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Geology

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GEOLOGIC EVOLUTION OF A PORTION OF THE MURPHY MARBLE BELT IN SOUTHWESTERN NORTH CAROLINA

by

JOSEPH T. FORREST

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

Thesis Director's signature :

Houston, Texas

May 1975
ABSTRACT

Joseph T. Forrest Jr.

The Murphy Marble Belt in Southwestern North Carolina comprises structures involving rocks of the Great Smoky Group and the "Murphy sequence", consisting of the Nantahala Slate, Tusquitee Quartzite, Brasstown Formation, Murphy Marble, Andrews Schist, Nottely Quartzite and the Mineral Bluff Formation. Great Smoky Group rocks were deposited in fluvial and deltaic environments, while Murphy sequence rocks were deposited under lagoonal, littoral, nearshore and shelf conditions. Age of the rocks is not certain, but is probably somewhere between late Precambrian to Middle Ordovician. There is no evidence of a great age difference between the Great Smoky Group and the Murphy sequence, as all formations are conformable and have gradational contacts. Two transgressive and an intervening regressive phase can be recognized in the depositional history.

Four phases of folding have been worked out in the study area, the first probably occurred in the Middle Ordovician and involved isoclinal folding, tectonic sliding and greenschist metamorphism. The second phase, bracketed between Middle Ordovician and Early Silurian, produced large folds with northwest dipping axial planes and was accompanied by amphibolite facies metamorphism. The third folding phase, characterized by similar folds and retrograde metamorphism in the greenschist facies, may have taken place in the Devonian. The final phase of folding was in post-Early Mississippian time and involved post-metamorphic warping of all previous structures.
ACKNOWLEDGEMENTS

The financial assistance of the Georgia Marble Company, the North Carolina Department of Mineral Resources, and Rice University are gratefully acknowledged.

Professor B.C. Burchfiel served as Thesis Director. His counsel during field visits and several readings of the thesis have been greatly appreciated.

Professors H. G. Ave L’alleme and John Merwin have also read several drafts of the manuscript. I thank them for their suggestions.

Finally I wish to acknowledge the patient help of my wife Christine who pushed me to finish the work.
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CHAPTER I

GEOLOGIC EVOLUTION
OF A PORTION OF THE MURPHY MARBLE BELT,
SOUTHWESTERN NORTH CAROLINA
INTRODUCTION

The Murphy Marble Belt is a sinuous northeast-trending structure in the Blue Ridge province of southwestern North Carolina and northern Georgia (Fig. 1). For approximately 120 miles, between Bryson City, North Carolina and Cartersville, Georgia, a distinctive sequence of rocks, informally referred to as the “Murphy sequence” is exposed in the core of this structure. These rocks bear affinities to the Lower Cambrian sequences of East Tennessee (Chilhowee Group, Shady Dolomite and Rome Formation) and are distinctly different from rocks of the Ocoee Series on which they lie.

The structure of the Murphy Belt has been an enigma. Previous interpretations have included a synclinorium (Keith, 1907), a window (Stose and Stose, 1944), an anticline (Van Horn, 1948), a monocline (Graham, 1967, ms), and a simple syncline (Hurst, 1953).

The Murphy Marble Belt is a critical area in the interpretation of Blue Ridge geology for several reasons. First, a consistent stratigraphic section can be seen there which is relatively undisturbed by major faulting. If the stratigraphy can be worked out in the Murphy Belt, it can be expanded to adjacent areas of the Blue Ridge where the facing of rock sequences is unknown. Secondly, the rocks of the Murphy Belt preserve many of their original sedimentary features and can be used for paleogeographic and environmental reconstruction. Thirdly, the lower metamorphic grade of the Murphy Belt rocks permits deciphering of superimposed folding and faulting events which have been obliterated by higher grade metamorphism in surrounding areas.

Location and Geographic Setting of Study Area

The area of this study is included on five 71/2’ topographic quadrangle sheets (Fig. 2) (Murphy, North Carolina; Marble, North Carolina; Peachtree, North Carolina; Andrews, North Carolina; Hayesville, North Carolina), all lying within Cherokee, Clay and Macon Counties, North Carolina. This area occupies a topographically depressed region between the high Unaka Mountains to the west and the ranges of the Blue Ridge to the east. All of the study area lies within the Nantahala National Forest and is approximately equidistant between the three cities of Atlanta, Georgia, Knoxville, Tennessee and Asheville, North Carolina. All drainage is in the basin of the Tennessee
Fig.1. Location of the Murphy Marble Belt in the Blue Ridge Province of Southwestern North Carolina and Northern Georgia.
River, and the area is part of the hydroelectric-flood control-social development project of the Tennessee Valley Authority. Principal rivers are the Hiwassee and Valley Rivers. Largest communities are Murphy and Andrews. Main livelihoods of the area are lumbering, dairying, and vegetable farming.

Field Work Conditions

Field mapping for this study was done on USGS 71/2' topographic quadrangle sheets, at a scale of 1 to 24,000. Though the area is one of heavy vegetation and deep weathering, outcrop control is quite good along roadcuts and mountain streams. Locations along streams were made using the topographic sheets and a barometric altimeter. Many traverses were made along timbering roads, but these are difficult to locate accurately on the maps as they are ephemeral features and rarely appear on the older topographic sheets. Cross-country traverses were made only in critical areas, since the heavy vegetation of the mountain slopes prevents one from locating himself with any accuracy.

Previous Work in the Area of the Present Study

The first geologic work in the Murphy Marble Belt was that of Arthur Keith (1907) in the Nantahala Quadrangle, mapped for the U.S. Geological Survey Folio Series. The Andrews, Marble, Peachtree, and Hayesville 7–1/2’ Quadrangles of the present study were included in the Nantahala Folio (Fig. 2). Keith recognized seven formations above the Great Smoky conglomerate – the Nantahala Slate, Tusquitee Quartzite, Brasstown Formation, Valleytown Formation, Murphy Marble, Andrews Schist, and the Nottely Quartzite. He classified these rocks as Lower Cambrian, based on lithologic correlations with the Chilhowee Sandstone-Shady Dolomite sequence (Keith, 1907, p.11).

The structure of the Murphy Marble Belt in the Nantahala Quadrangle was envisioned by Keith as a "general synclinal basin between two anticlinal uplifts"... "complicated by many small folds" (Keith, 1907, p.6). Keith extended his mapping of the Murphy Belt into the Murphy 30' Quadrangle (Keith did the Blue Ridge portion of this sheet, while C.W.Hayes was responsible for the Valley and Ridge), but there he lost confidence in his interpretation (P.B.King, personal communication, 1969), and
Fig. 2. Summary diagram of previous geologic work in the Murphy Marble Belt. The present study comprises areas 11 and 13.

1. Keith (1907)
2. Laforge and Phalen (1913)
3. Bayley (1928)
4. Van Horn (1948)
5. Nuttall (1951)
6. Hurst (1955)
7. Power and Reade (1962)
8. Hermon (1963)
9. Fairley (1965)
10. Graham (1967)
11. Forrest (1969)
12. Mohr (1971)
13. Forrest (1975)
the work was never published. In 1952, P.B. King synthesized Keith’s and Hayes’ work and their map of the Murphy 30’ Quadrangle was put in the open files of the U.S. Geological Survey.

After World War II, the Tennessee Valley Authority began a program to promote development of mineral deposits in its drainage area. The talc bodies of the Murphy Marble Belt had been mined sporadically since 1863, so a project was undertaken by Earl Van Horn to locate the known bodies and develop techniques for prospecting. At that time the best talc bodies were known only on the western side of the Marble Belt, so Van Horn restricted his mapping to that side. Van Horn’s maps cover portions of the Murphy and Marble Quadrangles of the present study. Van Horn did not use Keith’s stratigraphy, but divided the rocks into lithologic units, which, on the western side of the Belt, he thought formed a consistent mappable sequence, generally dipping steeply to the southeast. Cutting across these units was a cleavage which dips less steeply than the bedding, indicating to Van Horn that the western side of the Murphy Belt is on the western flank of an anticline overturned to the northwest (Van Horn, 1948, pp. 18–20). Since the rocks of the Murphy Belt sequence were exposed in the core of an anticline and thus below the Precambrian Ocoee Series, they were also classified as Precambrian (Van Horn, 1948).

FIGURE 2 summarizes all earlier works in the Murphy Marble Belt including areas not covered by this study.
CHAPTER II

STRATIGRAPHY
Fig. 3. Generalized stratigraphic section of metasediments of the Murphy Marble Belt in the Murphy, Andrews, Peachtree, Marble and Hayesville Quadrangles of Southwestern North Carolina.
INTRODUCTION

The rocks of the study area are divided into eight mappable units (Fig. 3). From oldest to youngest, these are the Great Smoky Group (undivided), Nantahala Slate, Tusquitee Quartzite, Brasstown Formation, Murphy Marble, Andrews Schist, Nottely Quartzite and Mineral Bluff Formation. The usage of these stratigraphic terms is not the same as originally proposed by Keith (1907) and Hurst (1955), but is a revised usage first proposed by Forrest (1969).

Great Smoky Group

Name and definition: Keith first applied the name Great Smoky Conglomerate to coarse-grained clastic rocks in the Great Smoky Mountains of North Carolina and Tennessee (Keith, 1904, p.6). The unit was later divided by Hurst (1955, pp. 8–45) into a number of formations, and the term 'Great Smoky' was given Group status. In this study the rocks have not been divided into formations, and thus the general term Great Smoky Group is applied to them.

The Great Smoky Group comprises a thick sequence of coarse- and fine-grained clastic rocks, lying below the Nantahala Slate. These rocks are quite distinct from the overlying rocks in the core of the Murphy Marble Belt, because of their relative immaturity, poor sorting and coarseness. Lithologies of the Great Smoky include conglomerates, metagreywackes, quartzites, laminated schists and siltstones.

Description: Conglomerates form the most distinctive facies of the Great Smoky Group. They include conglomeratic sandstones, coarse pebble conglomerates, and lithic pebble conglomerates, occurring in beds 1 to 50 feet thick. The conglomeratic sandstones often display grading of grain size from conglomerate to metagreywacke (Fig. 4). This grading has been used as a facing criteria, on the assumption that tops are in the direction of fining. This assumption has proven correct in places where other facing criteria, such as cross-bedding or flame structures, are also observed in the same outcrop.

The Great Smoky conglomerates have a very high content of detrital feldspar, commonly of pebble-size clasts. In some beds feldspar clasts may form 30 to 40 percent of the pebble-sized material. Matrix material of the conglomerates ranges from coarse sand to silt. Both clast- and matrix-supported conglomerates have been
Fig. 4. Graded bedding in sandstone of the Great Smoky Group. Facing is toward the lower right hand corner of the photo. At its base this bed consists of conglomeratic metasandstone, grading into metagreywacke in the middle and siltstone at the top.
Fig. 5. Medium-scale crossbedding in quartzites of the Great Smoky Group. Beds overturned to the southeast (right side of photo).
observed, but the clast-supported variety is far more common. The conglomerates are thicker and more numerous on the western side of the Murphy Belt than on the eastern side, suggesting that their source was to the west of the Murphy Belt.

Sandstones of the Great Smoky include metagreywacke and orthoquartzite. Orthoquartzites are least common, forming less than 1 to 2 percent of the sandstones. They usually show well-developed medium-scale cross-bedding (Fig. 5) and are well-sorted. The metagreywackes are massive to thin-beded with planar and persistent layering.

Schists of the Great Smoky Group are thinly laminated to very thin-beded and are always complexly crinkled and foliated (Fig. 6). They include cross-biotite, staurolite and garnet schists. The schistosity is due to parallel alignment of muscovite and subordinate biotite.

Where there are large fresh exposures of the Great Smoky one can often see a graded sequence going from pebble conglomerates to metagreywackes to laminated schists. In several places conglomerates filling erosional channels in schists have been observed (Fig. 7). Fragments of schist have been eroded from the channel floors and incorporated into the conglomerate, giving an excellent facing criterion (Fig. 8). In three exposures “flame structures” were observed in fine metagreywackes and siltstones (Fig. 9).

**Nantahala Slate**

**Name and definition**: Keith (1907, p.4) named the Nantahala Slate after exposures of the formation along the Nantahala River in Cherokee and Macon Counties, North Carolina. In the area of this study the formation consists of slate with subordinate quartzite lying over the Great Smoky Group and under the Tusquitee Quartzite. The Nantahala has an approximate range in thickness of from 200 to 2,000 feet.

**Description**: The characteristic lithology of the Nantahala is a thinly-laminated to a very thin-beded, dark blue slate (Fig. 10). The laminations of the formation show up as alternations of dark blue micaceous slate with lighter layers of impure quartzite. The predominance of slaty laminae gives the unit its dark blue color. Laminations in the Nantahala are generally planar and persistent, but locally small-scale ripple cross-laminae
Fig. 6. Laminated schists of the Great Smoky Group. Bedding is nearly vertical. $F_2$ schistosity dips to the northwest (left side of photo), while $F_3$ crenulation cleavage dips to the southeast (right side of photo). Lineation on $F_2$ surfaces is intersection of $F_3$ with $F_2$ cleavage.
Fig. 7. Great Smoky Group. Pebble conglomerate filling erosional channel in schist. Facing is to the southeast (right side of photo).
Fig. 8.  Detail of conglomerate bed in Great Smoky Group. Note large dark blue schist fragments eroded from channel in which conglomerate was deposited.
Fig. 9. Flames Structures in interbedded shales and sandstones of the Great Smoky Group. Facing is to the southeast (upper right hand corner of photo).
are present. In some places the bedding pinches and swells and is discontinuous, suggesting flaser bedding, but this effect may be tectonic rather than sedimentary.

Quartzites in the Nantahala become locally quite thick and may form beds 10 to 20 feet thick, especially at the top of the formation, which is gradational into the Tusquitee Quartzite. The contact between the two units is drawn where quartzites become the dominant rock type.

The groundmass of the slates consists of a fine-grained mixture of quartz, plagioclase and biotite, with porphyroblasts of garnet and biotite. A modal analysis of a typical specimen of Nantahala Slate is given below: (Sample number NSQ, from abandoned road metal quarry on the Joe Brown Highway, Murphy Quadrangle. 1500 point counts).

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>plagioclase</td>
<td>37.4%</td>
</tr>
<tr>
<td>quartz</td>
<td>33.2</td>
</tr>
<tr>
<td>biotite</td>
<td>20.6</td>
</tr>
<tr>
<td>pyrrhotite</td>
<td>7.8</td>
</tr>
<tr>
<td>garnet</td>
<td>0.8</td>
</tr>
<tr>
<td>carbonate</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Pyrrhotite is an abundant and characteristic accessory in the Nantahala commonly forming up to 10 percent of some samples. It occurs as thin laminae along bedding planes, and F2 cleavage surfaces and as massive vug fillings. It has never been observed in association with F3 cleavage planes. Gypsum also occurs commonly in the Nantahala as yellow and white encrustations and blooms on weathered surfaces of the slate.

**Tusquitee Quartzite**

**Name and definition**: The Tusquitee Quartzite was named by Keith (1907, p.4) for exposures of the formation in the Tusquitee Mountains of Clay County, North Carolina. In the area of this study the Tusquitee consists of quartzite with subordinate slate beds, lying above the Nantahala Slate and beneath the Brasstown Formation. The formation has a variable thickness, ranging from approximately 50 to 1,000 feet, being thinnest on the eastern side of the study area.
Fig. 10. Thin-laminated dark blue slate of the Nantahala Slate. Lighter patches in center of outcrop are calc-silicate granofels.
Fig. 11. Characteristic lithology of the Tusquitee Quartzite — feldspathic quartzite with thin discontinuous intercalations of black slate.
18.

**Description**: The characteristic lithology of the Tusquitee is coarse feldspathic quartzite with wispy intercalations of black slate (*Fig. 11*). Medium-scale cross-bedding occurs throughout the Tusquitee, but is usually seen only in fresh outcrops. Slate intercalations are most commonly paper thin, but range up to 50 feet thick in parts of the Tusquitee. In areas where slate beds are thick the formation may be difficult to distinguish from the Nantahala.

The feldspathic nature of the Tusquitee causes the unit to weather quite readily, and fresh exposures are rare. The Tusquitee is almost never a ridge-former, usually occupying a position below the Nantahala Slate on the slopes of high mountains. The quartzite weathers to a fine sandy saprolite which has the color and consistency of ground corn meal. "Ground corn meal" is in fact the term used by the inhabitants of the area to describe occurrences of saprolitic Tusquitee. Since the days of the earliest white settlers, the weathered Tusquitee sands have been used as an abrasive for scrubbing and polishing the wooden floors of the local mountain homes.

The plagioclase of the Turquitee is invariably "sericitized," thus its An content is indeterminable.

The following is a modal analysis of a typical sample of the Tusquitee Quartzite (sample number TQ3, from exposures on Lake Hiwassee, Murphy Quadrangle. 1500 point counts).

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>quartz</td>
<td>58.4%</td>
</tr>
<tr>
<td>plagioclase</td>
<td>23.2</td>
</tr>
<tr>
<td>sericite</td>
<td>16.4</td>
</tr>
<tr>
<td>biotite</td>
<td>1.6</td>
</tr>
<tr>
<td>zircon</td>
<td>present</td>
</tr>
<tr>
<td>opaque ores</td>
<td>present</td>
</tr>
</tbody>
</table>

**Brasstown Formation**

**Name and definition**: The Brasstown Formation was named by Keith (*1907, p.7*) after its typical exposures on Brasstown Creek, near the small village of Brasstown, North Carolina. The formation comprises thinly-laminated cross-biotite schists lying under the
Murphy Marble and over the Tusquitee Quartzite. The Brasstown is approximately 3,000 feet thick, but this thickness has almost certainly been tectonically affected. In addition to the schists which form the greater part of the formation (90 percent), the Brasstown also contains a few beds of quartzite and slate.

**Description:** The cross-biotite schists are quite distinctive in appearance. Individual laminae range from paper thin to two inches thick. Fresh exposures of the rock show dark blue gray laminae alternating with light blue gray laminae (*Fig. 12*). The laminae are generally planar and quite persistent, but in large exposures small-scale ripple cross-laminae (*Fig. 12*), and small scour and fill channels are present.

The groundmass of the pelitic schists of the Brasstown is composed of a fine-grained mixture of quartz, sericite and plagioclase. Porphyroblasts of garnet and biotite are studded throughout this matrix, and staurolite occurs in some areas.

Alignment of sericite and the flattening of quartz imparts an F\(_1\) schistosity to the rocks which is parallel to bedding along the limbs of F\(_1\) folds. The alternating dark and light layers of the schists are due to an enrichment in the dark laminae of sericite and opaque ore minerals and a relative lack of these materials in the lighter laminae. Biotite in the rocks is partially altered to chlorite. The following is a modal analysis of a typical pelitic schist from the Brasstown (sample Brf5, from Cherokee Quarry, Murphy Quadrangle, 1500 point counts):

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>sericite</td>
<td>37.7</td>
</tr>
<tr>
<td>quartz</td>
<td>25.25</td>
</tr>
<tr>
<td>plagioclase</td>
<td>16.50</td>
</tr>
<tr>
<td>biotite</td>
<td>14.75</td>
</tr>
<tr>
<td>opaque ores</td>
<td>4.75</td>
</tr>
<tr>
<td>garnet</td>
<td>1.00</td>
</tr>
<tr>
<td>chlorite</td>
<td>0.75</td>
</tr>
</tbody>
</table>

The quartzites of the Brasstown occur near the bottom of the formation and form a transition into the Tusquitee Quartzite. They are usually 1 to 10 feet thick and cross-bedding is locally present.

Dark blue beds of garnetiferous slate also occur in the Brasstown. They
Fig. 12. Typical thin-laminated cross-biotite schists of the Brasstown Formation. Note cross-laminations preserved in dark patch in center of photo.
are thinly laminated with persistent, planar bedding and are usually much less quartzose than the schists of the Brasstown or the Nantahala Slate.

Several cores drilled by the Georgia Marble Co. of Atlanta have passed entirely through the Murphy Marble into the underlying Brasstown. All of these to which the author has had access show that the Brasstown passes into the marble through a transition zone of dark calcareous marble, rich in sulfides and mica, calcareous cross-biotite and finally black graphitic mica schists.

Murphy Marble

Name and definition: The Murphy Marble was named by Keith (1907, p.5) for the town of Murphy, North Carolina. It is the most distinctive formation exposed in the area of this study. The unique character of the marble among the more pelitic and arenaceous rocks of the other formations provides the basis for the term ‘Murphy Marble Belt’. The Murphy Marble consists of dolomite and calcite marble, lying over the pelitic rocks of the Brasstown Formation and under the transitional rocks of the Andrews Schist. The formation ranges from 300 to 500 feet thick.

Description: Fresh exposures of the Murphy Marble are rare. On the eastern side of the Belt the marble is well known from drill cores and from abandoned and currently operating quarries (Figs. 13 and 14). On the western side of the Belt there are several abandoned pits that were worked for agricultural lime, but there have never been any building stone or gravel quarries.

In the area of this study the Murphy Marble invariably occupies low valleys. An especially helpful clue in distinguishing the marble, in areas where no outcrops are seen, is the occurrence of watercress in springs and sinkhole ponds over its trace. The wild vegetable apparently has a selective preference for calcareous water and soil. The calcareous nature of the formation makes it readily susceptible to solution and deep weathering. The amount of overburden on the marble ranges from 0 to 200 feet thick, maximum thicknesses being attained on the eastern side of the Belt. Solution cavities and small sinkholes are common. Sinkholes are especially well-developed on the eastern side of the Belt, from the vicinity of Marble northeast to Andrews, where the marble is subhorizontal and has its greatest outcrop width.

Talc deposits are a characteristic feature of the Murphy Marble. They
have been mined along the Belt since the 1860’s and have produced some of the finest
grade talc in the United States.* The talc bodies themselves occur near the stratigraphic
center of the marble (Van Horn, 1948).

Several small quartzite beds are known to occur in the marble at a few
places. These are insignificant and never exceed 10 to 15 feet in thickness.

The Murphy Marble consists of a number of highly variable facies. To
illustrate this variation the following log of 261 feet of core (drilled at Marble, North
Carolina and logged by Ernest Reade, geologist of the Georgia Marble Co. with whose
permission it is used) is presented:

<table>
<thead>
<tr>
<th>Feet</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 9</td>
<td>Overburden</td>
</tr>
<tr>
<td>9 to 28.5</td>
<td>Dark gray, coarse to medium grained, uniform sulfide marble.</td>
</tr>
<tr>
<td>28.5 to 30</td>
<td>Tan to grayish-tan, coarse to medium grained phlogopite marble.</td>
</tr>
<tr>
<td>30 to 33.5</td>
<td>Light gray, grayish-brown banded, coarse to medium grained marble with thin seams of brown micaceous marble.</td>
</tr>
<tr>
<td>31.5</td>
<td>Two veins 3/8” thick of sulfides.</td>
</tr>
<tr>
<td>33.5 to 38</td>
<td>Grayish-brown, medium grained marble with specks of mica and sulfides and minor 1/8” to 1” thick layers of brown to grayish-brown, fine to medium grained mica.</td>
</tr>
<tr>
<td>38 to 41.5</td>
<td>Light gray, coarse to medium grained marble with minor bands, 1/8” to 1” thick of chlorite mica marble and sulfide.</td>
</tr>
<tr>
<td>41.5 to 44</td>
<td>Very light gray and light gray, clouded, medium grained marble.</td>
</tr>
<tr>
<td>44 to 53.5</td>
<td>Dark gray, uniform, coarse to medium grained sulfide marble.</td>
</tr>
<tr>
<td>53.5 to 57.5</td>
<td>Light gray to medium grained marble with minor laminae of brown mica and sulfides.</td>
</tr>
</tbody>
</table>

* Approximately 95 percent of the talc marking crayons used in the United States are
produced by the Hitchcock Corporation at their mine in Murphy, North Carolina (Tennessee
Valley Authority, 1965, p.6). Waste material from the crayon manufacture is used as a
filler and for the manufacture of cosmetics.
<table>
<thead>
<tr>
<th>Feet</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>57.5 to 62.5</td>
<td>Gray and light gray, coarse to medium grained sulfide marble with thin layers of green chlorite sulfide marble.</td>
</tr>
<tr>
<td>61</td>
<td>Brown band of mica 1” thick.</td>
</tr>
<tr>
<td>62.5 to 65</td>
<td>Alternating layers of very light gray, pale pink and white, coarse to medium grained marble with thin laminae of phlogopite mica.</td>
</tr>
<tr>
<td>65 to 73</td>
<td>Dark gray, coarse to medium grained sulfide marble.</td>
</tr>
<tr>
<td>73 to 75</td>
<td>Mottled light gray and gray, coarse to medium grained sulfide marble with minor seams of brown mica.</td>
</tr>
<tr>
<td>75 to 80.5</td>
<td>Dark gray, coarse to medium grained sulfide marble.</td>
</tr>
<tr>
<td>80.5 to 82.5</td>
<td>Mottled light gray and gray, coarse to medium grained sulfide marble with minor seams of brown mica.</td>
</tr>
<tr>
<td>82.5 to 88</td>
<td>Dark gray, coarse to medium grained sulfide marble with a moderate number of thin light gray coarse to medium grained marble layers and occasional pale grayish-tan zones.</td>
</tr>
<tr>
<td>88 to 100.5</td>
<td>Alternating layers of gray, coarse to medium grained sulfide marble, light gray, medium grained marble and grayish-tan mica marble.</td>
</tr>
<tr>
<td>100.5 to 102.5</td>
<td>Banded light gray and grayish-brown, coarse to medium grained marble with thin laminae of brown mica.</td>
</tr>
<tr>
<td>102.5</td>
<td>1/2” zone of extremely coarse grained brown mica.</td>
</tr>
<tr>
<td>102.5 to 125.5</td>
<td>White, medium grained dolomite marble with minor gray shears, minor orange stained talc crystals. The upper 4” of the contact contain pale green tremolite.</td>
</tr>
<tr>
<td>125.5 to 145</td>
<td>White to very light gray, medium grained dolomite marble. Staining associated with numerous fractures.</td>
</tr>
<tr>
<td>145 to 150</td>
<td>White to very light gray, medium grained dolomite marble with an abundance of orange stained elongate pods and blebs of talc.</td>
</tr>
<tr>
<td>150 to 156.5</td>
<td>White to very light gray dolomite marble with minor areas having faint cream color.</td>
</tr>
<tr>
<td>Feet</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>156.5 to 179</td>
<td>White to very light gray dolomite marble with minor tan talc after tremolite.</td>
</tr>
<tr>
<td>179 to 184</td>
<td>Very light gray, medium grained dolomite marble with an average of 1/2 millimeter specks of dark gray talc.</td>
</tr>
<tr>
<td>184 to 198.2</td>
<td>White to very light gray, medium grained dolomite marble with an abundance of tan and orange talc specks. A 2” layer at the base of this unit contains brown talc in two 1/2” layers. The crystals range up to 2 millimeters in diameter and 1 centimeter in length.</td>
</tr>
<tr>
<td>198.2 to 202</td>
<td>Very light gray to white dolomite with minor pale green talc.</td>
</tr>
<tr>
<td>202 to 205.6</td>
<td>Light gray and gray, medium grained dolomite marble with pale green talc along fractures.</td>
</tr>
<tr>
<td>205.6 to 228.5</td>
<td>White to very light gray, medium grained dolomite marble with areas being abundant in greenish-gray talc bodies crystals. Occasional dark gray-stained fractures are present.</td>
</tr>
<tr>
<td>214.5</td>
<td>Tan staining of talc is abundant.</td>
</tr>
<tr>
<td>228.5 to 230.5</td>
<td>White to very light gray, medium grained dolomite marble with tan stained talc crystals.</td>
</tr>
<tr>
<td>230.5 to 236.5</td>
<td>Very light gray, medium grained dolomite with an abundance of pale cream staining and a trace of dark greenish-gray talcose minerals.</td>
</tr>
<tr>
<td>230.5 to 234</td>
<td>Vertical fractures are common.</td>
</tr>
<tr>
<td>236.5 to 238</td>
<td>White to very light gray, medium grained dolomite with an abundance of tan and brown stained talc.</td>
</tr>
<tr>
<td>238 to 251.5</td>
<td>Light gray and very light gray, faintly mottled, medium grained dolomite marble with small dark gray talc specks.</td>
</tr>
<tr>
<td>238 to 243</td>
<td>Open vertical joints are present.</td>
</tr>
<tr>
<td>251.5 to 257.5</td>
<td>White to very light gray dolomite marble with an abundance of pale tan staining and numerous thin, tan stained seams and minor crystals of talc.</td>
</tr>
</tbody>
</table>
Fig. 13. Dimension stone quarry of the Columbia Marble Co. at Regal, North Carolina, western exposure belt of the Murphy Marble.
Fig. 14. Blocks of Murphy Marble from Regal Quarry. Darker bands are graphite-rich laminae.
<table>
<thead>
<tr>
<th>Feet</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>257.5 to 261</td>
<td>Light gray, medium grained dolomite marble with a faintly banded appearance.</td>
</tr>
<tr>
<td>261</td>
<td>Drill hole ended.</td>
</tr>
</tbody>
</table>

**Andrews Schist**

*Name and definition*: Keith *(1907, p.5)* named the Andrews Schist for the town of Andrews, North Carolina, where its lithology and topographic expression are characteristically exposed. The formation consists of a thin unit of calcareous schist lying over the Murphy Marble and under the Nottely Quartzite and mineral Bluff Formation. The unit ranges from 300 to 500 feet thick.

**Description**: The Andrews consists of alternating layers of impure marble and cross-biotite schist *(Fig. 15)*. Beds in the unit range from paper-thin laminae to 10 feet thick. In thin section the pelitic layers of the Andrews are quartz-sericite schists with cross-biotite porphyroblasts, quite similar in mineralogy and texture to the cross-biotite layers of the Mineral Bluff Formation. Pyrite is widely distributed through the pelitic layers as thin laminae parallel to bedding. Fresh exposures of the Andrews have been seen in only two places in this study, but saprolites produced over the Andrews are quite distinctive: they are brightly colored red, yellow, blue and purple clays occurring as alternating layers. The calcareous beds of the formation form chalky white saprolitic layers, often highly contorted and folded.

The most characteristic feature of weathered Andrews Schist is the occurrence in the residuum over the formation of layers and concretions of iron oxide, presumably the result of oxidation of iron sulfide which occurs in abundance throughout the schist layers of the formation. The iron oxide has been mined intermittently from the 1830’s through the First World War. Numerous abandoned open pits exist along the strike of the formation and serve to readily distinguish it from the other units.*

* These pits were never more than two- or three-man operations, usually belonging to farmers whose land lay along the strike of the Andrews. None of the mines are now in operation, but the older residents of the area can invariably direct the geologist to several abandoned pits.
Fig. 15. Characteristic lithology of the Andrews Schist — alternating layers of impure marble (light bands) and cross-biotite schist (dark-gray bands). Black spots in the schist layers are cross-biotite porphyroblasts.
Fig. 16. Exposure of Nottely Quartzite along the western side of the Murphy Marble Belt.
Weathered areas of the Andrews commonly form a platform or terrace which rises 5 to 40 feet above the outcrop area of the Murphy Marble. Apparently the pelitic component of the Andrews causes it to be slightly less soluble than the marble (Keith, 1907, p.5).

At the top of the Murphy Marble the contact with the Andrews should be drawn at the level where the cross-biotite schist layers first appear intercalated with marble. These schist layers begin as thin laminae and increase in thickness towards the top of the Andrews until they become beds 5 to 10 feet thick. The increase in thickness and number of schist layers is accompanied with a decrease in thickness and number of marble layers, until finally the marble beds disappear and the Andrews grades into the bottom-most schist layers of the Mineral Bluff Formation. Where the Nottely Quartzite occurs between the Andrews and the Mineral Bluff, there is no difficulty in distinguishing the overlying and underlying units. But where the Nottely is absent, it is often quite difficult to draw a contact between the Andrews and Mineral Bluff. The contact should be placed at the horizon where the impure marble layers disappear, but fresh exposures of the units are rarely seen and other criteria, such as the occurrence of iron oxides, usually must be used to draw the contact.

Nottely Quartzite

Name and definition: The Nottely Quartzite was named by Keith (1907, p.5) for exposures along the Nottely River in North Carolina and Georgia. In the area of this study the Nottely occurs only along the west limb of the Murphy Belt in a single north-east-trending exposure, between the underlying Andrews Schist and overlying Mineral Bluff Formation.

Description: The Nottely consists of a thin- to medium-bedded, very pure and completely recrystallized orthoquartzite, ranging in thickness from 0 to 150 feet, with an average thickness of approximately 100 feet. The unit forms a very prominent straight ridge which can be traced along strike for almost forty miles on the western side of the Murphy Marble Belt. For the entire distance the quartzite is dipping uniformly at a high angle to the southeast (Fig. 16).
Well-developed medium-scale trough cross-beds occur throughout the Nottely Quartzite and have been particularly useful in determining the facing of the units of the belt (Fig. 17). The cross-beds are best seen where the Nottely has been weathered to a friable sand.

In the Marble Quadrangle of the present study the prominent ridge of Nottely along the western side of the area abruptly terminates. A thin (10 to 20 feet thick) quartzite is seen in one place beyond this point at the stratigraphic position of the Nottely (see Plate 1) but slightly further to the northeast the unit completely pinches out and the Andrews Schist directly overlies the Mineral Bluff Formation.

Mineral Bluff Formation

**Name and definition**: The Mineral Bluff Formation was named by Hurst (1955, p.55) for typical exposures of the unit in the northern Georgia community of Mineral Bluff. The formation is the youngest recognized in this study. It consists of pelitic phyllites and schists with intercalated thin and discontinuous quartzites, lying over the Nottely Quartzite on the west side of the Murphy Belt and on the Andrews Schist on the east side. The Mineral Bluff occupies the core of the Murphy Marble Belt and has the largest outcrop area of any unit mapped (see Plate 1).

**Description**: The phyllites and schists which comprise the great bulk of the formation are thinly laminated to thinly bedded. In fresh exposures they are dark to light gray-green. Weathered exposures and saprolites have distinctive variegated colors, most commonly dark reds, yellows, browns and greens.

The most distinctive feature of the Mineral Bluff phyllites is a prominent penetrative secondary foliation (associated with F3 folding event). This foliation occurs as very closely spaced laminations and is easily mistaken for bedding. Bedding is commonly discernible in the Mineral Bluff, but only rarely is it the dominant foliation of the formation. Dip slopes often form on the F3 foliation along roadcuts which expose the Mineral Bluff. Ledges of phyllite rise for 100 feet or more along a single foliation surface in the outcrops of the formation along Highway 64, on the Hiwassee River, east of Murphy, North Carolina. During heavy rains large slides of the Mineral Bluff are often seen along major roads due to sliding along these surfaces.
In thin section the pelitic phyllites of the Mineral Bluff consist of a very fine-grained mixture of sericite, plagioclase, quartz biotite and chlorite. Opaque ore minerals, commonly magnetite and ilmenite, often make up 3 to 5 percent of the matrix.

Thin black coatings of manganese oxide are characteristically seen on secondary foliation surfaces in weathered outcrops. Numerous small bull quartz veins are present in the phyllites in many places and veins of manganese oxide are sometimes associated with these.

The quartzites, which form 15 to 20 percent of the Mineral Bluff Formation range from thin sandy laminae to beds 50 to 100 feet thick. In composition they are metagreywackes, metasubgreywackes and orthoquartzites. The metagreywackes occur as thin laminae and as beds 1 to 3 feet thick. They usually show a graded relationship with the pelitic layers. One locality in the Marble Quadrangle has yielded a sample of graded schist and metagreywacke whose sense of grading has been reversed by metamorphism. This phenomena was recognized in only one place in this study, as it is readily visible only in sawed slabs, but it has been widely observed by Hurst (1955) in the Mineral Bluff Quadrangle of Georgia. Flame structures with graded beds were seen in one exposure in the Marble Quadrangle.

The thicker, more massive quartzite beds are usually orthoquartzites and bear a great resemblance to the Nottely Quartzite. They show the same well-developed secondary foliation present in the phyllites. In a few places remnants of cross-bedding were observed, but this feature has been largely obliterated by deformation.

As in the pelitic rocks of the Brasstown Formation, calc-silicate granofels occur widely throughout the Mineral Bluff.

The contact of the Mineral Bluff Formation with the Nottely Quartzite on the west side of the Murphy Belt is sharp and is exposed in a number of places (see Plate 1 for localities). On the east side of the Belt, where the Nottely is absent, the Mineral Bluff grades into the Andrews through a zone of cross-biotite schist.

**Calc-Silicate Granofels or “Pseudodiorite” Rocks**

**Name and definition:** In his mapping of the Nantahala Quadrangle, Keith found a large
number of small sill-like rocks which he called quartz diorites (Keith, 1907, p.5). He described these rocks as pervasively intruding the Nantahala region and attributed their emplacement to a post-Cambrian igneous event restricted in occurrence to certain parts of southwestern North Carolina and Northern Georgia (Keith, 1907, p.7). Later work convinced Keith that these quartz diorites were metasedimentary rather than igneous, and he thus renamed them “pseudo-diorites” (Keith, 1913). The name, though not at all meaningful or descriptive, has been proliferated in the literature by various workers in the Southern Appalachians (see Fairley, 1965, p.5 for references). Hadley (1963) studied these peculiar rocks in the Great Smoky Mountains and suggested that the name “calc-silicate granofels” more appropriately described their mineralogy and texture.

**Occurrence and field description**: Calc-silicate granofels occur as beds, ellipsoidal pods and boudins in every formation of the area, with the exception of the Murphy Marble and Andrews Schist. Their appearance in the field is distinctive — a light-colored (usually white) groundmass studded with porphyroblasts of garnet and hornblende or biotite (Fig. 18). The granofels are always parallel to the bedding of the host rocks in which they occur (Fig. 19). Beds of the material are rarely more than 1 foot thick, and are more commonly 4 to 6 inches thick. Pods and boudins are usually 4 to 6 inches thick and 1 to 2 feet long. The material is quite dense and hard in contrast to the less resistant schists in which it usually occurs. In some of the granofels relict thin bedding laminae and small scale cross-bedding are present.

Though the granofels are usually distinctive, in some rocks, notably the pelitic rocks of the Brasstown Formation, all gradations between pure granofels and host rocks may be seen. This gradation usually manifests itself by the appearance of hornblende porphyroblasts in typical pelitic schists. With an increase in the content of calc-silicate minerals (hornblende, plagioclase, clinozoisite, etc.) and a decrease in schistose, pelitic minerals (sericite, biotite), the schists grade into granofels. Interfingering of schists with the granofels is not uncommon in the Brasstown Formation.

Granofels are best developed in the pelitic rocks of the Brasstown and Mineral Bluff formations and least well developed in the arenaceous rocks of the Tusquiteee and Nottely Quartzites and Carbonates of the Andrews Schist and Murphy Marble.

**Thin section description**: The light groundmass of these rocks consists of a fine-grained granoblastic mixture of plagioclase and quartz. Plagioclase is rarely twinned. Garnet and
Fig. 17. Medium-scale cross-bedding in weathered Nottely Quartzite.
Fig. 18. Calc-silicate granofels or 'pseudo-diorite'. Light-colored groundmass of quartz and feldspar studded with porphyroblasts of garnet and hornblende or biotite.
Fig. 19. Field appearance of a typical calc-silicate granofels boudin parallel to bedding in the Brasstown Formation.
hornblende usually show sieve textures, but helicitic fabrics are preserved in some porphyroblasts. Garnet and hornblende are usually anhedral, with deeply embayed margins. Quartz and calcite are the most common inclusions in garnet, whereas quartz and plagioclase are predominant in hornblende. Traces of chlorite occur in garnet and as an alteration product of hornblende and biotite. Clinozoisite is common in the groundmass as subhedral to anhedral grains and as an alteration of hornblende. In the pseudodiorites which do not contain hornblende, biotite occurs as porphyroblasts and sericite occurs in the groundmass.

The following table gives modal analyses for 6 granofels from the area of this study (1500 point counts per sample).

<table>
<thead>
<tr>
<th>Minerals</th>
<th>MQA2</th>
<th>MQA4</th>
<th>MQA3</th>
<th>337PQ</th>
<th>MQA1</th>
<th>417PQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>plagioclase</td>
<td>44.4</td>
<td>38.0</td>
<td>45.0</td>
<td>27.3</td>
<td>52.0</td>
<td>28.2</td>
</tr>
<tr>
<td>quartz</td>
<td>35.6</td>
<td>32.3</td>
<td>35.0</td>
<td>36.0</td>
<td>29.4</td>
<td>42.8</td>
</tr>
<tr>
<td>hornblende</td>
<td>15.2</td>
<td>20.6</td>
<td>9.8</td>
<td>17.0</td>
<td>—</td>
<td>14.8</td>
</tr>
<tr>
<td>garnet</td>
<td>1.6</td>
<td>4.7</td>
<td>3.6</td>
<td>0.3</td>
<td>10.4</td>
<td>4.4</td>
</tr>
<tr>
<td>clinzoisite</td>
<td>—</td>
<td>—</td>
<td>5.6</td>
<td>10.3</td>
<td>—</td>
<td>4.8</td>
</tr>
<tr>
<td>biotite</td>
<td>0.8</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>4.4</td>
<td>0.2</td>
</tr>
<tr>
<td>sericite</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>calcite</td>
<td>0.8</td>
<td>Trace</td>
<td>1.0</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>chlorite</td>
<td>0.8</td>
<td>—</td>
<td>Trace</td>
<td>8.3</td>
<td>0.6</td>
<td>3.6</td>
</tr>
<tr>
<td>opaque ores</td>
<td>0.8</td>
<td>4.0</td>
<td>Trace</td>
<td>0.7</td>
<td>3.0</td>
<td>1.2</td>
</tr>
<tr>
<td>apatite</td>
<td>—</td>
<td>Trace</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Interpretation: The granofels are thought to have been originally sedimentary for the following reasons:

1. Their occurrence as beds which invariably are parallel to the bedding of the host formation.
2. Their gradational nature with pelitic schists.
3. The presence of bedding laminae and cross-beds within them.

The predominance of calcium and calc-silicate minerals in the granofels suggests that these rocks were originally calcareous concretions and beds of calcareous shale. Similar conclusions have been proposed by Emmons and Laney (1940, p. 1849), Hurst (1955, p. 20) and Fairley (1965, p. 30), and Hadley (1963, p. 56).
Interpretation of environments of deposition of formations of the Murphy Marble Belt

Based on the observations of lithology and sedimentary structures described in the previous section, the following environmental interpretations are made for each formation of the Murphy Marble Belt.

**Great Smoky Group** : The discontinuity of the conglomerates along strike, their occurrence in erosional channels and their immature mineralogy (high content of detrital feldspar) suggest they were deposited in meandering river channels. The succession of graded facies commonly seen in the Great Smoky — pebble conglomerates, metagreywacke and laminated schists — may represent a river channel, point bar, floodplain sequence (fining upward sequence). The few orthoquartzites that are present may be point bar sands or may represent local littoral conditions. In general, the rocks of the Great Smoky appear to have been fluvially deposited, perhaps on an alluvial coastal plain or delta.

**Nantahala Slate** : Fine-grain size and regularity of laminations in the greater part of the Nantahala suggest a low energy environment of deposition. The graphite and sulfide suggest reducing conditions. Because the Nantahala lies conformably between two formations which probably represent high energy conditions, it seems unlikely that it was deposited in deep water, as suggested by Hurst (1955, p.57). The Nantahala is interpreted as a tidal flat or lagoonal deposit.

**Tusquitee Quartzite** : The Tusquitee is intimately related to the Nantahala because it contains many beds and laminae of slate similar to the Nantahala Slate (i.e., it interfingers with the Nantahala). The sheetlike geometry of the Tusquitee, the medium-scale cross-beds and the inter-tongueing with the Nantahala suggest that the Tusquitee represents a barrier bar, seaward of the lagoonal area in which Nantahala Slate was accumulating.

**Brasstown Formation** : The persistent, thin, parallel laminations of the Brasstown suggest a low energy environment of deposition. Sulfides and graphite are not present so the conditions of deposition were probably oxidizing. The abundance of pseudodiorite in the Brasstown suggests that conditions were right for carbonate deposition in the environment. The quartzites at the base of the Brasstown indicate interfingering with the Tusquitee. The Brasstown is interpreted as being deposited on an open marine shelf, seaward of the Tusquitee barrier bar.
Murphy Marble: Sedimentary features in the Murphy Marble have not been well preserved and are not useful in interpreting environments of deposition. If the regional lithologic correlation of the Murphy Marble with the Shady Dolomite is correct (Keith, 1907, p.11; Hurst, 1955, pp.7-8), then the Shady-Murphy facies was a widespread one at the time of its deposition. A carbonate facies at the stratigraphic position of the Shady is recognized throughout the Appalachians (Palmer, 1971, p.212; Rodgers, 1970, pp.213-214). This suggests that the Murphy Marble was deposited on a carbonate shelf of widespread extent.

Andrews Schist: The Andrews Schist consists of alternations of carbonate and detrital material and as such represents a transition environment between the carbonate shelf of the Murphy Marble and the detrital sedimentation of the Nottely Quartzite and the Mineral Bluff Formation.

Nottely Quartzite: The orthoquartzitic nature and cross-bedding of the Nottely suggest a high energy, littoral or barrier bar environment. Since the Nottely grades eastward into pelitic sediments, the shoreline during Nottely deposition must have been to the west.

Mineral Bluff Formation: This predominantly pelitic unit is quite similar in facies to the Brasstown Formation. The thin persistent laminations of the Mineral Bluff suggest low energy conditions. The absence of abundant graphite and sulfides exclude reducing conditions. The pelitic portions of Mineral Bluff are interpreted as being deposited under open marine shelf conditions, similar to depositional environment of the Brasstown. The numerous intercalated orthoquartzites in the Mineral Bluff represent the inter-tongueing of the pelitic rocks with littoral and barrier bar facies of the Nottely.

Interpretation of Facies Relationships

The formations of the Murphy Marble Belt and the Great Smoky Group have gradational and conformable contacts. Because these rocks now occur in vertical succession, they must have potentially existed as lateral equivalents (Walther's Law). Using this concept, the following sequence of environmental relationships and events is proposed.

The Murphy Marble Belt as a Linear Clastic Shoreline: The rocks of the Murphy Belt were deposited along a linear clastic shoreline (Selley, 1970, pp.95-116). Two transgressive
and one regressive phase of the shoreline can be recognized in the stratigraphy. Fig. 20 shows a diagrammatic sketch of the paleogeography of the region during the first phase of shoreline transgression. Great Smoky rocks were being deposited on a deltaic or alluvial coastal plain. Studies of the Great Smoky rocks in areas to the north of the Murphy Belt suggest a north-western source for their detrital material (Hadley, 1963, pp. 67–68). A continental or cratonic area was probably exposed to the west of the present site of the Murphy Marble Belt. Seaward of the area of Great Smoky deposition was a lagoon or tidal flat area behind a barrier bar. Nantahala Slate was being deposited in the lagoon, Tusquitee Quartzite on the barrier bar. To the east of the barrier bar was a broad open marine shelf in which pelitic schists of the Brasstown Formation were accumulating. The present succession of formations goes from Great Smoky at the bottom to Nantahala Slate, Tusquitee Quartzite, and Brasstown Formation at the top. The shoreline during this period was therefore transgressing from east to west.

The beginning of deposition of the Murphy Marble represents a widespread change in the source area. Perhaps the continental area to the west had been peneplaned and was no longer supplying large quantities of detrital material. Deposition of pelitic rocks on the marine shelf was succeeded by carbonate accumulation (Fig. 21).

The period of carbonate deposition was apparently relatively short; the Murphy Marble is not very thick. The Andrews Schist signals the beginning of renewed detrital deposition and shoreline regression. Uplift in the source area to the west readily accounts for this detrital influx and regression.

Following uplift of the source area, deposition on the open marine shelf is again dominated by pelitic and arenaceous material (Nottely Quartzite and pelitic portions of the Mineral Bluff). The shoreline regression which followed this renewed detrital sedimentation was again succeeded by shoreline transgression.

**Age of the Murphy Marble Belt Rocks and Great Smoky Group**: The Precambrian boundary has traditionally been drawn between the top of the Great Smoky Group and the Nantahala Slate. The rationale for this has been the abrupt change in sedimentary character of the rocks between the Great Smoky and the Murphy Sequence (Hurst, 1955, p. 9; King, et al, 1958). As shown in the previous sections, the rocks of the two sequences may have been deposited contemporaneously in some areas, and there may be no great age difference between them. The rocks are different in sedimentary character because they were deposited in different environments, not because they were deposited
Fig. 20. Diagrammatic sketch of paleogeography of the Murphy Marble Belt during early stage of shoreline transgression.
Fig. 21. Diagrammatic sketch of paleogeography of the Murphy Marble Belt during later stage of transgression, following peneplanation of source area and beginning of carbonate deposition.
at different times. There seems, therefore, to be no valid reason for drawing a time boundary between the Great Smoky Group and the Nantahala Slate.

Correlation of the Murphy Marble with the Shady Dolomite and the Nantahala—Tusquitee—Brasstown Formation with the Chilhowee Group has been used as a basis for calling the Murph, sequence Cambrian (Keith, 1907, p.11). If there are widespread transgressions and regressions recorded in these sequences, then the rocks are not necessarily of the same age in different localities. Keith's correlations are, therefore, only lithologic correlations.

McLaughlin and Hathaway (1973) have recently reported articulate brachiopod fragments and one complete gastropod from cores of the Murphy Marble taken at the Hewitt Quarry, Swain County, North Carolina. They have tentatively classified these fossils as Early Paleozoic, and state that they may be as young as Ordovician.

If the lithologic correlations of the Murphy sequence with the Shady-Chilhowee Group are correct, and if the fossil finds of McLaughlin and Hathaway do prove to be Ordovician in age, then clearly the Murphy sequence, and possibly the Great Smoky Group, are time-transgressive sequences.
CHAPTER III

STRUCTURAL GEOLOGY
TECTORNIC MAP OF A PORTION OF THE MURPHY MARBLE BELT

by
JOSEPH T. FORREST

EXPLANATION

STRATIGRAPHIC SYMBOLS

<table>
<thead>
<tr>
<th>mbf</th>
<th>Mineral Bluff Fm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>nq</td>
<td>Nottely Quartzite</td>
</tr>
<tr>
<td>as</td>
<td>Andrews Schist</td>
</tr>
<tr>
<td>mm</td>
<td>Murphy Marble</td>
</tr>
<tr>
<td>brf</td>
<td>Brasstown Fm.</td>
</tr>
<tr>
<td>tq</td>
<td>Tusquitee Quartzite</td>
</tr>
<tr>
<td>ns</td>
<td>Nantahala Slate</td>
</tr>
<tr>
<td>gsg</td>
<td>Great Smoky Gp.</td>
</tr>
</tbody>
</table>

TECTORNIC SYMBOLS

- Stratigraphic contacts
- Axial surface traces:
  - $F_1$ folds
  - $F_3$ folds
  - $F_1$ slide traces
- Metamorphic isograds
  - biotite zone B
  - garnet
  - staurolite
INTRODUCTION

The area shown on Plate 1 has been divided into statistically homogeneous subareas using the techniques described by Turner and Weiss (1963, pp.147–151) and by Whitten (1966, pp.80–90). These subareas are summarized in Plate 2 and are referred to throughout the following discussion. All orientation diagrams were plotted on the lower hemisphere of an equal area net and contoured by the Schmidt method (see Turner and Weiss, 1963, pp.61–62). Diagrams with less than twenty (an arbitrarily chosen number) data points were not contoured.

The discussion of the structural geology is divided into two parts. In the first part each structural subarea is described. In the second part the subareas are interpreted and related to the larger scale-structures of the area.

Description of Structural Subareas

Subarea A : Subarea A, in the northwest corner of the Murphy Quadrangle, is underlain predominantly by rocks of the Great Smoky Group. The subarea is homogeneous with respect to a number of structural elements, including bedding and two cleavages.

Diagram 1 (Plate 2) is a plot of poles to bedding planes in Subarea A, showing a well-defined maximum corresponding to a plane with orientation N43E81NW.

Throughout Subarea A there is a penetrative schistosity in pelitic rocks which dips consistently to the northwest at a shallower angle than bedding (Fig. 6). This schistosity only occurs in rocks of amphibolite metamorphic grade and is caused by alignment of muscovite and biotite. Diagram 2 (Plate 2) shows a maximum (corresponding to a plane with orientation N34E56NW) defined by poles to this schistosity. This schistosity is interpreted as an F2 schistosity.

The intersection of bedding and the F2 schistosity of Diagram 2 produces a lineation (L2x0) whose orientation is shown in Diagram 3. These lineations are plunging to the northeast and southwest at shallow angles.

Cutting across the northwest-dipping bedding and F2 schistosity of Subarea A is a southeast-dipping, non-penetrative, crenulation cleavage (Fig. 7). Since this cleavage folds F2 schistosity, it is interpreted as an F3 cleavage. Diagram 4 (Plate 2) is a plot of poles to this cleavage. The orientation of the cleavage appears to be fanned as it varies across strike from shallow-dipping in the northwest to more steeply dipping on the southeast.
The lineation of bedding and F3 crenulation cleavage intersections (L3X0) is shown in Diagram 5 (Plate 2). This lineation plunges at small angles to the northeast and southwest, as does the bedding-F2 schistosity lineation.

The intersection of F2 schistosity and F3 crenulation cleavage described above also produces a lineation which plunges at shallow angles to the northeast and southwest. This lineation is shown on the geologic map and is homogeneous in Subarea A but it is not an important tectonic element in this study and a diagram of its orientation was not prepared.

A remarkably consistent southwest-plunging lineation in Subarea A is shown in the orientation of the axes of elongated pebbles in conglomerates of the Great Smoky Group. These axes are plotted in Diagram 6 (Plate 2). Note that the axes are subparallel to L2X0 and L3X0. There is no field evidence to determine if they are related to F2 or F3. But since F2 is the penetrative deformation of Subarea A, it seems most likely that the elongate pebbles are related to F2.

Subarea B: Subarea B lies immediately to the southeast of Subarea 1 and includes rocks of the Nantahala Slate, Tusquitee Quartzite, Brasstown Formation, Murphy Marble, and the Andrews Schist.

Poles to bedding, shown in Diagram 7 (Plate 2), again form a well-defined maximum, with bedding striking northeast, and dipping southeast at a high angle. The maxima corresponds to a plane oriented N45E72SE.

The southeast-dipping F3 cleavage cuts across bedding in Subarea B as in Subarea A. In Subarea B it is no longer a crenulation cleavage, but a penetrative cleavage, which pervades the Murphy Belt in all subareas. Diagram 20 (Plate 2) is a synoptic diagram of poles to this cleavage from Subareas A through I. The diagram shows that the F3 cleavage has been broadly warped, but a very well-defined maximum is apparent, defining a plane oriented N48E55SE. This maximum corresponds to the orientation of this cleavage from subareas in which warping is not significant and is thus a valid representation of the original orientation of the cleavage. Cleavage from Subarea B has been included in Diagram 20, and its orientation corresponds to the maximum of this plot. The cleavage dips southeast at a slightly shallower angle than bedding.

Boundary between Subareas A and B: The boundary between Subarea A and Subarea B is
drawn along a line of vertical bedding and has a northeast trend. North-west of the boundary, bedding dips steeply northwest and is cut by a penetrative F2 schistosity, also dipping northwest. Non-penetrative F3 crenulation cleavage cuts the F2 schistosity and dips to the southeast. On the southeast side of the boundary bedding dips steeply southeast; the northwest-dipping F2 schistosity becomes less prominent and disappears; and the southeast-dipping F3 cleavage becomes penetrative and the dominant secondary foliation. At first appearance it would seem plausible that the boundary between the two subareas is an unconformity. But detailed observations of the contacts of the stratigraphic units show that they are all gradational and conformable. The boundary is, therefore, thought to be a secondary structural feature and its interpretation is discussed in a later section.

Subarea C: Subarea C comprises rocks of the Mineral Bluff Formation and occupies a position in the center of the study area.

The southeast-dipping F3 cleavage described in Subareas A and B is very well-defined in Subarea C, as shown in Diagram 8 (Plate 2). The maximum that this diagram defines corresponds to an orientation of the cleavage of N45E60SE.

Subarea D: Subarea D, in the southeast corner of the Murphy Quadrangle and the southwest corner of the Peachtree Quadrangle, includes rocks of the Murphy Marble, Brasstown Formation, Tusquitee Quartzite, Nantahala Slate, and the Great Smoky Group. The map pattern of these rocks on Plate 1 shows that they form two folds in this subarea.

A plot of poles to bedding planes around the folds of Subarea D (Diagram 9) produces a girdle whose pole is the axis of the folds. This fold axis (α) has an orientation of 48E.

Diagram 10 shows a plot of poles to F3 cleavage planes in these folds. The statistically-determined orientation of the cleavage is N52E61SE.

Diagram 11 is a plot of bedding-F3 cleavage intersection lineations (L3X0) for Subarea D. There is quite a variation in the bearing and plunge of these lineations, but a maximum is apparent. Its orientation is 49S83E.

Using an average value of the trend of the axial surface of the folds in Subarea D of N51E (this value was measured from the geologic map, plate 1) and the statistically-determined fold axis, it is possible to construct a mean axial plane for the folds of this Subarea (Fig. 22). Since this constructed axial plane corresponds exactly with the statistically-determined value of F3 cleavage in the fold, the F3 cleavage is genetically related to the folds.
Fig. 22. Geometric construction of mean axial surface of folds in Subarea D using estimated average trend of axial surface trace and statistically determined fold axis (β).
and is 'axial plane' to them. The mean value of the bedding-cleavage intersection lineations is also plotted on Fig. 22. The fact that it does not fall directly on the statistical (and constructed) axial plane is probably due to an insufficient number of data points and to the fact that the actual axial surface of these folds is not planar but has been warped by a later folding event.

Subarea E: Subarea E, in the southeast part of the Peachtree Quadrangle and the central portion of the Hayesville Quadrangle, includes rocks of the Brasstown Formation, Tusquitee Quartzite, Nantahala Slate, and the Great Smoky Group.

The geologic map shows that Subarea E encompasses an area of macroscopically visible folds. Diagram 12 (Plate 2) is a plot of poles to bedding planes in these folds. The girdle produced by this plot has a $\beta$ axis oriented 16N64E. F3 cleavage is pervasive in these folds and has a mean orientation of N56E52SE, as shown in Diagram 13 (Plate 2).

The average trend of the axial surface of these folds, as measured from the geologic map, is N50E. Using this value and the statistically-determined value of the fold axis, the mean axial plane of the folds can be constructed (Fig. 23). The close correspondence of this constructed axial plane with the mean value of F3 cleavage in the folds shows that the cleavage is 'axial plane' to the folds. Since this cleavage is the same as that discussed in Subarea D, the folds of Subarea E are of the same generation as those of Subarea D (i.e. they are F3 folds).

Diagram 14 shows the orientation of bedding-F2 cleavage intersection lineations ($L_{3XO}$) in Subarea E. There is considerable variation in the orientation of these lineations. They define a very poor girdle which corresponds approximately with the mean cleavage plane of Diagram 13. There is one strong maximum in this diagram which corresponds to a mean lineation with orientation 25N71E. This orientation is in general agreement with the statistically-determined $\beta$ axis (16N64E). The variation in orientation of these lineations is a reflection of the variation of the fold axis. The axis is not precisely rectilinear in this subarea, but it has an overall trend and plunge of 16N64E. A diagrammatic sketch of the geometry of these folds, showing the variation of their axes, is shown in Fig. 24.

Subarea F: Subarea F includes rocks of every formation in the Murphy Marble Belt and forms the largest subarea delineated in this study.

Two large folds dominate Subarea F. Diagram 16 is a plot of poles to bedding
Fig. 23. Geometric construction of mean axial surface of folds in Subarea E, using estimated average trend of axial surface trace and statistically determined fold axis (β).
Fig. 24. Diagrammatic sketch of folds in Subarea E. Note variation in fold axes but overall northeast plunge of folds.
in these folds. This diagram shows a well-defined girdle with a pole whose orientation is 20S52W, the axis of the folds (\( \beta \) axis).

Subarea F contains F3 cleavage, as do Subareas A through E, but it cuts across the trace of the axial surface of the Subarea F folds and is thus not related to their formation. The estimated average value of the trace of the axial surface of Subarea F folds is N70E. Using this value and the statistically-determined \( \beta \) axis, orientation of the mean axial surface of Subarea 6 folds is determined as N70E50SE (Fig. 25).

Subarea G: Subarea G includes rocks of the Great Smoky Group, Nantahala Slate, Tusquique Quartzite, and Brasstown Formation. The subarea includes the high, rugged Snowbird Mountains west of Marble, North Carolina.

Diagram 17 (Plate 2) is a plot of poles to bedding planes in Subarea G. The plot defines a weak girdle whose pole is a \( \beta \) axis with an orientation of 15S54W.

Subareas G and H: These two subareas show homogeneity with respect to the folding of F3 cleavage. The pervasive southeast-dipping F3 cleavage which has been described in all previous subareas can be traced into these two areas where it becomes folded around a later axis (F4). Diagram 18 is a plot of poles to cleavage planes in Subareas G and H. The plot shows a weak incomplete girdle with possible \( \beta \) axis oriented 24S20W.

Subarea I: Subarea I includes rocks of the Great Smoky Group. The rocks of this subarea were originally mapped by Keith (1907, geologic map) as “Archean Basement” upon which the Murphy Marble Belt sequence and Great Smoky conglomerate were unconformably deposited. Indeed, the rocks of this area look somewhat different from the equivalent rocks on the west side of the Murphy Belt. The rocks of Subarea I are higher grade schists and gneisses, intruded by numerous pegmatites. Traverses across this boundary show that there is no unconformity, that the rocks of the Great Smoky Group grade into the more gneissic rocks and are equivalent to them.

Diagram 21 shows a plot of poles to schistosity and gneissosity in Subarea I. Though few measurements are shown, the points tend to be clustered in a maximum which falls within the maximum formed by plotting poles to the pervasive southeast-dipping F3 cleavage of adjacent areas. On this basis the schistosity and gneissosity of Subarea I are correlated with the southeast-dipping F3 cleavage.
Fig. 25. Geometric construction of mean axial surface of folds in Subarea F, using estimated average trend of axial surface trace and statistically determined fold axis ($\beta$).
Interpretation of Major Structures

From the pattern of the geologic map (Plate 1) and the analysis of homogeneous subareas (Plate 2), at least four phases of folding and faulting can be recognized. They are described below in the order of their occurrence:

\( F_1 \): The symmetrical repetition of stratigraphic units on both sides of the Murphy Marble Belt suggests that the Belt is a major fold of regional extent. Since the rocks in its core are younger than the rocks which surround it, the fold must be generally synclinal. In the Mineral Bluff Quadrangle of Northern Georgia, where the Murphy Belt has been mapped in detail by Hurst (1955), the structure appears to be a tight, narrow isoclinal fold, with southeast-dipping axial plane (Hurst, 1955, plate 1). This isoclinal is traceable by topography from the Mineral Bluff area to the North Carolina State line (see topographic map of the Culberson, North Carolina-Georgia 7-1/2' Quadrangle), where the eastern limb of the Murphy Belt diverges from its parallelism with the western limb and becomes involved in the series of folds included in the area of this study. This divergence can be seen in the extreme southwestern corner of the Murphy Quadrangle (Plate 1). The western limb of the Belt continues its straight northeast trend to the vicinity of Marble, North Carolina where it too outlines a series of folds. There can be little doubt that the synclinal axial surface trace recognized in the Mineral Bluff, Georgia area continues northward through the Culberson, North Carolina area and then northeastward along the western limb of the Murphy Belt in the present study area. This fold is referred to as the “Murphy Syncline”.

The great width of the Belt north of the Georgia State line requires that additional folds be accommodated within it to the east of the axial surface trace of the Murphy syncline. Two isoclinal folds have been mapped on the east limb of the Belt and are thought to be of the same generation as the Murphy syncline. These are the folds of Subarea F (Plate 2). They are informally referred to as the Valley River Anticline and the Fires Creek Syncline.

The axial surface trace of the Valley River anticline occurs along the flanks of the Valley River Mountains of the Marble and Andrews Quadrangles and Braden Mountain of the Peachtree Quadrangle. Southwest of Peachtree, North Carolina the axial surface trace of the fold passes into the pelitic rocks of the Mineral Bluff Formation and is no longer directly traceable by stratigraphy. The trace of the axial surface has been inferred and drawn on the geologic map using geometric restrictions imposed by later folding events. The \( F_2 \) folds
of the area are ‘similar’ folds; therefore, the axial surfaces of F₁ folds have been folded into ‘similar’ geometrics around F₃ axes.

The Fires Creek syncline, which has been very sketchily mapped in this study, occupies the area between the Tusquitee Mountains of the Hayesville Quadrangle and the Valley River Mountains of the Marble and Andrews Quadrangles. The trace of the axial surface of the fold follows approximately the course of Fires Creek in the deep gorge between the two parallel ranges. At Peachtree, North Carolina this trace also passes into the Mineral Bluff Formation, but it can be confidently drawn across the crest of Mission Mountain (Peachtree Quadrangle) from the attitude of bedding along the flanks of this peak.

An S₁ schistosity, parallel to bedding, is visible both in outcrop and thin sections in pelitic rocks from many parts of the study area. This schistosity is caused by the alignment of sericite and flattened quartz in the plane of bedding and is correlated with F₁ folds. In the nose of the Fires Creek anticline at Peachtree, North Carolina, F₁ schistosity, perpendicular to bedding, can be seen in several outcrops of the Mineral Bluff Formation. The fact that S₁ is parallel to bedding along the limbs of F₁ folds is further evidence of their originally isoclinal geometry.

The Murphy syncline, Valley River anticline, and the Fires Creek syncline are curviplanar, curvilinear isoclinal folds. Their axial surface traces have an overall northeast trend, but in the area of the present study they are distorted by later events, principally by F₃. The Murphy syncline must be an extremely deep structure; it can be followed along strike as a tight, narrow belt for over one hundred miles. The Valley River and Fires Creek folds are structurally higher, parasitic folds on the eastern limb of the deeper, more fundamental, Murphy syncline.

The three F₁ folds were originally planar, rectilinear folds. Their present curviplanar, curvilinear geometries are the result of later folding. Subarea F preserves a cylindrical portion of the Valley River and Fires Creek folds. The fold axis in this subarea is oriented 208°52′W. How confidently this reflects the original fold axis orientation of F₁ folds is not known. Since the F₁ synclines have closures to the northeast, they must have a general southwest plunge.

The original orientation of the axial surfaces of F₁ folds is a problem. Isoclinal geometry, bedding plane schistosity, and “slides” (see discussion below) are all features commonly associated with recumbent folds in complexly folded terranes.
(see Whitten, 1966, pp.358-476, pp.565-568, for numerous examples). The occurrence of these features with F₁ folds in the study area suggests that the first generation folds may have been recumbent. However, this is not certain, and it should be pointed out that the subsequent geometry of the Murphy Belt can be derived from F₁ folds with any axial surface orientation. Fig.26 is a diagrammatic sketch of the geometry of F₁ folds before the development of slides.

F₁ slides: According to Fleuty (1964, p.454), a slide is a fault “formed in close connection with folding, which is broadly conformable with a major geometric feature (either fold limb or axial surface) of the structure, and which is accompanied by thinning and/or excision of members of the rock-succession affected by the folding”. The term is used here in this sense.

Two faults mapped in the area appear to be slides associated with F₁ folds. The Mary King Mountain Slide, named after the mountain along whose northwestern base it occurs, is a slide on the southeast limb of the Fires Creek syncline. In the area of Martins Creek, North Carolina, in the Murphy Quadrangle, this slide is folded around the noses of two F₃ folds (see Plate 1). Recent road work at the New Martins Creek Baptist Church has exposed saprolitic breccias for a short distance along the trace of the fault.

The Braden Mountain slide, also named for the mountain along whose base it occurs, is a slide between the southeast limb of the Murphy syncline and the northwest limb of the Valley River anticline (see Plate 1). This slide appears to be only subparallel to the limbs of the isoclines, as its trace cuts deep into the core of the Valley River fold (see Plate 1).

The amount of displacement on these slides is unknown. Displacement on the Mary King Mountain slide is probably not great, as it juxtaposes rocks not widely separated in the stratigraphic column and dies out very rapidly just east of Martins Creek. Displacement on the Braden Mountain slide may be slightly greater as it juxtaposes the youngest and oldest rocks of the map area. Trace of the Braden Mountain slide is unknown after it passes into the Mineral Bluff Formation at Peachtree, North Carolina. Fig. 27 shows the geometry of F₁ folds after F₁ sliding.

F₂: A second phase of folding, recorded in the rocks of Subarea A, is imposed upon F₁ folds. The penetrative northwest-dipping schistosity of this subarea is ascribed to this F₂ event. The bedding cleavage relationship of the subarea demonstrates that there is a synformal structure to the east of the subarea and an antiform to the west, both structures overturned to the
Fig. 26. Diagrammatic sketch of $F_1$ folds before development of $F_1$ slides.
Fig. 27. Location of F1 slides on the limbs of F1 isoclinal folds.
southeast. Since the cleavage diverges markedly in dip from the dip of the bedding (see Diagrams 1 and 2, Plate 2), F2 folds are probably open. The bedding-cleavage intersection lineation in Subarea A suggests that the F2 folds have essentially horizontal axes with shallow plunges to the northeast and southwest. The axial surface trace of the F2 synform, which is postulated east of Subarea A, is not seen in the study area; it probably does not occur within the Murphy Marble Belt rocks, but further to the east in higher grade “Blue Ridge” rocks. The tectonic significance of this observation is discussed in a later section on regional speculations.

F3: The prominent southeast-dipping cleavage, which pervades the Murphy Marble Belt, and the folds associated with it are assigned to an F3 event. The relative age of this event is known because its cleavage folds F2 cleavage in Subarea A. The folds of this generation are overturned to the northwest and have southeast-dipping axial surfaces in the southwest portion of the study area. In the area of Marble, North Carolina, and further to the northeast, the axial surfaces of F3 folds appear to become folded and are regionally recumbent to locally overturned.

The two most prominent F3 folds which affect the study area are those of Subarea D. These are referred to here as the Martins Creek antiform and Yellow Knob synform.

The axial surfaces of these folds can be traced by their associated cleavage from the vicinity of Martins Creek, North Carolina northeast to Andrews, North Carolina. Though the area around Andrews was not mapped in this study, it is known from the work of Van Horn that this region is complexly folded (see geologic map of Van Horn, 1948). The axial surfaces of the folds in the Martins Creek area are also the axial surfaces of the two major folds mapped by Van Horn in the Andrews area (Fig. 28). The Martins Creek and Yellow Knob folds are thus major cross-folds on the limbs of the earlier F1 and F2 structures. It should be noted that although the Martins Creek and Yellow Knob folds are an antiform and synform, respectively, in Subarea D, the plunge of their axes is quite variable along the axial surface trace. The antiform of Subarea D may become synformal in places, and the synform may become antiformal. The designations Martins Creek antiform and Yellow Knob synform should be used only in Subarea D, though the folds continue beyond this area.

Another set of prominent mesoscopically visible F3 folds seen in the study
Fig. 28. Similar geometry of F3 folds.

A. Map view of Murphy Marble Belt between Andrews and Martins Creek, North Carolina. Stratigraphic contact is top of Brasstown Formation. Lines ab and cd are axial surface traces of major F3 folds.

B. Same view as A, after removal of F4 warping. Note that ab and cd are same length as parallel lines ef and gh, thus proving similar geometry of F3 folds.
area are those of Subarea E. These are referred to as the Wiggins Top antiform and the Carroll Mountain synform.

F3 folds have similar geometry. The axial surface distance, for example, between the same stratigraphic horizons at Martins Creek and at Andrews, is approximately the same distance as that measured along a parallel line between the two limbs of the fold further to the west. The Martins Creek and Yellow Knob folds are thus quite large similar folds, (Fig. 28). This suggests that the narrow isoclinal portion of the Murphy Marble Belt, which can be traced southward from the North Carolina Line, may have been thinned considerably.

Diagram 15 (Plate 2) is a plot of bedding-F3 cleavage intersection lineations and F3 minor fold axes. These lineations fall along a girdle which has the same mean orientation as F3 cleavage. The kinematic significance of this situation has been discussed by Ramsay (1960). It means that F3 folds were formed by slip on the S3 cleavage surfaces associated with them. Fig. 29 shows geometry of the Murphy Belt following F3.

**Interpretation of the Boundary Between Subareas 1 and 2**

Location of the boundary between Subarea A, where the southeast-dipping F3 cleavage is non-penetrative, and Subarea B, where the cleavage is penetrative, is not fortuitous. Cleavage planes are planes of movement (see Discussion immediately above). In the transition zone between areas of crenulation cleavage and penetrative cleavage, the amount of movement in the cleavage plane must become greater in the direction of the penetrative area. Therefore, as one goes from Subarea A to Subarea B, the greater amount and intensity of slip in the southeast-dipping cleavage planes has rotated the northwest-dipping beds of Subarea A to a vertical position along the boundary, to a southeast-dipping orientation in Subarea B (Fig. 30).

F4 : An F4 event is best displayed in the regional warping of F3 axial surfaces and cleavages. Diagram 20 (Plate 2), a plot of poles to F3 cleavage, shows that F4 folds in F3 cleavage have an orientation of 26S27W. F4 folds are not commonly visible on the outcrop scale in F3 cleavage, but the local and regional variation in the attitudes of the cleavage leave little doubt that such an event has affected the area. In one large roadcut in the Murphy Quadrangle, folded F3 cleavage has been observed. The folds have northwest-dipping axial planes and incipient crenulation cleavage and are plunging to the southwest, just as Diagram 20 predicts.

The very wide outcrop area of the Murphy Marble, northeast of Marble, North
Fig. 29. Diagrammatic sketch of the Murphy Marble Belt following F3 folding.
Fig. 30. Diagrammatic sketch illustrating the transformation from Subarea A to Subarea B by rotation of bedding from northwest dip to southeast dip by movement on southeast-dipping S₃ cleavage planes.
Carolina, is accounted for by the F₄ event. In this region axial planes of F₃ folds have been folded to near recumbency. In the area of Andrews, North Carolina the F₃ axial surfaces in some places have been completely overturned to the northwest by the F₄ event.

Diagram 17 of Subarea G shows the effect of F₄ on bedding. The rocks of this subarea apparently were relatively planar following the F₃ bedding. A plot of poles to bedding yields a girdle whose pole is the F₄ axis ($\beta =$B). Subarea G is therefore a cylindrical portion of an F₄ fold in bedding.

F₄ folds are open and concentric with planar axial surfaces (that dip northwest). F₄ axes are curvilinear in bedding and rectilinear in F₃ cleavage.

Summary of Structural Evolution

Fig. 31 summarizes the style of folding and geometry of the various events recognized in the study area. Structural evolution of the area can be summarized as follows:

1. The first folding event (F₁) produced isoclinal folds. Their axial surface orientations at the time of formation are not known, but they may have been recumbent. Late in the F₁ event attenuation of the isoclines became great enough to cause sliding between their limbs. Axial plane schistosity was produced during F₁.

2. The second folding event (F₂) produced large synforms and antiforms, with northwest-dipping axial surfaces. These folds were probably broad and open, but their geometry is not well known, as only one limb is preserved in the study area. A penetrative axial plane schistosity was produced in areas of amphibolite grade metamorphism.

3. The third folding event produced antiforms and synforms with southeast-dipping axial surfaces. These folds have “similar” geometry and formed by slip on F₃ cleavage planes which are the dominant secondary foliation of the area.

4. An F₄ folding event has broadly warped earlier folds and axial surfaces around northwest-dipping axial planes.

REGIONAL STRUCTURAL SPECULATIONS

Correlation of Folding and Faulting Events

Detailed geologic mapping in the Mineral Bluff Quadrangle of Georgia has
<table>
<thead>
<tr>
<th>FOLD GENERATION</th>
<th>FOLD TYPE AND STYLE</th>
<th>ORIGINAL GEOMETRY OF AXIAL SURFACE AND FOLD AXES</th>
<th>GEOMETRY OF AXIAL SURFACE AND FOLD AXES AFTER LATER FOLDING EVENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>F₁</td>
<td>Tight, narrow, similar, isoclinal anticlines and synclines. Slides associated with last stages of folding. Penetrative schistosity.</td>
<td>Planar rectilinear</td>
<td>Curviplanar Curviplanar</td>
</tr>
<tr>
<td>F₂</td>
<td>Broad open synforms and antiforms. Axial surfaces dipping NW. Penetrative schistosity in higher metamorphic zones.</td>
<td>Planar curvilinear</td>
<td>Curviplanar Curviplanar</td>
</tr>
<tr>
<td>F₃</td>
<td>Open to isoclinal similar folds. Axial surfaces dipping SE. Crenulation cleavage and penetrative cleavage.</td>
<td>Planar Curvilinear</td>
<td>Curviplanar Curviplanar</td>
</tr>
<tr>
<td>F₄</td>
<td>Open, broad warping of earlier cleavage and bedding. NW-dipping axial surfaces. Crenulation cleavage locally developed, but not common.</td>
<td>Planar curvilinear axes in bedding. Rectilinear axes in F₃ cleavage.</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 31. Summary of folding events, their characteristics and geometries.
been carried out by Vernon Hurst (1955). He believes that the Murphy Marble Belt in that area is a simple 'bent fold' with essentially only one phase of deformation (Hurst, 1955, pp. 72–73). Hurst's geologic map of the Mineral Bluff area shows clearly that he recognized structures there that are consistent with several periods of folding. In the northwest portion of the quadrangle, Hurst shows a large area of northwest-dipping cleavage which he refers to as 'flow cleavage'. The description of this cleavage reveals that it has been crinkled, defining a southeast-dipping crenulation cleavage (Hurst, 1955, pp. 75–83). Unfortunately, Hurst does not discuss the significance of northwest-dipping cleavage to the structural evolution of the Mineral Bluff Quadrangle.

The northwest-dipping cleavage of the Mineral Bluff Quadrangle is probably of the same folding generation as the F2 schistosity of Subarea A in this study. The southeast-dipping crenulation cleavage of the Mineral Bluff area is correlated with the F3 cleavage which is so pervasive in the present study area. Hurst described his southeast-dipping cleavage as cutting across the Murphy syncline, but not having an axial plane relationship to it. The present author has traced the F3 cleavage from his own study area through the Culberson Quadrangle and into the Mineral Bluff Quadrangle. It is clearly the same cleavage which Hurst described. Therefore, the author surmises that the F2 and F3 cleavages of the Murphy Belt in North Carolina are developed in the Mineral Bluff Quadrangle in Georgia.

Geologic mapping in the Great Smoky Mountains National Park has been done by the U.S. Geological Survey. Hadley and Goldsmith (1963) have mapped the Eastern half of the park, which lies at the northern terminus of the Murphy Marble Belt. They have described several generations of structures in the Smokies which may be correlative with structures mapped in the present study. In the Cataloochee anticlinorium at the southeastern side of the park, Hadley and Goldsmith describe the following situation (Hadley and Goldsmith, 1963, p. 85):

Along the southeast slope of Mt. Sterling Ridge . . . most cleavage dips northwest . . . In a few places northwestward-dipping and southeastward-dipping cleavage occur in the same outcrop, where they appear to represent competing cleavage directions rather than a single cleavage arched with the folding of the anticlinorium.

To the southwest of the Cataloochee Anticlinorium, gneissic rocks are exposed in a window through the Greenbriar thrust sheet in the Ravensford anticline. A stereonet projection of poles to foliations in the gneiss shows clearly that two foliations exist in the
rocks — one dipping northwest, the other dipping southeast (Hadley and Goldsmith, 1963, p. 76, Fig. 28D).

Clearly, two of the periods of folding, recognized in the Murphy Marble Belt area of the present work, can be seen in widely divergent areas to the southwest and northeast. This suggests that these folding episodes were of regional extent rather than localized occurrences. A widespread phase of folding in the Blue Ridge with southeastward overturning (axial surfaces dipping northwest) has not been previously discussed in the literature.

In Subarea A of the present study area, the F2 cleavage-bedding relationship shows that a synformal structure must exist to the south-east of the Murphy Marble Belt. The widespread occurrence of this F2 cleavage to the south and north of the Murphy Belt suggests that this structure may be quite large. If such a large scale feature does exist in the Blue Ridge, then it should be visible on the regional geologic map patterns of the area. The author would like to make the following speculation about the relationship of the Murphy Marble Belt, the Dahlonega Belt, and this large synformal structure which apparently must exist southeast of the Murphy Belt:

The Murphy Marble Belt and Dahlonega Belt as limbs of a Large Synform in the Blue Ridge

The Dahlonega Belt, or Ashland-Wedowee Belt, trends northeast through Cherokee, Dawson, Lumpkin, White, Habersham, and Rabun Counties, Georgia (Geologic Map of Georgia, 1939). The structure and stratigraphy of the Belt is essentially unknown, as no detailed geologic work has ever been done in the area. Reconnaissance mapping by William Fairley suggests that the Belt contains feldspathic metasandstones, siliceous carbonates, and schists which may be equivalent to the Murphy Marble Belt sequence and metagreywacke and schist equivalent to the Great Smoky Group (Fairley, 1972, p. 72). If these correlations are correct, then the structure of the Dahlonega Belt must be generally synclinal.

The 1939 Geologic Map of Georgia shows that in the vicinity of Ballground, Georgia the Murphy Marble Belt and the Dahlonega Belt converge. The Whitestone thrust fault, originally proposed by Bayley (1928) to explain the distribution of the Murphy Marble in the Tate, Georgia area is shown separating the two zones. Fairley (1965) has demonstrated in the Tate, Georgia area that the Whitestone thrust does not exist. Therefore, the extension of the fault southward, to a position between the Murphy and Dahlonega Belts, is not justified. If there is no fault between the two belts, then the convergence is either
stratigraphic, in which case the Murphy Marble Belt rocks lie stratigraphically above and below Pre-cambrian basement rocks, or the convergence represents the nose of a major fold.

The present author favors the latter proposal — that the Murphy Belt turns around on itself in Cherokee County, Georgia, and becomes the Dahlonega Belt. The terrane between the two belts is therefore a synformal structure of major proportions. Is this fold the same one suggested by the regional distribution of northwest-dipping (F2) cleavage along the northwest limb of the Murphy Belt and in the Great Smoky Mountains?

It is interesting to note that if an F2 axial surface trace does exist between the Murphy Belt and the Dahlonega Belt, and it is projected northeast along strike, it runs into the Spruce Pine synclinorium of West-central North Carolina.
CHAPTER IV

METAMORPHISM
INTRODUCTION

The rocks of the Murphy Marble Belt have been metamorphosed in two facies of regional metamorphism — the greenschist facies and the amphibolite facies. Metamorphic isograds, based on the occurrence of biotite, garnet and staurolite, have been mapped (Plate 1) and demonstrate a Barrovian facies series for the area. The metamorphism appears to have been progressive during the first two phases of deformation, retrogressive during F3 and to have ended before the last folding event.

F₁ metamorphism: Evidence for metamorphism during F₁ is preserved in pelitic rocks of the Murphy Belt, especially in the Brasstown Formation. In thin sections of the Brasstown, one sees a schistosity developed parallel to bedding. This schistosity is formed by the parallel alignment of sericite and a fine-grained mixture of quartz and plagioclase in the bedding plane. The plagioclase is rarely twinned and difficult to distinguish microscopically. In the Valley River anticline, in rocks of the Mineral Bluff Formation, the author has observed this schistosity cutting across bedding at a right angle. The schistosity is thus definitely related to F₁ folding and not to simple compaction. F₁ foliation is poorly preserved in other formations other than the Brasstown. In the Great Smoky Group it has been obliterated by recrystallization during F₂, in the Mineral Bluff Formation by recrystallization during F₃. In the Nantahala Slate cleavage and schistosity are poorly developed, probably because of the high quartz content of the formation.

The assemblage muscovite-quartz-plagioclase is the highest grade assemblage observed in pelitic rocks of the Murphy Belt for the F₁ metamorphism. The F₁ metamorphism is therefore assigned to the quartz-albite-muscovite-chlorite subfacies of the greenschist facies, as defined by Winkler (1967, p.95).

F₂ metamorphism: The thermal peak of metamorphism in the Murphy Belt appears to have occurred during the F₂ folding event. F₂ penetrative schistosity is restricted in occurrence to rocks of this facies. This schistosity is best developed and preserved on the western side of the Belt in rocks of the Great Smoky Group (Fig. 7). In this area F₁ schistosity has been obliterated, though bedding — F₂ schistosity (L₀X₂) intersection lineations are still well preserved. In thin sections the F₂ schistosity is an intergrowth of predominantly muscovite with subordinate biotite, quartz and plagioclase. Porphyroblasts of biotite, garnet and
staurolite occur throughout the schists. These commonly contain helicitic inclusions of F1 schistosity. Correlation of the metamorphic thermal peak with F2 folding is based on the fact that F2 schistosity only occurs within or near the staurolite metamorphic zone (Plate 1). The biotite, garnet and staurolite zones were not developed during F1, since the isograds cut across F1 folds and do not appear to have been involved in them. The isograds, though, have been folded during F3.

As one crosses the greenschist-amphibolite facies boundary (i.e. the staurolite isograd) the F2 schistosity disappears. In rocks of the Nantahala Slate, along the boundary of the two metamorphic facies, F2 foliation is manifested as a widely spaced fracture cleavage. In higher units, within the greenschist facies, F2 foliation does not appear at all.

**F3 metamorphism:** The most pervasive deformational event seen in the study area occurred during F3 folding. This event took place after the metamorphic thermal peak and was accompanied by retrograde metamorphism in the greenschist facies. The evidence for this is best seen in rocks of the Great Smoky Group, Brasstown Formation, and the Mineral Bluff Formation.

In the Great Smoky schists, within the staurolite zone, along the western side of the Murphy Belt, F3 foliation is a widely spaced crenulation cleavage folding F2 schistosity. In thin sections it is seen that there was little or no recrystallization associated with F3 cleavage in this area. The folding was purely mechanical. But, in Great Smoky schists exposed in the cores of the Yellow Knob and Martins Creek folds, F3 foliation is more closely spaced and has involved shear and recrystallization. F2 biotite has been warped and retrograded to chlorite.

In the Brasstown Formation included within the garnet and biotite zones, the F3 cleavage is almost penetrative and has involved shear and recrystallization. Chlorite porphyroblasts are commonly seen growing within the F3 cleavage planes and biotite associated with F1 and F2 is partially retrograded to chlorite.

F3 cleavage in the Mineral Bluff Formation is almost always penetrative within the study area. Movement and recrystallization in the cleavage planes has obliterated bedding and any earlier schistosities. The commonly observed assemblage which has crystallized to form the F3 cleavage is chlorite — sericite — quartz — plagioclase. On this basis the F3 metamorphism is assigned to the quartz-albite-muscovite-chlorite subfacies of the greenschist facies (*Winkler, 1967*).
F4: The F4 event was apparently postmetamorphic, as no metamorphic effects have been observed in association with it.

Timing of Metamorphic and Deformational Events

No direct evidence is available from the study area to determine the timing of the metamorphism and deformation. The following attempt to assign ages is only preliminary. It is based, to some extent, on tenuous correlations with events described by Hadley and Goldsmith (1963) from the Great Smoky Mountains, where better timing criteria are available.

Middle Ordovician deformation

The Middle Ordovician rocks immediately northwest of the Blue Ridge have abnormally thick clastic deposits (Neuman, 1955, pp. 168–171) of the same age as the well-documented Blountian phase of "Taconic Orogeny" recognized in the Northern Appalachians (Rodgers, 1953, p. 94). The Middle Ordovician disturbance suggested by these clastics is the earliest Paleozoic tectonic event recognized in the Southern Appalachians. Hadley and Goldsmith (1963, p. 107) have suggested that the early folding in the Great Smokies, with the low angle thrusts (Greenbriar, Dunn Creek and Snag Mountain Faults) and development of low angle foliation in the basement rocks may have occurred during this event. The present author suggests that the isoclinal folds, accompanying slides and greenschist metamorphism, which are the earliest events of the Murphy Belt, may also have formed during Middle Ordovician tectonism. If the new fossil finds of McLaughlin and Hathaway (1973, pp. 418–419) do prove to be Ordovician, as they have suggested, then the earliest possible time for first deformation of Murphy Belt rocks is Ordovician.

Middle Ordovician – Early Silurian metamorphism and deformation

F2 deformation in the Murphy Belt was contemporaneous with the thermal peak of metamorphism in the area. Butler (1972, pp. 321–325) has summarized evidence suggesting that the peak of regional metamorphism in the Blue Ridge was attained at least 430 m. y. ago. If this thermal peak was attained contemporaneously in all parts of the Blue Ridge, then F2 tectonism in the Murphy Belt must have occurred some time between Middle Ordovician and 430 m. y. ago.

Lower to upper Devonian deformation

Long, Kulp and Eckelmann (1959, p. 594) have reported very consistent
ages of 340 m. y. made on muscovites and biotites from pegmatites and enclosing gneisses ("Carolina Gneiss") in the Spruce Pine district. Aldrich, Wetherill, Davis and Tilton (1958, p.1128) have reported a somewhat older age of 375 m. y. for these same pegmatites. Probably, therefore, these pegmatites were intruded within the time range of 375 to 340 m. y. ago, that is Lower to Upper Devonian.

Pegmatites of Subarea I in the Murphy Belt are intruded into gneisses presumably correlative with those of the Spruce Pine district and are along strike with the Spruce Pine area. The present author therefore proposes that the pegmatites of the present study were possibly of the same age as those further to the north. Since the Murphy Belt pegmatites are both intruded parallel to and often cut across F3 cleavage, they may be nearly contemporaneous with or slightly later than F3. The author therefore proposes that F3 deformation and retrograde metamorphism occurred sometime within the time span Lower to Upper Devonian.

Hadley and Goldsmith (1963, p.107) have proposed that the 375 to 340 m. y. pegmatite event was contemporaneous with the main regional metamorphism in the Great Smokies and therefore accompanied their second phase of deformation. This correlation is based solely on the speculation that the pegmatites of the Bryson City District probably accompanied the thermal maximum. Clearly the pegmatites of the Murphy Belt, which occur along strike of the Bryson City pegmatites, postdate the thermal maximum. The present author therefore rejects Hadley and Goldsmith’s argument of a 375 to 340 m. y. age for the thermal peak of regional metamorphism. Hadley and Goldsmith (1963, p.107) recognized a third phase of deformation and a period of retrograde metamorphism in the Smokies following the thermal peak. This author proposes that this “Later Post-Ocoee deformation” is correlative with the F3 deformation and retrograde metamorphism of the Murphy Belt and took place before or during the 375 to 340 m. y. event (Lower to Upper Devonian).

**Late Paleozoic, post-Early Mississippian deformation**

The Great Smoky, Gatlinburg and Oconaluftee faults of the Great Smoky Mountains are clearly late postmetamorphic features. They displace cleavage and display well-preserved slickensides (Hadley and Goldsmith, p.83). In addition, the Great Smoky Fault involves Early Mississippian rocks to the northwest of the National Park (Neuman and Wilson, 1960). These late faults are correlated by Hadley and Goldsmith (1963, p.107)
with mild folding of structures in the foothill belt; north of the Smokies. The F4 deformation of the Murphy Belt is also postmetamorphic and involves gentle folding of previous structures. On the basis of their postmetamorphic timing and structural style, this author proposes that the F4 deformation of the Murphy Belt is correlative with post-Early Mississippian deformation in the Great Smokies.
1. **Rocks of the Murphy Marble Belt** and Great Smoky Group were deposited along a linear clastic shoreline which existed on the east coast of North America sometime during the period from Late Precambrian to Middle Ordovician. Great Smoky rocks represent deposition in fluvial and deltaic environments, while Murphy Belt rocks represent lagoonal, littoral, nearshore and marine shelf conditions. Two periods of marine transgression and an intervening regressive stage occurred during the deposition of the Murphy and Great Smoky sequence. There is no good evidence for the age of the rocks of the Murphy Belt, but recent fossil finds suggest the Murphy Marble may be as young as Ordovician. In any case there appear to be no grounds for drawing a major time boundary between the Great Smoky Group and Murphy sequence; they are gradational, conformable and approximate time equivalent groups of rocks.

2. The first deformation of the Murphy Belt occurred in Middle Ordovician time and was characterized by isoclinal folding, tectonic sliding along fold limbs and by progressive regional metamorphism in the greenschist facies.

3. A second deformation in the Murphy Belt occurred sometime between Middle Ordovician and Early Silurian. This phase was one of backfolding, characterized by large folds with northwest dipping axial planes. The thermal peak of Blue Ridge metamorphism accompanied this deformation, producing amphibolite grade rocks in the Murphy Belt.

4. Between Lower and Upper Devonian time a third deformation affected the Murphy Belt. This phase produced large folds of similar geometry. This period was also one of regional thermal cooling, as the metamorphism which accompanied the deformation was retrogressive in the greenschist facies.

5. A final phase of tectonism is recorded in the Murphy Belt in Post-Early Mississippian time. It is characterized by gentle warping of all previous structures and was post-metamorphic.
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PLATE 2

STRUCTURAL SUBAREAS

of a Portion of the Murphy Marble Belt
<table>
<thead>
<tr>
<th>Subarea</th>
<th>Diagrams</th>
<th>Structural Element</th>
<th>Contours points per 1/4 area</th>
<th>Measurements</th>
<th>Orientation of axis, plane or girdle</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>( \pi s_0 )</td>
<td>1-3-4-7-9-11</td>
<td>35</td>
<td>N43E81NW</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>( \pi s_2 )</td>
<td>1-2-3-4-5-6</td>
<td>25</td>
<td>N34E56NW</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>( L_{x_0} )</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>( \pi s_3 )</td>
<td>1-2-3-4-5</td>
<td>22</td>
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</tr>
<tr>
<td></td>
<td>5</td>
<td>( L_{x_0} )</td>
<td>18</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>elongate pebble axes</td>
<td>8</td>
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<td></td>
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<tr>
<td>B</td>
<td>7</td>
<td>( \pi s_0 )</td>
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<tr>
<td>C</td>
<td>8</td>
<td>( \pi s_0 )</td>
<td>1-4-8-16-24-48</td>
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<td>D</td>
<td>9</td>
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<tr>
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<td>1-4-6-12-18-28</td>
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<tr>
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<td>1-2-3-4-7-11</td>
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<tr>
<td>G &amp; H</td>
<td>18</td>
<td>( \pi s_3 )</td>
<td>1-4-6-8-12</td>
<td>58</td>
<td>24S20W</td>
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<td>( L_{x_0} )</td>
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<td>A - H 19</td>
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<tr>
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<td>1-6-15-20-40-50</td>
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<td></td>
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<tr>
<td>1 21</td>
<td>π5s</td>
<td>9</td>
<td></td>
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</table>
GEOLOGIC MAP OF
MURPHY M
SOUTHWESTERN

JOSEPH

TOPOGRAPHIC BASE BY TENNESSEE VALI

SCALE

1

EXPLAIN

STRATIGRAPHIC SYMBOLS

Formation contacts ~—~
MAP OF A PORTION OF THE GEOLOGY MARBLE BELT, WESTERN NORTH CAROLINA

BY

JOSEPH T. FORREST

BASED ON U.S. GEOL. SURV. SCALE 1:24,000

1/2 0 1 mile

EXPLANATION

TECTONIC SYMBOLS

Strike and Dip of Foliation
bedding
SECTION OF THE
WETL
CAROLINA

SYMBOLS

Dip of Foliations:
STRATIGRAPHIC SYMBOLS

Formation contacts

mbf  Mineral Bluff Formation

nq  Nottely Quartzite

as  Andrews Schist

mm  Murphy Marble

brf  Brasstown Formation

tq  Tusquitee Quartzite

ns  Nantahala State

gsg  Great Smoky Group
TECTORIC SYMBOLS

Strike and Dip of Foliations:
bedding \(40^\circ\)
vertical bedding \(90^\circ\)
\(F_2\) schistosity \(19^\circ\)
foliation of unknown origin \(25^\circ\)
\(F_3\) cleavage \(30^\circ\)
\(F_3\) schistosity \(37^\circ\)
\(F_4\) cleavage \(42^\circ\)

Lineations:
Intersection of:
\(S_2\) and \(S_0\) \(20^\circ\)
\(S_3\) and \(S_0\) \(13^\circ\)
\(S_3\) and \(S_2\) \(10^\circ\)
elongate pebble axes \(9^\circ\)
minor folds \(51^\circ\)

Axial surface traces:
major \(F_1\) folds \(-F_1-F_1\)
major \(F_3\) folds \(-F_3-F_3\)
ns  Nantahala State

gsg  Great Smoky Group
Axial - top
major F₁ folds
major F₃ folds

Facing criteria:
graded bedding
cross bedding
flame structures
channels

F₁ slides

Metamorphic isograds:
staurolite

garnet
unmarked areas within biotit