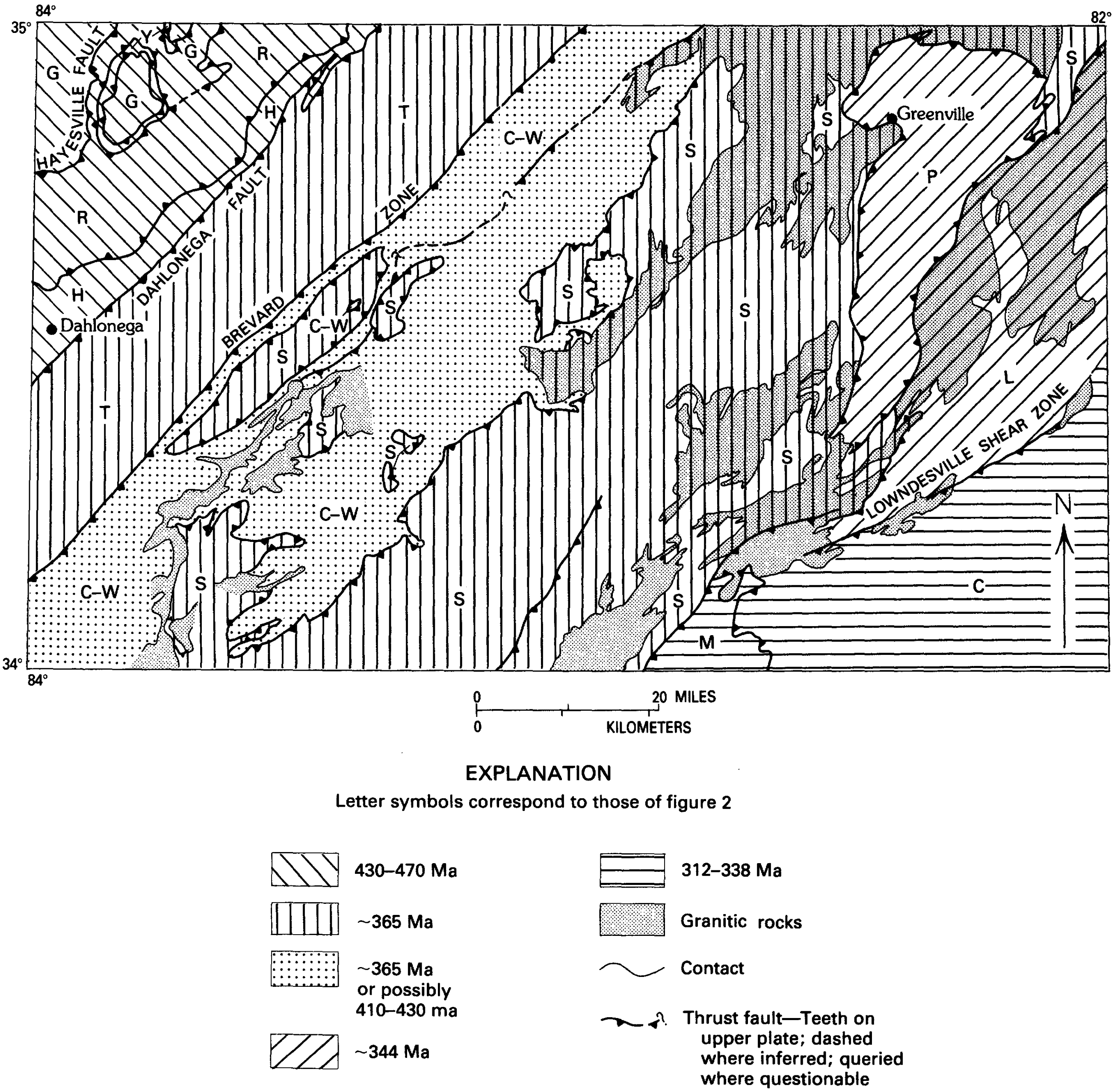

Figure 5. Generalized tectonic map of the Greenville 1°×2° quadrangle showing interpreted regional metamorphic ages for various thrust sheets.

350 Ma (Davis, 1980; Horton, 1981), but in the study area, recent unpublished radiometric zircon age data (T. Stern, written commun., 1986) suggest that the mylonites of the Lowndesville shear zone were formed between 312 and 344 Ma. The Brevard zone and the Lowndesville shear zone form the tectonic boundaries for three of the major allochthonous terranes in the study area, and they must have been subject to major tectonism approximately 312–356 Ma.

DISCUSSION

Rocks in all thrust sheets are polymetamorphic and polydeformed. Some rocks contain two postregional metamorphic schistosity or cleavage surfaces, and some rocks have been folded at least four times (Nelson, 1985). Small patches of retrograded rocks are irregularly dispersed in all thrust sheets, but the most intensely retrograded rocks are in or close to the Brevard zone or the

Lowndesville shear zone. Locally, a diamictite contains some medium-grade metamorphic boulders and rock fragments whose foliation-schistosity trends are discordant to the regional schistosity of the enclosing matrix. This suggests that the boulders and their source rock unit within the same thrust sheet had a previous prograde metamorphic history. Other evidence to support preregional metamorphic events, however, is rare, and most probably, if there were early prograde events, much of the evidence was destroyed as each thrust sheet was regionally metamorphosed under relatively high grade conditions.

Even though considerable isotopic dating has been done in the southern Appalachians, the orogenic evolution and age of metamorphism of some allochthonous terranes in the orogen remain enigmatic. The Greenville quadrangle is underlain by a series of stacked thrust sheets extending from the Blue Ridge province through the Inner Piedmont and into the Piedmont province. Some of these thrust sheets correlate with terranes where the regional metamorphism has been dated. For example, the Great Smoky thrust sheet, the Richard Russell thrust sheet, and the Helen thrust sheet form a large part of the terrane that was metamorphosed 430–470 Ma (Butler, 1972). Rocks within the Tallulah Falls thrust sheet, however, appear to have conflicting isotopic dates. Rock units of the Tallulah Falls thrust sheet were previously thought to correlate with rocks to the northeast that were regionally metamorphosed between 430 and 470 Ma (Butler, 1972); however, these rocks to the northeast are now believed to be from the Great Smoky and the Richard Russell thrust sheets. To the southeast, some rocks in the Tallulah Falls thrust sheet probably correlate with units of the Ashland-Wedowee belt (Hurst, 1973). Odom and others (1976) presented Rb-Sr data that suggest some metasedimentary units of the Ashland-Wedowee belt were regionally metamorphosed about 370 Ma. Preliminary unpublished U-Pb zircon ages suggest that the regional metamorphism in the Tallulah Falls thrust sheet is probably no older than 351–373 Ma (T. Stern, written commun., 1986) and thus may represent the same metamorphic event reported by Odom and others.

The age of regional metamorphism for the Inner Piedmont, which includes the Chauga-Walhalla thrust complex, the Six Mile thrust sheet, and the Laurens thrust sheet in the Greenville quadrangle, is also incompletely understood. To the northeast, rocks of these thrust sheets appear to be on strike with Inner Piedmont rocks that were regionally metamorphosed between 410 and 430 Ma (Butler, 1972), but to the southwest, the rocks of these thrust sheets extend into and form the Inner Piedmont terrane that Dallmeyer (1978) suggests was metamorphosed about 365 Ma.

Preliminary, radiometric dating studies suggest that rocks of the Chauga-Walhalla thrust complex were not regionally metamorphosed earlier than about 400–424 Ma (T. Stern, written commun., 1986), and these studies agree well with Butler's (1972) age of Inner Piedmont metamorphism at 410–430 Ma, but these rocks could also have been regionally metamorphosed during the 365 Ma event of Dallmeyer. Preliminary U-Pb zircon ages suggest that regional metamorphism for the eastern part of the Six Mile thrust sheet occurred no earlier than about 365–391 Ma (T. Stern, written commun., 1986). These limits suggest a closer correspondence to the 365 Ma regional metamorphism date of Dallmeyer. Preliminary U-Pb zircon dating for rocks in the Laurens thrust sheet suggests that regional metamorphism occurred no earlier than about 344–359 Ma (T. Stern, written commun., 1986). This seems to preclude using the 410–430 Ma for metamorphism of the Laurens thrust sheet that Butler used for the Inner Piedmont farther to the north. The 344–359 Ma for metamorphism is closer to and may be a late stage of the 365 Ma event of Dallmeyer (1978).

Within the Greenville quadrangle, the Inner Piedmont is bounded on the northwest by the Brevard zone, which separates the Tallulah Falls thrust sheet on the northwest from the Chauga-Walhalla thrust complex on the southeast. Farther to the southwest in Georgia and Alabama, the Brevard zone does not form a major terrane boundary, as some rock units from the Ashland-Wedowee belt extend from the west across the Brevard zone and into the Inner Piedmont (Medlin and Crawford, 1973). Because of this, Dallmeyer has pointed out that the Ashland-Wedowee belt and some rocks of the Inner Piedmont were probably regionally metamorphosed about 365–370 Ma.

Butler (1972) suggests that belts southeast of the Inner Piedmont and east and northeast of the Greenville quadrangle were regionally metamorphosed between 380 and 420 Ma. In the Greenville quadrangle, rocks underlying the Charlotte thrust sheet (fig. 1) lie immediately southeast of the Inner Piedmont along the Lowndesville shear zone. Preliminary U-Pb zircon studies suggest that the Charlotte thrust sheet was regionally metamorphosed approximately 312–338 Ma (T. Stern, written commun., 1986), and here the age of regional metamorphism does not correspond with the 380–420 event farther to the northeast. Medlin (1968) reported that postmetamorphic plutons in the Charlotte thrust sheet have K-Ar age dates of 380, 386, and 387 Ma. These dates appear anomalous; they do not correspond with recent U-Pb zircon dates, but they do correspond with the 380–420 Ma event of Butler (1972).

Fullagar and Kish (1981) presented Rb-Sr mineral age data for a part of the Inner Piedmont, represented by the Laurens thrust sheet, the Paris Mountain thrust sheet, and the Charlotte thrust sheet. These Rb-Sr mineral ages, within the report area, range from 254 to 280 Ma. The Fullagar and Kish study shows that the youngest mineral ages are in the western part, and they suggest that this results from more recent uplift and erosion of the rocks underlying the western Piedmont. The 254–280 Ma mineral ages (Permian) for parts of the Laurens thrust sheet, the Paris Mountain thrust sheet, and the Charlotte thrust sheet are probably the results of rapid cooling of an earlier thermal event. Throughout the Greenville quadrangle, several postpeak regional-metamorphic stages of cleavage development and mica crystallization exist in these cleavage planes. I suggest that Permian mineral ages might represent slightly earlier, but postregional, metamorphism thermal-deformation events that may not have been very intense nor extensively developed.

CONCLUSIONS

While the precise timing of regional metamorphic events in specific thrust sheets within the Greenville quadrangle is imperfectly known, the following pattern seems to be present. The oldest regional metamorphic event, exclusive of the Middle Proterozoic event in the basement rocks, occurs in the rocks of thrust sheets northwest of the Tallulah Falls thrust sheet (fig. 5). The youngest prograde metamorphic event appears to be in the rocks of the Charlotte thrust sheet in the southeast part of the quadrangle. Generally the Chauga-Walhalla thrust complex, the Six Mile thrust sheet, the Laurens thrust sheet, and the Charlotte thrust sheet appear to have been regionally metamorphosed at successively younger intervals from west to east.

Rocks that compose the thrust sheets northwest of the Tallulah Falls thrust sheet appear to have been regionally metamorphosed during the Paleozoic between 430 and 470 Ma (Butler, 1972) (fig. 5). Immediately to the southeast, rocks of the Tallulah Falls thrust sheet seem to have been metamorphosed between 365 and 370 Ma. Next to the southeast, in the Inner Piedmont, rocks of the Chauga-Walhalla thrust complex could have been metamorphosed either during the 410–430 Ma event of Butler (1972) for the Inner Piedmont or during the 365 Ma event for the Inner Piedmont to the south (Dallmeyer, 1978). Rocks of the Six Mile thrust sheet were probably metamorphosed during the 365 Ma event suggested by Dallmeyer. The Laurens thrust sheet appears to have been metamorphosed no earlier than 344 Ma or during a later phase of the 365 Ma event. The rocks of the Charlotte thrust sheet exposed in the Greenville quadrangle were probably regionally metamorphosed between 312 and 338 Ma.

At the present time, a sketchy and imperfect understanding exists of the metamorphic and deformational history of the thrust sheets underlying the Greenville quadrangle. The distribution and position, as well as the present metamorphic grade and age, of the thrust sheets underlying the Greenville quadrangle show that they have evolved through a complex deformation and metamorphic history. Thrust sheets with varying ages and grades of metamorphism are juxtaposed, and some thrust sheets have anomalous ages of metamorphism. Deformation along some of the major thrust faults covers a long time interval; some faults are pre- to synmetamorphic, and parts of some earlier faults appear to have been reactivated later under a brittle regime. I suggest that the present distribution of the thrust sheets results from telescoping of previously metamorphosed thrust sheets during a long interval of intermittent westward transport of much of the thrust stack onto the North American craton during the Paleozoic and that selected assemblages of thrust sheets were metamorphosed during one of several metamorphic events and assembled into their present position as outlined below.

The Helen thrust sheet was emplaced upon the Great Smoky thrust sheet before the 430–470 Ma regional metamorphic event. Later, during an interval that began before, but extended into, the period of regional metamorphism, the Richard Russell thrust sheet and the Young Harris slice were thrust over both the Helen and the Great Smoky thrust sheets along the Hayesville fault. The Hayesville fault is a pre- to synmetamorphic fault, but some postmetamorphic movement along the fault between the Richard Russell and Helen thrust sheets has occurred (Nelson, 1985), perhaps as a back thrust. The Great Smoky thrust sheet, the Helen thrust sheet, and the Richard Russell thrust sheet, along with the Young Harris slice, form a northwest thrust sheet assemblage that was metamorphosed 430–470 Ma.

The metamorphosed Tallulah Falls thrust sheet was emplaced upon the Helen thrust sheet along the Dahlonega fault probably before 356 Ma. In places, lower grade rocks (garnet zone) of the Helen thrust sheet are juxtaposed with migmatite and sillimanite grade rocks of the Tallulah Falls thrust sheet; this juxtaposition suggests that the two thrust sheets were separated during metamorphism of the Tallulah sheet that occurred about 365 Ma.

Rock units of the Chauga-Walhalla thrust complex were metamorphosed between 365 and 430 Ma (fig. 5). The preferred date is close to 365 Ma because rocks of this thrust complex are close to and probably correlate with some rocks that Dallmeyer (1978) indicates were metamorphosed 365 Ma. The Six Mile thrust sheet was also metamorphosed at approximately the same time, while the Paris Mountain and the Laurens thrust sheets were metamorphosed slightly later, about 344 Ma. Thrust sheets of the Inner Piedmont exposed between the Brevard zone and the Lowndesville shear zone form a distinct thrust sheet assemblage considered to have been metamorphosed during the same event that extended from 344 to 365 Ma. The Chauga-Walhalla thrust complex, which forms the northwest part of this thrust sheet assemblage, was thrust onto the Tallulah Falls thrust sheet along the Brevard zone about 356 Ma (Odom and Fullagar, 1973) when the mylonites and blastomylonites of the Brevard zone formed. Subsequently rocks in the Brevard zone were brittly deformed over a long interval.

The Six Mile thrust sheet was thrust onto the Walhalla thrust sheet along an unnamed postmetamorphic fault. When the Laurens thrust sheet was emplaced onto the Six Mile sheet is unknown, but the Paris Mountain thrust sheet was emplaced after the Laurens and Six Mile sheets were joined. The metamorphosed and deformed Charlotte thrust sheet was thrust upon parts of the Six Mile and Laurens thrust sheets along the Lowndesville shear zone between 312 and 344 Ma.

If the present interpretation is correct, the various thrust sheet assemblages were metamorphosed during one of three periods of regional metamorphism—312–338 Ma, 344–365 Ma, or 430–470 Ma—younging from northwest to southeast. Except for the northwestermost assemblage, the thrust sheets or thrust sheet assemblages were metamorphosed before emplacement upon thrust sheets to the northwest. After the major thrust sheets or assemblages of thrust sheets were joined, they were thrust as a unit along a master decollement to their present position upon unmetamorphosed Paleozoic rocks of the Valley and Ridge near the close of the Paleozoic.

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